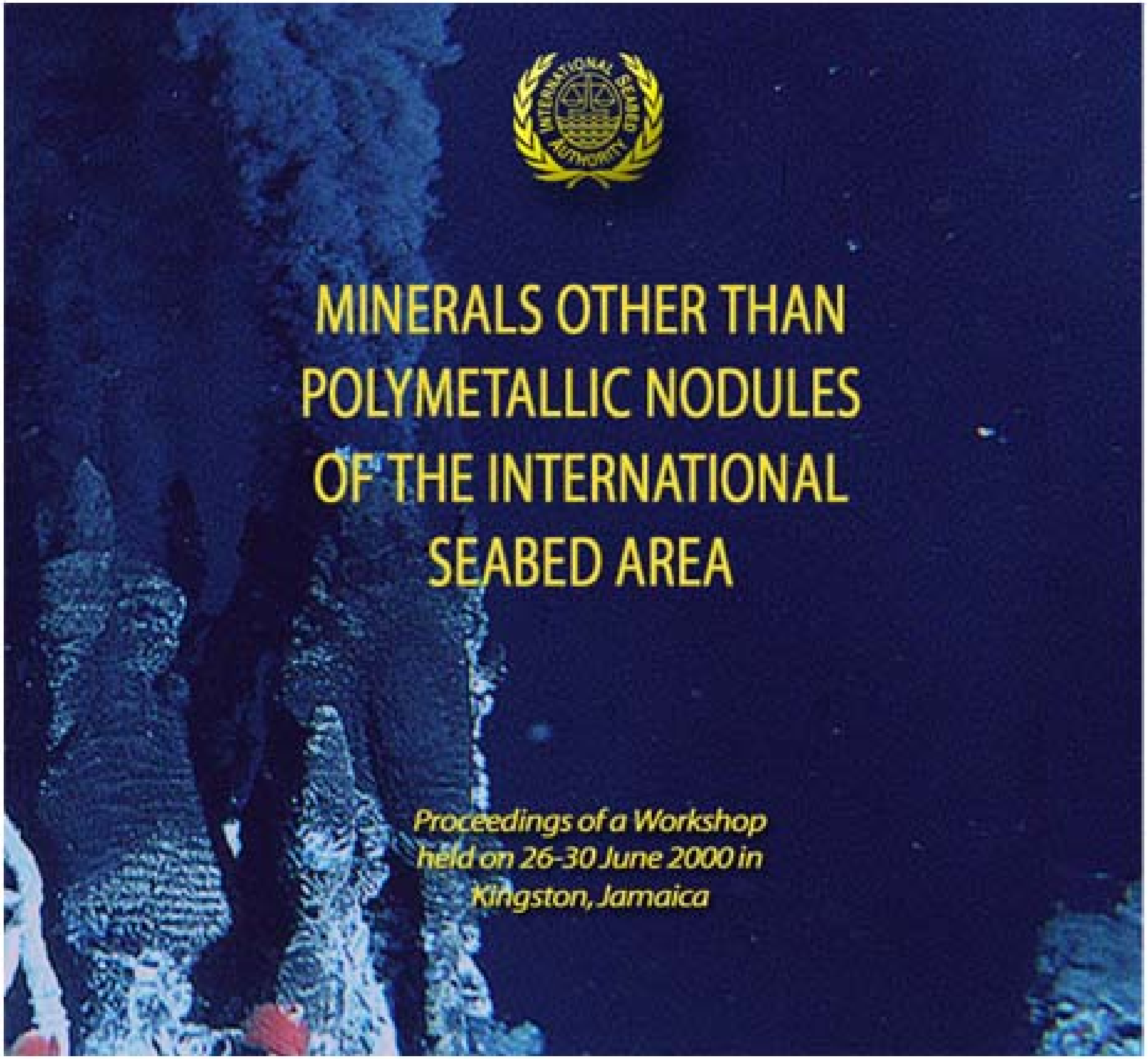
Proceedings of the International Seabed Authority Workshop held on 26-30 June 2000 in Kingston, Jamaica



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Workshop on Minerals Other than Polymetallic Nodules Of the International Seabed Area

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Minerals Other than Polymetallic Nodules of the International Seabed Area

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FOREWORD

This publication contains the proceedings of a workshop convened by the International Seabed Authority on mineral resources other than polymetallic nodules, to be found in marine areas beyond the limits of national jurisdiction (the Area). It is the third in the series of workshops that have been convened by the International Seabed Authority to inform the international community of scientific and technological developments that are taking place with regard to marine mineral resources. In 1998, at the resumed Fourth session of the Authority, the representative of the Russian Federation made a request to the Authority to adopt rules, regulations and procedures for exploration for seafloor massive polymetallic sulphides deposits and cobalt-rich manganese crusts. To prepare the Authority for work in this regard, it was decided to convene this workshop on the future development of minerals other than polymetallic nodules in the Area. It was decided at the outset that a comprehensive effort would be made to obtain information and understanding on the present knowledge base for the possible exploration and exploitation of these other resources, in particular seafloor massive polymetallic sulphides deposits and cobalt-rich ferromanganese crusts. It is recognized that while a good deal of scientific research has been accomplished, the transition from marine scientific research to prospecting and exploration for these resources, and then to their commercialisation will require a certain amount of flexibility in rule making.

To date, the work of the Authority has focused on the exploration for deep seabed polymetallic or ferromanganese nodules that are to be found in the international area. Under the parallel system prescribed for deep seabed polymetallic nodules, a prospector who seeks an exploration contract from the Authority is to submit "an application that covers a total area, which need not be a single continuous area, sufficiently large and of sufficient estimated commercial value to allow two mining operations. The application shall indicate the coordinates of the area, defining the total area and dividing it into two parts of equal estimated commercial value and shall contain all the data available to the applicant with respect to both parts of the area"[1/].

[1/] United Nations Convention on the Law of the Sea, Annex III; Resolution II, paragraph 3(a).

The Authority designates one of two areas as reserved area for exploration either by its operating arm, the Enterprise, or by the Authority in association with developing States. The other area is allocated to the applicant as a contract area.

For deep seabed polymetallic nodules that lie on and in sediment that covers the seafloor in the abyssal plains of the world's ocean, this requirement has worked and seven entities have obtained exploration contracts with the Authority under that system. Given the difference in the nature of the deposits, a fundamental question for consideration is whether the parallel system will work for seafloor massive sulphides and ferromanganese crust deposits. Would work done during prospecting be sufficient to delineate two seafloor massive polymetallic sulphides deposits or two cobalt-rich ferromanganese crust deposits of equal estimated commercial value? Should a different system be devised to meet the objective of the parallel system that was based on the principle that there should be opportunity for all to participate in the exploitation of the mineral resources in the Area?

Based on the need to provide the international community with a response to these and other related matters, the workshop was convened with the following objectives:

(a) To obtain information and understanding on marine minerals of the Area for which rules, regulations and procedures for prospecting, exploration and exploitation are yet to be adopted by the Authority, with an emphasis on seafloor polymetallic massive sulphides and ferromanganese crust deposits; and in the case of the latter two deposits,

(b) To obtain information on their distribution, the marine environment where they are found, metals of commercial interest, resource potential and developments with regard to research and exploration for these deposits.

The workshop also addressed the nature of regulatory regimes in some countries that have established marine mineral industries. This was particularly with regard to the information and data that contractors are required to submit in these different regimes.

The report on the workshop is divided into four parts. Part 1 of the proceedings provides a background to marine minerals including developments in science that have increased the international community's knowledge of these resources. It focuses on current knowledge of seafloor massive sulphides and ferromanganese crust deposits, their distribution in the oceans and in the Area, associated flora and fauna and steps to be taken to protect and conserve them from the impacts of mining, the metals of commercial interest contained in these deposits and technologies available for explore for exploration, the experiences of a company with an exploration license for seafloor massive sulphides in Papua New Guinea's exclusive economic zone that is presently engaged in raising finance for exploration, The workshop also heard a presentation on Papua New Guinea's recently enacted legislation for seafloor massive sulphides in its exclusive economic zone within the context of the exploration license that it is granted for seafloor massive sulphides. The act and some of its provisions relating to data and information are presented. Part 1 also contains a paper and presentation on current national and international programmes for the development of seafloor massive sulphides, and a comparative evaluation of the possible economic returns from mining massive sulphides, ferromanganese crusts and deep seabed polymetallic nodules.

Part 2 focuses on the Authority's task to adopt rules, regulations and procedures for prospecting and exploration for seafloor massive sulphides and cobalt-rich ferromanganese crusts in the Area. In this respect, the Secretary-General of the International Seabed Authority informed participants of issues that had to be taken into account based on the experience gained from developing similar rules, regulations, and procedures for deep seabed polymetallic nodules of the Area that was followed by discussions.

Part 3 examines prospects for the development of other marine minerals to be found in the Area (petroleum and submarine methane hydrates) and includes a statistical evaluation of the resource potential of placer deposits, phosphorites, evaporates, seafloor massive sulphides, polymetallic nodules, cobalt-rich ferromanganese crusts, hydrocarbon deposits and gas hydrates of the continental shelf beyond the 200-mile limit of the world's margins. This part also contains case studies on the development of the Namibian offshore diamond industry and of an environmental baseline that was established to help protect important fisheries that are associated with the Benguela Current.

Part 4 focuses on regulatory and promotional frameworks in countries that have established profitable marine mining industries. It begins with a status report of the data and information requirements of Namibia's legislation with respect to offshore diamond exploration and mining, followed by the information and data that are required of contractors operating in marine areas in Norway, Brazil and Indonesia, in respect of offshore hydrocarbons and natural gas, and the role of SOPAC in promoting exploration for marine mineral resources in the Pacific region.

During the five days of the workshop, 21 formal presentations that included slides and videos were made and a great deal of valuable discussions and interaction took place among the participants. Slides and videos during the workshop demonstrated state-of-the-art technologies that could be applied to exploration for seafloor massive sulphides deposits, the types of mineral resources to be found in the Area and the oasis of life to be found in and around seafloor polymetallic massive sulphides deposits among other things.

On behalf of the International Seabed Authority, I wish to express my gratitude to the participants in the workshop, especially the scientists for the valuable information that they provided during the workshop on the marine scientific research being undertaken that has resulted in discovery of these new and exciting mineral resources.

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EXECUTIVE SUMMARY

The workshop on mineral resources of marine areas beyond the limits of national jurisdiction ("the Area") was held in Kingston, Jamaica from 26 to 30 June 2000. This was the third in the series of workshops convened by the International Seabed Authority to address issues of concern to the international community related to the development of marine mineral resources of the international seabed Area.

At the fourth session of the Authority in 1998, the Russian Federation requested the Authority to adopt rules, regulations and procedures for prospecting and exploring seafloor massive sulphide deposits and ferromanganese crusts of the Area. It is to be recalled that up until then, the only type of marine mineral resources of the Area that have been the subject of the Authority's rule making are deep seabed polymetallic nodules. Found in the abyssal plains, a system for prospecting, exploration and exploitation of polymetallic nodules has been extensively prescribed in the body of the United Nations Convention on the Law of the Sea and its Annex III (Basic Conditions for Prospecting, Exploration and Exploitation), in the modifications made to Part XI of the Convention, and contained in "The Agreement Relating to the Implementation of Part XI of the United Nations Convention on the Law of the Sea", and in the Regulations on Prospecting and Exploration for polymetallic Nodules in the Area (ISBA/6/A/18). With regard to the request by the Russian Federation therefore, the immediate question is the applicability of the system prescribed for deep seabed polymetallic nodules to the types of mineral resources contained in the request.

Article 136 of the Convention declares the Area and its resources as the common heritage of mankind. Both deep seabed polymetallic nodules of the Area as well as seafloor massive sulphides and ferromanganese crusts of the Area are the common heritage of mankind. Under the system prescribed for deep seabed polymetallic nodules, taking into account the common heritage principle, a prospector who seeks an exploration contract from the Authority is to submit "an application that covers a total area, which need not be a single continuous area, sufficiently large and of sufficient estimated commercial value to allow two mining operations. The application shall indicate the coordinates of the area, defining the total area and dividing it into two parts of equal estimated commercial value and shall contain all the data available to the applicant with respect to both parts of the area"[1]. Within a prescribed period of time, the Authority designates one of the two areas identified for mining operations, as reserved for exploration either by its operating arm, the Enterprise, or by the Authority in association with developing States. The area containing the second of the two areas identified for mining operations is then allocated to the applicant.

Based on the need to provide the international community with a response to these and other related matters, the workshop was convened with the following objectives:

a) To obtain information and understanding on marine minerals of the Area for which rules, regulations and procedures for prospecting, exploration and exploitation are yet to be adopted by the Authority, with an emphasis on seafloor massive sulphides and ferromanganese crust deposits; and in the case of the latter two deposits,

b) To obtain information on their distribution, the marine environment where they are found, metals of commercial interest, resource potential and developments with regard to research and exploration for these deposits.

The workshop also addressed the nature of regulatory regimes in some countries that have established marine mineral industries. This was particularly with regard to the information and data that contractors are required to submit in these different regimes.

[1] United Nations Convention on the Law of the Sea, Resolution II, paragraph 3(a)

The report on the workshop is divided into four parts. Part 1 of the proceedings provides a background to marine minerals including developments in science that have increased the international community's knowledge of these resources. It focuses on current knowledge of seafloor massive sulphides and ferromanganese crust deposits, their distribution in the oceans and in the Area, associated flora and fauna and steps to be taken to protect and conserve them from the impacts of mining, the metals of commercial interest contained in these deposits and technologies available for explore for exploration, the experiences of a company with an exploration license for seafloor massive sulphides in Papua New Guinea's exclusive economic zone that is presently engaged in raising finance for exploration, The workshop also heard a presentation on Papua New Guinea's recently enacted legislation for seafloor massive sulphides in its exclusive economic zone within the context of the exploration license that it is granted for seafloor massive sulphides. The act and some of its provisions relating to data and information are presented. Part 1 also contains a paper and presentation on current national and international programmes for the development of seafloor massive sulphides, and a comparative evaluation of the possible economic returns from mining massive sulphides, ferromanganese crusts and deep seabed polymetallic nodules.

Part 2 focuses on the Authority's task to adopt rules, regulations and procedures for prospecting and exploration for seafloor massive sulphides and cobalt-rich ferromanganese crusts in the Area. In this respect, the Secretary-General of the International Seabed Authority informed participants of issues that had to be taken into account based on the experience gained from developing similar rules, regulations, and procedures for deep seabed polymetallic nodules of the Area that was followed by discussions.

Part 3 examines prospects for the development of other marine minerals to be found in the Area (petroleum and submarine methane hydrates) and includes a statistical evaluation of the resource potential of placer deposits, phosphorites, evaporates, seafloor massive sulphides, polymetallic nodules, cobalt-rich ferromanganese crusts, hydrocarbon deposits and gas hydrates of the continental shelf beyond the 200-mile limit of the world's margins. This part also contains case studies on the development of the Namibian offshore diamond industry and of an environmental baseline that was established to help protect important fisheries that are associated with the Benguela Current.

Part 4 focuses on regulatory and promotional frameworks in countries that have established profitable marine mining industries. It begins with a status report of the data and information requirements of Namibia's legislation with respect to offshore diamond exploration and mining, followed by the information and data that are required of contractors operating in marine areas in Norway, Brazil and Indonesia, in respect of offshore hydrocarbons and natural gas, and the role of SOPAC in promoting exploration for marine mineral resources in the Pacific region.

During the five days of the workshop, 21 formal presentations that included slides and videos were made and a great deal of valuable discussions and interaction took place among the 60 participants. Slides and videos during the workshop demonstrated state-of-the-art technologies that could be applied to exploration for seafloor massive sulphide deposits, the types of mineral resources to be found in the Area and the oasis of life to be found in and around massive sulphide deposits among other things. A video of the presentations and discussions during the workshop has also been produced.

1. Metallogenesis of marine mineral resources

In a presentation encompassing a wide-range of topics on the marine minerals industry, Professor Peter Rona of Rutgers University, USA introduced participants to, inter alia, the types of marine mineral resources that have attracted commercial interests and that are found from coastlines to the deep ocean basins, operations to recover metals in deposits of gold, tin, chromium, titanium, monazite, zircon and barium from marine placer deposits, other operations to recover diamonds, sand and gravel and phosphorites, deep seabed polymetallic nodules, and the discovery of seafloor mineralisation starting with the Atlantis II Deep in the Red Sea in the 1960s and culminating with that of seafloor massive sulphides in the late 1970s.

Professor Rona pointed to the significant impact of the theory of plate tectonics for increasing our knowledge about marine mineral resources, particularly with regard to deposits that have been found in the deep ocean basins and in the Area. Prior to this theory, he indicated that ocean basins were viewed as big bathtubs or passive containers. Marine metal and non-metal, non-fuel mineral deposits were considered to be primarily derived from erosion of continental rocks and carried into the sea by rivers in solid (sediment) or dissolved phases. Such a view adequately explained the marine minerals known at that time. Knowledge of such deposits comprising beach and placer deposits of heavy minerals containing metals and non-metals of terrigeneous origin, eroded from continental rocks and transported to the oceans primarily by rivers, and polymetallic nodules and other authigenic deposits that were thought to have firmed from dissolved chemicals that were transported by rivers to the ocean.

The theory of plate tectonics shifted emphasis away from the continents as the sole source of material for marine minerals. Professor Rona explained that according to this theory, the earth's outermost layer, the lithosphere, which is about 100km thick, is segmented into some ten major plates and numerous minor plates. The boundaries between plates are delineated by earthquakes produced by motions between plates and mostly lie beneath the ocean. In particular, divergent plate boundaries where plates are separating are manifested as a submerged volcanic range that extends more or less continuously through the world's ocean basin. This submerged volcanic mountain range, the largest geographic on earth as stated by Professor Rona, is know as the Mid-Ocean Ridge, extends for approximately 60,000 km, and is the location of significant hydrothermal activity. Molten rocks or magma up well from the earth's interior beneath the submerged mountain range, cooling, congealing and constructing the lithosphere which spreads apart to either side of the submerged mountain, forming two diverging conveyor belts of new lithosphere at a rate of centimetres per year.

Metallogenesis of marine minerals is now viewed as the product of both continental sources of metals external to the ocean and sources at submerged plate boundaries internal to the ocean, he stated.

With regard to marine mineral resources, Professor Rona started his presentation discussing placer deposits that are ore deposits mechanically eroded from source rocks on the continent and then deposited in sediments on the continental margin. He stated that the present knowledge of these resources is confined to the most accessible, or those that are exposed on or near the sea floor; although there could be deposits deeply buried as well within the sediments of the continental margin.

Professor Rona informed the workshop that numerous sites exist on continental shelves around the world where heavy minerals containing metals and non-metals are concentrated, but of these only a small number are or have actually been mined. These materials are eroded from rocks exposed on land and are transported by rivers to the ocean where they are concentrated by waves, tides and currents as placer deposits. With reference to metals, the outstanding resource is tin that is dredged from shallow water (water depth less than 30 metres) at several sites offshore Thailand (Thai Muang; Tongkah Harbour, Takua Pa), Indonesia (Copat Kelabat Bay, Laut Tempilang; Belitung), and Myanmar (Heinze Basin) where tin minerals (cassiterite) were derived by erosion and transportation from continental granites. Gold-bearing sands and gravels have been intermittently (depending on the price) dredged from shallow water (water depth less than 15 metres) at several sites offshore Alaska (Nome, Bluff Solomon) and New Zealand (Gillespie's Beach). Titanium (which is to be found in the minerals limonite and rutile), zirconium (in zircon), Rare Earth Elements (monazite), and the radioactive element thorium (monazite) have been recovered at several shallow water (water depth less than 5 m) sites offshore South Africa, Madagascar, and India. Chromium (to be found in the mineral chromite) is recovered at a site offshore Central Sulawesi island, Indonesia, and barium at a site offshore Alaska.

With reference to non-metals, Professor Rona noted that a viable industry has developed exploring for and dredging diamond-bearing gravels offshore Namibia (Chameis Bay) and South Africa (Groen River, Broadacres, Casuarina Prospect) in shallow water (exploration water depth to 400 metres; dredging water depth to 140 metres). The most widely recovered marine mineral he however stated is sand and gravel dredged from beaches and shallow offshore bars at numerous sites worldwide for use in construction materials (concrete) and to replenish beaches. Freshwater is a marine mineral resource critical to life and which may be extracted from seawater by various desalination processes and exists in solid form in the ice sheets of Antarctica and Greenland. Although desalination, which is an energy intensive process, is mainly being used in the oil-based economies of Middle Eastern maritime states, desalination plants are spreading to other parts of the world. The element phosphorous is also critical to agriculture and occurs where it has precipitated from deep seawater as the mineral phosphorite at present and past locations of up welling along sections of continental shelves primarily within the trade wind belts (0 to 30 degrees North and South latitude). All phosphorite is presently mined from land deposits precipitated during higher stands of sea level in the geological past, but extensive deposits exist on continental shelves of agriculture-intensive countries like India. He demonstrated that for metals and non-metals, there are fewer than 20 sites that have been or are operational in terms of marine mining.

In terms of seafloor mineralisation, he mentioned that the first discovery was in the Red Sea when in the course of a transit during the International Indian Ocean Expedition in the 1960s, echo sounders got reflections from layers within the water column that were totally anomalous. Usually, he remarked, the reflections come back from the seafloor. When sampling, it was found that the reflectors were layers of highly salty metal and rich water at certain places along the axis of the Red Sea. The Red Sea it turns out is a part of a plate boundary where the seafloor is spreading is, i.e., moving Saudi Arabia and Africa further apart. Along its axis, hot rocks are welling up from the earth's interior in this submerged plate boundary. The mineral deposits that are to be found in certain basins along it, came about as a result of the interaction of the hot metal enriched volcanic rocks up welling at the plate boundary, the restricted circulation of seawater that led to the deposition/precipitation of thick layers of rock salt in the basins, and down welling of cold, heavy seawater through the volcanic rocks and rock salt, forming a metal brine that is both saltier and richer in metals. While there are several deep basins are to be found in the Red Sea, the Atlantis II Deep, just west of Mecca is the largest seafloor hot spring deposit known on earth and is particularly enriched in zinc and is also known to contain silver and gold. Professor Rona noted that this process was extremely efficient for concentrating metals since the metals precipitate as particles that collect at the seafloor, and form the metalliferous sediments of the Red Sea. The latest estimate of the size of this deposit is 94 million tonnes dry weight with about 2 per cent zinc. Since this deposit is to be found within the 200 n-mile zone of Saudi Arabia and Sudan, they undertook a joint survey of this deposit in 1979 with the German firm Preussag. As part of this study, a mining test using an adapted offshore oil-drilling vessel was conducted. The test showed that it while it was feasible to mine these deposits; mining would not yield the required returns. The discovery of these deposits did not however, trigger an interest in marine mineral resources because it was thought to be an exceptional case related to an early stage of rifting with the special layers of salt, which were very efficient at transporting metals.

In 1978, a French/Mexican/American expedition made a transit across a portion of the submerged volcanic mountain range called the East Pacific Rise, off Mexico just south of the Gulf of California. A standard geological transit was planned. The water depth is about 2,000 metres and the transit was across the submerged volcanic mountain range. In the course of the transit, mounds up to about 10 metres high and very different from the normal volcanic rocks of the deep sea floor were encountered. Scientists at IFREMER in France found the samples to be sulphide rocks, and thus the first discovery of massive sulphides in the deep ocean basin was made. Many scientific discoveries were made this way by chance, serendipity, he said.

The following year (1979), the American submersible "Alvin", made a dive at the same location. The implication of seafloor polymetallic massive sulphides deposits was that they are deposited from very hot, hot springs but nothing was identified during the dives in 1978 to support this supposition. During the Alvin survey, a chimney that was several metres high, billowing clouds of black smoke was discovered. The name "Black Smoker" has since been used to describe this phenomenon. The smoke was made up of mineral particles. While it was not possible to take temperature measurements or samples on this cruise due to the heat that melted the plastic windows on the submersible, newer heat tolerant instruments were used later. Temperatures were found to be nearly 400 degrees Celsius, and while temperature measurements were being taken, it was found that these structures were mineralised chimneys deposited from the hot springs that flowed up through them. The cavities inside the chimneys were lined with bright crystals of sulphides of iron and copper. The chimneys grew up to tens of metres high, and then simply collapsed and toppled over, accumulating these massive sulphides deposits around their base.

Another unexpected surprise was the discovery of a dense and spectacular biological community at 2000 metres depth, under pitch darkness. An oasis of life was found with new forms of life such as the giant tubeworms, which grow about as high as a person and grew in a shell-like casing made of the same material as our fingernails. Many new features to this body were found in the cracks between the lava flows. There were clams growing to exceptionally large sizes in an environment where the hot spring discharges were enriched in hydrogen sulphide. As a result of a high level of haemoglobin in their blood to extract oxygen from this toxic environment these clams have become adapted to the environment. Research on these animals will help in the studies of survival in toxic environments, he said.

With regard to support for this ecosystem, Professor Rona explained that bacterial material was blowing out and accumulating like a snowfall over the sea floor in these hot spring areas. It has now been found out that these bacteria are using chemicals, particularly the hydrogen sulphide that is dissolved in the hot springs from the underlying rocks, as an energy source to grab carbon, hydrogen and oxygen from the surrounding water and combine them into carbohydrate, sugar and starches to sustain themselves and the higher forms that live on the bacteria such as the tube worms. Thus it was not only just an oasis of life on the deep sea floor, but also an oasis of life that is distinct from the life on the surface of land, which is dependent on the energy from the sun with green plants using that energy to manufacture their food at the base of the food chain.

Professor Rona also explained through slides that some white spots growing like flowers on the sea floor in these hot spring areas are nourished by bacteria growing in warm water coming up through cracks. During the dive, dome shaped chimneys several metres high were encountered, discharging blue-white smoke. These were named " white smokers". The area in which they were found was dubbed as the 'Kremlin Area' because they reminded the scientists of the domes on the Old Russian churches. Higher temperature discharges were also encountered and at the very edge of a cluster of black smokers at the very top of a particular mound, a mass of white material could be seen. Professor Rona further went on to explain that black smokers discharge very turbulently, engulf surrounding cold water which is near freezing, with the result that temperature drops very rapidly. Within a metre or metres of these black smokers, the temperature is again very close to the ambient temperature. Temperature measurements showed that the heat output here was about the same heat output from one of a complex of black smokers. These are therefore also geothermal resources in addition to mineral resources, Professor Rona pointed out.

Hot springs have been found along the axis of the East Pacific rise where the hot material is welling up at a relatively fast spreading rate. Professor Rona stated that the East Pacific rise is part of the Pacific Ocean basin that is referred to as the "Ring of Fire" because it is the most volcanically active region of the earth. He informed participants that it was initially thought that hot springs would only occur in the Pacific because of the high levels of volcanic activity as compared with other parts of the world oceans where there is less volcanic activity such as the Atlantic and the Indian Oceans. Professor recalled an expedition that he led to the submerged volcanic mountain range between North America and North West Africa in search of hot springs, based on clues derived from activity in the submerged volcanic range near the island of Iceland. The expedition confirmed the presence of hot springs in the Atlantic, and gave birth to the term "Geyser" or a hot spring in which water intermittently boils, sending a tall column of water into the air, based on the clues for these springs in the Atlantic that were obtained from Geysir, in Iceland.

At the base of the toppled chimneys, a study of the material in the oxidation ring of this rubble was made. It was found that most of the material is sulphide minerals that have been oxidized, but an extremely tiny bright spot, no more than a pin head, was also discovered. That bright spot was a grain of pure gold, and indeed the first grain of pure gold that was found at one of these deposits in the deep ocean basin. The significance of this finding was that prior to this discovery though gold was known to be associated with massive sulphides, it was thought to be concentrated after the deposits were uplifted onto land by water processes. This discovery showed for the first time that gold was concentrated in these deposits on the deep sea floor.

Professor Rona stated that divergent plate boundaries with the potential for the occurrence of massive sulphides deposits lie primarily in the international seabed area with exceptions mostly in the volcanic island chains of the western Pacific. The volcanic island chains form at convergent plate boundaries where the lithosphere bends down and descends into the Earth's interior where it is destroyed to counterbalance the creation of lithosphere at divergent plate boundaries. The components of seafloor hydrothermal systems consisting of hot rocks at depth beneath the seafloor as a heat source, seawater as the circulating fluid, and permeable pathways through volcanic rocks that contain metals are present at discrete sites on two sides of these volcanic island chains. The settings favourable for the formation of massive sulphide deposits and associated manganese deposits on the two sides of the volcanic island chains are the calderas (collapsed centres) of seafloor volcanoes and seafloor spreading centres in the back arc basins. These seafloor-spreading centres are similar to, but generally smaller scale than, the submerged volcanic mountain range at divergent plate boundaries. Examples of these settings at the front and back sides of volcanic island chains are, the Sunrise deposit in the calderas of an active seafloor volcano in the fore-arc side of the Isu-Ogasawara Arc south of Japan and the PACMANUS hydrothermal field in the Manus back-arc basin on the north side of Papua New Guinea, respectively. A characteristic of these mineralised seafloor sites in the western Pacific is that they lie not only within the 200 nautical mile zone of adjacent coastal states but, in certain cases, lie in overlapping 200 nautical mile zones.

Professor Rona pointed out that there was also another type of hydrothermal deposit in the deep ocean which is less known. These deposits are found where lower temperature solutions discharge within kilometres of higher temperature fields. These lower temperature solutions deposit a very pure manganese deposit i.e., a manganese crust. The deposits contain over fifty percent manganese.

Going from the deep ocean basins to the types of deposits that have a double source, that is the continents on the one hand and the deep ocean basin on the other hand, Professor Rona explained that before plate tectonics all the manganese in marine mineral deposits was thought to be supplied by manganese dissolved from continental rocks and carried into the ocean by rivers. While this may have been provided an adequate explanation for the composition of polymetallic nodules, the hot springs are a second source of the metals in polymetallic nodules. It has been found that the composition of nodules in terms of these metals - cobalt, nickel, iron and manganese varies in different parts of the oceans, in relation to their proximity to hot springs and other factors. The Clarion-Clipperton zone has highest enrichment in the eastern equatorial Pacific. Then going out from here, the manganese nodules in the deep abyssal plains of the ocean basins, there are manganese crusts that accumulate on bare rock volcanic surfaces both on the submerged volcanic mountain range and on sea mounds and these are the cobalt rich ferro-manganese crusts. These accumulate in water depths roughly between 400 and 4000 metres, and accumulate to thickness up to some tens of centimetres.

With regard to seafloor polymetallic massive sulphides, Professor Rona pointed out that unlike polymetallic nodules that occurred as a layered deposit, seafloor polymetallic nodules were three-dimensional deposits with a depth element that had to be taken into account in resource assessment. The next step now was to determine the third dimension, the sub sea floor. This was done in 1994 with an offshore oil drilling ship modified for drilling in the deep ocean, called the Joides Resolution. A consortium of 20 countries working together on the ocean drilling programme supported the programme. The drilling established that that it takes thousands to tens of thousands of years to form a sizable massive sulphide deposit. Massive sulphide deposits are not renewable resources. It has been contended that active seafloor massive sulphides are renewable resources that will regenerate by precipitation from hot springs almost as quickly as the sulphides are removed. This may be true only for individual active mineralised chimneys that have been observed to regenerate within days to years after removal. The drilling also gave geologists an opportunity to observe volcanogenic massive sulphide (VMS) deposits in process of formation. Hitherto VMS deposits were mined in land for centuries for iron, copper, zinc, silver and gold without understanding how they were formed.

Lastly, Professor Rona touched upon the environmental considerations and the huge marine biodiversity teeming with millions of species. Investigations revealed that new species are found in every square metre of sediments sampled. Sediments look barren but it is actually full of life. With reference to the deep sea hot springs themselves, every hydrothermal field examined to date has some species that are not found in any other field. Marine organisms and microbes are associated with marine mineral deposits in all regions of the ocean. These are vital environmental considerations in exploration and mining, because of their value for preserving biodiversity, understanding evolution, and manufacturing useful products, he stated

Seafloor massive sulphides deposits and ferromanganese crust deposits of the Area – Distribution, resource potential, environmental impact and regulatory regime.

2. Seafloor massive sulphides deposits and their resource potential.

Professor Peter Herzig started his presentation on polymetallic massive sulphide deposits on the modern seafloor and their resource potential by stating that the discovery of high-temperature black smokers, massive sulphides, and vent biota at the crest of the East Pacific Rise at 21°N in 1979 confirmed that the formation of new oceanic crust through seafloor spreading is intimately associated with the generation of metallic mineral deposits at the seafloor.

Following the discovery of black smokers at the East Pacific Rise, Professor Herzig noted that there was a rapid growth in the number of hydrothermal deposits found on fast-spreading mid-ocean ridges. So many deposits were found along fast-spreading segments of the East Pacific Rise, and virtually nowhere else, that it became widely accepted that slower-spreading ridges could not support productive hydrothermal activity. However, in 1985, the discovery of black smokers in the large TAG hydrothermal field at the Mid-Atlantic Ridge offered compelling evidence that slow-spreading ridges may also be important settings for sulphide deposits. He further noted that slow-spreading ridges as important settings for sulphides deposits had been confirmed by the discovery of a number of large massive sulphides occurrences along the mid-Atlantic Ridge (Logatchev, Snakepit, Broken Spur, Lucky Strike, Menez Gwen) and the Central Indian Ridge (Sonne Field). Shortly after the discovery at the East Pacific rise, large sulphide deposits were also discovered in sediment-filled basins in the Gulf of California (Guaymas Basin). The Ocean Drilling Programme intersected about 100m of massive sulphides in the large Middle Valley deposit on the Juan de Fuca Ridge, offshore Canada.

Professor Herzig stressed however that the majority of known sites are located at the East Pacific Rise, the Southeast Pacific Rise, and the Northeast Pacific Rise, mainly because the first discovery of an active high-temperature hydrothermal system was made at the East Pacific Rise off shore Baja, California. Only one site has so far been located at the ridge system of the Indian Ocean, close to the Rodriguez Triple Junction. Regarding the present state of knowledge of sulphides deposits on the mid-Atlantic Ridge and in the Indian Ocean, Professor Herzig remarked that this is a function of limited prospecting activity in these areas. He concluded this part of his presentation by stating that only about 5% of the 60,000 km global oceanic ridge system have been surveyed and investigated in some detail.

Next, Professor Herzig turned to the processes taking place at the hot springs. He stated that at oceanic spreading centres, seawater penetrates deeply into the newly formed oceanic crust along cracks and fissures, which are a response to thermal contraction and seismic events typical for zones of active seafloor spreading. The seawater circulating through the oceanic crust at seafloor spreading centres is converted into an ore-forming hydrothermal fluid in a reaction zone, which is situated close to the top of a sub axial magma chamber. Major physical and chemical changes in the circulating seawater include (i) increasing temperature, (ii) decreasing pH, and (iii) decreasing Eh.

He pointed out that sulphide mineralisation at back-arc spreading centres has some mineralogical characteristics that are similar to hydrothermal precipitates at volcanic-dominated mid-ocean ridges. Commonly, pyrite and sphalerite are the dominant sulphides. Chalcopyrite is common in the higher temperature assemblages, but pyrrhotite is rare. Barite and amorphous silica are the most abundant non-sulphides. A variety of minor and trace minerals such as galena, tennantite, tetrahedrite, cinnabar, realgar, orpiment, and complex, non-stoichiometric Pb-As-Sb sulfosalts characterize many of the deposits forming in back-arc rifts. The first examples of visible primary gold in seafloor sulphides were documented in samples of lower temperature (>300^{o}C) white smoker chimneys from the southern Lau Basin and occur as coarse-grained (18 microns) co-depositional inclusions in massive Fe-poor sphalerite.

As regards metal content, Professor Herzig observed that despite the moderate tonnages reported for several seafloor deposits, the samples that had been recovered were obtained from only about 50 deposits, lacked information about the depth of the deposits and represented no more than a few hundred tonnes of material. Based on existing data and lacking information on the third dimension, he stated that it was premature to comment on the economic significance of seafloor massive sulphides deposits. Analyses of sulphides samples have indicated that these deposits may contain important concentrations of metals that are comparable to those found in ores from massive sulphide mines (volcanogenic massive sulphides deposits (VMS)) on land. He noted that the estimated concentrations of base metals in seafloor massive sulphides tend to be higher than land-based sulphides deposits, partly because of a strong bias in sampling. He explained that a large number of seafloor sulphides are recovered during submersible operations. A bias in the analytical data arises because sulphide chimneys which are relatively easy to sample are often the focus of the study. However, they are unlikely to be representative of the bulk composition of the deposits as a whole (e.g. 11 analysed samples from the Southern Juan de Fuca site have an average Zn content of greater than 34 % by weight) and little is known about the interiors of larger sulphides mounds and the underlying stock work zones.

Professor Herzig stated that systematic sampling of both high- and low-temperature assemblages across the surfaces of some large active areas (e.g. the TAG hydrothermal field, the Explorer Ridge and the Galapagos Rift) provides information that is more representative of the range of sulphides precipitates which comprise large deposits. Sufficient sampling to obtain realistic estimates of metal concentrations has been conducted at only a few sites (e.g. Middle Valley, the Explorer Ridge and the Galapagos Rift) while quantitative assessment of contained metals has been possible only for the Atlantis II Deep in the Red Sea. He also stated that adequate information about the continuity of base and precious metal concentrations in the interiors of the deposits could only be obtained by drilling, as has been successfully demonstrated at the TAG mound (Ocean Drilling Programme Leg 158) and the Middle Valley site (Ocean Drilling Program Leg 139, Ocean Drilling Programme Leg 169).

While noting that the continuity of seafloor sulphide outcrops are difficult to determine, and that the depth of possible mineralisation is difficult to assess, Professor Herzig stated that estimates for several deposits on the mid-ocean ridges range between 1-100 million tonnes. He also stated that the largest deposits are found on failed and heavily sedimented but still hydrothermally active oceanic ridges. He reiterated the importance of drilling for resource estimation, informing the workshop that drilling carried out by the Ocean Drilling Programme during Legs 139 and 169 at the sediment-covered Middle Valley deposit on the northern Juan de Fuca Ridge has delineated about 8-9 million tonnes of sulphide ore. He further informed participants that during both legs of the drilling programme, about 100 m of massive sulphides and 100 m of stock work were drilled at the Bent Hill site. At this site, he stated that the results of the drilling programme indicate that the sub seafloor stock work zone is underlain by a stratified Cu-rich horizon ("deep copper zone") with copper grades ranging up to 17 %.

With regard to the known sizes of seafloor sulphides deposits and compared to their counterparts on land (VMS), Professor Herzig made the following observations:

> The TAG hydrothermal mound located at 3,650 meter water depth at the Mid-Atlantic Ridge 26°N was drilled during Ocean Drilling Programme Leg 158 in 1994 to a total depth of 125 m. It was estimated that the active TAG mound contains about 2.7 million tonnes of sulphides ore above the seafloor and approximately 1.2 million tonnes of sulphides in the sub seafloor stock work.
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> A comparison of the size of seafloor sulphides deposits with some of the ancient ore bodies and ore districts on land indicates that extremely large deposits such as Kidd Creed in Canada (135 million tonnes) or Neves Corvo in Portugal (262 million tonnes) are yet to be discovered at the seafloor.

Among the known marine sulphides deposits, Professor Herzig stated that the largest known marine sulphide deposit is the Atlantis II Deep in the Red Sea, which was discovered more than ten years before the first black smoker at the East Pacific Rise. The Atlantis II Deep mineralisation he further stated, consists of metalliferous muds, instead of massive sulphides. This difference, he stated, is a consequence of the high salinity that hydrothermal fluids acquire by circulation through thick miocene evaporites at the flanks of the Red Sea rift. He reported that detailed evaluation of the 40 square kilometre deposit has delineated 94 million tonnes of dry ore with metal grades of 2.0% Zinc, 0.5% Copper, 39 ppm silver, and 0.5 ppm gold which results in a total precious metal content of roughly 4,000 tonnes of silver and 50 tonnes of gold. As previously stated by Professor Rona, Professor Herzig informed the workshop that a pilot mining test of the metalliferous muds in the Atlantis II Deep, at a depth of 2,000 m, has shown that this deposit can be successfully mined.

With regard to the precious metal content of seafloor massive sulphides, Professor Herzig noted that high gold grades have been found in a number of seafloor deposits at the mid-ocean ridges, in particular in samples from the back-arc spreading centres. He stated that the average gold content of deposits at the mid-ocean ridges range from 0.2 ppm gold up to 2.6 ppm gold, with an overall average of 1.2 ppm gold. In volcanic-dominated, sediment-free deposits, high-temperature (350°C) black smoker chimneys composed of copper and iron sulphides typically contain less than 0.2 ppm gold. Here, much of the gold is lost to a diffuse hydrothermal plume. He further noted that higher concentrations of primary gold have been found in lower-temperature (<300°C), sphalerite-dominated assemblages with sulfosalts and late-stage barite and amorphous silica. Examples that he gave included the Axial Seamount (6.7 ppm gold) and the Snakepit site (10.7 ppm gold). He stated that comprehensive sampling of a few large, mature deposits at sediment-free ridges in the northeast Pacific and mid-Atlantic oceans indicates typical average gold content of deposits in the range of 1-2 ppm gold. He also stated that local enrichment of more than 40 ppm gold at the TAG hydrothermal field is a consequence of remobilisation and reconcentration (hydrothermal reworking) of gold during sustained venting of hydrothermal fluids through the sulphides mounds (i.e. zone refining).

Professor Herzig stated that the seafloor deposit with the highest grade of gold that has been found is located at Conical Seamount in the territorial waters of Papua New Guinea close to Lihir Island. Gold grades from samples collected from the summit plateau of this seamount (2.8 km basal diameter at 1,600 m water depth) range up to 230 ppm gold, with an average of 26 ppm gold, for the 40 samples analysed.

On likely deposits that may attract contractors for exploration and mining, Professor Herzig stated that of the more than 100 sites of hydrothermal mineralisation currently known at the modern seafloor, only about 10 deposits may have sufficient size and grade to be considered for future mining, although information on the thickness of most of these deposits unknown. He identified these potential mine sites as the Atlantis II Deep in the Red Sea, the sites at Middle Valley, the Explorer Ridge, the Galapagos Rift, and the East Pacific Rise at 13°N in the Pacific Ocean, the TAG hydrothermal field in the Atlantic Ocean; as well as the Manus Basin, the Lau Basin, the Okinawa Trough, and the North Fiji Basin in the western and south-western Pacific ocean. He noted that all of these potential mine sites, except for the sites at the East Pacific Rise at 13°N and TAG hydrothermal field, are located in the exclusive economic zones of coastal states (Saudi Arabia, Sudan, Canada, Ecuador, Papua New Guinea, Tonga, Japan, and Fiji).

With respect to the future development of seafloor massive sulphides, Professor Herzig stated that if drilling proves that high-grade gold mineralisation is widespread and abundant, Conical Seamount would become the first marine gold deposit to be mined. In addition to the high concentrations of gold in this deposit, Professor Herzig pointed to the advantages of this site, such as its occurrence at comparatively shallow depth (1,050 m), its location within the territorial zone of Papua New Guinea, the fact that it is inactive (no disturbance of fauna) and almost sediment-free (no plume development due to mining activities), and that a processing plant is available on Lihir which is only 25km away. He suggested that such an event would have significant impact on the future development of seafloor mining for base and precious metals. Considering all circumstances, he concluded that seafloor polymetallic massive sulphides mining is likely to take place in the current decade. In this regard, he reminded participants that the offshore oil industry was launched only about 35 years ago, and there is no doubt in his mind that this has been a very successful endeavour.

3. Regional and local variability in the spatial distribution of cobalt-rich ferromanganese crusts in the world's ocean

Dr. Yubko's presentation was on the regional and local variability in the spatial distribution of cobalt-rich ferromanganese crusts in the world's Oceans. At the outset he mentioned that the study of cobalt-rich ferromanganese crusts has reached a stage that justifies addressing the issue from the point of view of exploration and subsequently exploitation. Dr. Yubko stated that after research initiated in the 1970s, a number of scientific and commercial companies from France, Germany, Japan, Russia and the United States had been engaged in active research.

He informed the workshop that the first Russian study was carried out on separate guyots of the Marcus-Neccer of the Central Pacific Ridge in 1968 and 1970 using the research vessel Vitiaz. He explained that ever since, a number of cruises have been carried out and valuable data including published data are available. He pointed out that the information in the Russian database has been incorporated in different kinds of maps- namely, bathymetric, geological and the metallogenic. He explained that a typical ferromanganese crusts ore field might have dimensions of 120 km to 80 km at the base with depth intervals of 1300m to 1500m. He pointed out that the guyot, where the Russian study was conducted, an associated structure whose base is at a depth of 3,000 m has complicated this particular ore field. The average slopes have a dip range of 20° to 30°. He also explained that the parameters for making a commercial decision about the ore field were controlled by the thickness, structure and composition of the crusts.

4. Hydrothermal sulphide mineralisation of the Atlantic – Results of Russian investigations, 1985-2000

The results of Russian investigations on hydrothermal sulphide mineralization in the Atlantic were presented in a paper prepared by Dr. Cherkashev. In his paper, Dr. Cherkasev states that fourteen (14) hydrothermal fields were studied by the Russian Federation in the Pacific and Atlantic Oceans using the submersibles Pisces and Mir. Studies were conducted at the Rainbow, Lucky Strike and Logachev hydrothermal fields. He informed the workshop that investigations of the Mid-Atlantic Ridge which were started in1985 are still in progress. The work has resulted in the discovery of the new hydrothermal sulphide fields, Logachev–1 and Logachev–2.

5. Cobalt-rich ferromanganese crusts: Global distribution,composition, origin and research activities

Dr James R. Hein, Senior Geologist at the United States Geological Survey made a presentation to the workshop on the origin, composition of and distribution of cobalt-rich ferromanganese crusts deposits in the world's oceans.

He informed the workshop that cobalt-rich ferromanganese crusts occur throughout the world's oceans on the seafloor and on the flanks and summits of seamounts, ridges, plateaus, and abyssal hills where the substrate rocks have been swept clean of sediments, at least intermittently, for millions of years. Ferromanganese crusts form at water depths of about 400 – 4,000 meters, with the thickest and most cobalt-rich crusts occurring at depths of about 800 – 2,500 meters. Formed by the precipitation of the elements of interest from cold ambient bottom waters of the oceans, crusts accumulate as pavements of mineral deposits up to 250mm thick on hard-rock surfaces to be found in the areas described above, and contain iron, manganese (generally in equal amounts), cobalt, nickel, platinum, titanium, and the rare earth elements, tellurium, thallium, phosphorus and others. Cobalt is the metal of greatest commercial interest in crusts and ranges in concentration from 0.19 to 0.74 % in various parts of the world's oceans. Nickel (1.1%) and platinum (1.9%) to be found in some crusts deposits are also of commercial interest. Compared with polymetallic nodules that are found in the abyssal plains, Dr. Hein pointed out that while elements such as iron, cobalt, platinum, lead, arsenic, bismuth, bromine, vanadium, phosphorous, calcium, titanium, strontium and the rare earth metals are more strongly enriched in crusts deposits, polymetallic nodules are more enriched in copper, nickel, zinc, lithium, aluminium, potassium and cadmium.

Dr. Hein informed participants that interest in deep-sea ferromanganese crusts deposits following their discovery during the Challenger Expeditions of 1873 – 1876 occurred during the various campaigns in the 1960s and 1970s for polymetallic nodule deposits. Although up until the

1970s ferromanganese crusts deposits were not usually distinguished from polymetallic nodule deposits, it was noted during this period that topographic highs (seamounts and ridges) in the central Pacific ocean, had deposits with the highest cobalt content in the world's oceans. Ferromanganese crusts and their economic potential began to be distinguished from polymetallic nodules as a result. Interest in these deposits accelerated as a result of political instability in three of the largest land-based producers of cobalt, namely Zaire, Zambia and Zimbabwe in the 1970s. These deposits were contemplated as alternate secure sources of cobalt.

Dr. Hein stated that the Technical University of Clausthal of Germany carried out the first systematic investigation of ferromanganese crusts in the Line Islands south of Hawaii in 1981 during a seven-month period. That cruise made breakthrough discoveries in knowledge of crust distributions and chemical relationships, including metal enrichments. Technology used included large dredges, seismic profiling, and bottom photography. Subsequent research cruises by German investigators, the United States Geological Survey (USGS) and the University of Hawaii to submarine edifices in the central Pacific Ocean further refined knowledge of crusts distribution and chemical relationships.

According to Dr. Hein, interest in ferromanganese crusts studies accelerated in the United States following the proclamation by President Reagan in 1983 of the establishment of an Exclusive Economic Zone by the United States of America. In his proclamation, President Reagan made special mention of cobalt-rich ferromanganese deposits. Research cruises after the proclamation have established that the most promising cobalt rich ferromanganese deposits are to be found within the exclusive economic zones of the Marshall Islands, Johnston Island, Line Islands and on the Blake plateau in the Atlantic Ocean.

Japan, the Russian Federation, Germany, the United Kingdom, France, Australia, New Zealand, Korea and China conducted other systematic ferromanganese crusts investigations during the 1970s, 1980s and 1990s. Dr. Hein said that the Japanese Geological Survey directed its efforts at crusts deposits in the abyssal polymetallic nodule provinces, the Japanese EEZ, and in international waters around the mid-Pacific mountain ranges. Based on 37 research cruises dedicated to ferromanganese crusts prospecting that he was aware were undertaken during 1981 and 1999, Dr. Hein estimated that approximately US $70 million had been invested in the early stages of ferromanganese crusts deposits development.

Dr. Hein informed workshop participants that at the present time, with regard to the distribution of crusts deposits, they have been found throughout the world's ocean basins: from the farthest northern parts of the Pacific Ocean, in the Atlantic Ocean, and down to the Antarctic ridge. They occur in water depths of about 400 – 4,000 meters, but more commonly at 1000 – 3000 meters. The thickest crusts occur on the summits of seamounts, in summit terraces, and in summit saddles. The most cobalt-rich crusts are found between 800 – 2,500 meters water depth, primarily because of the oxygen minimum zone (OMZ). The area of the ocean basins highest in cobalt content is the central equatorial Pacific Ocean basin. The Indian and Atlantic Oceans are not dominated by seamounts like this part of the Pacific Ocean. In addition, since these two ocean basins are much smaller than the Pacific, and are affected by huge rivers such as the Amazon, and huge deserts such as the Sahara, a lot of wind blown detritus finds its way into these ocean basins, diluting the grade of crusts. In general therefore, Dr. Hein stated that the dominant areas of crusts with high cobalt content are neither the Atlantic Ocean basin, nor the Indian Ocean basin, nor the continental margins of the Pacific Ocean, but far away in the central Pacific Ocean basin at seamounts to be found there.

With regard to biological communities that inhabit seamounts, Dr. Hein noted that very few studies have addressed seamount biological communities around crusts deposits even in the central equatorial Pacific Ocean basin. He stated that the studies that had been done concentrated on seamounts with a sediment cap and on biological communities living on (epifauna) and in (in fauna) that sediment. Fewer studies have addressed communities dwelling on the rock outcrops. Initial results indicate that seamount biological communities are relatively low density and low diversity species, because of the low oxygen content in the oxygen minimum layer. He stressed the need to understand the nature of the biological communities around these deposits so that the appropriate information can be incorporated in environmental impact information.

Dr. Hein suggested that based on the nature of ferromanganese crusts deposits, the initial stages of exploration would be to find extensive, thick, high-grade deposits. Later stages of exploration would be dedicated to identifying and mapping the precise group of mineable crusts. For continuous mapping of deposits, Dr. Hein stated that multibeam echo sounders, side-scan sonars, and single and multi-channel seismic systems would be appropriate. Sampling of deposits could be satisfactorily performed with dredges and corers. Other tasks during exploration would include bottom video photography, water column sampling, and laboratory analysis of crusts and substrate for composition and physical properties

Twelve criteria have been developed for exploration for and mining of cobalt-rich ferromanganese crusts deposits by Dr. Hein and his colleagues at the USGS. These comprise six regional and six site-specific criteria. The regional criteria are: (1) large volcanic edifices shallower than 100-1500 meters; (2) volcanic edifices older than 20 Ma; volcanic structures not capped by large atolls or reefs; (4) areas of strong and persistent bottom currents; (5) a shallow and well developed Oxygen Minimum Zone (OMZ), and (6) areas isolated from input of abundant fluvial and eolian debris. Site-specific criteria are: (1) subdued small-scale topography; (2) summit terraces, saddles and passes; (3) slope stability; (4) absence of local volcanism; (5) average cobalt content greater than 0.8%, and (6) average crust thickness greater than 40mm.

With regard to future research on deep-sea ferromanganese crusts, Dr. Hein recommended about ten subjects, including, determining the role of micro biota in the formation and growth of crusts, determining the oceanographic and geologic condition that produce very thick crusts, and continue environmental and ecological studies of seamount communities.

6. Impact of the development of seafloor massive sulphides on deep-sea hydrothermal vent ecosystems

Dr. Juniper spoke on the potential impact of the mining of polymetallic sulphides deposits on deep-sea hydrothermal vent ecosystems. He stated that hydrothermal vent science is now in its third decade of discovery. He noted that more than 100 vent sites have been documented along the 60,000 km of global mid-ocean ridge system. He pointed out that as vent sites become the focus of mineral exploration and deep-sea mining, it would become necessary to develop mitigative measures to avoid significant loss of habitat or extinction of populations. In his presentation he gave a technical overview of vent biology and ecology. Dr. Juniper stated that high animal densities and the presence of unusual species are now known to be common characteristics of deep-sea hydrothermal vents in the world's oceans, with the composition of fauna varying between sites and regions. He noted that deep-sea hydrothermal vents occupy very small areas of the seafloor and many sites contain animal species found nowhere else.

He pointed out that since the discovery of hydrothermal vent communities, several interesting questions have been raised by biologists regarding vent colonization, community survival in extreme conditions, and gene flow along the global ridge system. Dr. Juniper informed participants that the results of studies indicate that most hydrothermal vent species colonise new sites by producing larvae, that are transported by ocean currents. He stated that as gene flow is maintained through the exchange of larvae, the populations and assemblages of species would continue to resemble each other. New techniques in molecular technology are being used to study this subject.

He stated that more vent species have been discovered on the northeastern Pacific rise than on any other spreading ridge, because of a longer history of research in this area, and the area's relation with seafloor spreading. In this regard, he pointed out that the significant archetypical organisms (tubeworms) of vents in the eastern Pacific were conspicuously absent from the known vent sites in the Mid-Atlantic Ridge. He noted that seafloor eruptions provoke rapid and significant changes in the location and style of venting and said that the biological consequences of perturbation of the hydrothermal systems are considerable. He pointed out that active hydrothermal vents are extremely dynamic environments and studies of how vent communities respond to local environmental change could provide an appreciation of their capacity to recover from human perturbations.

Dr. Juniper said that global hydrothermal vent faunas are one of the most unusually adapted assemblages of organisms found in the oceans.

Occurring at extreme physical and chemical conditions, the organisms survive on chemosynthetic food sources. The fauna is therefore extremely unique. He also said that scientific studies suggest that vent communities have the ability to re-establish at severely disturbed sites as long as there are hydrothermal emissions to support microbial chemosynthesis. He noted that some large seafloor polymetallic sulphide deposits are hydrothermally inactive and provide no habitat for a specialised vent fauna. This would suggest that mining would pose little threat in such areas. He offered a word of caution however that mining would effectively eliminate the habitat formed by extinct deposits.

Of the potential mining impacts, he noted that activities are likely to be concentrated in very limited area. At these locations the extraction process will result in removal of the substratum and production of a particulate plume. Some of the organisms are likely to be killed by the mining equipment while others risk smothering by material settling from the particulate plume. The particulates could also clog hydrothermal conduits and deprive the vent communities of their vital fluid supply. Further, at sedimented hydrothermal sites, digging out the deposits would produce a more extensive plume that could completely eradicate the local vent fauna

Dr. Juniper suggested that guidelines aimed at protection of vent species would require provision for site specific issues such as whether mining will occur on active or inactive hydrothermal sites, and the geographic range of the affected vent species. He pointed out that standard environmental impact assessment criteria would also apply to hydrothermal vent species.

7. Technical requirements for exploration and for mining of seafloor massive sulphides deposits and cobalt-rich ferromanganese crusts

In a second presentation, Professor Herzig described the technical requirements for exploration and mining of seafloor massive sulphides deposits and cobalt-rich ferromanganese crusts based on a paper prepared jointly by him and Sven Petersen. Introducing the subject, Petersen stated that the first requirement would be an appropriate research vessel equipped with a multibeam ECO-sounder system to map the seafloor and produce a bathymetric map of the seafloor. A side-scan sonar system would be used to obtain information on the reflectivity of the seafloor, making it possible to distinguish false CARPS from sedimented areas, and larva flows from sedimented ponds. The information on the reflectivity of the seafloor would then be translated into a tectonic map. A deep-towed video camera system would be utilized to provide on-line observation of the seafloor. The systems would be attached to a research using with coaxial cable or fibre optic cables.

In his slide presentations, Professor Herzig illustrated the operational aspects of the systems and the deployment of various types of sediment corers and grabs. He explained that for manganese nodule exploration, a free-fall grab system was commonly deployed. For sampling sulphide sediments, Professor Herzig explained that the system has to be modified as in the case of land mining operations. He gave an overview of various research vessels and how they have operated, including the different types of equipment used for the collection of sediment cores and water samples.

He stated that drilling of seafloor polymetallic sulphide deposits is essential to obtain samples and information from the interior of hydrothermal mounds and chimney complexes. The drilling vessel JOIDES RESOLUTION operated by Ocean Drilling Programme at Texas A&M University had carried out scientific drilling at the Middle Valley sulphides deposits on the Juan de Fuca Ridge, offshore Canada during the TAG Programme. He explained that in addition to drilling vessels such as the JOIDES RESOLUTION, first generation portable seafloor drilling and coring systems are now available, jointly developed and constructed by a team from the United States of America and Australia. The performance specifications of this portable remotely operated is a maximum penetration of 100 m at an operating depth of around 2,000 m on rock core diameter of 40mm. A second drill, called the Benthic Multicoring System, has been constructed by a team from Australia and Japan and is installed on the research vessel Hakurei, Maru No. 2. This system uses conventional diamond rotary–rock and soil sampling tools. It can operate at water depths of 6,000 m. Individual cores have a diameter of 44 mm at a maximum coring depth of 20m. Professor Herzig's presentation covered a wide variety of deep sea submersibles starting from JAGO with depth capability of 400 m. to the Nautile, Mir1 and Mir2, and Shinkai which can go up to depths of 6000 to 6500 m.

His presentation also brought out the comparative advantages / drawbacks between submersibles and remotely operated vehicles (ROVs). He pointed out that ROVs could remain for a limited time at the bottom of the sea and have the advantage of far reduced cost relative to submersibles. There is also the advantage of no risk to pilots and scientists. On the other hand, in a submersible it is possible to obtain on screen video on both the ship and on land very valuable information.

On the subject of the technology for cobalt crusts, he explained that the exploration process is very similar to the process for manganese sulphide deposits. He stated that in contrast to polymetallic sulphides which mainly occur at or within volcanic rocks or sediments at oceanic rifts such as mid-ocean ridges, cobalt bearing ferromanganese crusts deposits form on the flanks of seamounts at water depths ranging from 800 m to 2,500m. They grow on substrate rocks as a result of metal precipitation from cold ambient seawater close to the oxygen minimum zone. Mining of crust fields involves efficient fragmentation of *in situ* crusts from the substrate rock to avoid dilution of metal grade. This problem is yet to be addressed successfully, he said. He pointed out that interest in ferromanganese crusts deposits is new and advanced mining equipment has not yet been developed. He also pointed out that even in respect of metallurgical processing, the focus should be on efficient recovery of not only cobalt but also platinum.

8. Financing exploration for seafloor massive sulphides deposits

Julian Malnic's presentation was concerned with the financing of seafloor massive sulphides deposits exploration. Focusing on the experience of his company, Nautilus, Malnic gave an outline of information that investors will look for and the kind of returns that they would expect. Mr. Malnic said that since exploration for seafloor massive sulphides was relatively new, there was really no good statistical models on which assumptions could be based.

Mr. Malnic recalled how in 1997 world attention was focussed on the granting of exploration licenses for the first seafloor massive sulphides deposits to Nautilus in the exclusive economic zone (EEZ) of Papua New Guinea. He also recalled that there was much publicity and the responses were encouraging. In the course of raising the finances for exploring these deposits, he explained that one of the important expectations of mining companies and investors has been that the grade of the ore should be of high order. Mining high grades means processing less rock in the case of massive sulphides. He observed that the fundamental difference between polymetallic nodules and ferromanganese crusts, and massive sulphides lies in their respective grades. He pointed out that while the earlier discoveries of polymetallic sulphides deposits during the TAG research only revealed low grades, the new class of deposits in the PACMANUS Basin have high zinc, copper and gold contents. He pointed out that a 1.1 tonne chunk of mineralization recovered by Nautilus assayed 51 percent zinc.

With respect to the technology involved, he stated that it is actually a simple extension of what is already being utilized by the oil and gas industry. In his view, the possibility of developing a massive sulphide mining system is attractive to the mining industry and there were several advantages of mining massive sulphides in comparison to terrestrial mining by virtue of the lower discovery costs, shorter development lead time, no land owner disturbances, cheaper plant and transport systems and similar factors.

9. Papua New Guinea's Mining Act for seafloor massive sulphides deposits

Dr. James Wanjik reported on data and reporting requirements for seafloor massive sulphides under Papua New Guinea's Mining Act. He stated that prospecting and exploration for massive sulphides is a new activity unlike marine scientific research. The 1992 Mining Act of Papua New Guinea was mainly intended for activities onshore. Following the ratification of the United Nations Convention on the Law of the Sea, an offshore minerals policy has been drafted but not yet finalized. He pointed out that depending on the outcome of the offshore minerals policy, the Mining Act of 1992 may be amended or new legislation for offshore minerals exploration and mining may be enacted.

Under the existing Mining Act, Mr. Wanjik explained that, no mineral exploration or mining can take place in the country without the expressed authority of the State. Licences issued under the Act cover exploration, mining lease, special mining lease, etc. The draft policy document covers mineral deposits including sand, gravel, diamonds, black sands, oil, naturally occurring hydrocarbons, polymetallic nodules, ferromanganese crusts and polymetallic sulphides deposits. Based on the application of land licensing procedures, it has been proposed that there should be five different types of tenements to be issued for offshore mining. These are Prospector's Rights, Exploration Licence, Mining Lease, Lease for Mining Purpose and Mining Easement. The Prospector's Right would normally be for three years in unrestricted areas on a non-exclusive basis. The Exploration Licence will be for an initial period of five years in an area of 1,000 sub blocks corresponding to 3,410 sq km, with exclusive rights. The pilot mining test will be a part of the Exploration Licence to test the mining technology and the system. The Mining Lease will be for a term which is negotiable, and covers an area less than the area covered by the Exploration Licence, with exclusive rights. The Lease for Mining Purposes is again an exclusive right for installation of facilities for mining purposes and is need dependent. The Mining Easement is also need dependent but with non-exclusive rights for the purpose of use the of structures like pipes, access ways, etc. Offshore mining procedures also provide for necessary environmental approvals prior to granting of exploration or mining tenements. Dr. Wanjik stated that by introducing prospector's rights as a form of license separate from exploration, the confusion between marine scientific research and exploration has somewhat been removed.

In terms of data, information and reporting requirements, Dr. Wanjik noted that the Mining Act of 1992 does not distinquish between prospecting and exploration. The reporting matters include geological mapping, geochemistry, geophysics, drilling, bulk sampling and pre-feasibility and feasibility studies. The requirements under the draft offshore minerals policy are more specific and cover the broad areas of resources, environment and technology. In respect of resources, Dr. Wanjik stated that data and information are required to ascertain the extent of the resources and for resources to be classified as mineable reserves. On environment, Dr. Wanjik informed the workshop that data and information relating to factors such as salinity, pressure, chemistry, deep-sea currents, benthic flora and fauna and their habitats are required to enable appropriate design or modification of exploration and mining technology. As regards technology, while cautioning that this matter was sensitive, he said that data and information on its innovation and development are essential.

Dr. Wanjik mentioned that practice has shown that the major difficulty confronting the Government is not so much with reporting, but is with auditing the report and the actual work undertaken during the term of the exploration licence. He pointed out that there is a deficiency at the moment in undertaking the auditing task.

10. Current national and international programmes of investigation for seafloor hydrothermal activity

In his presentation, Prof.Chris German of the Challenger Division for Seafloor Processes of Southampton Oceanography Centre described national and international programmes of investigation of seafloor hydrothermal activity. Dr. German, introducing himself also mentioned that he represents an organization called Inter Ridge, which is an international collaboration of around 20 different nations. The collaboration is mainly on an academic level to study aspects of mid-ocean ridge research. He noted that the mid-ocean ridge is one of the most difficult areas to access, and is situated in some of the most remote parts of the ridge system. He described the Mid-Ocean Ridge as a chain of mountains that run the entire length of the oceans starting from the Arctic down through the Atlantic, through the Indian Ocean and out to the Pacific Ocean. The chain, he continued, extends to around 60,000 km of an almost continuous geologic feature and is also the largest potential ecosystem in the world. He further noted that the study of the mid-ocean ridges is relatively new and not much is known about them. He described what seafloor vents are and provided information on their global distribution and significance. He also described some of the current techniques used for locating sites of hydrothermal activity.

Dr. German explained that individual high temperature vents at mid-ocean ridges might be around 10 cm in diameter at their mouth yet over time they grow and form chimneys anywhere from 1 m to 30 m tall. A typical vent field would comprise of several such chimneys spread out over an area approximately 100 m across. Throughout this area there could be a number of low-temperature vents also, emitting hot water from the seabed. Even the low temperature vents emitting around 10-30^{o}C of water, are considerably warmer than typical ocean water, which is normally around 2-3^{o}C. The significance is that in the vicinity of this warm water, a majority of vents specific biota are present.

Dr. German observed that although the mid-ocean ridge extends as a near continuous volcanic chain, it does not exhibit the same activity everywhere. He stated that one of the important features associated with the range is plate spreading, which is fastest across much of the equatorial and southern East Pacific Rise (10-20 cm per year), with intermediate spreading rates in the eastern and central Indian Ocean and extreme NE Pacific (5-7 cm per year), and much slower spreading rates throughout the Atlantic ocean (2-3 cm per year), and along the SW Indian and Arctic Ridges (less than 2 cm per year) after. Dr. German remarked that it almost took a decade of further research to locate the first "black smoker" on the slow-spreading mid-Atlantic ridge. The first seafloor hydrothermal vent was discovered along the fast spreading east Pacific Rise. He pointed out that the discovery of vents in the slow spreading ridge was initially dispensed with based on the theory that hydrothermal activity could not occur at ridges that exhibited less than certain threshold-spreading rates. At the time, he continued, hydrothermal vents have been discovered even along the SW Indian Ocean which is one of the world's slowest spreading ridges. However, he pointed out that the abundance of hydrothermal venting correlates with the spreading rate, thus hydrothermal activity is most abundant along the south eastern Pacific Rise followed by the north eastern Pacific Rise, the Juan de Fuca Ridge in the NE Pacific Ocean, and the central mid-Atlantic Ridge.

Dr. German explained that the majority of currently active hydrothermal fields are in the fast spreading ridges. He noted that it may well be that the most economically interesting concentrations of polymetallic sulphides are actually produced in fault-controlled systems along slow-spreading ridges. He theorized that as faulting can play an important role in controlling the distribution of hydrothermal venting, ridge crests, as well as fresh volcanism, there is scope for important hydrothermal circulation throughout all the world's ocean ridge systems. With respect to international ventures, he stated that the French and US research programmes would complete a preliminary evaluation of the entire mid-ocean ridge from the Bouvet triple junction in the south Atlantic to the Rodrigues triple junction in the central Indian Ocean, by Spring 2001.

He informed participants of a new international research programme that has been initiated in the Knipovich Ridge, north of Iceland and immediately south of Spitsbergen. The venture is a joint Japanese/Russian research programme with additional participation from US, UK and other European researchers. He also informed participants of an even more ambitious programme scheduled to begin in 2001, in which two icebreaker expeditions are planned using the US icebreaker, Healy and the German research vessel, Polarstern. This venture, he stated, will investigate hydrothermal venting along the Gakkel Ridge that extends north of Spitsbergen directly across the ice-covered Arctic Ocean Basin.

On techniques for locating hydrothermal activity, Dr. German stated that the most popular method is through integrated geophysical and geochemical approaches. In this method, multibeam swath bathymetric maps for navigation are essential. The optimal approach is then to deploy deep-towed side-scan sonar equipment with *in situ* real-time continuous optical backscatter sensors. These instruments would intercept particle-laden "black smokers" and when such signals are intercepted, detailed geological sidescan sonar images of the underlying seafloor can be provided. Once a hydrothermal site has been located, the evaluation of deposits as a resource potential can be initiated using a tethered or manned deep ocean vehicle. Submersibles and remotely operated vehicles can be deployed. Dr. German also pointed out that the limitation to the majority of the current investigative methods is that they focused primarily on black smoker type hydrothermal sources, the typical sulphides forming systems throughout the deep Mid-ocean Ridge of the Area. These sulphides forming systems are inefficient in terms of the generation of massive sulphides because a substantial proportion of the metallic minerals that are precipitated are not deposited, and instead are dispersed widely to the surrounding seafloor by hydrothermal plumes. He noted that while such plumes cannot be detected using in situ optical sensors, they can be detected by relying on chemical indicators of dissolved gases, notably methane.

Another scenario according to Dr. German is where hydrothermal fluids erupt from the mid-ocean ridge close to the edge of continental margins and sediment erosion and deposition completely buries the ridge axis. This would indicate extensive massive sulphide deposit activity forming at depths within the sediments, offering well-focused and accessible forms of deposits.

11. A comparison of possible economic returns from mining deep seabed polymetallic nodules, seafloor massive sulphides and cobalt-rich ferromanganese crusts

Mr. Jean-Pierre Lenoble's presentation was on a comparison of the possible economic returns from mining deep-sea polymetallic nodules, polymetallic massive sulphides and cobalt-rich ferromanganese crusts. At the outset of his presentation, he pointed out that the presentation was based on certain geological and statistical assumptions. His evaluation was also based on the research and data collected by French groups.

After a brief description of the characteristics of the deep-sea deposits and technologies that can be used for their exploitation, Mr. Lenoble made comparison of the three types of de[posits on the basis of the value of a tonne of *in situ* ore. The economics of mineral deposits, he stated, is related to the profitability of the operation. Any feasibility study will need to take into account the characteristics of the mineral deposits, suitable technology to mine it, processing technology, commodity prices and the requirements for the protection of the environment. From a miner's point of view, he stated that the resource must become a profitable reserve for economic viability. He stated that the present level of knowledge on deep-sea mineral deposits is insufficient to define reserves.

In his presentation, he noted that the comparison was between three types of resources, namely, deep-sea polymetallic nodules, cobalt-rich ferromanganese crusts deposits and polymetallic sulphides deposits. The parameters for the evaluation were two-fold; evaluation of the tonnage and metal content and secondly, the state of art of mining and processing technologies. After a brief description of the discoveries and research on the three types of resources, Dr. Lenoble referred to metal prices and trends in the metal markets from 1960 to the present, in respect of the most important metals - nickel, cobalt, manganese, copper, zinc, lead, silver and gold. He demonstrated that most prices had declined since 1980. He attributed the high cobalt prices in the 1980s to the Zaire disturbances and the increase in manganese prices after 1974 to the use of ferrosilicon manganese alloys that replaced ferromanganese alloys. He showed that since 1980 prices of lead, zinc, copper, manganese, nickel and even gold have shown a general decrease in trend while silver prices were relatively constant and cobalt prices on variable.

On technology, he stated that much work has been done for nodule deposits, and several engineering studies have been carried out for cobalt crusts. However, in respect of polymetallic sulphides, mining technology was an open question. The inhibiting parameters for exploitation he noted was that in the case of polymetallic nodules, deposit depth is around 5,000 metres as compared with 1,000 metres for cobalt crusts and around 2,500 metres for sulphides.

On the morphology of deposits, he noted that nodules deposits are a two-dimensional system, cobalt crusts is more or less a two-dimensional system but with a factor of thickness that has to be taken into account, while in the case of sulphides, it is typically a three-dimensional system. On the range of tonnage, he further noted that for nodule deposits the required size is in the range of 50 million tonnes whereas cobalt crusts would be around 10 times less and sulphides could be in the range of 8.5 to 10 times less than the required size for a nodule deposit.

In respect of the technology for lifting the nodules, Dr. Lenoble stated that the French study demonstrated that the system would be a self-propelled dredge, crawling on the seafloor with a collector that crushes the nodules and allows the material to be introduced into a long flexible hose connected to a rigid pipe. The crushed nodules would then be lifted to the semi-submersible surface platform, in rigid steel pipes by airlifts or hydraulic lifts. Pumping them through a flexible hose would carry out the transfer of the nodules from the platform to the ore carrier. In respect of cobalt crusts, mining would be by some similar kind of dredge cutter modified in such a way that the first layer of the crust could be scraped out. The lifting could be by a hydraulic system.

As regard sulphides, the technology is open although leaching methods are being contemplated.

Dr. Lenoble mentioned that the assumptions for comparative value were based on the French research programme in respect of polymetallic nodules in the Clarion-Clipperton Zone. In respect of cobalt-rich crusts, the study was based on deposits on the Niau atoll. (Tuamotu). In respect of massive sulphides, he mentioned that there was absence of credible information and the calculations were based on two sets of values; namely, the arithmetic mean of metal contents from different sulphides deposits and secondly, on the data available from the PACMANUS deposits in the Papua New Guinea. His conclusions were as follows:

The mean values of *in situ* ores are very similar except in respect of the sulphides. The cost of mining and processing will make a difference. The cobalt crust could be mined at 1,000 metres, the massive sulphides at 2,500 metres and the nodules at 5,000 metres. However, the costs were not directly proportional to the depths and the scale effect could be in favour of nodule mining that can envisage a higher annual capacity than the other two. Energy consumption would be more important for scraping and excavating the crusts and massive sulphides in comparison to harvesting nodules. The risk of failure of the mining system is another concern. The more complex the geometry of deposits, the more sophisticated the equipment would be and correspondingly less reliable. Nodules can be classified as relatively easy deposits, in comparison to the moderately difficult cobalt crusts and more difficult sulphides. The protection of the natural environment is another major concern. Most of the sulphides are discovered in areas of intense biological activity. Mining might destroy almost entirely such marine life. Sulphides mining should be authorized only in areas where biological activity is extinct and such areas are difficult to locate. For the time being he concluded, no commercial operation is envisaged because the knowledge of deposits is too poor, mining technology is not available or metal prices are too low. For some of the deposits, all these conditions exist together. There is no clear legal regime at present for cobalt crusts and massive sulphides.

12. Issues to be taken into account in developing a framework for the exploitation of seafloor massive sulphides and cobalt-rich ferromanganese crusts of the Area

The International Seabed Authority has adopted rules, regulations and procedures for exploring for one type of marine mineral resource since its establishment. This marine mineral resource is deep seabed polymetallic nodules. The request to formulate rules, regulations and procedures for two other types of marine minerals (seafloor massive sulphides and cobalt-rich ferromanganese crusts) was the reason for convening this workshop. Information on the characteristics of these mineral deposits, in particular information relating to the applicability of the system of exploration that had been developed for deep seabed polymetallic nodules to these other types of mineral resources was a pressing concern of the Authority.

The Secretary General of the Authority, Mr. Nandan initiated discussions on this subject, by inter alia, providing participants with the historical background to the system of exploration for polymetallic nodules and led discussions on the applicability of this system to a system of exploration for the two new types of mineral resources. The Secretary-General explained that the system of exploration for polymetallic nodules in the Area is extensively prescribed in the body of the Convention and in its Annex III. He noted that Part XI of the Convention that governs the Area has undergone some modifications by the 1994 Implementing Agreement.

In the system of exploration for polymetallic nodules, Mr Nandan explained that a prospector could engage in prospecting without any time limit. The Convention provides that a prospector may notify the Authority that it is prospecting and give a description in broad terms as to area or areas that it is prospecting. Prospecting does not confer any rights to the prospector, and more than one prospector can work in the same area at the same time. Prospecting is not defined in the Convention except that in Resolution II, there is a definition of what activities a pioneer investor can undertake during the pioneer period that leads to an application for an exploration license. Some of the activities that are listed there go far beyond marine-scientific research and prospecting per se; it actually involves much more than that, and it goes into part of exploration activities. The two terms, prospecting and exploration are not defined.

If warranted, the prospector could submit an application to the Authority for an exploration license. The system requires that in its application, the prospective contractor submit two sites of equal estimated commercial value. One is given back to him under a contract for exploration, and the other is reserved for the Enterprise of the Authority for development as determined by economic circumstances. The rationale behind this system, known as the parallel or the dual system was basically a compromise. There was a debate in the Conference as to whether the Authority should be the sole operator in the seabed, through its operating arm the Enterprise, or whether the Authority should be no more than a licensing body to give license, and basically legitimise claims in the international area, and in due course perhaps collect some royalties. There was a conflict between these two approaches. As a compromise, the then United States Secretary of State, Mr. Henry Kissinger suggested to have a bit of both approaches: an applicant would come with two sites of equal commercial value, the Authority can choose one and reserve it for development by the Enterprise, and issue a contract for the other to the applicant.

A couple of other questions arose as well. One problem was that a number of entities had gone ahead and identified some of the prime areas, and there was concern that all the prime sites would have gone by the time the Authority began to operate. So there had to be some kind of banking system for reserved areas for the Authority, so that the Enterprise or developing countries for that matter, could also actively participate in seabed mining. Participation was sought not only in terms of benefits that would be ultimately derived, but also in terms of being able to explore for and mine polymetallic nodules that had been declared the common heritage of mankind.

The next question that arose at the Conference as described by the Secretary-General was that with respect to exploring for and possibly undertaking a mining operation, the Authority would be starting from scratch. It had no funds to engage in exploration and subsequent mining whereas the consortia that were active at the time were well-established entities. Many of them included mining companies that had capital, or access to capital and therefore a situation would be created that seemed somehow unfair between Authority and the consortia. The United States in response stated that the industrialized countries could contribute towards the first operation of the Enterprise in the following way: one half of the capital required for the operation would be contributed in cash by States parties and the other half would be in the form of bonds to be deposited with the Authority or to be used to raise funds or cashed if this became necessary. This formula was incorporated in the provisions contained in article 11 of Annex IV of the Convention.

The next issue was technology, because even if money was available, the Enterprise had neither the technology nor the technical know-how to actually participate in the parallel system. To that question, the answer provided was that there would be some provision for making technology available on a fair and reasonable commercial basis in the Convention. That is the fundamental basis on which the whole parallel system developed, and that is how the system for nodules was provided for in the Convention.

The subsequent 1994 Implementation Agreement eliminated the provision that required states parties to contribute in cash or in the establishment of bonds b for the first operation of the Enterprise. Instead, it substituted a joint-venture operation for the first operation of the Enterprise, and thereafter it requires the Council to determine how subsequent operations will proceed. The 1994 Implementation Agreement also addressed the ideological problem with the transfer of technology provisions in the Convention. As the transfer of technology provisions evolved in the Convention they came to be seen as provisions for compulsory transfer of technology rather than technology transfer in the context of the dual or parallel system. The final formulation for transfer of technology in the Convention was as follows: if the Enterprise or a developing country operating in the seabed was not able to otherwise obtain technology in the open market, then the Authority could ask the contractor to make available the same technology at a fair and reasonable commercial price. That provision was modified in the1994 Implementation Agreement so that States whose nationals have the technology are required to assist in obtaining the technology on a fair and reasonable commercial price. The obligation is therefore shifted from the contractor to the Sponsoring State.

The Secretary-General pointed out that there was rigidity in the system that was prescribed for deep seabed polymetallic nodules. He recalled that during the Conference, proposals from the United States were designed to make sure that all decisions that had to be taken were already prescribed and incorporated in the Convention, so that there was no flexibility or discretion for the Authority. This position of the United States resulted in the Group of 77 adding their own little bit, so that inflexibility compounded itself in the system and rules that evolved.

Based on this experience, the Secretary-General stated that as regards seafloor massive sulphides and cobalt-rich ferromanganese crusts it is necessary to bear in mind, firstly that the political and ideological problems that were raised when the rules and regulations for deep seabed polymetallic nodules were being formulated will surface again. Secondly, that the inflexibility of the regime for nodule exploration would need to be examined, to determine whether that regime will be suitable for seafloor massive sulphides and cobalt-rich ferromanganese crust deposits.

The Secretary-General noted that during the period of the Conference, not much was known about the exploitability of deep seabed polymetallic nodules. He stated that there was a lot of speculation and that misleading calculations and exaggerations were made. As regards seafloor massive sulphides and cobalt-rich ferromanganese crusts, he pointed out that the international community might know even less about these resources. He observed that in political negotiations people seek all kinds of safeguards. In practice, however, things are different and more rational. As far as these types of new mineral resources are concerned, he stated that it is necessary for the international community to understand their nature and distribution for rule making. Looking at the system that has been devised for deep seabed polymetallic nodules, the first question that needs to address is whether this system is applicable to seafloor massive sulphides and cobalt-rich ferromanganese crusts.

In this regard, the Secretary-General he noted that the mineral resources for which the Authority is to formulate rules and regulations were unlike polymetallic nodules, being localized deposits as compared to polymetallic nodules that were distributed over large areas. He therefore posed the question of the applicability of the dual or parallel system. Assuming that a different kind of system were selected, for example one where the applicant is not required to submit two deposits of equal estimated commercial value, he asked participants how best the issue of participation by developing countries could be addressed. Participation he further observed had to be seen in the context of the resources being the common heritage of mankind. If mineable deposits are in fact discovered, he stated that some kind of equity for the Authority (carried interest) in the mining operations would have to be agreed upon.

Finally, with respect to formulating rules, regulations and procedures for exploring for these new types of mineral resources, while noting how little was known about them, he pointed to the need to progressively develop a code rather than providing a rigid system that goes from exploration to exploitation as was the case for polymetallic nodules, and later find that some of it is not useful. Returning to his earlier points in respect of prospecting, he said, it needs to be considered whether the approach adopted for nodules where prospecting does not give any proprietary rights and that more than one operator/contractor can prospect in the same area should be applied for crusts and sulphides too. In practical terms, the Secretary-General observed that it is not clear how beneficial or how difficult it will be for somebody to invest in prospecting, only to find that somebody else is working in the same area and has an equal claim to an exploration license. Finally, he asked whether the experience of the oil industry where blocks are delineated and offered to contractors could shed light on the matter.

Prospects for other marine minerals that may be found in the Area

13. Petroleum potential and development prospects in deep-sea areas of the world

Dr. Vysotsky, Director of JSV VNIIZarubezhgeologia of the Russian Federation presented a paper he prepared together with Mr. A. Gloumov, Deputy Minister in the Ministry of Natural Resources of the Russian Federation on "Petroleum Potential and Development Prospects in Deep-Sea Areas of the World". At the outset Dr. Vysotsky pointed out that the term "deepwater" as used in the paper was in a geological sense, covering water depths more than 500m.

Tracing the history of offshore petroleum development, Dr. Vysotsky said that exploratory drilling dated back to the 1960s, while development began in the 1980s when deepwater petroleum exploration expanded rapidly. He also said that it was only in the 1990s that hydrocarbon exploration and development was extended to far greater depths in the oceans. He said that sedimentary basins of various sizes, structure and geologic history are essential components of hydrocarbon resource evaluation. He emphasized that the classification of sedimentary basins has to be supplemented by geologic models of all the recognized ocean basin types. He pointed out that detailed investigation of ocean basins and hydrocarbon description has enabled quantitative estimates of the resources and the petroleum potential in the various regions of the world to be determined. He stated that a total of 120 petroliferous basins occur partly or entirely within the abyssal zone of the world's ocean floor or in water depths of more than 500 m.

According to Dr. Vysotsky, as estimated by VNIIZarubezhgeologia, the Russian Petroleum Institute, the initial total recoverable oil and gas resources of the world are 540 Gt[1/] and 546 Tm^3 [2/] respectively. By comparison, Dr. Vysotsky said that VNIIZarubezhgeologia estimates indicate that the initial total in-place hydrocarbon resources in deep-sea areas of the world are about 200 Gt, including more than 110 Gtoe[3/] liquids and 85 Tm[3/] non-associated and solution gas.

Using world actual average liquid and gas recovery factors of approximately 30 percent for oil and solution gas; 65 percent for condensate, and 80 percent for non-associated gas, Dr. Vysotsky said that the aggregate ultimate recoverable hydrocarbon resources in the deep-sea areas of the world are estimated as 99 Gtoe, comprising 36 Gt of oil and condensate, and 63 Tm[3/] non-associated and solution gas.

With regard to geographical distribution of deep-sea hydrocarbon resources, Dr. Vysotsky said that Latin America is estimated to have 26.7 Gtoe, Africa is estimated to have 25.8 Gtoe, North America is estimated to have 10.5 Gtoe, Western Europe is estimated to have 9.4 Gtoe, South Asia is estimated to have 8.7 Gtoe, Australia and Oceania is estimated to have 7.8 Gtoe, Southeast Asia is estimated to have 6.0 Gtoe, the Far East is estimated to have 3.0 Gtoe, and the Middle East is estimated to have 0.9 Gtoe. In this regard, Dr. Visotsky said that the bulk of oil resources (70 percent) and gas resources (60 percent) are in the Atlantic Ocean and are mostly confined to Cratonic and pericontinental (passive and active margins) basins.

1/ Gt – Gigatonnes – a metric unit of mass or weight equal to 1 billion metric tons (tonnes) or about 2.2046 ytillion pounds.

2/ Tm^3 - Teracubic meters or 1 trillion cubic metres = 10^{12} cubic metres.

3/ Gtoe – 1 Gigatonne of oil equivalent.

At the beginning of 2000, a total of 148 oil and gas fields had been discovered between 200 and 2,324 metres of water in the Gulf of Mexico. Of this total, Dr. Vysotsky said that a total of 20 deepwater discoveries had been made offshore Brazil. He said that according to the latest estimates, the Roncador and Marlin fields are the world's largest offshore deepwater fields.

In Africa, Dr. Vysotsky said that by the beginning of the year tem deepwater offshore discoveries had been made in Nigeria and 21 discoveries had been made in Angola. One of the discoveries in Nigeria was the Agbami field which is the largest in the country's history. Occurring in water depths of between 1,460 – 1,5167 metres, Dr. Vysotsky said that the Agbami field has recoverable reserves of 240 Mmt. In all, Dr. Vysotsky said that a total of 37 offshore discoveries had been made in West Africa at the beginning of 2000.

14. Submarine methane hydrates – Potential fuel resource of the 21st century

Dr.Erhlich Desa, Director of National Institute of Oceanography, India presented a paper on the "potential of submarine methane hydrate deposits as fuel resource of the 21st century". He stated that the Government of India is greatly interested in the development of gas hydrates for this purpose, and has constructed a probability map of gas hydrate distribution around the coast of India. Seismic data from offshore oil development are being studied.

Dr. Desa described submarine methane hydrates as ice like crystals formed from natural gas and water. The water molecules form the lattice, with methane, a gas molecule, occupying the void and stabilizing the lattice. Dr. Desa said that methane hydrates are transparent, translucent and have poorly defined crystal formats.

They vary in colour from, white, grey and yellow and may either cement sediments in which they occur or fill the pore spaces in un-cemented sediment grains. Existing within a limited pressure and temperature range, Dr. Desa further states that one unit of hydrate when released from its pressure temperature curve, forms about 164 units of gas and about 0.8 units of fresh water.

With regard to current knowledge about methane hydrates, Dr. Desa stated that approximately 10,000 gigatonnes of carbon are stored in methane hydrates. He informed participants that this amount of organic carbon is twice the amount contained in currently known fossil fuel. Even if only a small percentage of this amount is recoverable, Dr. Desa said that this represented a major stock of energy.

On the subject of how methane hydrates are formed, Dr. Desa explained that they are produced primarily from microbial and thermogenic processes. In the microbial process, Dr. Desa pointed that organic debris within the sediments is decomposed by a complex sequence called methanogenesis into methane by bacteria in an anoxic environment. Decomposition takes place either by acetate fermentation or by the reduction of carbon dioxide. Hydrocarbons, including methane, are formed in the thermogenic process by thermal cracking of organically derived materials. Dr. Desa indicated that this generally occurs at depths greater than 2 kilometres in sedimentary basins where temperatures are in excess of 100° centigrade. He also pointed out that thermogenic methane might also be formed by thermal degradation of oil at even greater depths and by maturation of coal.

On prospecting and exploration of submarine methane hydrates, Dr. Desa states that while their presence is detected in drill cores, over large areas gas hydrates can be detected by using acoustical methods such as seismic reflection profiles. He mentioned that chlorinity anomalies in pore water, pore water redox levels, sediment grain size, carbon isotope signatures, and benthic biomass are all proxies that can be used in prospecting for gas hydrates. He also said that pockmarks or gas-escape features of the seafloor are another proxy that can be used in prospecting for gas hydrates. Dr. Desa mentioned that such information is acquired from high-resolution acoustic investigations (side scan imagery, shallow sub bottom profiling). He also mentioned that for the study of any proxies, surficial and shallow sub-surficial sediment samplers are required. An advanced technique that he mentioned is through specially designed pressure core samplers (PCS) within which gas samples can be stored up to minus eighty degrees (-80°C) for later analysis.

Dr. Desa informed participants that a number of ideas have been discussed for the production and recovery of submarine methane hydrates. These are based on either converting the gas to a fuel, to thermally stimulate the hydrates and melt them, to depressurise it under the hydrate seal or by inhibitor injection using methanol. After production and recovery, Dr. Desa pointed out that the next task was transportation. The three ideas that are being discussed are:

Through pipelines on the continental shelf

By reducing methane to carbon monoxide and hydrogen and transporting these products, and

Facilitating the reaction of methane with water on the seafloor to obtain hydrate free of sediment. The pure hydrate is then stored in zeppelin shaped storage tanks, towed to shallow water infrastructure, and safely decomposed into water and gas in a controlled environment.

Dr. Desa mentioned that in addition to India, the United States of America, Japan, Canada, the European Union and Russia have all demonstrated a keen interest in the development of submarine methane hydrates. The significance of methane hydrates he stated is in their tremendous resource potential to meet the world's energy needs. Dr. Desa stated that in a patent search of the United States, Japanese and European Patent Offices it was discovered that during 1998 and 1999, 400 patents had been issued indicating how people and organizations were positioning themselves for the commercialisation of submarine methane hydrates.

15. A case study in the development of the Namibia offshore diamond mining industry

Dr. Ian Corbett, Group Mineral Resources Manager of the De Beers Placer Resources Unit, South Africa, made two presentations. His first presentation was concerned with the development of the offshore diamond mining industry in Namibia. His second presentation was on the development of environmental baselines in a large-open ocean system off southern Namibia by De Beers Marine.

Dr. Corbett gave a brief account of the discovery of diamonds offshore Namibia, and the regional setting for diamonds in the basins of the Namib Desert. He explained that the Orange River is largely responsible for the introduction of diamond in the southwest continental margins of Namibia. His presentation covered the complex eco-system on the continental shelf of Namibia that is influenced by the Benguela current and the Orange River. He explained that the kimberlites were transported by the Orange River onto the continental shelves. The river system has been in existence for 65-80 million years transporting kimberlites onto the West Coast. He gave a brief account of geological features including the Gondwana break-up and the formation of the Atlantic Ocean. He also elaborated on the physical characteristics of the diamond deposits and exploration and evaluation techniques used by De Beers. Dr. Corbett informed participants that De Beers Marine operates two vessels with sampling capabilities. One of the vessels, the Douglas Bay, is equipped with a "mega drill" and the second vessel, the Coral Sea, is equipped with a large-bore "decadrill" system. In addition, De Beers has operated the Jago submersible from the vessel Zealous for environmental studies.

Providing an overview of deep-water marine systems, Dr. Corbett stated that the recovery of diamonds is a very sensitive and complex process. Once diamonds are recovered by the drilling system, they are not touched by human hands in the entire processing operation. Diamond recovery, he further stated, is a non-chemical process, the low density material is discharged overboard and returned to the seabed while the high density material is dried prior to X-ray screening to separate the diamonds from non-fluorescent materials. Dr. Corbett pointed out that extraction is achieved utilizing dense media separators that are passed through an X-ray sorting system that identifies the diamonds.

He stated that the overall philosophy of De Beers is to maximize the time utilized in the mining operations. The objective is to carry out safe operations for periods of two years or more on ship-based activities, giving time for scheduled in-port maintenance. Refueling is normally done at sea to reduce time off station. He stated that the vessel Debmar Pacific with 1027 days holds the record for a vessel remaining at sea.

16. A case study in the development of an environmental baseline in a large open-ocean system offshore Southern Namibia.

In his second presentation, Dr. Corbett described how De Beers developed an environmental baseline in a large open-ocean system, offshore southern Namibia. He explained that the continental shelf of Namibia is strongly influenced by the Benguela current that is recognized as one of the main up welling sites in the world. This region is characterized by high biological productivity resulting in significant fish stocks adjacent to the area where diamond mining is carried out. Dr. Corbett informed participants that the continental shelf of South Africa and Southern Namibia is particularly known for its stocks of pelagic and demersal fisheries. In accordance with De Beers's philosophy, Dr. Corbett stated that De Beers initiated environmental studies on the impact of diamond mining on fisheries even when there was no legislative requirement to do so.

Dr. Corbett pointed out that the southern Namibian coast is influenced by high-wave energy driven from the Southern Ocean. As a consequence of the strong wind and wave regimes, the upper water layers are subjected to high levels of turbulence. He further pointed out that although strong northward currents predominate, the Benguela counter-current could be observed to transport suspended sediments introduced by the flooding of the Orange River to the south. The predominant flow of bottom water is to the south, he stated. Up welling introduces dissolved nitrates and other nutrients into the region making the waters of the Benguela ecosystem extremely productive. This region supports pelagic fisheries, principally anchovy and sardine and demersal species, mainly hakes that are commercially valuable.

He mentioned that fisheries account for the presence of around 225-bottom trawling vessels operating on the western margin of South Africa and Namibia. In addition, rock lobster represents an important shallower-water industry in southern Namibia, especially in Luderitz where diamonds were first found. Dr. Corbett stated that two factors are significant in the Benguela system; the first is the formation of low-oxygen water that adds to the large-scale natural variability, and the second is periodic flooding of the Orange

River resulting in the introduction of large volumes of suspended sediments onto the continental shelf.

Dr. Corbett gave a brief account of the environmental studies that have been carried out and an overview of the environmental management requirements in accordance with Namibian legislation. His written paper, he said, also gives an account of the results of environmental impact assessments that have been carried out. He mentioned the decision of De Beers to deploy a research submersible to allow direct observation of the seafloor. He stated that direct visual observation and deployment of Jago with extensive high-resolution sonar coverage proved to be extremely valuable understanding the full spectrum of the underwater conditions. He emphasized the multi-faceted operational requirements for such studies and how De Beers has encouraged collaborative approaches. He noted that such an approach could be of relevance even in respect of deepwater mining of polymetallic nodules and crusts.

17. Evaluation of the non-living resources of the continental shelf beyond the 200-mile limit of the world's margin

Dr. Lindsay Parson, a government scientist at the Southampton Oceanography Centre, United Kingdom, reported on an evaluation of Non-Living Resources of the Continental Shelf Beyond the 200-Mile Limit of the World's Continental Margins. His paper examined the non-living resource potential in the "legal" continental shelf as defined under Article 76 of the 1982 United Nations Convention on the Law of the Sea. Dr. Parson explained the legal regime elaborated under that Article and the methodologies prescribed for the delineation of the outer limits of the continental shelf.

Thereafter, he described the several types of mineral resources in the extended continental shelves around the world, including their potential. His paper, he explained, was based on statistical evaluations of known occurrences and reserves, the geologic environment favourable for their formation, models for sediment type and thickness and basement composition. Eight different types of non-living resources were assessed, namely placer deposits, phosphorites, evaporites, polymetallic sulphides, manganese nodules, cobalt-rich crusts, hydrocarbon deposits and gas hydrates. His written paper contains the various statistical information and data.

He stated that whatever the potential worth of non-living resources in the extended legal continental shelf regions around the world, with the exception of conventional gas and oil and possibly gas hydrates, these resources will remain unrecoverable until technology advances to enable access to resources to be found at significant water depths, and when economic conditions make the recovery and production of these resources competitive with land-based resources. He was of the view that identification of the resources is one thing, but calibration and quantification in terms of sampling is a different matter.

18. Status report of the data and information requirements of Namibia's offshore diamonds industry

Ms. Inge Zaamwani, Managing Director of Namdeb Diamond Corporation of Namibia gave a Status Report on the data and reporting requirements of Namibia's offshore diamond mining industry. She gave a brief account of the geological situation of Namibia, the political framework and the offshore mineral resource potential. The main legislative framework she informed participants, is the Namibian Minerals Act. She mentioned that like Papua New Guinea and Brazil, the Namibian Act makes no distinction between prospecting and exploration, whether onshore or offshore.

Ms. Zaamwani reported that the Namibian Minerals Act covers the three main mining phases- namely, reconnaissance, prospecting and mining. She said that prospecting is defined as the "intentional searching whether by way of excavations or otherwise for any mineral or group of minerals with a view to delineating or evaluating deposits or concentrations of any such minerals or group of minerals but does not include mining". Prospecting licenses may be non-exclusive or exclusive. She also said that normally, prospectors could apply for an Exclusive Prospecting Licence, which is granted for an initial period of three years with a right to renewal for a further period not exceeding two years at a time. Currently, in Namibia 404 Exclusive Prospecting Licences have been issued. Of these, 239 were for diamonds, with 127 of them being for offshore areas.

Ms. Zaamwani pointed out that as the Act does not differentiate between onshore and offshore mining, operators experience some difficulties. In particular, since the Act does not cater for modern technology essential for offshore geophysical surveys, certain procedural and logistical problems are encountered. Ms. Zaamwani said that the Ministry of Mines requires that all raw data collected during the surveys must be submitted to it. She said that most operators use contractors based outside Namibia, and data is normally taken to Capetown and processed using very specialized proprietary computer systems. Since the raw data has to be submitted to the Ministry, she said that costly administrative processing is involved. She pointed out that the raw data is of very little use to the Ministry, as it does not have the technical capacity to interpret such data.

Ms. Zaamwani said that during the term of a licence, the information and data are kept confidential in closed files until such time as the license area is relinquished or abandoned. Upon relinquishment, the information and data are transferred to an open file and is used by the Geological Survey for investment promotion. She pointed out that any interested third party could have access to the open files, free of charge. The rationale of free access to data she said, is that a new company or investor interested in an area that has been looked at previously need not go through the entire process. She stated that Namibia also attaches immense importance to the protection of the marine environment and the law requires that an environmental impact assessment statement must be submitted before prospecting can be allowed. She concluded by saying that the Minerals Act contains provisions for submission of data and information in a very comprehensive manner.

19. Status report on the data and reporting requirements of Norway's offshore licensing policies as it relates to petroleum exploitation

Dr. Bente Nyland, Project Director in Norway's Petroleum Directorate reported on the Data and information requirements of Norway's petroleum industry. Providing an overview of Norway's petroleum industry, Dr. Nyland informed participants that Norway's offshore sedimentary basins covered an area of approximately 1.4 million sq km. Of this amount, about 60 percent is open for petroleum activities but only around 10 per cent are licensed areas. Dr. Nyland stated that petroleum operations play a substantial role in the Norwegian economy and contribute a major share of the revenue to the state. Norway ranks as the world's second largest exporter of crude oil after Saudi Arabia. She also said that Norway is the world's tenth largest exporter of gas and supplies 10 percent of Western Europe's consumption.

With regard to production, she pointed out that petroleum operations in Norway are mainly in the North Sea that has been divided between Norway and its neighbours using the median line principle by agreements with the UK and Denmark in 1965. The border with Russia in the Barents Sea is still under negotiation. With regard to licensing, she stated that the Norwegian continental shelf is divided into quadrants each comprising 12 blocks covering 15 minutes latitude and 20 minutes longitude. The average area of a North Sea block is around 600 sq km. A licensee can cover more than one block.

Dr. Nyland said that the Petroleum Act of 1996 specifies that the proprietary right to regulate petroleum deposits in the Norwegian continental shelf be vested in the State. The Act regulates petroleum operations, the granting of permits and licenses to explore, produce and transport recovered materials. She said that the procedural requirements are detailed in the Act. In areas not available for exploration activities, the Norwegian Petroleum Directorate can undertake regional geophysical and geological investigations for the purpose of understanding the geological conditions and hydrocarbon potential of such areas. Dr. Nyland informed participants that a scientific research license can be granted to Norwegian or foreign scientific institutions through a permit which would normally cover one particular investigation. The permit is generally free and allows licensees to carry out geophysical and geological surveys. The permit does not confer any exclusive right to undertake research in the areas covered by the permit. It also does not give any right or priority to exploit possible natural resources. Upon conclusion of the surveys, a report must be submitted on the extent and execution of the research including the results, and must be published. Dr. Nyland pointed out that it is only in areas where sufficient regional data are available, and after environmental assessment studies, that the Norwegian Parliament can open the area for general exploration. In such cases, companies can apply for the reconnaissance license for geological, geophysical, petrophysical, geochemical and geotechnical surveys, including shallow drilling. She added that such licenses do not give the holder exclusive rights or allow regular exploration drilling activities. The next stage in the license regime is a production license that confers an exclusive right for exploration, drilling and production of petroleum. She stated that a license area is granted to oil companies for a period that can extend up to 10 years. The production license allows drilling exploration wells after the environmental, economic and social impacts of such operations have been fully assessed.

Dr. Nyland explained that the Norwegian Petroleum Act provides for data information and reporting that are detailed in the regulations and guidelines. These encompass physical data, prognosis and plans, reported events, permits and agreements, statistics and other relevant reports relating to the activity. There are also guidelines for data quality, media readability, format, archival efficiency, electronic reporting and administrative information. The Norwegian Directorate is entitled to all information the oil industry has regarding their activities in Norway. Data not owned by the license group is confidential for five years, while marked available data is confidential for ten years. Sensitive information and interpretations are confidential for 20 years. Data from areas relinquished or surrendered are not considered confidential. All navigation data is public.

20. Status report of the data and reporting requirements of Brazil's offshore mining policy as it relates to prospecting and exploration

Dr. Roberto Macedo, Adviser to the President of Petrobras Brazil, read a paper jointly authored with Walter Sa Leitão on the data and information requirements of Brazil's offshore petroleum industry. He provided participants with an overview of the various types of resources that Brazil has in its offshore area. To begin with, he stated that offshore sand and gravel are one of the most important superficial sedimentary deposits, the easiest to exploit, and one of the lowest in terms of economic value since its transportation costs overtake the resource value. Similarly, limestone was also considered a low-value mineral resource with heavy transportation costs. Sulphur was a by-product of natural gas and petroleum refining, and considering Brazil's dependence on imported sulphur; it could be a key resource for offshore exploration. However, he noted that the exploration potential of this resource has not been properly evaluated. Sub-sea coal mining could be a possibility but considering Brazil's enormous land reserves, offshore coal mining is not foreseen in the near future. The phosphates content off the Brazilian shore is very low. Brazilian marginal evaporites are again considered as having only a small potential. As regards polymetallic nodules in Brazil, there is only one record of such resources on the northeast coast at a depth of around 2200 metres. Polymetallic sulphides deposits occur in the meso-oceanic offshore ridge close to the St. Peter and Paul rocks.

He emphasized that the most important marine mineral resource for Brazil is petroleum and natural gas. He pointed out that Brazil is one of the leading offshore petroleum and natural gas producers in the world, and that the Brazilian company, Petrobras, carries out both activities. Dr. Macedo informed participants that natural gas reserves are found in the Campos Basin offshore Rio de Janeiro where the Roncador fields have the largest natural gas reserves in Brazil. Dr. Macedo said that Brazil's legislative measures including data and information requirements are contained in the Law of 1997 commonly referred to as the Law of Petroleum. The National Petroleum Agency (ANP) is the regulatory agency for offshore activities. Several measures and regulations are set forth in a number of ordinances issued since the establishment of ANP. These regulations cover a wide range of activities, the terms and conditions of concessions, and contracts and obligations of the concessionaires including payment of certain taxes. Offshore mining is a very recent activity in Brazil. He stated that rules and regulations including those relating to environmental protection have come into force only recently.

21. The offshore mineral policy of Indonesia

Dr. Hasjim Djalal, Special Adviser to the Minister of Ocean Exploration and Fisheries of Indonesia provided an overview of the Indonesian Offshore Minerals Policy. Dr. Djalal informed participants that under the Indonesian Constitution, offshore would cover the archipelagic waters of Indonesia and the 12 miles of territorial sea around them. In accordance with Indonesia's Constitution the geographic area of interest was from, all resources contained in those waters and their seabed were appertained to the Republic of Indonesia. Following the 1982 United Nations Convention on the Law of the Sea, he said that Indonesia has delineated most of its continental shelf through bilateral agreements with its neighbours. The Government of Indonesia controls all scientific research, exploration, construction of installations and structures on the continental shelf. Mining of oil and natural gas in Indonesia including in all islands, in the seabed of archipelagic waters, the territorial sea, and the continental shelf can be done only through a state company.

He gave a brief overview of Pertamina State Oil Company and its activities. Pertamina, he informed participants, has formulated model terms of production sharing contracts/agreements that have been widely used. The contracts clearly state that all mineral oil and gas existing within the statutory mining territory of Indonesia are national riches controlled by the state. Pertamina has an exclusive authority to mine, while the contractor could assist Pertamina in accelerating the exploration and development of other resources within the contract area. The term of the contract is for 30 years and at the end of the first six years, the contractor shall have the option to request a four-year extension. The contract shall terminate if after the first six years or the extension thereto, no petroleum in commercial quantities is discovered. In the event of a petroleum discovery, Dr. Djalal told participants that development is in that portion of the contract area. On or before the end of the initial three years, the contractor is required to relinquish 25% of its initial contract area. Similarly, on or before six years, a further 25% of the contract area has to be relinquished. On or before the tenth year, the contractor is required to relinquish further areas so that the remaining area is not be more than 20% of the original contract area, or any other specific area subject to negotiation, whichever is less. The contractor is required to maintain a reasonable exploration effort and if during two consecutive years, does not submit exploration programmes, Pertamina may require the contractor either to submit an exploration programme, or relinquish such part of the contract area.

Dr. Djalal also explained certain other procedural requirements. He pointed out that the mining legislation in Indonesia treats oil and gas somewhat differently from hard minerals. While the exploration and exploitation of oil and gas are largely based on the production sharing system, in respect of minerals, it is based on a licensing system in which the licensed mining companies are obliged to pay mining fees, taxes, and royalties to the government. The difference is basically because it is relatively easier to delineate the oil and gas reserves in comparison with delineation of hard mineral reserves. The presentation did not further elaborate on the subject, but only mentioned that in respect of offshore mining, Indonesia had some offshore tin mines that were very close to the shorelines, and are generally regarded as an extension of mining on land.

22 The role of the South Pacific Applied Geosciences Commission (SOPAC) in promoting exploration for marine mineral resources in the Pacific region

Mr. Alfred Simpson, Director of the South Pacific Applied Geosciences Commission (SOPAC), presented a paper prepared together with Cristelle Pratt, K. Kojima and R. Koshy on "The role of SOPAC in promoting exploration of marine mineral resources in the Pacific Region". He gave a brief history of SOPAC, its regional setting and the various activities and cooperative cruises relating to marine scientific research that SOPAC had been involved with. Mr. Simpson informed participants that SOPAC had established a comprehensive database on marine mineral resources and provides advice and support for marine mineral research and development to its members. He pointed out that marine scientific research campaigns by SOPAC have identified key resources of polymetallic massive sulphides, manganese nodules and cobalt-rich manganese crusts within the 200-mile Exclusive Economic Zones of some of the Pacific island community countries.

In respect of manganese nodules, he stated that the work by the SOPAC/Japan programme has shown that the cobalt metal content and resource density of the manganese nodule resources in the exclusive economic zone of the Cook Islands are significantly more than in the Clarion-Clipperton Zone. The SOPAC/Japan programme has also identified manganese nodule deposits in the exclusive economic zones of Kiribati and Tuvalu.

In respect of cobalt-rich manganese crusts, Mr. Simpson said that discoveries of such deposits, up to 15 cm thick on terraces and submerged platforms zones had been made in the exclusive economic zones of Kiribati and Tuvalu, the Republic of the Marshall Islands, Samoa, Guam and the Federated States of Micronesia. The chemical composition of the crusts, he also stated, is similar to that of manganese nodules with the exception that the cobalt content is 3-5 times that of manganese nodules. With regard to polymetallic massive sulphides deposits, Mr. Simpson stated that such deposits were first discovered in 1984 in the Southern Lau Basin in water depths of around 1800 m. Further discoveries were made in 1986 in the Manus Basin, Woodlark Basin and Northern Lau Basin. In 1988, the North Fiji Basin deposits were discovered. Mr. Simpson further stated that preliminary results of research cruises conducted in the exclusive economic zone of Vanuatu and the Solomon Islands indicate that there is hydrothermal activity in these areas. He noted that polymetallic massive sulphides that are rich in copper, zinc, lead, silver and gold are being heralded as "bonanza resources" especially in view of their high gold content. Mr. Simpson pointed out that although large amounts of polymetallic sulphide data are now available, no drilling of any of these deposits has yet been undertaken to estimate the volumes or ore contained in them. Additionally, he said, little is known about the costs to extract and process the ore.

He stated that the SOPAC database includes geochemistry, structural characteristics, genetic environment, mineralization characteristics and geographic location of manganese nodules and cobalt-rich crusts samples. It also has data on geology, geochemistry, morphology and environmental parameters, geographic position and ore deposit information in respect of polymetallic massive sulphides. Mr. Simpson informed participants that environmental management components are integrated in the research programmes of the organizations in the SOPAC region. Mr. Simpson informed participants that the offshore mineral policy for the SOPAC members is contained in the Madang guidelines which covers all aspects of offshore mining development; namely, the legal and licensing regime, the fiscal regime, the environmental guidelines, the marine scientific research requirements, stakeholder issues, benefit distribution mechanism and dispute settlement. SOPAC, he concluded, provides advice and assistance to Pacific island countries to build and implement effective systems and procedures for deep-sea mineral exploration and development.

Part 1

Developing a Legal Framework for Exploring for Seafloor Massive Sulphide Deposits and Cobalt-Rich Ferromanganese Crusts

Chapter 7 Technical requirements for exploration for and mining of seafloor massive sulphides deposits and cobalt-rich ferromanganese crusts
Professor Peter Herzig and S. Petersen

Chapter 8 Financing exploration for seafloor sulphides deposits.
Julian Malnic

Chapter 9 Status report on the data and Reporting Requirements of Papua New Guinea's Polymetallic Massive sulphides Deposits.
James Wanjik

Chapter 10 Current National and International Programmes of Exploration for Seafloor Massive Sulphides and State-of-the-art Techniques and Operations in Exploration
Dr. Chris German, Challenger Division for Seafloor Processes, Southampton Oceanography Centre, United Kingdom.

Chapter 11 A Comparison of Possible Economic Returns from Mining Deep Seabed Polymetallic Nodules, Seafloor Massive Sulphides and Cobalt-Rich Ferromanganese Crusts
Jean-Pierre Lenoble, Chairman, Legal and Technical Commission (ISA), France

CHAPTER 1

METALLOGENESIS OF MARINE MINERAL RESOURCES

Dr. Peter A. Rona, Professor, Institute of Marine and Coastal Sciences and Department of Geological Sciences, Rutgers University New Brunswick, New Jersey, United States of America

1. Introduction

Our vision of marine mineral resources is expanding rapidly as our knowledge of the ocean advances. Ocean basins were regarded as passive containers of the ocean until the advent of the theory of plate tectonics in the 1960's. According to the view of the ocean basins as passive containers, marine metal and non-metal non-fuel mineral deposits were considered to be primarily derived from the erosion of continental rocks and carried into the ocean by rivers in solid (sediment) or dissolved phases. This view adequately explained the marine minerals known at that time. These minerals comprised beach deposits and placer deposits of various heavy minerals containing metals and non-metals of terrigeneous origin, that is, derived from erosion of continental rocks and transported into the ocean primarily by rivers (Table 1; Figure 1). River input is also considered to be an adequate source of dissolved metals to form manganese nodules and crusts, phosphorites, and other types of authigenic deposits (Table 1), that is, those mineral deposits precipitated from elements dissolved in seawater.

Table 1: Classification of marine mineral resources (modified from 23 and 25)

Region	ORIGIN	Mode of occurrence			
		Unconsolidated (Mineral)	Consolidated	Fluid	Heat
Continental Margin (shelf, slope and rise)	Terrigeneous (derived by erosion of continental rocks)	Non-metals: Beach deposit: Siliceous sand and gravel (quartz) Placer deposit: Diamond Metals: Placer deposit: heavy mineral and native metal concentrates Barium (barite, witherite) Chromium (chromite) Gold Iron (hematite, magnetite, siderite) Rare Earth Elements (monazite, basanite) Tin (cassiterite) Titanium (ilmenite, rutile) Thorium (monazite) Tungsten (scheelite, wolframite) Zirconium (zircon)		Seawater solutes: Salt (halite, sodium chloride) Magnesium Magnesium compounds Bromine Others: Bicarbonate Boric acid Calcium Fluorite Potassium Strontium Sulphate Thorium	
	Biogenic (produced by organisms)	Beach deposit: Lime (calcite, aragonite) Mud, sand shells Precious coral Pearl (primarily cultured)	Coal Limestone Gas hydrates (methane) Sulphur (pure and as sulphate)	Petroleum (oil and gas)	

	Authigenic (precipitated from sea water)	Lime (calcite and aragonite), mud, sand shells Beach or placer deposit: Iron sands (glauconite) Placer or solid layered deposit: Phosphorite (apatite, fluorapatite, etc.)	Cobalt-iron-manganese-platinum crusts Phosphorite Potash Salt (halite, sodium chloride) Sulphur (pure and as sulphate)		
	Diagenetic (produced by alteration of existing material)	Placer deposit: Phosphorite (apatite, fluorapatite, etc.)	Solid layered deposit: Phosphorite		
	Volcanogenic (produced by volcanic processes)		Lode and vein deposits (all elements) Massive sulphide deposits (copper, iron, zinc, silver, gold)	Freshwater	Geother mal energy
	Meteoric (produced by atmospheric processes)			Freshwater (desalination of seawater)	
Ocean Basin	Biogenic			Petroleum (oil and gas)	
	Authigenic	Manganese nodules (manganese, iron, nickel, cobalt, copper)	Cobalt-iron-manganese-platinum crusts		

	Volcanogenic	Metalliferous sediments (manganese, iron, copper, lead, zinc, gold, silver)	Manganese encrustations Massive sulphides (copper, iron, zinc, silver, gold) Nickel-platinum sulphides Chromium (chromite) Sulphur (pure and as sulphate and sulphide)	Hydrothermal fluids (heat and metals)	Geothermal energy

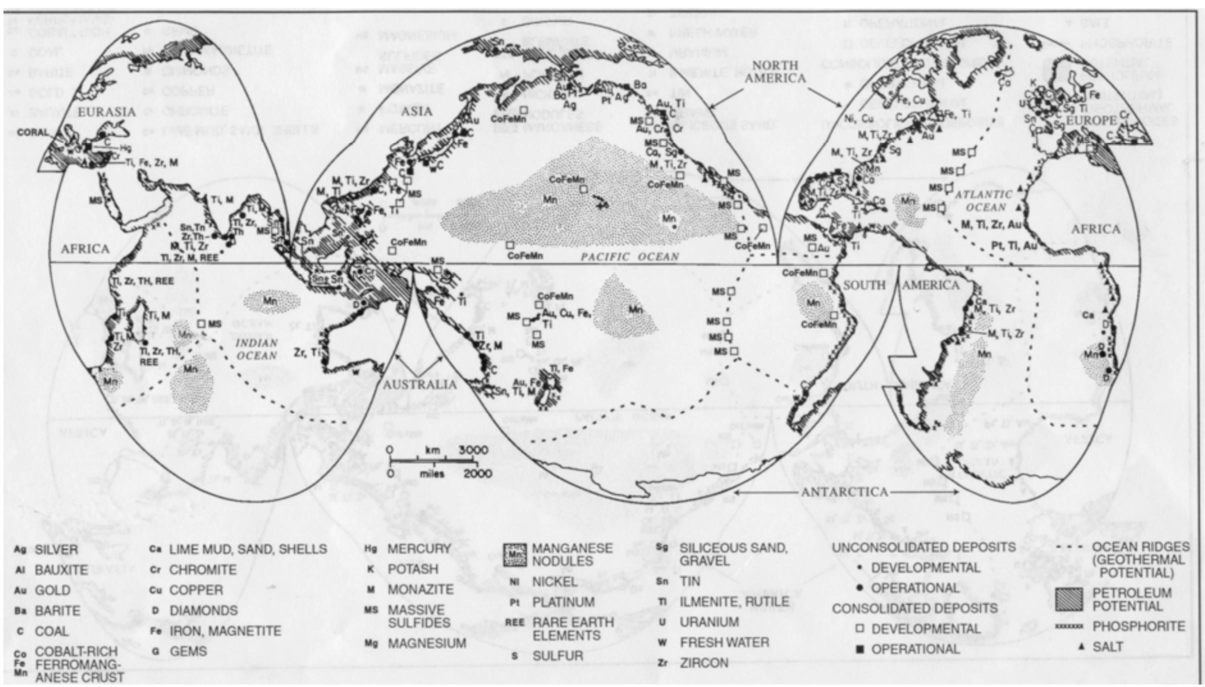

Figure 1. Global distribution of marine minerals (2, 23-26)

The theory of plate tectonics shifted emphasis in Earth processes from the continents to the oceans by showing that the Earth's outermost layer, the lithosphere about 100 kilometres thick, is segmented into some 10 major plates and numerous minor plates. The boundaries between plates are delineated by earthquakes produced by motions between plates and mostly lie beneath the oceans (Figure 2). In particular, divergent boundaries where plates are separating are manifested as a submerged volcanic mountain range that extends more-or-less continuously through all the ocean basins of the world. This submerged volcanic mountain range is the largest geographic feature on Earth, but is hidden from view because the ocean mostly covers it. Molten rocks or magma buoyantly up well from the Earth's interior beneath the submerged volcanic mountain range, cools, congeals, and accretes to either side of the submerged volcanic mountain range, and forms two diverging conveyor belts of new lithosphere in the process of seafloor spreading at a rate of inches centimetres (inches) per year. These globe-encircling divergent plate boundaries transfer heat and materials from the Earth's interior to the lithosphere.

The ocean basins are leaky as containers of the oceans because the seafloor is penetrated by fractures. Cold, dense, heavy seawater flows kilometres downward through the fractures and is assimilated into the rocks of the Earth's interior over much of the ocean basin. However, where the cold, heavy seawater encounters the magma up welling beneath the submerged volcanic mountain range at divergent plate boundaries, the seawater is heated, expands, and the lighter fluid buoyantly rises. As the heated seawater rises, it dissolves various elements that are present in low concentrations in the rocks through which it flows, particularly metals (1). The metals concentrated in the up welling solutions link with sulphur from seawater and from the rocks to precipitate as metallic sulphide deposits beneath and on the seafloor. The remaining high-temperature (up to 400 degrees Celsius; 750 degrees Fahrenheit), metal-rich solutions discharge at the seafloor and almost instantaneously precipitate the metals to form the cloud of black metallic mineral particles known as "black smokers" that may buoyantly continue to rise up to hundreds of meters into the overlying water column.

The divergent plate boundary at the globe-encircling submerged volcanic mountain range constitutes a global system of exchange of heat and materials from the Earth's interior to the lithosphere and into the ocean in amounts that impact the ocean environment and contribute greenhouse gases (carbon dioxide and methane) to global change. Hydrothermal mineral deposits, including massive sulphides concentrated by hot aqueous solutions, are a product of this system. Geothermal energy is another by-product (Table 1). Chemical energy transferred from the Earth's interior by hot springs at sites along the submerged volcanic mountain range not only concentrates metallic mineral deposits, but also energizes microbes at the base of an ecosystem of new life forms at the hot springs. This hot spring ecosystem in the ocean is largely independent of photosynthesis, which is the energy source of ecosystems on land.

As a consequence of knowledge gained through the theory of plate tectonics, the ocean basin is no longer considered a passive sink for material washed in from land, but is an active source of heat and materials that creates marine mineral resources. Metallogenesis of marine minerals is now viewed as the product of both continental sources of metals external to the ocean and sources at submerged plate boundaries internal to the ocean. The purpose of this paper is to provide a concise scientific overview of the origins, seafloor settings, distribution, exploration methods and environmental considerations of marine mineral deposits with emphasis on metallic minerals of the deep ocean to assist policymakers who are developing rules, regulations and procedures for the exploration and exploitation of these potential resources.

2. Marine Minerals Related to Continental Sources

2.1 Metals

Numerous sites exist on continental shelves around the world where heavy minerals containing metals and non-metals are concentrated (Figure 1; Table 1), but of these only a small number are or have been actually mined. These materials are eroded from rocks exposed on land and transported by rivers to the ocean where they are concentrated by waves, tides and currents as placer deposits. With reference to metals, the outstanding resource is tin, which is dredged from shallow water (water depth less than 30 meters) at several sites offshore Thailand (Thai Muang; Tongkah Harbour, Takua Pa), Indonesia (Copat Kelabat Bay, Laut Tempilang; Belitung), and Myanmar (Heinze Basin) where tin minerals (cassiterite) were derived by erosion and transportation from continental granites ([2/], [3/]). Gold-bearing sands and gravels have been intermittently (depending on the price) dredged from shallow water (water depth less than 15 meters) at several sites offshore Alaska (Nome, Bluff Solomon) and New Zealand (Gillespie's Beach) (4/). Titanium (minerals ilmenite and rutile), zirconium (zircon), Rare Earth Elements (monazite), and the radioactive element thorium (monazite) have been recovered at several shallow water (water depth less than 5 m) offshore South Africa, Madagascar, India (2/). Chromium (chromite) is recovered at a site offshore Central Sulawesi Island, Indonesia, and barium at a site offshore Alaska (2/).

2.2 Non-Metals

With reference to non-metals, a viable industry has developed exploring for and dredging diamond-bearing gravels offshore Namibia (Chameis Bay) and South Africa (Groen River, Broadacres, Casuarina Prospect) in shallow water (exploration water depth to 400 meters; dredging water depth to 140 meters) (2/, 5/). The most widely recovered marine mineral is sand and gravel dredged from beaches and shallow offshore bars at numerous sites worldwide for use in construction materials (concrete) and replenishment of beaches. Freshwater is a marine mineral resource critical to life and agriculture that may be extracted from seawater by desalination and exists in solid form in the ice sheets of Antarctica and Greenland. Although desalination, which is an energy intensive process, is mainly being used in the oil-based economies of Middle Eastern maritime states, desalination plants are spreading to other parts of the world. The element phosphorous is also critical to agriculture and occurs where it has precipitated from deep seawater as the mineral phosphorites at present and past locations of up welling along sections of continental shelves primarily within the trade wind belts (0 to 30 degrees North and South latitude). All phosphorites is presently mined from land deposits precipitated during higher stands of sea level in the geological past, but extensive deposits exist on continental shelves of agriculture-intensive countries like India.

3. Marine Minerals Related to Deep Ocean Sources

3.1 Massive Sulphides and Manganese Deposits

As described, divergent plate boundaries expressed as a submerged volcanic mountain range that extends through all the major ocean basins of the world (Figure 2) are part of a global exchange system of heat and materials from the Earth's interior to the lithospheric plates. However, seafloor hot springs and associated hydrothermal mineral deposits do not occur continuously along the axis of this submerged volcanic mountain range. They are highly localized at specific sites along that axis where the right conditions are present. These conditions comprise hot rocks kilometres beneath the seafloor connected to faults and fractures that create permeable pathways for the circulation of seawater to produce hot springs.

The fields of hot springs and mineral deposits are generally small, with diameters up to several hundred meters. Polymetallic massive sulphides containing iron, copper, zinc, silver and gold in variable concentrations (also known as massive sulphides meaning that the deposits contain at least 60 percent metallic sulphides minerals) are precipitated where high-temperature hot springs discharge through mineralised chimneys ([1/]). Deposits of relatively pure manganese oxide (c. 50 percent manganese by weight) may accumulate at low-temperature hot springs (to tens of degrees Celsius or Fahrenheit) at some distance (kilometres) from the high-temperature hot springs (6).

Once formed at the axis of a submerged volcanic mountain range, massive sulphide and manganese deposits may be carried to either side of the divergent plate boundary on conveyor belts of spreading lithosphere where the deposits may be buried beneath lava flows and sediment.

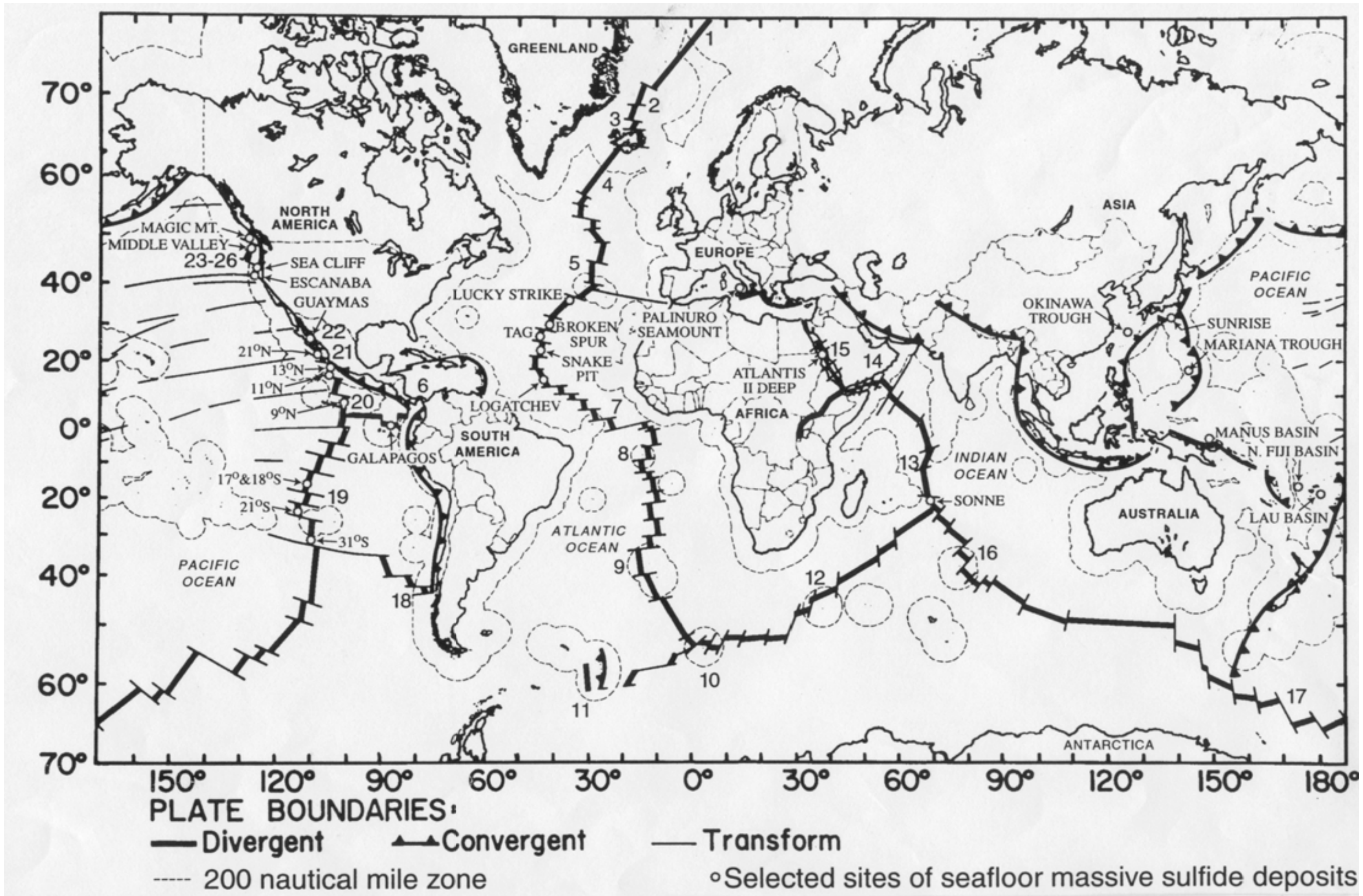

Figure 2. World map showing plate boundaries, the 200 nautical mile zone extending from coastal states, and sites at plate boundaries where some of the larger massive sulphide deposits have been found (27). Only a small percentage of prospective areas of the deep seafloor have been explored in sufficient details to find such deposits. Numbers indicate locations where the submerged volcanic mountain range at divergent plate boundaries lies within the 200-mile zone of a coastal state, as listed in table 2.

The black smoker chimneys discharging high-temperature solutions are only the tip of the iceberg. The largest massive sulphide deposit presently known in the ocean is the TAG hydrothermal field situated at the same latitude as Miami, Florida in a valley at the centre of the Mid-Atlantic Ridge, the submerged volcanic mountain range that extends along the centre of the Atlantic Ocean from Iceland to the north to the southern tips of South America and Africa to the south (6/). A cluster of black smokers vigorously discharges from the top of a mound the size and shape of the athletic stadium, the Houston Astrodome (200 meters diameter; 40 meters high) in the TAG field (Figure 3).

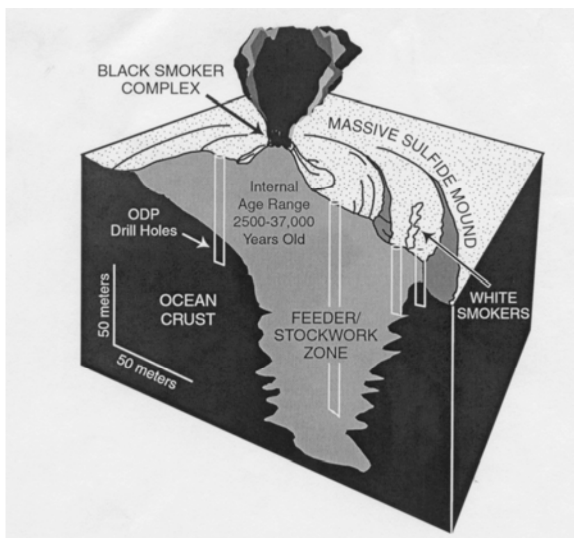

Figure 3. Diagram showing characteristic surface and subsurface features of a seafloor massive sulphide mound based on drilling of the TAG active sulphide mound by the Ocean Drilling Programme (28, 7). A massive sulphide mound the size and shape of the sports stadium, the Houston Astrodome, is underlain by a feeder/stockwork zone produced by the upflow of hot, buoyant metal-rich solutions which discharge near the centre of the mound into the ocean as black smokers. Ages measured on massive sulphide samples recovered in cores from the drill holes range between 2,500 and 37,000 years old.

The third dimension, sub-seafloor, was revealed by a suite of holes drilled into this mound in 1994 by the drill ship JOIDES RESOLUTION of the international Ocean Drilling Program (ODP), a government-sponsored consortium of 20 nations. Cores recovered from the drill holes revealed that the three-dimensional shape of the mound is that of a lens composed primarily of massive sulphides underlain by a stem-shaped feeder or stockwork zone where the hot solutions are welling up and replacing the normal volcanic rocks of the ocean crust (Figure 3) ([7]). The drilling clearly established two points:

1) Renewable resource: It has been contended that active seafloor massive sulphides are renewable resources that will regenerate by precipitation from hot springs almost as quickly as the sulphides are removed. This may be true for individual active mineralised chimneys that have been observed to regenerate within days to years after removal. However, absolute dating of the ages of massive sulphides inside the TAG active mound range between 2,500 and 37,000 years old (Figure 3) indicating that it takes thousands to tens of thousands of years to form a sizable massive sulphide deposit. Massive sulphide deposits are not renewable resources.

2) The size, shape and composition of the TAG active mound is similar to that of a class of ancient mineral deposits, Volcanogenic Massive Sulphide (VMS) deposits, that have been mined on land for centuries for iron, copper, zinc, silver and gold without understanding how they were formed. The TAG active mound and other similar massive sulphide mounds on the seafloor enable economic geologists to observe VMS deposits in process of formation, which gives them unparalleled insight to guide their exploration for and mining of ancient counterparts on land.

Divergent plate boundaries with the potential for the occurrence of massive sulphide deposits lie primarily in the international seabed area with exceptions shown in Figure 2 and listed in Table 2 ([8]). The largest number of exceptions lies in the volcanic island chains of the western Pacific (Figure 2). The volcanic island chains form at convergent plate boundaries where the lithosphere bends down and descends into the Earth's interior where is destroyed to counterbalance the creation of lithosphere at divergent plate boundaries (Figure 4). The components of seafloor hydrothermal systems consisting of hot rocks at depth beneath the seafloor as a heat source, seawater as the circulating fluid, and permeable pathways through volcanic rocks that contain metals are present at discrete sites on two sides of these volcanic island chains (Figure 4): 1) the front or seaward-facing side; 2) the back or landward-facing side behind the volcanic islands. The settings favourable for the formation of massive sulphide deposits and associated manganese deposits on the two sides of the volcanic island chains are the calderas (collapsed craters) of seafloor volcanoes and seafloor spreading centres in the back arc basins. These seafloor-spreading centres are similar to, but generally smaller scale than, the submerged volcanic mountain range at divergent plate boundaries.

Table 2: Submerged, volcanic mountain ranges (divergent plate boundaries) within 200 nautical miles (370 km) of land (location identified by number in Figure 2; modified from 8)

Location	Ocean	Oceanic Ridge	Land	Country
1	Greenland Sea-Norwegian Sea	Mohns Ridge	Svalbard Islands Jan Mayan Island	Norway Norway
2	Greenland Sea-Norwegian Sea	Iceland-Jan Mayan Ridge	Jan Mayan Island Greenland Iceland	Norway Denmark Iceland
3	Greenland Sea-Norwegian Sea	Kolbeinsey Ridge	Iceland	Iceland
4	North Atlantic	Reykjanes Ridge	Iceland	Iceland
5	North Atlantic	Mid-Atlantic Ridge	Azores Islands	Portugal
6	Caribbean Sea	Cayman Spreading Centre	Cayman Islands	Jamaica
7	Equatorial Atlantic	Mid-Atlantic Ridge	St. Peter and St. Paul Rocks	Brazil
8	South Atlantic	Mid-Atlantic Ridge	Ascension Island	United Kingdom
9	South Atlantic	Mid-Atlantic Ridge	Tristan de Cunha Gough Island	United Kingdom United Kingdom
10	South Atlantic	Mid-Atlantic Ridge	Bouvet Island	Norway
11	South Atlantic-Scotia Sea	Scotia Spreading Centre	South Sandwich Islands	United Kingdom
12	Indian Ocean	South-West Indian Ridge	Prince Edward Islands, Marion Island	Republic of South Africa
13	Indian Ocean	Carlsberg Ridge	Chagos Archipelago	United Kingdom
14	Indian Ocean	Gulf of Aden Spreading Centre	Democratic Republic of Yemen	Democratic Republic of Yemen
15	Red Sea	Red Sea Spreading Centre	Yemen Saudi Arabia Ethiopia Sudan Egypt	Yemen Saudi Arabia Ethiopia Sudan Egypt
16	Indian Ocean	South-East Indian Ridge	Amsterdam Island St. Paul Island	France France
17	Antarctic Ocean	Pacific-Antarctic Rise	Antarctica Antarctica	Australian Claim New Zealand Claim
18	Pacific Ocean	Chile Rise	Chile	Chile
19	Pacific Ocean	East Pacific Rise	Easter Island	Chile
20	Pacific Ocean	Galapagos Spreading Centre	Galapagos Islands	Ecuador
21	Pacific Ocean	East Pacific Rise	Mexico	Mexico
22	Pacific Ocean	Gulf of California Spreading Centre	Baja California	Mexico
23	Pacific Ocean	Gorda Ridge	Oregon, California	USA
24	Pacific Ocean	Juan de Fuca Ridge	British Columbia	Canada
25	Pacific Ocean	Endeavour Segment	British Columbia	Canada
26	Pacific Ocean	Explorer Ridge	British Columbia	Canada

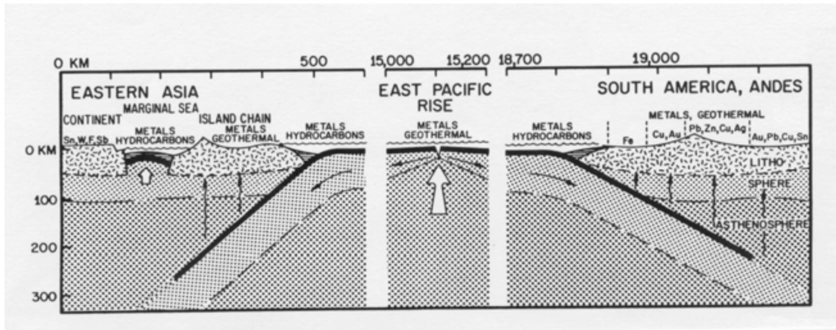

Figure 4. A diagrammatic east-west cross-section of the Pacific Ocean between South America and eastern Asia shows the relation of potential mineral and energy resources to submerged divergent (East Pacific Rise) and convergent (Pacific margins) plates, as discussed in the text (8). Metal deposits including massive sulphides may occur in ocean crust represented by the black layer at the top of the lithosphere.

Examples of these settings at the front and back sides of volcanic island chains are, respectively: 1) the Sunrise deposit in the collapsed crater of an active seafloor volcano in the fore arc side of the Isu-Ogasawara Arc south of Japan (9), and; 2) the PACMANUS hydrothermal field in the Manus back arc basin on the north side of Papua New Guinea (10), which is under development for mining. A characteristic of these mineralised seafloor sites in the western Pacific is that they lie not only within the 200 nautical mile zone of adjacent coastal states but, in certain cases, lie in overlapping 200 nautical mile zones.

The massive sulphide and manganese deposits precipitated from relatively high-and low-temperature hot springs, respectively, occur primarily in the volcanic rocks of the ocean crust that is typically the upper 5 kilometres of the lithosphere. Metallic mineral resources of the Earth's mantle, which underlies the ocean crust, are poorly known because of limited exposures of these deeper sub-seafloor rocks. The types of deposits anticipated in the upper mantle comprise chromium in the form of podiform chromite deposits and nickel- and platinum-rich mineral phases.

4. Marine Minerals Related to Continental and Deep Ocean Sources

4.1 Manganese Nodules

Ever since John Mero published his book, "The Mineral Resources of the Sea", in 1965 ([11]) when he has a graduate student studying marine geology, manganese nodules have been the quintessential deep ocean mineral. Mero's estimates of the *in situ* value of the metals contained in manganese nodules without accounting for the substantial costs of recovery and refining created a "gold rush" mentality about marine minerals at that time which contributed to drive the development of the UN Convention on the Law of the Sea (UNCLOS). The golf- to-tennis-ball sized nodules lie on and in sediment that covers the seafloor in the vast expanses of the abyssal plains of the world's ocean basins (Figure 1). The portion of the nodules that protrudes above the surface of the seafloor sediment is precipitated from metals dissolved in seawater (authigenic or hydrogenous origin; Table 1), while the underside of the nodules accumulates from metals dissolved in the pore water of the sediment (diagenetic process; Table 1) over millions of years. The metals come from two sources. Manganese and other metals are dissolved by weathering of rocks on continents and transported into the ocean by rivers. At the same time hot springs at sites along submerged volcanic mountain ranges (divergent plate boundaries) discharge dissolved metals into the ocean. The result is a mixture of copper, nickel, manganese, cobalt and iron in the nodules that varies in different regions of the ocean related to proximity to sources of the metals and other factors.

4.2 Cobalt-rich Ferromanganese Crusts

Sources of metals that form cobalt-rich ferromanganese crusts of the deep ocean are derived from both continental and deep ocean sources and are precipitated from seawater like manganese nodules ([12]). The metals in addition to iron and manganese include cobalt, nickel, platinum, and titanium depending on proximity to different sources. These metals precipitate at slow rates over millions of years as crusts up to about 25 cm thick on hard-rock substrates of seamounts and submerged volcanic mountain ranges between ocean depths of 400 and 4000 meters. These crusts are most widespread in the Pacific Ocean because of the large number of seamounts present. Recovery and refining of these crusts is more challenging than that of manganese nodules that lie loose on the seafloor or massive sulphides that form compact mounds, because the crusts adhere to the hard rock substrate over large areas.

5. Exploration Methods for Marine Minerals

Exploration for a seafloor mineral deposit involves many variations to achieve two basic objectives:

1) Determine where the mineral deposit is located.

2) Determine physical, chemical and, in cases, biological properties of the deposit and its seafloor setting.

1) Finding the deposit: The first objective, determination where a seafloor mineral deposit is located, involves starting the exploration within the seafloor province where that type of mineral deposit is known to occur, but at unknown distances from deposits that may be present within that province. Then apply complementary exploration methods that will sense diagnostic properties of that type of deposit and its specific setting starting at some distance from a potential deposit and gradually coming closer, which is, closing range to the deposit. The systematic exploration strategy to find a deposit on the seafloor is to progressively close range from far to near according to the sensitivity to detection of physical and chemical properties of the deposit (Table 3).

Table 3. Exploration strategy to find a seafloor mineral deposit (modified from 14, 15)

Distance (m) to a seafloor mineral deposit (e.g. massive sulphide deposit in an active hydrothermal field)	**Platform: Method**
10^4 to 10^6 (10 to 1,000 km)	Ship: Regional water sampling Concentration gradients of dissolved and particulate metals (Fe, Mn) and dissolved gasses (^3He, CH_4, H_2)
	Ship: Regional sediment sampling Concentration gradients of Fe and Mn
10^3 to 10^4 (1 to 10 km)	Ship: Bathymetry
	Ship: Magnetics
	Ship: Gravity
	Ship: Long-range side-looking sonar
10^2 to 10^3 (100 to 1,000 m)	[1]ROV or [2]AUV: Short-range side looking sonar
10^1 to 10^3 (10 to 1,000 m)	[1]ROV or [2]AUV: Seafloor images
10^1 to 10^2 (10 to 100 m)	Ship: Dredging
10^1 to 10^2 (10 to 100 m)	[3]HOV, [1]ROV or [2]AUV: Near-bottom water, sediment rock sampling, imagery
10^0 to 10^1 (1 to 10 m)	[3]HOV or [1]ROV: imagery, in situ measurements, sampling

[1]ROV: Remotely Operated Vehicle
[2]AUV: Autonomous Underwater Vehicle
[3]HOV: Human Occupied Vehicle

Let us consider this approach of closing range to a potential mineral deposit using as an example an actively forming massive sulphide deposit in the seafloor province of a submerged volcanic mountain range at a divergent plate boundary (13-15). This strategy was successfully used to discover the TAG hydrothermal field on the Mid-Atlantic Ridge, the first hot springs and massive sulphide deposits found anywhere in the deep Atlantic Ocean ([16]). Hot springs associated with an active massive sulphide deposit will discharge certain metals in dissolved and particulate form (iron and manganese) and dissolved gases (helium) that can be carried by deep ocean currents for distances of hundreds of kilometres from a source. These components can be detected in water samples recovered from appropriate depths by standard shipboard water sampling methods. Certain of these metallic mineral particles from black smokers will settle through the water column to the seafloor where the metallic mineral component can be detected in cores of seafloor sediments. The general location of seafloor hot springs can found by following concentration gradients of these metallic signals in the water column and in seafloor sediments. At ranges of tens to several kilometres (thickness of the water column in the deep ocean), shipboard bathymetric and magnetic methods and near-surface towed side-scan sonar can be employed to determine the seafloor setting and detect a characteristic magnetic signature ([17/], [18/]) of either an active or inactive massive sulphide deposit. When within kilometres of the hot springs, various *in situ* sampling (water, particles, seafloor sediment) and imaging (photos, video, and side-scan sonar) methods can be used on various types of unmanned deep submergence vehicles at altitudes up to tens of meters above the seafloor to locate the massive sulphide deposit. These unmanned deep submergence vehicles comprise Remotely Operated Vehicles (ROV) which are tethered to the ship and controlled though an electrical or electro-fibre optic cable with a real-time video link to the operators, and Autonomous Underwater Vehicles (AUV) which are free-swimming and are programmed to perform imaging, sampling and other measurement procedures. Manned submersibles, also known as Human Occupied Vehicles (HOV), may be used for direct observation, sampling and measurements after the massive sulphide deposit has been targeted (15).

2) Characterizing the deposit: Having found the marine mineral deposit, the next objective is to accurately determine the detailed physical, chemical and, in cases, biological properties of the deposit and its seafloor setting. This may be accomplished using the "nested survey" strategy, which starts with surveying the seafloor setting of the deposit and progressively obtains more detailed information of the deposit itself employing many of the same exploration methods used to find the deposit ([19/]). Following through with the case of the deep ocean massive sulphide deposit, the exploration methods described so far provide direct information on that part of the massive sulphide deposit exposed on the seafloor and only indirect information on the portion beneath the seafloor. Recall that in

describing the active sulphide mound in the TAG hydrothermal field, the surface expression is only the "tip of the iceberg" (Figure 3). Drilling is required to directly determine the third dimension including grade and tonnage of a massive sulphide deposit on the seafloor just as for such as deposit on land. For massive sulphide bodies on land hundreds of holes each tens to hundreds of meters long spaced meters apart may be drilled to recover almost continuous cores of the material penetrated. These cores are used to determine the shape, grade and tonnage of the massive sulphide mound and underlying feeder/stockwork zone (Figure 3). Present capability to drill a massive sulphide body at a water depth of several kilometres in the deep ocean is far more limited. For example, the active sulphide mound in the TAG hydrothermal field is one of only two such mounds that have been drilled to date by the Ocean Drilling Program (ODP). ODP Leg 158 spent two months at sea in 1994 and with formidable technical difficulty drilled 17 holes up to 125 meters long with overall core recovery of 12 percent ([7/]). Drilling methods for massive sulphide deposits and associated volcanic rocks in the deep ocean are being improved, but will fall far short of land standards for the foreseeable future.

6. Environmental Considerations

Marine organisms are associated with marine mineral deposits and must be considered with reference to exploration and mining activities. Some observations of biodiversity of these organisms in the context of seafloor settings exclusive of and associated with deep ocean hot springs are, as follows:

1) Deep ocean exclusive of hot springs:

   - Marine species diversity in the deep ocean is comparable to that in tropical rainforests ([20/]).

   - The species diversity of marine life is so high that an investigation found new species in every square meter of seafloor sediment sampled ([21/]).

2) Deep ocean hot springs at massive sulphide deposits:

- Every seafloor hydrothermal field examined to date has some species that are not found in any other field ([22/]).

Varieties of heat-loving microbes (thermophiles) are associated with the seafloor hot springs at polymetallic massive sulphide deposits. These microbes are of great interest to science and to industry. Analysis of their genetic material indicates that certain of these microbes are at the base of the tree of life and their study may elucidate the origin of life. Bioactive compounds found in these microbes are already employed in replicating DNA for forensic and medical applications (polymerase chain reaction), enhancing flow in deep oil wells, and hold promise for use in high-temperature industrial processes, as well as for pharmaceuticals applicable to cancer and other diseases.

7. Summary and Conclusions

Continental margins (continental shelf, slope and rise) have great potential for a broad spectrum of metallic and non-metallic mineral deposits (Figure 1). However, actual mining to date has been limited to a small number of placer metal (tin, gold, titanium, chromium, barium, zirconium, and rare earth elements) and non-metal (diamond, thorium, lime, sand and gravel, water) deposits (Table 1). The most common and widespread materials comprising sand and gravel (construction and beach replenishment), seawater for desalination into freshwater (domestic and agricultural water supply), and phosphorite (fertilizer) hold particular potential for future growth because water, shelter and food are essential for survival. The need exists for an up-to-date estimate of the annual quantity and value of marine minerals produced.

In contrast to external processes of erosion, river transport, and motions of the ocean that concentrate minerals derived from continental rocks onto continental margins, internal processes predominate in concentrating minerals in the deep ocean. These deep ocean processes involve transfer of heat and material from the Earth's interior to the lithosphere and ocean at submerged plate boundaries with concentration of massive sulphide deposits (copper, iron, zinc, silver and gold) by hot aqueous (hydrothermal) solutions over thousands of years as a product of these processes (Figure 2; Table 2). Manganese nodules (manganese, nickel, iron, copper, cobalt) which lie on and in sediment that covers the vast abyssal plains of the deep ocean and cobalt-rich ferromanganese crusts that accumulate on bare rock outcrops of seamounts and submerged volcanic mountain ranges accumulate slowly (millions of years) by precipitation from seawater. None of these types of marine minerals are renewable resources, as they all require thousands to millions of years to accumulate (Figure 3). Marine organisms and microbes are associated with marine mineral deposits in all regions of the ocean and must be considered in exploration and mining operations because of their value for preserving biodiversity, understanding evolution, and manufacturing useful products. Knowledge of marine minerals is expanding rapidly driven by advances in basic scientific research on Earth and ocean processes.

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SUMMARY OF THE PRESENTATION AND DISCUSSIONS ON SEAFLOOR MASSIVE SULPHIDES DEPOSITS AND THEIR RESOURCE POTENTIAL

Presentation

Professor Peter Rona of the Institute of Marine and Coastal Sciences, Rutgers University thanked the Secretary-General and his Deputy for the opportunity to contribute to this important workshop. He said that he had been requested to give a broad overview of marine minerals, with particular emphasis on seafloor massive sulphides deposits of the deep ocean basin. He stated that on the subject of marine mineral resources, he would start with those mineral deposits that are derived from continental sources, and then move on to deposits that are derived from deep ocean sources, and then deposits that are derived from a combination of continental and deep ocean sources. He said that his presentation would conclude with some exploration and environmental considerations. Based on the International Seabed Authority's request, he also said that his presentation would be from the perspective of a policymaker, whose object was to frame the rules, regulations and procedures for exploration and mining of these potential resources of the ocean.

Professor Rona started his presentation by nothing that the International Community's vision of ocean minerals is expanding very rapidly in response to the development of new scientific knowledge of the oceans and of the earth. Starting in the 1960s, before the advent of the theory of plate tectonics, he further noted that the ocean basins were though of as large passive containers for the ocean. Professor Rona explained that as a consequence of the knowledge gained through the theory of plate tectonics, the ocean basin was no longer considered a passive sink for material washed in from land, but is an active source of heat and materials that create marine mineral resources. He further explained that metallogenesis of marine minerals is now viewed as a product of both continental sources of metals external to the ocean and sources at submerged plate boundaries internal to the ocean.

With regard to marine mineral deposits, Dr. Rona stated that marine metal and non-metal, non-fuel mineral deposits were considered to be primarily derived from the erosion of continental rocks and carried into the sea by rivers in solid (sediment) or dissolved phases. The minerals accumulated as beach and placer deposits of various heavy minerals containing metals and non-metals of terrigeneous origin. Dr. Rona identified two provinces for mineral occurrences. First, the province of the continental margin consisting of the continental shelf, slope and rise and then the deep ocean basin with the submerged volcanic mountain ridge that runs through all the ocean basins of the world and the vast abyssal plains.

He noted that in relation to placer deposits which are mechanically eroded from source rocks on the continent and are deposited in sediments on the continental margin, it is only the most accessible of these deposits in particular those that are exposed on or near the sea floor, that we have know about. He pointed out that placer deposits may also be deeply buried within the sediments of the continental margin utilizing a global map he showed the distribution of marine placer deposits around the world. He stated that there are probably fewer sites of metals and non-metals, fewer than about 20 sites that have actually been operational. He identified on the map gold placer sites off Alaska that have been intermittently active depending on the price of gold. He stated that there is hardly any activity involving marine placer deposits off South America. He identified locations of offshore coral deposits off Great Britain and Italy. In relation to Africa, he noted that diamonds have developed into an important industry and said that the workshop looked forward to learning more about that from Mr. Corbett. Professor Rona informed participants that off south East Asia there are a number of metal sites - chromite sites off in Indonesia and Sulawesi Island, a gold site off New Zealand, and tin mining sites offshore Thailand and Indonesia With regard to common materials - sand and gravel he noted that this marine mineral that is very important for the construction industry and for concrete has represented nearly half of the offshore hard mineral mining industry. Another important untapped resource he explained are marine phosphorites which precipitate from deep sea water rich in phosphate as the deep water up wells in certain areas of the ocean basins specifically, those areas in the trade wind belts, up to 30 degrees north and south of the equator.

Professor Rona described seawater as a chemical soup that contains many salts. He identified sodium chloride as a product of the salts, stated that an even more important production is desalination, separating fresh water from seawater. While noting that desalination is practiced in certain parts of the world, Dr. Rona emphasized that this practice is growing because the need for an adequate and safe supply of water is one of the world's principal needs. Professor Rona informed participants that various desalination methods including reverse osmosis have been developed to extract fresh from salt water. He noted that these methods are energy intensive, but concluded that they will come into increasing use.

The theory of plate tectonics, according to Dr. Rona has revealed ocean basins as poor containers for the ocean. The sea floor, he continued, is now known to be full of fracture, where in many places on the deep seafloor, heavy, cold, dense seawater penetrates through these fractures. Seawater sinks down through the ocean, lithosphere and is re-assimilated into the earth’s interior. Professor Rona informed participants that in certain places where there are hot, molten rocks or magma at depth, seawater is heated, expands, becomes lighter, and buoyantly rises through the fractures with significant chemical actively. Elements, dissolved from the volcanic rocks of the ocean crust, rise up to the seafloor with the seawater. At or beneath the seafloor, the rising seawater is cooled and is mixed with the surrounding seawater. As a result of this process, Dr. Rona explained that metals are deposited and discharged from the seafloor as spectacular black smoker vents.

In relation to areas where one finds hot rocks welling up at depths beneath the seafloor, Dr. Rona described these areas as seafloor spreading. At spreading centres, Professor Rona continued, the hot rocks well up, cool, solidify, and accrete to either side of a submerged volcanic mountain range, forming two conveyor belts of new ocean lithosphere at a rate of centimetres per year. With regard to the geographical distribution of seafloor spreading centres, Dr. Rona described then as global, part of the largest, geographic feature one earth, and hidden from sight because it is covered by seawater. Professor Rona informed participants that this submerged volcanic mountain range that extends through all the major ocean basins is called the Mid-Ocean Ridge.

Focussing on sites of sea floor mineralisation that have been discovered, Dr. Rona informed participants that the first discovery came by chance in the 1960s in the Red Sea at the same time of the development of the theory of plate tectonics. Professor Rona described an international Indian Ocean expedition, during which various ships that were transiting through the Red Sea coming to and from the Indian Ocean, ran the echo sounders on their ships in the course of transits, and got reflections from layers within the water column that were totally anomalous. He pointed out that usually the reflections from the echo sounders come back from the sea floor. When samples were taken in the area, it was found that the reflect surfaces were layers of highly salty metal and rich water at certain places along the axis of the Red Sea. Dr. Rona explained that the Red Sea is a part of a plate boundary where sea floor spreading is occurring, i.e. carrying Saudi Arabia and Africa apart at a slow rate of centimetres per year. Professor Rona further explained that Saudi Arabia and Africa are about 200 kilometres apart at this time. Along the axis of the Red Sea where the hot rocks are welling up from the earth's interior in this submerged plate boundary, there are several deep basins from which hot springs are welling up from the sea floor. The largest of these basins is the Atlantis II Deep he pointed out, just west of the sacred city of Mecca.

Professor Rona remarked that the thick layers of rock salt, formed at a time when the Red Sea’s circulation was restricted by surrounding landmasses, represented a special phenomenon. He noted that at that time there was more inflow and evaporation than inflow. He briefly reviewed the history of the formation of these deposits; namely the penetration of cold, heavy seawater into the lithosphere, the subsequent dissolution of metals and salts into this heavy seawater as it passes through volcanic rocks, the heating of this body of water by the hot rocks and the up welling of it beneath the axis of the Red Sea, and its final discharge as a metal rich brine that is heavier than surrounding seawater. Dr. Rona described this process of concentration of metals as a most efficient one. He noted that the Red Sea brines deposit is the largest seafloor hot spring deposit known on earth at this time. With regard to the resource evaluation of the metals to be found in the Atlantis II Deep, Professor Rona informed participants that the volume of brines had been estimated at 94 million tonnes dry weight containing 2 percent zinc and 0.5

percent copper. In addition, small but significant amounts of silver and gold had been found in the deposits.

In connexion with the mining of this deposit, Professor Rona described the efforts by the German geophysical company Preussag and the Governments of Saudi Arabia and Sudan to do this with the assistance of slides. Dr. Rona noted that the deposit occurred within the Exclusive Economic Zones of Sudan and Saudi Arabia. He said that in 1979, a pre-pilot feasibility-mining test, using an adapted offshore oil-drilling vessel (the Sedco) was carried out. Given the consistency of the brines that Dr. Rona described as Jello, a hydraulic suction cutter head was used. Dr. Rona stated that this technological configuration was successful in sucking up the metalliferous brines and raising them up to the surface vessel. On the surface vessel, which was equipped for processing through flotation techniques, Dr. Rona explained that by bubbling air through the sediments a significant fraction of the zinc was separated out from the slurry. While the feasibility of mining was demonstrated, the economic feasibility of the operation is yet to be demonstrated.

In 1978, a French/Mexican/American expedition, using the French manned submersible CYANA, made a transit across a portion of the global submerged volcanic mountain range called the East Pacific Rise, off Mexico just south of the Gulf of California. Dr. Rona stated that the expedition was planning to do a standard geological transit in water depth of about 2,000 metres across the submerged volcanic mountain range. In the course of this transit, Dr. Rona informed participants that the expedition encountered curious green mounds, up to about 10 metres high, that they were very different from the normal volcanic rocks of the deep sea floor. Out of curiosity, he continued, the expedition sampled the material and then continued its traverse, describing the geology and structure of the East Pacific rise. At IFREMER in France, a visiting geologist saw these rocks, and asked where the rocks had been recovered. Dr. Rona said that the green rocks turned out to be massive sulphides rocks, the first massive sulphides specimens to be found in the deep ocean basin. Professor Rona pointed out that many scientific discoveries are made by chance, serendipity. He explained that the scientists in the expedition immediately came together and wrote a classic paper that made the cover of the prestigious international scientific journal "Nature". The subject of the paper was the first deep-sea polymetallic sulphides deposit making the connection between the Red Sea and the deep ocean. The paper showed that as an ocean basin continues to open, about one of these submerged sea floor spreading centres; the deposits continue to be formed.

Continuing his presentation, Dr. Rona said that the next year in 1979, the American submersible ALVIN, made a dive at the same location. He noted that the implication of these polymetallic massive sulphides deposit was that they are deposited from very hot, hot springs, but that nothing was observed on the dives with the CYANA in 1978. He pointed out that an objective of the dives in 1979 with Mexicans, French and Americans working together was to look for the hot springs. He said that the expedition landed in the normal volcanic rocks of the deep sea floor and started the normal deep ocean sea floor that was paved with volcanic rocks. Dr. Rona said that within kilometres of those curious green mounds, the expedition came upon a chimney, several metres high, billowing clouds of black smoke. The expedition members stated that "This looks like a factory smoke stack", thus the name "Black Smoker". The black smoker he informed participants, is composed of mineral particles that crystallize from the hot springs. He pointed out that the expedition was unable to take temperatures or samples and thus its members were fortunate to come back alive because the plastic windows on the submersible could have melted in the temperatures to be found at the site. Dr. Rona said that the expedition returned a year later with new heat tolerant instrumentation found out that the temperatures went up to about nearly 400 degrees Celsius. The expedition also found that the structures were mineralised chimneys deposited from the hot springs that flowed up through them. The cavities inside the chimneys were lined with bright crystals of sulphides of iron and copper- iron and copper sulphides and that these chimneys grew up to tens of metres high, and then simply collapsed and toppled over, accumulating an apron of polymetallic massive sulphides around their base.

Dr. Rona remarked that another unexpected surprise was the discovery of a dense and spectacular biological community at 2000 metres down in pitch darkness and shut off from the light of the sun. An oasis of life was found, not only of life but also of new life forms such as giant tubeworms, which grow about as high as a person. He pointed out red plumes on the top of the tubeworms, giant clams growing to exceptionally large sizes were found growing in the cracks between the lava flows, and hot springs that were discharging enriched in hydrogen sulphide. Dr. Rona informed participants that the clams have specially adapted to conditions and that they have a high level of haemoglobin in their blood to extract oxygen from this toxic environment and survive. He noted that studies on these life forms help in studies of survival in toxic environments.

Dr. Rona stated that a question that the members of the expedition asked themselves was how this ecosystem that contained this oasis of strange new life forms in the deep dark ocean, was being supported. He stated that it was discovered that support was in the form of bacterial material that blows out of cracks in the seafloor and that accumulates like snow fall in the hot spring areas. It was found that the bacteria microbes use chemicals, in particular hydrogen sulphide that is dissolved in the hot springs and that comes from the underlying rocks, as an energy source to obtain carbon, hydrogen and oxygen from the surrounding seawater. They then combine them into carbohydrates to sustain themselves. He said that the microbes, in turn, sustain the higher life forms that eat them such as the tubeworms and clams. Professor Rona emphasized that the oasis of life at the hot springs on the seafloor were therefore completely district from life as seen on land which is dependent on energy from the sun with green plants using that energy to manufacture food at the base of the food chain. He noted that in the ecosystem at the hot springs on the deep seafloor, the energy source is the earth's interior chemical energy.

He identified some findings about the microbes. These included the tree of life, Eucaryota and multi-celled organisms such as Archaea. He informed participants about the use of some of these microbes in replicating the genetic material called DNA. He also said that new uses for these microbes were being discovered all the time. In this regard, he described the use of an enzyme produced by these thermophiles to enhance the flow of oil in wells, and new applications of the bioactive compounds for pharmaceuticals.

Professor Rona recalled that the initial hot springs that were discovered were along the axis of the East Pacific Rise where the hot material wells up at a relatively fast spreading rate. He stated that the East Pacific Rise is part of the Pacific Ocean basin referred to as the "Ring of Fire" because it is the most volcanically active region of the earth. He further stated that after this discovery, it was initially felt among the scientific community that slower spreading centres in the Atlantic and Indian Ocean mountain ranges would not have hot springs.

Dr. Rona described an expedition that he led that resulted in the discovery of the first black smokers, polymetallic massive sulphide deposits, and vent ecosystem in the Atlantic while overcoming the consensus of the scientific community that such phenomena could only occur in the volcanically more active Pacific. He pointed out that his team had certain clues that there should be hot springs in the Atlantic such as where the submerged volcanic mountain range projects above water in the island of Iceland.

Professor Rona described the exploration strategy used by his team to discover the TAG hydrothermal field on the Mid-Atlantic ridge, the first hot springs and massive sulphides deposits found anywhere in the deep Atlantic Ocean. He acknowledged the strong support that the team obtained from the United States National Oceanographic and Atmospheric Administration (NOAA), which provided various instruments for remote and direct sensing of the seafloor. He also provided participants with a broad view of how various techniques were used in the discovery of the TAG deposits.

The strategy outlined by Professor Rona for finding an actively forming deposit consisted of using knowledge of the seafloor province where such a deposit could occur and utilizing the physical and chemical properties of the deposit to identify its exact location.

To address the question of where hot springs may be found on the mid-Atlantic ridge, Dr. Rona said that one of the tools used were water samples. If there were indeed hot springs, metals from the hot springs would be carried out by currents for hundreds of kilometres. Elevated levels of certain metals would indicate the presence of hot springs somewhere on the deep seafloor. Another tool used was to determine if there were elevated levels of metal particles in the normal deep-sea sediments. Thus is because the metal particles coming out of the black smokers would also be carried out by the currents over great distances and would settle on the deep-sea sediments. By following concentration gradients of these metals in the water column and in the sediments on the seafloor, Professor Rona stated that his team felt that it would progressively get close to the possible source of these materials.

Using slides, Professor Rona took participants on a tour of the exploration work that was conducted. There were images of the dives by the submersible Alvin, the production of bathymetric contour maps using satellite navigation, discovery of the target deposit, photographs of the deposit, sampling of the deposit, identification of new life forms and drilling the deposit to enable its volume to be determined.

With regard to some of the technologies used, Dr. Rona presented participants with images of, *inter alia*, the water sampling bottle used to ascertain if there were elevated levels of certain metals in the water column, a sediment core showing dark layers of sediment containing enriched metals in the sediment, the echo sounder(s) used to determine the depth and shape of the seafloor, how satellite navigation is used to give positioned accuracy and how instruments aboard the Alvin submersible were used to make various measurements like temperature, to sample and to drill the deposit.

Professor Rona presented some slides of the TAG hydrothermal field showing the broad array of biodiversity that is to be found in association with the massive sulphides deposit. Starting in normal seafloor around the mound, lava flowed normally and deep sea sediments were shown looking very much like a desert. Suddenly, the colour oasis of the mound came into view, followed by the hot springs themselves. There were bright green rocks (massive sulphides) and different types of fish. There were also chimneys up to several metres high that are no longer active. Closer to the mound were dome shaped chimneys, several metres high that were discharging blue-white smoke. These are the white smokers made up primarily of iron sulphides (pyrite). Professor Rona informed participants that because these dome shaped chimneys reminded his team of the domes on Old Russian churches like St. Stephen's in the Kremlin area, they dubbed the area the "Kremlin Area". A little further from this area, they encountered a higher temperature discharge and a cluster of black smokers venting intensively. Around these black smokers was a mass of moving and wriggling white material. These materials turned out to be shrimp of a new variety swarming over the active black smokers. Each of the shrimp was about 5 centimetres and the team initially named them 'Rimicaris exocculata' or 'Dweller in the rift without eyes'. Upon dissecting the shrimp on land, they discovered a plate with a reflecting organ connected by nerve ganglia to the brain of the shrimp. A chemical analysis of the organ found a compound in it called rhodopsin, which is uniquely associated with the eyes of other animals. He informed participants that it is speculated that the shrimp may have developed this unique eye as an adaption to feeding on bacteria at the hot springs.

Professor Rona described another cruise that was made in 1994 to determine what happens beneath the seafloor at the TAG mound. The vessel used was an offshore drilling ship that was modified for drilling in the deep ocean. Called the Joides Resolution, Professor Rona informed participants that a consortium of 20 countries that work together on the Ocean Drilling Programme (ODP) supports it. He further informed participants that with great difficulty, 17 holes were drilled into these massive sulphides deposits. Based on these drill holes, Professor Rona showed the components of the deposits: the massive sulphide itself, the feeder zone where the hot solutions well up, and the stock work where the minerals are deposited in a fracture network. Professor Rona said that based on radiometric dating of the TAG mound deposit, it had been determined that the range of dates inside the deposit was between thousands to tens of thousands years old. He concluded his presentation on the TAG mound by informing participants that this massive sulphide deposit, is one of the largest seafloor deposits yet found in the world.

Professor Rona stated that by studying these analogues in the deep ocean basin, a very helpful key is provided to economic geologists on land. These geologists in turn help marine geologists to explore and understand massive sulphides that are forming on the deep seafloor. Dr. Rona compared the assessment of a polymetallic massive sulphides deposit on land with its counterpart on the deep seafloor. He stated that on land, geologists drill hundreds of cores into that deposit to determine size, grade, tonnage and distribution of mineralised zones. On the seafloor, pointing out that Professor Herzig was co-chief scientist on the TAG mound drilling expedition, Dr. Rona stated once again that 17 holes were drilled into that deposit. He informed participants that overall core recovery was 12 per cent as compared with nearly continuous recovery of cores that are just spaced metres apart for ancient massive sulphides on land. They observed that sampling ability for that type of assessment on the seafloor is limited and would remain like that for the foreseeable future.

Having presented information on seafloor massive sulphides, Professor Herzig turned his attention to mineral deposits that may be found beneath the ocean crust in the upper mantle of the earth. He presented a map showing the entrance to the Persian Gulf and the coastal State of Oman. He pointed out that this area had one of the best exposures of ocean crust, thrust up from the seafloor and exposing the upper portion of the earth's mantle between the curst. He pointed out a chromite deposit and said that in future chromite, platinum and nickel sulphides deposits may be discovered in the deep ocean.

Dr. Rona said that the ocean lithosphere that is created at the submerged volcanic mountain ranges in the Atlantic and eastern Pacific oceans are destroyed at plate boundaries around the Pacific. In this way, the earth counterbalances the lithosphere that is created at the submerged volcanic mountain range. He said that where the lithosphere is destroyed, volcanic island chains are created and behind volcanic island chains, there are spreading centres very similar to those at ocean ridges. Dr. Rona showed participants two provinces related to the volcanic island chains in the western Pacific Ocean; an area in from of the arc and a spreading centre behind the arc called the 'back arc basin'. He stated that a new discovery of polymetallic massive sulphides had been made in front of the arc just south of Japan, in the Isu Ogasuwara arc, called the sunrise deposit. In relation to back arc basin deposits, Professor Rona provided an example in the Manus basin called the Pacmanus deposit that is under development by Nautilus Minerals of Australia. He expressed his desire to hear more about this deposit from Mr. Julian Malnic.

He noted that another product of hot springs, in addition to minerals and biological organisms is heat. He illustrated potential areas within the Pacific Ocean basin that are potential geothermal resources. He suggested that so far geothermal energy has only been practiced to tap where the submerged volcanic mountain range intersects land such as in the Gulf of Mexico. He also informed participants that one such deposit was being exploited in Cero Prieto in the Gulf of Mexico.

With regard to marine mineral deposits that have a double source, the continents on the one hand and the deep ocean basin on the other hand, Dr. Rona indicated that a primary example was polymetallic nodules. He stated that prior to the advent of plate tectonics, it was thought that all the manganese in this resource was supplied by manganese dissolved from continental rocks and carried into the ocean by rivers. He noted that while this hypothesis may have been adequate to explain the source of manganese and some of the associated metals, the composition of the nodules in terms of cobalt, nickel, iron and manganese is related to proximity to sources of hot springs and other factors.

On environmental considerations, Professor Rona mentioned that the seafloor contains a high biodiversity with millions of species. He said that the species diversity of marine life is so high that an investigation found new species in every square metre of sediments sampled. He noted that although sediments appear barren, they are actually full of life. With regard to hot springs, Dr. Rona said that every hydrothermal field examined to date has some species that are not found in any other field. He mentioned the need for environmental assessment prior to mining and working towards a common taxonomy for these animals.

Dr. Rona ended his presentation by noting that only 5 percent of the deep ocean basins have been explored. He emphasized that all deposits that have been found are associated with some living organisms. He concluded by saying that the international community's discoveries of mineral and living resources will continue to expand with advances in scientific knowledge of earth and ocean processes.

SUMMARY OF DISCUSSIONS

The discussions that took place following Professor Rona's presentation focussed on the massive sulphides deposits in the Red Sea (the metalliferous sediments), some of the differences between this deposit and known massive sulphides deposits on the ocean floor, characteristics of ocean floor massive sulphides deposits, and the potential for harnessing geothermal energy from the ocean floor.

A participant with eight years experience in the effort to delineate and mine the Red Sea deposits pointed out that the first significant data and information on these deposits were obtained in 1947 by the Albatross research vessels of Sweden. This expedition recorded enormous changes in temperature and salinity at depth in the Red Sea. Temperatures increase with depth, from 20°C at the surface to 27°C at a depth of 2,000 metres, and precipitously to 60°C at a depth of 2,200 metres. He also said that the change in salinity was similar; it is ten times as much as normal ocean salinity. He wanted to know whether Dr. Rona's remarks on the exploration and exploitation of ocean floor massive sulphides were applicable to the Red Sea deposits. He also wanted to know whether or not it was possible to find deposits such as the Red Sea deposits on the mid-Atlantic ridge or the East Pacific rise.

With regard to the discovery of the Red Sea deposits, Dr. Rona while agreeing that the Swedish Deep-Sea Expedition led by Professor Hans Petterson in 1947 and 1948 recorded the anomalies in temperature and salinity, informed participants that at the time, the anomalies did not spark any interest. The data on these anomalies were only examined in the 1960s following measurements taken by echo sounders.

On the matter of the feasibility of mining the Red Sea deposits, Dr. Rona restated that the feasibility of mining the Red Sea deposits had been proven. His understanding was that they were not being mined due to economic reasons. Another participant wanted to know if there were any plans to mine these deposits and what factors would be taken into account by the Government of Saudi Arabia in this regard.

The reasons why the Red Sea deposits are yet to be mined, it was pointed out, was not merely because of the economics of the project, but due to returns that could be obtained from competing projects. Participants were informed that in the 1980s when oil prices dropped, investors (Saudi Arabia and Sudan) could not support a project that required an investment of over US$2 billion with a return on investment of between 11-17 percent.

Asked whether or not it would be possible to discover metalliferous sediment type massive sulphides deposits on the deep ocean floor, Dr. Rona pointed to the differences in the process of deposit formation in the Red Sea and in the deep ocean floor. In the case of the deep ocean floor, Dr. Rona requested participants to visualize black smokers that vent metal particles in the smoke that rises up in the water column. He said that because this smoke is warmer than the surrounding water, it draws the surrounding water in, mixes with it, and comes closer to the density of the surrounding water. Depending on the size of the vents, the smoke levels out at altitudes of between 100 and 200 metres when its density is equal tot hat of the surrounding seawater, and spreads out at the level carrying the metal particles and vent organisms in a very slow, mid-depth circulation. Dr. Rona pointed out that in the deep ocean floor, much of the metal particles are lost to the final deposit though this mid-depth circulation. With regard to the Red Sea deposits, Dr. Rona stated once again that it is one of the most efficient ore concentrating systems because as the hot springs discharge, all the metals that they vent are contained within the basins along the axis of the Red Sea.

A participant informed the workshop that the structure of the Red Sea is very unique. He said that the Red Sea in general is very narrow and deep. He noted that generally the brine pools are found at the intersection of spreading centres and transform faults. He also said that there were over 21 brine pools in the Red Sea with average depths of 200 metres, that there were no active currents at the bottom, no turbulence, and that it was a closed system.

Another participant while agreeing with the differing conditions identified earlier and noting the similarity of the tectonic environment in the Red Sea to that of the Gulf of California (large transform faults intersecting small spreading centres) stated that in the Gulf of California there were no brine pools. He emphasized that the key to brine pools was salt. He noted that the hot springs in the Red Sea are more saline than the surrounding seawater. As a result, instead of the smoke buoyantly rising, it accumulates the metals into the ponds and makes for a very efficient system for concentrating the metals.

Asked what happens to massive sulphides deposits when the ocean floor parts from the axis of the submarine mountain ridge, Professor Rona provided a number of possibilities as to their fate. One possibility that he said had been observed was their uplift and incorporation into the conveyor belts of lava and material on either side of the submerged volcanic range. He also said that in this process, the massive sulphides deposits are being decomposed/oxidized on the seafloor. Another possibility he identified was that they could be covered by sediments and by lava flows and undergo, chemical changes that could help preserve them. He suggested that such deposits would be difficult exploration targets because they would be buried. He also referred to an exploration method that had been developed base don a magnetic signature that is associated with hot springs.

Another participant stated that in Dr. Rona's presentation he had said that there were distinct biological organisms at the massive sulphide mounds but that their larvae could spread through the sub mid-ocean current. He wanted to find out if there was a gradient to describe the larvae going from the mound to other areas. In response, Dr Rona stated that there are different species at different vents and that the farther away from the vent that one looked, the greater the differences with the vent communities. He noted that the eco-system at vents in the Pacific Ocean was dominated by large tube-worms and giant clams while in the Atlantic, the ecosystem was dominated by new varieties of shrimp. He referred to the forthcoming presentation by Dr. Juniper as a better opportunity for a response to this question.

Another participant wanted to know whether or not any of the geothermal energy associated with hot springs on the ocean floor had been harnessed. If so, he also wanted to know where. Dr. Rona said that at the head of the Gulf of Mexico, there is a large geothermal power plant called Cero Prieto and that northward in the Imperial Valley of Southern California, a number of geothermal wells have been developed. He noted that while much geothermal energy is being released into the deep ocean, transmission losses are very high and that so far, it has proven ineffective or not feasible to transmit this energy over long distances from the deep ocean.

Finally, Dr. Rona was asked if any massive sulphides deposits had been discovered in island arc environments of the oceans. Dr. Rona responded in the affirmative, pointing to the sunrise deposit just south of Japan in the Isu Ogasuwara arc and in the Manus Basin.

CHAPTER 2

SEAFLOOR MASSIVE SULPHIDES DEPOSITS AND THEIR RESOURCE POTENTIAL

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Since 1979, polymetallic massive sulphide deposits have been found at water depths up to 3,700 m in a variety of tectonic settings at the modern seafloor including mid-ocean ridges, back-arc rifts, and seamounts. Many of the sulphides deposits consist of a black smoker complex on top of a sulphides mound that commonly is underlain by a stockwork zone. It has been widely established that circulating seawater that is modified in a reaction zone close to a sub axial magma chamber is the principal carrier of metals and sulphur that are leached out of the oceanic basement. Precipitation of massive and stockwork sulphides at and beneath the seafloor takes place in response to mixing of the high-temperature (up to 400°C) metal-rich hydrothermal seawater fluid with ambient seawater. Polymetallic seafloor sulphide deposits can reach a considerable size (up to 100 million tonnes) and often carry high concentrations of copper (chalcopyrite), zinc (sphalerite), and lead (galena) in addition to gold and silver. Extremely high concentrations of gold have recently been found in a new type of seafloor mineral deposit previously only known as epithermal (magmatic) gold deposits on the continents. Due to the high concentration of base and precious metals, seafloor polymetallic sulphide deposits have recently attracted the interest of the international mining industry. The recovery of those deposits appears to be both economically and environmentally feasible due to certain advantages over land-based deposits and will likely become reality within this decade. For logistical and technical reasons, future mining operations will largely focus on deposits in national rather than international waters.

1. Introduction

The discovery of high-temperature black smokers, massive sulphides, and vent biota at the crest of the East Pacific Rise at 21°N in 1979[1,2] confirmed that the formation of new oceanic crust through seafloor spreading is intimately associated with the generation of metallic mineral deposits at the seafloor. It was documented that the 350°C hydrothermal fluids discharging from the black smoker chimneys at this site at a water depth of about 2,600 m continuously precipitate metal sulphides in response to mixing of the high-temperature hydrothermal fluids with ambient seawater. The metal sulphides including pyrite, sphalerite, and chalcopyrite eventually accumulate at and just below the seafloor and have the potential to form a massive sulphide deposit. It has also been documented that circulation of seawater through the oceanic crust is the principal process responsible for the formation of massive sulphide deposits in this environment. Seawater that deeply penetrates into the oceanic crust at seafloor spreading centers is being modified to a hydrothermal fluid with low pH, low Eh, and high temperature during water-rock interaction above a high-level magma chamber. This fluid is than capable of leaching and transporting metals and other elements that eventually precipitate as massive sulphides at the seafloor or as stockwork and replacement sulphides in the sub seafloor. The resulting massive sulphide deposits can reach considerable size ranging from several thousand to about 100 million tonnes. High concentrations of base (copper, zinc, lead) and in particular precious metals (gold, silver) in some of these deposits have recently attracted the interest of the international mining industry.

In the two decades since the discovery of hydrothermal vents at the mid-ocean ridges, significant massive sulphides deposits have been discovered documented in more than a dozen different volcanic and tectonic settings around the world at water depths up to 3,700 m. Polymetallic sulphide deposits are found on fast-, intermediate-, and slow-spreading mid-ocean ridges, on axial and off-axis volcanoes and seamounts, in sedimented rifts adjacent to continental margins, and in subduction-related arc and back-arc environments (Figs. 1 and 2).

Land-based massive sulphide deposits and polymetallic sulphides at the seafloor are products of the same geological and geochemical processes and many analogies can be drawn between modern examples and base metal deposits currently being mined on land[3, 4,5,6,7]. Detailed geological, mineralogical, and geochemical analyses of massive sulphides from back-arc spreading centers of the western and south-western Pacific have indicated that these subduction-related sites represent the closest modern analogues of the majority of the economically important land-based deposits which occur in felsic volcanic rocks instead of mid-ocean ridge basalts[8]. Modern seafloor hydrothermal systems are thus excellent natural laboratories for understanding the genesis of volcanic-hosted massive sulphide deposits, and this knowledge can be translated directly to the ancient geological record on land, where evidence for the origin and nature of mineral deposits is often obscured by millions of years of geological history.

2. Geologic Setting

Following the discovery of black smokers at the East Pacific Rise, there was a rapid growth in the number of hydrothermal deposits found on fast-spreading mid-ocean ridges. So many deposits were found along fast-spreading segments of the East Pacific Rise, and virtually nowhere else, that it became widely accepted that slower-spreading ridges could not support productive hydrothermal activity. However, in 1985, the discovery of black smokers in the large TAG hydrothermal field at the Mid-Atlantic Ridge[9] offered compelling evidence that slow-spreading ridges may also be important settings for sulphide deposits. This idea has since been confirmed by the discovery of a number of further large sulphide occurrences along the Mid-Atlantic Ridge (Logatchev, Snakepit, Broken Spur, Lucky Strike, Menez Gwen[10, 11,12,13]) and the Central Indian Ridge (Sonne Field[14, 15,16]).

Shortly after the discovery at 21°N, large sulphide deposits were also discovered in sediment-filled basins in the Gulf of California (Guaymas Basin[17]). The idea that sedimented ridges might also be important sites for sulphide accumulation was confirmed in 1991 and 1996, when the Ocean Drilling Program intersected about 100 m of massive sulphides in the large Middle Valley deposit on the Juan de Fuca Ridge off-shore Canada[18, 19].

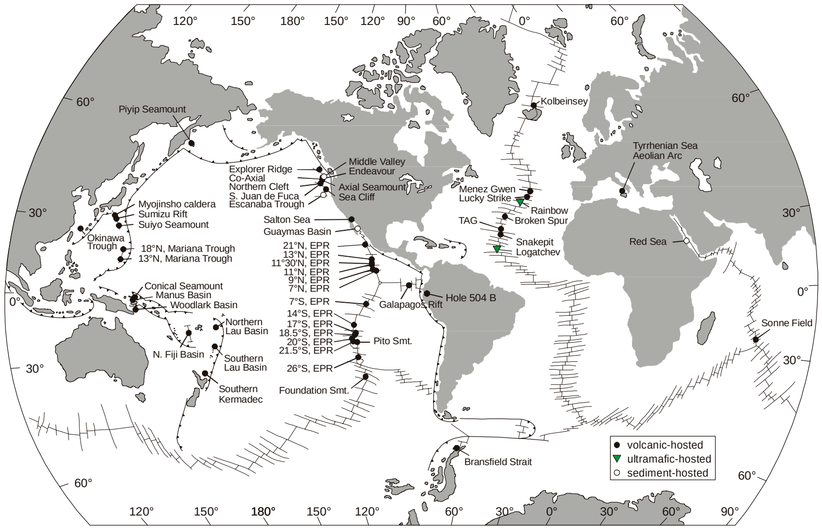

Figure1. Location of hydrothermal systems and polymetallic massive sulphide deposits at the modern seafloor.

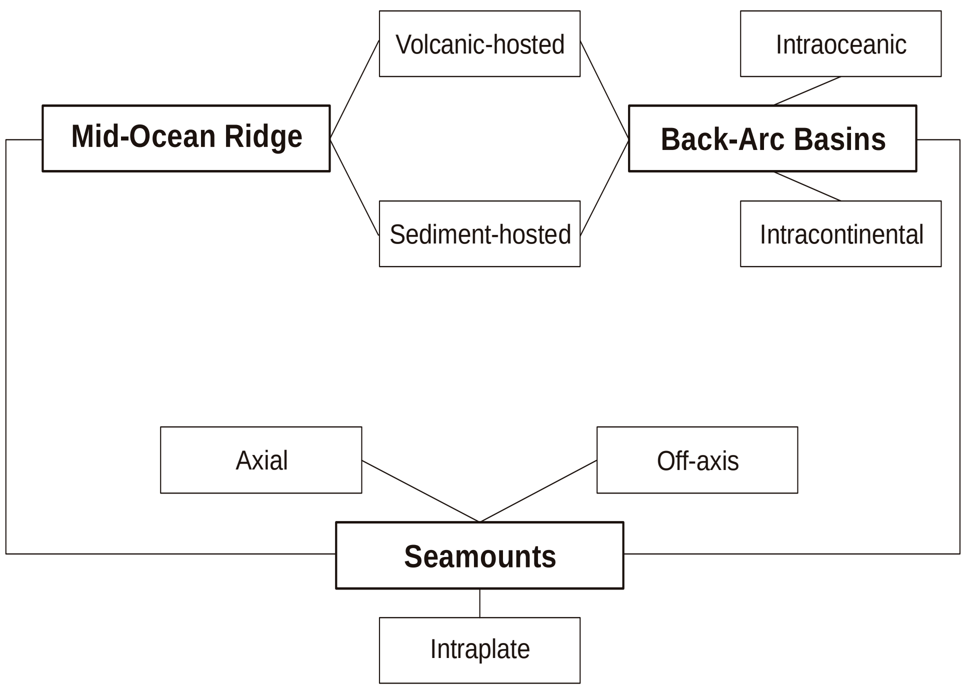

Figure 2. Simplified Diagram Showing the Diverse Geological Environments for the Occurrence of Seafloor Hydrothermal Systems. Polymetallic Massive Sulphide Deposits have been Found in all Settings Except for Intraplate Seamounts.

The first sulphide deposits reported in back-arc spreading centers were found in the Central Manus Basin[20] and the Mariana Trough[21, 22]. These discoveries led to extensive exploration of the marginal basins and the arc and back-arc systems of the western and southwestern Pacific in the late 1980s. The complex volcanic and tectonic settings of convergent margins in the Pacific suggested that a number of different deposit types might be present in this region. A wide range of mineral deposits have since been found in back-arc rifts at different stages of opening (immature versus mature), on volcanoes along the active volcanic fronts of the arcs, as well as in rifted fore-arc environments. Well-known examples of polymetallic massive sulphide deposits have been described from mature back-arc spreading centers such as the North Fiji Basin[23], along propagating back-arc rifts such as the Valu Fa Ridge in the southern Lau Basin[24], and in nascent back-arc rifts such as the Okinawa Trough[25]. In 1991, extensive sulphide deposits were found to be associated with felsic volcanism in the Eastern Manus Basin[26], and hydrothermal deposits have also been located in the western Woodlark Basin, where seafloor spreading propagates into the continental crust of Papua New Guinea[27]. Today, more than 100 sites of hydrothermal mineralisation are known at the modern seafloor[28, 29,30] including at least 25 sites with high-temperature (350-400°C) black smoker venting.

The majority of sites that have been discovered so far are located at the East Pacific Rise, the Southeast Pacific Rise, and the Northeast Pacific Rise, mainly because the first discovery of an active high-temperature hydrothermal system was made at 21°N at the East Pacific Rise off shore Baja California. Only one site has so far been located at the ridge system of the Indian Ocean, close to the Rodriguez Triple Junction[14, 15,16]. The scarcity of sulphide deposits on the Mid-Atlantic Ridge and in the Indian Ocean is, at least to a large extent, a function of restricted exploration activity in these areas. It has been assumed that today only about 5% of the 60,000 km of oceanic ridges worldwide have been surveyed and investigated in some detail.

3. Hydrothermal Convection

At oceanic spreading centers, seawater penetrates deeply into the newly formed oceanic crust along cracks and fissures, which are a response to thermal contraction and seismic events typical for zones of active seafloor spreading. The seawater circulating through the oceanic crust at seafloor spreading centers is converted into an ore-forming hydrothermal fluid in a reaction zone that is situated close to the top of a sub axial magma chamber (Fig. 3). Major physical and chemical changes in the circulating seawater include (i) increasing temperature, (ii) decreasing pH, and (iii) decreasing Eh.

The increase in temperature from about 2°C to values >400°C[31, 32] is a result of conductive heating of a small percentage of seawater close to the solidified top of a high-level magma chamber[33]. This drives the hydrothermal convection system and gives rise to black smokers at the seafloor. High-resolution seismic reflection studies have indicated that some of these magma reservoirs may occur only 1.5-3.5 km below the seafloor[34, 35]. The crustal residence time of seawater in the convection system has been constrained to be 3 years or less[36]. Data from water/rock interaction experiments indicate that, with increasing temperatures, the Mg^{2+} dissolved in seawater (about 1,280 ppm) combines with OH-groups (which originate from the dissociation of seawater at higher temperatures) to form $Mg\ OH_2$, which is incorporated in secondary minerals such as smectite (<200°C) and chlorite (>200°C) [37,38,39,40]. The removal of OH-groups creates an excess of H^+ ions, which is the principal acid-generating reaction responsible for the drop in pH from seawater values (pH 7.8 at 2°C) to values as low as pH 2[41]. Exchange of H^+ for Ca^{2+} and K^+ in the rock releases these elements into the hydrothermal fluid. The leaching of Ca^{2+} balances the continuous removal of Mg^{2+} from seawater. Endmember hydrothermal fluids are defined as presumed deep-seated high-temperature fluids computed by extrapolating compositions and physical parameters back to Mg=0 on the assumption of quantitative removal of Mg. At high temperatures, however, the formation of epidote (Ca fixation) also results in an excess of H^+ that further contributes to the acidity of the hydrothermal fluid. These reactions take place at water/rock ratios of less than five and commonly close to one[42]. The oxygen which is present in the circulating seawater in the form of sulphate is removed partly by precipitation of anhydrite and partly through conversion of igneous pyrrhotite to secondary pyrite and the oxidation of Fe^{2+} to Fe^{3+} forming Fe-oxyhydroxides and secondary magnetite in the basalt[40]. Partial reduction of seawater SO_4^{2-} contributes to the formation of H_2S, but most of the reduced S in the fluid is derived from the rock itself.

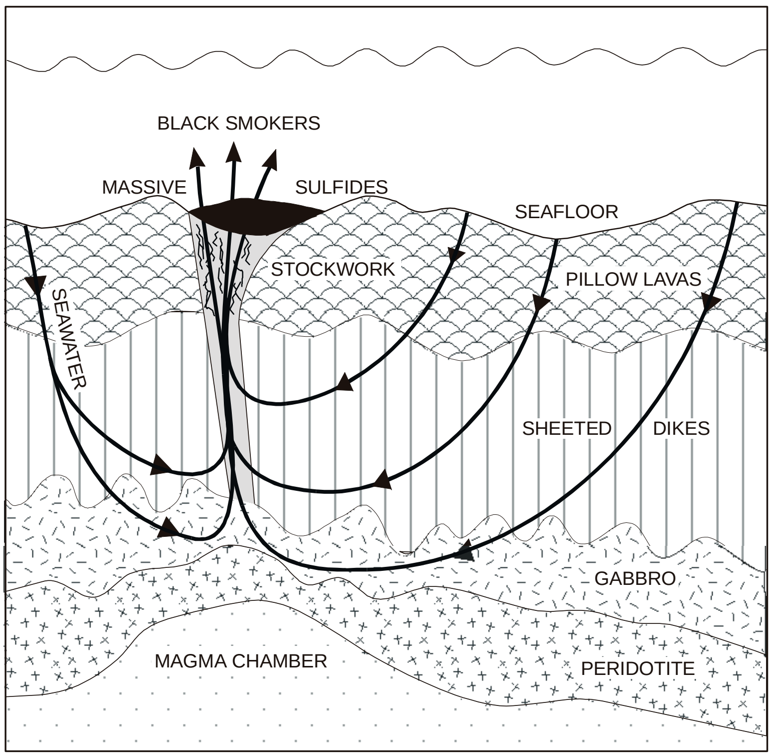

Figure 3. Model showing a seawater hydrothermal convection system above a sub axial magma chamber at an oceanic spreading center. Radius of a typical convection cell is about 3-5 km. Depth of the magma chamber usually varies between 1.5 and 3.5 km.

This highly corrosive fluid is now capable of leaching elements such as Li, K, Rb, Ca, Ba, the transition metals Fe, Mn, Cu, Zn, together with Au, Ag and some Si from the oceanic basement[43]. Sulphide droplets in the basalt are considered to be the major source for metals and S[44]. The metals are mainly transported as chloride complexes at high temperatures and, in some cases, as bisulphide complexes (in particular Au) at lower temperatures.

Due to its increased buoyancy at high temperatures, the hydrothermal fluid rises rapidly from the deep-seated reaction zone to the surface along major faults and fractures within the rift valley or close to the flanks of the rift. In particular the intersections of faults running parallel and perpendicular to the ridge axis are the loci of high-velocity discharge black smokers and massive sulphide mounds. The sulphide precipitation within the upflow zone (stockwork) and at the seafloor (massive sulphides) is a consequence of changing physical and chemical conditions during mixing of high-temperature (250-400°C), metal-rich hydrothermal fluids with cold (about 2°C), oxygen-bearing seawater (Fig. 4).

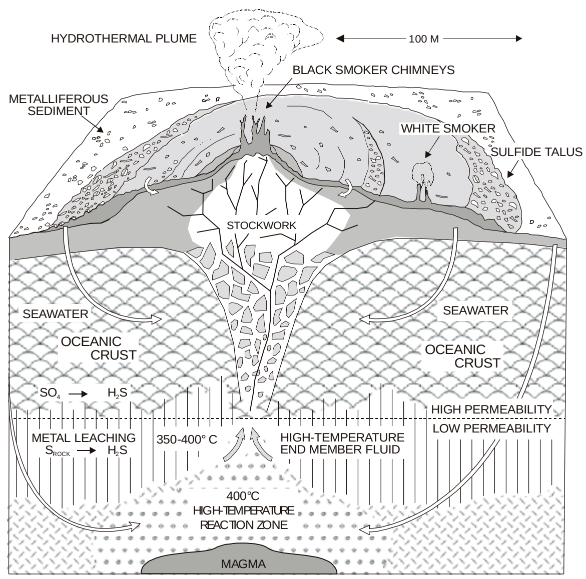

Figure 4. Cross-section showing the principal components of a seafloor hydrothermal system.

4. Mineralogy

The mineralogy of seafloor sulphide deposits (Table 1) has been documented in a number of detailed studies of samples from various sites[22, 45,46,47,48,49,50,51,52]. The mineral paragenesis of sulphide deposits at volcanic-dominated mid-ocean ridges usually includes assemblages that formed at temperatures ranging from about 300-400°C to less than 150°C. High-temperature fluid channels of black smokers and the interiors of sulphide mounds commonly consist of pyrite and chalcopyrite together with pyrrhotite, isocubanite, and locally bornite. The outer portions of chimneys and mounds are commonly composed of lower temperature precipitates such as sphalerite/wurtzite, marcasite, and pyrite, which are also the principal sulphide minerals of low-temperature white smoker chimneys. Anhydrite is important in the high-temperature assemblages, but is typically replaced by later sulphides, amorphous silica, or barite at lower temperatures.

Sulphide mineralisation at back-arc spreading centers has some mineralogical characteristics that are similar to hydrothermal precipitates at volcanic-dominated mid-ocean ridges. Commonly, pyrite and sphalerite are the dominant sulphides. Chalcopyrite is common in the higher temperature assemblages, but pyrrhotite is rare. Barite and amorphous silica are the most abundant non-sulphides. Many of the deposits forming in back-arc rifts are characterised by a variety of minor and trace minerals such as galena, tennantite, tetrahedrite, cinnabar, realgar, orpiment, and complex, non-stoichiometric Pb-As-Sb sulfosalts. The first examples of visible primary gold in seafloor sulphides were documented in samples of lower temperature (<300°C) white smoker chimneys from the southern Lau Basin[53, 54] and occur as coarse-grained (18 microns) co-depositional inclusions in massive, Fe-poor sphalerite.

Table 1: Mineralogical Composition of Seafloor Polymetallic Sulphides Deposits

	Back-Arc Deposits	**Mid-Ocean Ridge Deposits**
Fe-sulphides	pyrite, marcasite, pyrrhotite	pyrite, marcasite, pyrrhotite
Zn-sulphides	sphalerite, wurtzite	sphalerite, wurtzite
Cu-sulphides	chalcopyrite, isocubanite	chalcopyrite, isocubanite
Silicates	amorphous silica	amorphous silica
Sulphates	anhydrite, barite	anhydrite, barite
Pb-sulphides	galena, sulfosalts	
As-sulphides	orpiment, realgar	
Cu-As-Sb-sulphides	tennantite, tetrahedrite	
Native metals	gold	

5. Metal Contents

Despite moderate tonnages in several seafloor deposits, recovered samples from about 50 deposits worldwide represent no more than a few hundred tonnes of material. Based on existing data and lacking information on the third dimension it is premature to comment on the economic significance of seafloor massive sulphides. Published analyses of sulphide samples, however, indicate that these deposits may contain important concentrations of metals that are comparable to those found in ores from massive sulphide mines on land. Estimated concentrations of base metals in seafloor massive sulphides tend to be higher, which in part may be due to a strong bias in sampling.

A large number of seafloor sulphides are recovered during submersible operations. A bias in the analytical data arises, because sulphide chimneys which are relatively easy to sample are often the focus of study. However, they are unlikely to be representative of the bulk composition of the deposits as a whole (e.g., 11 analysed samples from the Southern Juan de Fuca site have an average Zn content of greater than 34 wt.%) and little is known about the interiors of larger sulphide mounds and the underlying stockwork zones. Systematic sampling of both high- and low-temperature assemblages across the surfaces of some large active areas (e.g., TAG hydrothermal field, Explorer Ridge, Galapagos Rift) are more representative of the range of sulphide precipitates which comprise large deposits. Sufficient sampling, which has lead to potentially realistic estimates of metal concentrations, has been achieved at only a few sites (e.g., Middle Valley, Explorer Ridge, Galapagos Rift) while quantitative assessment of contained metals has been possible only for the Atlantis II Deep in the Red Sea. Adequate information about the continuity of base and precious metal concentrations in the interior of the deposits can only be provided by drilling, as successfully demonstrated at the TAG mound (Ocean Drilling Program Leg 158[55]) and the Middle Valley site (Ocean Drilling Program Leg 139[18], Ocean Drilling Program Leg 169[56]).

Comparison of close to 1,300 chemical analyses of seafloor sulphides reveals systematic trends in bulk composition between deposits in different volcanic and tectonic settings (Table 2). The sediment-hosted massive sulphides (e.g., Escanaba Trough, Guaymas Basin), while being somewhat larger than deposits at the bare-rock mid-ocean ridges, appear to have lower concentrations and different proportions of base metals. Massive sulphides from these deposits average 4.7 wt.% Zn, 1.3 wt.% Cu, and 1.1 wt.% Pb (n=57). This reflects the influence of thick sequences of turbidite sediments on hydrothermal fluids ascending to the seafloor and the tendency for widespread precipitation of metals beneath the sediment-seawater interface. Calcite, anhydrite, barite, and silica are major components of the hydrothermal precipitates and may significantly dilute the base metals in sediment-hosted deposits. On basaltic, sediment-free mid-ocean ridges, sulphides are precipitated largely around the vent site, resulting in smaller deposits, but higher concentrations of metals. The largest deposits for which there are representative suites of samples (e.g., Explorer Ridge, Endeavour Ridge, Axial Seamount, Cleft Segment, East Pacific Rise, Galapagos Rift, TAG, Snakepit) have a narrow range of metal concentrations, and average 8.5 wt.% Zn and 4.8 wt.% Cu, but have only low concentrations (0.1 wt.%) of Pb (n=1,259, Table 2). Anhydrite, barite, and silica are important constituents of some chimneys, but on average they account for <20 % of the samples analysed.

Vent fluid compositions at all of the bare-rock mid-ocean ridge sites are remarkably similar, reflecting the high-temperature reaction of seawater with a uniform basaltic crust at greenschist facies conditions[57, 58,59]. Therefore, large variations in base metal concentrations between deposits on the mid-ocean ridges likely reflect a sampling bias or differences in the conditions of formation of the deposits. For example, zinc-rich deposits at Axial Seamount and the Southern Juan de Fuca site appear to have formed at lower average temperatures (<300°C) than Cu-rich deposits (>300°C) elsewhere at the mid-ocean ridges.

Relative to samples from sediment-starved mid-ocean ridges, massive sulphides forming in basaltic to andesitic environments of intraoceanic back-arc spreading centers (e.g., Mariana Trough, Manus Basin, North Fiji Basin, Lau Basin) are characterised by elevated average concentrations of Zn (16.5 wt.%), Pb (0.4 wt.%), and Ba (12.6 wt.%), but low contents of Fe (13.0 wt.%, n=573, Table 2). Polymetallic sulphides in the Okinawa Trough, where rhyolites and dacites are a product of back-arc rifting in continental crust, have low Fe contents (6.2 wt.%) but are enriched in Zn (20.2 wt.%) and Pb

(11.8 wt.%), and have high concentrations of Ag (2,304 ppm, maximum 1.1 wt.%), As (1.8 wt.%), and Sb (0.7 wt.%, n=40, Table 2). High Sb and As contents are accounted for by the presence of tetrahedrite, stibnite, and As-sulphides (i.e., realgar and orpiment) in these assemblages.

Table 2: Bulk Chemical Composition of Seafloor Polymetallic Sulphides

Element	Intraoceanic Back-Arc Ridges	Intracontinental Back-Arc Ridges	Mid-Ocean Ridges
Pb (wt.%)	0.4	11.8	0.1
Fe	13.0	6.2	26.4
Zn	16.5	20.2	8.5
Cu	4.0	3.3	4.8
Ba	12.6	7.2	1.8
As (ppm)	845	17,500	235
Sb	106	6,710	46
Ag	217	2,304	113
Au	4.5	3.1	1.2
(N)	573	40	1,259

The bulk composition of seafloor sulphide deposits in various tectonic settings is a consequence of the nature of the volcanic source rocks from which the metals are leached. Potential source rocks identified in the different tectonic environments range from MORB and clastic sediments at the mid-ocean ridges, to lavas of bimodal composition (andesite, basalt) in intraoceanic back-arcs and felsic volcanics (dacite, rhyolite) which are typical for young intracontinental back-arc rifts. These compositional variations are reflected by differences in the composition of the respective vent fluids. For example, chemical analyses of endmember fluids from the Vai Lili hydrothermal field which occurs in andesites of the Valu Fa Ridge in the southern Lau Basin indicate much higher concentrations of Zn, Pb, as any other elements compared to typical mid-ocean ridge fluids. Massive sulphides from the Okinawa Trough[25] are even more enriched in Pb than massive sulphides from the Lau Basin, which is likely a consequence of the high Pb contents of rhyolites and andesites in the source region and the characteristics of the hydrothermal fluids generated in this environment. High Pb and Ba contents of sediment-hosted seafloor sulphides simply reflect the elevated Pb and Ba contents of individual components in the sediment (e.g., feldspar). Similar trends in the bulk composition of massive sulphide deposits are widely recognised in ancient terrains[3, 52,60].

6. Size And Tonnage

Considering that estimates of the continuity of sulphide outcrop are difficult, and that the thickness of the deposits is commonly poorly constrained, estimates for several deposits on the mid-ocean ridges suggest a size of 1-100 million tonnes, although the depth extend of mineralisation is difficult to assess. The by far largest deposits are found on failed and heavily sedimented but still hydrothermally active oceanic ridges. Drilling carried out by the Ocean Drilling Program during Legs 139 and 169 at the sediment-covered Middle Valley deposit on the northern Juan de Fuca Ridge has indicated about 8-9 million tonnes of sulphide ore[56] (Table 3). During both legs, about 100 m of massive sulphides and 100 m of stockwork were drilled at the Bent Hill site. The sub seafloor stockwork zone is underlain by a stratiform Cu-rich horizon ("deep copper zone") with copper grades ranging up to 17 wt.% Cu[56]. This significant discovery now represents an important new exploration target for the land-based mineral industry. The TAG hydrothermal mound located in 3,650 m water depth at the Mid-Atlantic Ridge 26°N was drilled during Ocean Drilling Program Leg 158 in 1994 to a total depth of 125 m[55, 61]. It was estimated that the active TAG mound contains about 2.7 million tonnes of sulphide ore above the seafloor and approximately 1.2 million tonnes of sulphides in the sub seafloor stockwork[62]. A comparison of the size of the modern deposits with some of the ancient ore bodies and ore districts indicates that extremely large deposits such as Kidd Creek in Canada (135 million tonnes) or Neves Corvo in Portugal (262 million tonnes) so far have not been discovered at the modern seafloor.

Table 3: Size and Tonnage

- Atlantis II Deep (Red Sea)	94 mt
- Middle Valley (Juan de Fuca Ridge)	8-9 mt
- 13°N Seamount (East Pacific Rise)	5-10 mt
- TAG (Mid Atlantic Ridge)	4 mt

The largest known marine sulphide deposit is still the Atlantis II Deep in the Red Sea, which was discovered more than ten years before the first black smoker at the East Pacific Rise[63]. The Atlantis II Deep mineralisation largely consists of metalliferous muds, instead of massive sulphides, which is a consequence of the high salinity that the hydrothermal fluids acquire by circulation through thick Miocene evaporites at the flanks of the Red Sea rift. A detailed evaluation of the 40 km² deposit has indicated 94 million tonnes of dry ore with 2.0 wt.% Zn, 0.5 wt.% Cu, 39 ppm Ag, and 0.5 ppm Au[64, 65,66] (Table 4) which results in a total precious metal content of roughly 4,000 tonnes of Ag and 50 tonnes of Au. A pilot mining test at 2,000 m depth has shown that this deposit can be successfully mined.

Table 4: Atlantis II Deep (Red Sea)

Surface area	40 km²
Tonnage	94 mt
Base metal grades	2.0 wt.% Zn
	0.5 wt.% Cu
Precious metal grades	39 ppm Ag
	0.5 ppm Au

Estimates of sizes between 1-100 million tonnes for individual massive sulphide deposits on the seafloor thus are well within the range of typical volcanic-associated massive sulphide deposits on land. However, most occurrences of seafloor sulphides amount to less than a few thousand tonnes, and consist largely of scattered hydrothermal vents and mounds usually topped by a number of chimneys with one or more large accumulations of massive sulphide. More than 60 individual occurrences have been mapped along an 8 km segment of Southern Explorer Ridge, but most of the observed mineralisation occurs in two large deposits with dimensions of 250 m x 200 m[67]. The thickness of the deposits is difficult to determine unless local faulting has exposed their interiors. Typical black smokers are estimated to produce about 250 tonnes of massive sulphide per year. Thus, a local vent field with a few black smokers can easily account for a small size sulphide deposit, pending on the duration of activity. Reports of explored dimensions of deposits based on visual estimates from submersibles may be accurate to only +/-50% of the distances given and commonly include weakly mineralised areas between larger, discrete sulphide mounds (thereby over-estimating the continuity of sulphide outcrop). Reports based on transponder navigated camera tracks are probably accurate to +/-20%, but the extent of coverage is limited due to the slow tow-speeds and the narrow image. No geophysical tools currently provide a good basis for estimating the area of sulphide outcrop. High-resolution, deep-towed side-scan sonar may be refined to provide more accurate information over larger areas.

7. Occurrence And Distribution Of Gold

Gold grades are locally high in samples from a number of seafloor deposits at the mid-ocean ridges[50, 68,69,70], and in particular in samples from the back-arc spreading centers[54]. Average gold contents for deposits at the mid-ocean ridges range from <0.2 ppm Au up to 2.6 ppm Au, with an overall average of 1.2 ppm Au (n=1,259, Table 5) In volcanic-dominated, sediment-free deposits, high-temperature (350°C) black smoker chimneys composed of Cu-Fe-sulphides typically contain <0.2 ppm Au. Here, much of the gold is lost to a diffuse hydrothermal plume. The gold content of massive sulphides from the interior of hydrothermal mounds is supposed to be similar to the gold content of the high-temperature chimney assemblages. Higher concentrations of primary gold occur in lower-temperature (<300°C), sphalerite-dominated assemblages with sulfosalts and late-stage barite and amorphous silica at Axial Seamount (6.7 ppm Au[68, 70]). Comprehensive sampling of a few large, mature deposits at sediment-free ridges in the Northeast Pacific and Mid-Atlantic indicates typical average gold contents in the range of 1-2 ppm Au.

Local enrichment of more than 40 ppm Au (TAG hydrothermal field[71]) is a consequence of remobilisation and reconcentration (hydrothermal reworking) of gold during sustained venting of hydrothermal fluids through the sulphide mounds (i.e., zone refining).

The gold contents of sulphides from deposits in sedimented rifts (e.g., Guaymas Basin) are typically <0.2 ppm Au. Here, the interaction of hydrothermal fluids with organic-rich sediments causes strongly reducing conditions that limit the amount of gold that can be transported in hydrothermal solutions. However, Cu-rich sulphides from the Escanaba Trough are an exception as they contain up to 10 ppm Au with an average of 1.5 ppm Au. This is likely explained by an enriched source in the underlying sediments[72, 73]. The metalliferous muds in the Atlantis II Deep have bulk gold contents of about 0.5 ppm Au[64], but sulphide-rich horizons have gold contents from <0.5 up to 4.6 ppm Au and average close to 2 ppm Au[66].

Polymetallic sulphides from a number of back-arc spreading centers have revealed particular high concentrations of gold averaging between 3-30 ppm Au[54]. Gold appears to be most abundant in sulphides associated with immature seafloor rifts in continental or island arc crusts. These settings are dominated by calc-alkaline volcanics including andesites, dacites, and rhyolites (e.g., Okinawa Trough, Lau Basin, Manus Basin). Polymetallic sulphides from the Valu Fa Ridge in the Lau back-arc have gold contents of up to 29 ppm Au with an average of 2.8 ppm Au (n=103, Table 5). These samples represent the first known examples of visible primary gold in polymetallic sulphides at active vents[53, 54]. In the Okinawa Trough, gold-rich sulphide deposits with up to 14 ppm Au (average 3.1 ppm, n=40) occur in a back-arc rift within continental crust and resemble Kuroko-type massive sulphides[25, 74,75]. Preliminary analyses of sulphides reported from the Central Manus Basin (Vienna Woods) indicate average gold contents of up to 30 ppm Au (n=10) and maximum concentrations of more than 50 ppm Au. The average gold content of massive sulphides in the Eastern Manus Basin (Pacmanus) is 15 ppm with a maximum of 54.9 ppm Au (n=26[76]) High gold contents up to 21 ppm Au have been found in barite chimneys in the Western Woodlark Basin, where seafloor spreading propagates into continental crust off Papua New Guinea[77, 78].

The richest gold bearing seafloor deposit found to date is located at Conical Seamount in the territorial waters of Papua New Guinea close to Lihir Island. Maximum gold concentrations in samples collected from the summit plateau of this seamount (2.8 km basal diameter at 1,600 m water depth, top at 1,050 m) range up to 230 ppm with an average of 26 ppm for 40 samples analysed[79, 80].

Table 5: Primary Gold Grades in Polymetallic Massive Sulphides from the Modern Seafloor

	Au (ppm)		
	Range	**Average**	**(N)**
Immature Back-Arc Ridges (Intermediate to felsic volcanics)			
Lau Basin	0.01-28.7	2.8	103
Okinawa Trough	0.01-14.4	3.1	40
Central Manus Basin	0.01-52.5	30.0	10
Eastern Manus Basin	1.30-54.9	15.0	26
Woodlark Basin	3.80-21.1	13.1	6
Mature Back-Arc Ridges (MOR-type volcanics)			
Mariana Trough	0.14- 1.7	0.8	11
North Fiji Basin	0.01-15.0	2.9	42
Mid-Ocean Ridges (MORB)	0.01-10.7	1.2	1,259
Conical Seamount (PNG) (Magmatic-epithermal system)	0.01-30.0	26.0	40

8. Resource Potential Of Seafloor Sulphide Deposits

Out of the more than 100 sites of hydrothermal mineralisation currently known at the modern seafloor, only about 10 deposits may have sufficient size and grade to be considered for future mining, although information on the thickness of most of those sulphide deposits is not yet available (Table 6). These potential mine sites include the Atlantis II Deep in the Red Sea, Middle Valley, Explorer Ridge, Galapagos Rift, and the East Pacific Rise 13°N in the Pacific Ocean, the TAG hydrothermal field in the Atlantic Ocean, as well as the Manus Basin, the Lau Basin, the Okinawa Trough, and the North Fiji Basin in the western and south-western Pacific. All of these sites except two (East Pacific Rise 13°N and TAG hydrothermal field) are located in the Exclusive Economic Zones of coastal states including Saudi Arabia, Sudan, Canada, Ecuador, Papua New Guinea, Tonga, Japan, and Fiji. Scientific drilling so far has been carried out by the Ocean Drilling Program to a depth of 125 m at the TAG hydrothermal field and to about 200 m at Middle Valley. Leg 193 of the Ocean Drilling Program is scheduled for December/January 2000/2001 to explore the third dimension of the Eastern Manus Basin (Pacmanus site). The Atlantis II Deep is still the only deposit that has been evaluated by a commercial company (Preussag, Germany) in the late 1970s based on standards usually applied by the minerals industry to land-based ore deposits. A pilot mining test has successfully demonstrated that the metalliferous muds occurring below the surface of a 60°C brine not only in the Atlantis II Deep can be continuously mined[81, 82].

Table 6: Possible Sites for Mining of Seafloor Massive Sulphide Deposits

Deposit	Ocean Area	Water Depth	Jurisdiction	Country
Atlantis II Deep	Red Sea	2,000-2,200 m	EEZ	Saudi Arabia
Middle Valley	Northeast Pacific	2,400-2,500 m	EEZ	Sudan
Explorer Ridge	Northeast Pacific	1,750-2,600 m	EEZ	Canada
Lau Basin	Southwest Pacific	1,700-2,000 m	EEZ	Canada
North Fiji Basin	Southwest Pacific	1,900-2,000 m	EEZ	Tonga
Eastern Manus	Southwest Pacific	1,450-1,650 m	EEZ	Fiji
Basin	Southwest Pacific	2,450-2,500 m	EEZ	Papua New Guinea
Central Manus	Southwest Pacific	1,050-1,650 m	EEZ	Papua New Guinea
Basin	West Pacific	1,250-1,610 m	EEZ	Papua New Guinea
Conical Seamount	East Pacific	2,600-2,850 m	EEZ	Japan
Okinawa Trough	East Pacific	2,500-2,600 m	EEZ	Ecuador
Galapagos Rift	Central Atlantic	3,650-3,700 m	EEZ	International
EPR 13°N				
TAG				

Preussag has also performed active exploration for massive sulphide deposits in the Galapagos Spreading Center 86°W in the mid 1980s during the

GARIMAS project (Galapagos Rift Massive Sulphides), which consisted of three cruises with the German vessel SONNE. At that time it was concluded, that the Galapagos deposits are not sufficiently large and continuous to be economically mined.

It is also unlikely that deposits such as the TAG hydrothermal field, which is located in international waters at the Mid-Atlantic Ridge, the 13°N seamount at the East Pacific Rise or the Sonne hydrothermal field at the remote Rodriguez Triple Junction in the Southern Indian Ocean will become mining targets in the near future. This is also true for many of the sulphides deposits along the East, Northeast and Southeast Pacific Rises. However, in this decade, marine mining appears to be feasible under specific conditions ideally including (1) high gold and base metal grades, (2) site location close to land, i.e., commonly within the territorial waters (200 nm Exclusive Economic Zone or even 12 nm zone) of a coastal state, (3) shallow water depth not significantly exceeding 2,000 m (although the technology exists for mining in deeper water, cf. Table 7).

Table 7: Requirements for a Pilot Mining Site

- Sufficient size an tonnage
- High base metal and/or gold grades
- Site location close to land (200 nm or 12 nm zone)
- Water depth not significantly >2,000 m
- Field inactive and sediment-free (small environmental impact)

Under those circumstances, massive sulphides mining can be economically attractive considering that the entire mining system is portable and can be moved from mine site to mine site (Table 8). An investment into mining systems and ships is thus not tied to a certain location as is the case on land, where a typical mine development in a remote area including all infrastructure requires an initial investment of US$350-500 million.

Table 8: Advantages of Seafloor Massive Sulphides Mining

- Entire mining system is portable and can be easily moved from site to site
- No specific infrastructure required /roads, railway, airport, town etc.)
- No shafts or other mine development needed
- No acid mine drainage
- No overburden, no waste disposal

Seafloor massive sulphides mining will likely focus on relatively small areas of the seafloor and largely be restricted to the surface (strip mining) and shallow subsurface (open cast mining) to recover sulphide mounds and chimney fields at and replacement ore bodies just below the seafloor. Environmental impact studies are yet to be carried out and will likely indicate that mining of seafloor massive sulphides deposits has only a relatively small environmental impact. For example, the high density of the sulphide particles (about 4 g/cm^3) will cause immediate redeposition of any sulphide debris produced by mining equipment such as large TV-controlled hydraulic grabs or continuous mining systems with cutter heads and airlift. Due to the large surface exposed to seawater, some of the liberated sulphide debris will oxidise in a way that is not different from the oxidation of inactive massive sulphides in many of the seafloor deposits described. Acid mine drainage, which usually causes significant environmental problems in land-based sulphide mines, will not have to be considered at the seafloor due to the diluting effect of the surrounding seawater (cf. Table 8).

Sediment that could be disturbed by mining and possibly be transported by bottom currents would potentially create a major hazard to the marine ecosystem[83]. Amos et al.[84] have pointed out that the greatest unknown and the greatest potential hazard with respect to manganese nodule mining is the behaviour and effect of sediment plumes at the seafloor, within the water column, and at the surface. While the bottom water will be directly affected by sediment disturbance due to mining equipment, the impact on the water column and the surface will be due to discharge of sediments that have been lifted along with the manganese nodules. However, a significant sediment cover is commonly not present at most seafloor sulphide deposits (except for

Middle Valley and the Guaymas Basin) and thus has not to be taken into account. Consequently, mining of selected seafloor sulphide deposits, in particular those that are inactive and not inhabited by any kind of vent fauna, is feasible and does not create a larger environmental impact than the construction of a large harbour facility (cf. Table 7).

In December 1997, the Government of Papua New Guinea granted the first two marine exploration licences for seafloor sulphide deposits to an Australian-based mining company[85]. The licences cover an area of about 5,000 km^2 in the Manus back-arc basin and include the Vienna Woods (Central Manus Basin) and the Pacmanus (Eastern Manus Basin) sites, which are located on the west side of New Ireland. Mineralisation occurs at a water depth of 2,500 m (Vienna Woods) and 1,450-1,650 m (Pacmanus). Preliminary analyses of sulphides from both deposits indicate high average gold contents (see above) along with high concentrations of base metals. However, only a limited number of samples has been analysed so far and information about the depth extent of the mineralisation is still lacking.

A recent discovery of gold mineralisation at a seamount in a modern fore-arc environment of the Southwest Pacific suggests that a number of previously unexplored settings at the seafloor may be prospective for gold-rich hydrothermal systems. Mapping of largely uncharted waters in the Tabar-Feni island chain off Papua New Guinea revealed the position of several previously unknown volcanic cones about 10 km south of Lihir Island[86, 87]. Conical Seamount, the largest of the seamounts south of Lihir (Fig. 5 and Fig. 6), is host to a new type of marine mineral deposit, characterised by extremely high concentrations of gold and a style of mineralisation that indicates the participation of gold-rich magmatic fluids (as opposed to circulating seawater) in the formation of this deposit[71, 87,88]. Samples of trachybasalt (1,200 kg) collected from the crater of Conical Seamount at a depth of 1,050 m contain up to 230 ppm Au (avg. 26 ppm, n=40, Table 5) with several dozen grains of native gold (up to 30 micron) identified as inclusions in sphalerite, galena, and amorphous silica. High concentrations of gold are uniformly associated with high concentrations of elements such as As, Sb, and Hg, known as the "epithermal suite" typical for the so-called epithermal (i.e., magmatic) gold deposits on land. The style of mineralisation is similar to that of the giant Ladolam gold deposit (1,300 tonnes Au content, daily production

60 kg Au) located on the neighbouring island of Lihir and it may be assumed that Conical Seamount represents a submarine analogue of this world-class terrestrial gold mine.

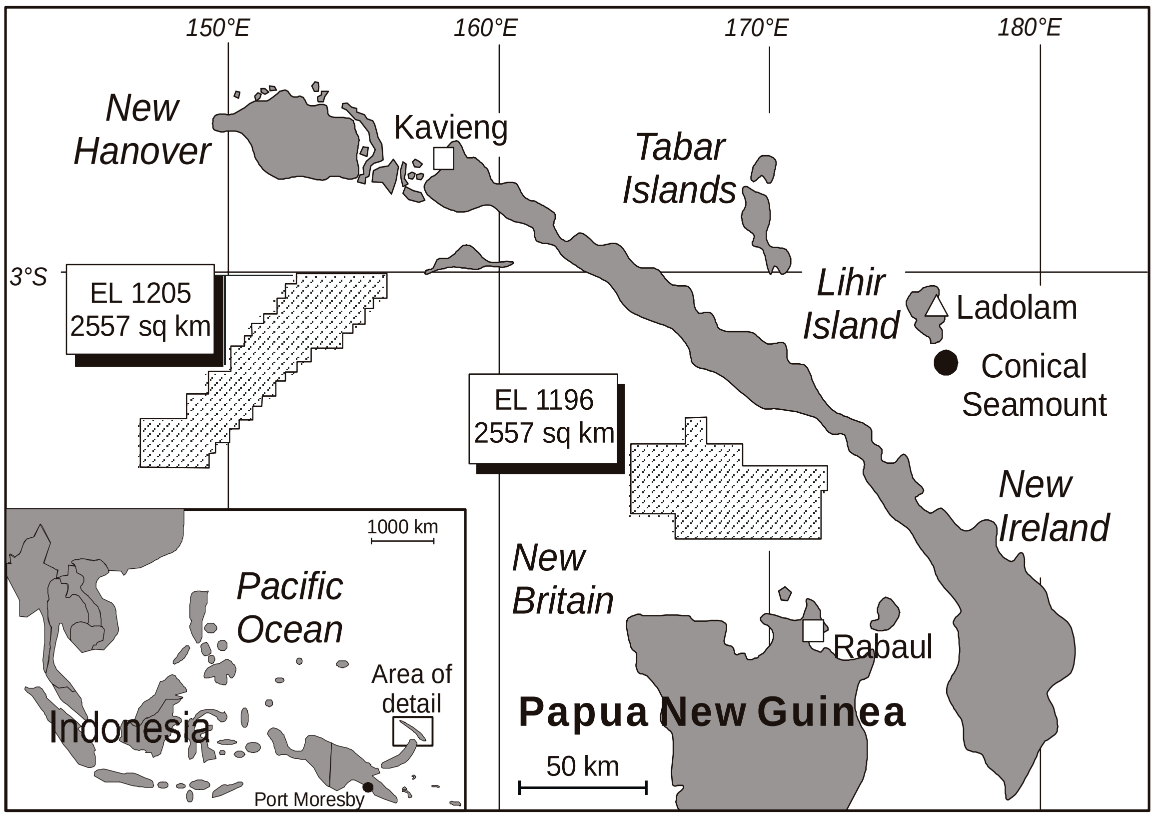

Figure 5. Map of the Manus Basin west of New Ireland showing the location of areas covered by an exploration licence granted to an Australia-based mining company by the Government of Papua New Guinea (after[85]). Notice the location of Conical Seamount south of Lihir Island and the Ladolam gold deposit on Lihir Island.

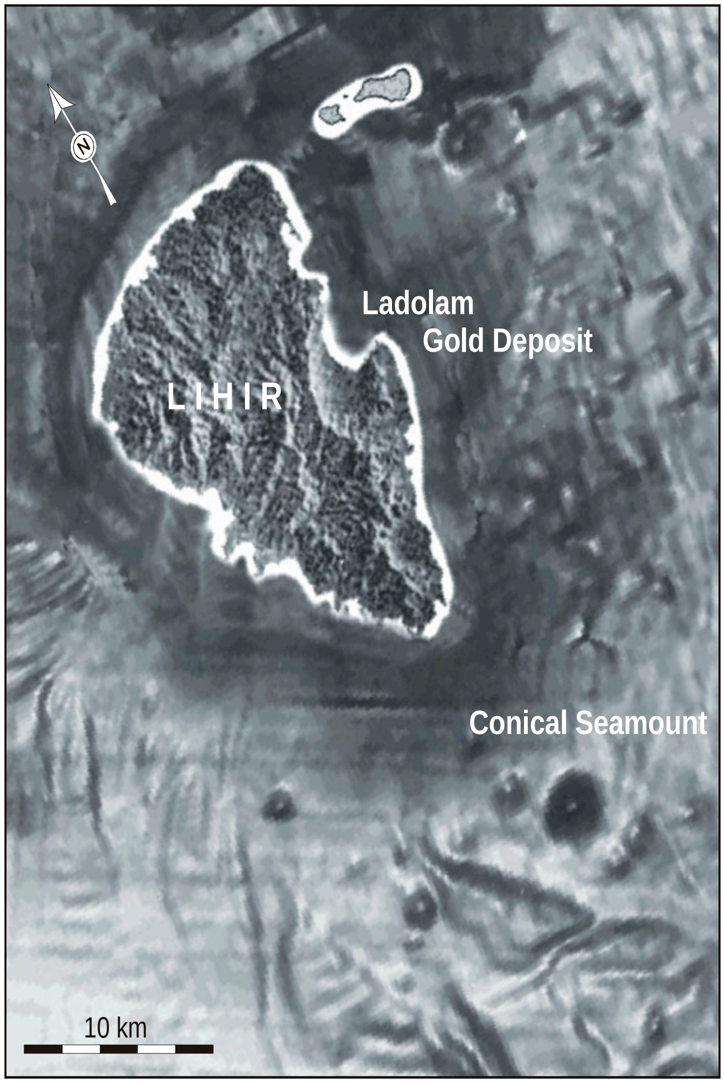

Figure 6. Bathymetry-based shaded relief of the Lihir Island group with the location of volcanic cones south of Lihir including Conical Seamount, which is host to a new type of submarine gold mineralisation.

9. Perspective

If further exploration through drilling proves that high-grade gold mineralisation is widespread and abundant, Conical Seamount may become the first marine gold deposit to be mined. In addition to high concentrations of gold, the advantages of this site include shallow water depth (1,050 m) and the location within the 12 nm zone of Papua New Guinea. Furthermore, the deposit is inactive (no disturbance of fauna) and almost sediment-free (no plume development due to mining activities, cf. Table 7). Processing of the gold ore could take place in the 25 km distant Ladolam gold processing plant on Lihir. If this scenario becomes reality, it will have a very significant impact on the future development of seafloor mining for base and precious metals. Given the known distribution of potentially mineable sulphide deposits on the seafloor, it is very likely that most, if not all, future development of sulphide mining will take place in national rather than international waters (Table 6,9).

Table 9: Seafloor Massive Sulphides Mining

- Majority of potential mine sites are located in Exclusive Economic Zones
- Drilling is essential to reliably assess resource potential and economic feasibility
- Pilot mining site needs to be identified to test technology and to carry out an environmental impact study

Considering all critical factors (Table 10), mining of seafloor polymetallic massive sulphide deposits is likely to take place in the current decade. In this context it should be remembered, that only about 35 years ago, the oil industry went off shore and there is no doubt that this was a very successful endeavour. Today, the international mining industry is about to follow .

Table 10: Critical Factors for Mining of Seafloor Polymetallic Sulphides

- Reliable size and tonnage calculation based on drilling and coring
- Chemical analyses of representative bulk samples to establish average metal grades
- Development and test of suitable mining techniques and systems
- Economic feasibility analysis
- Environmental impact study

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SUMMARY OF THE PRESENTATION AND DISCUSSIONS ON SEAFLOOR MASSIVE SULPHIDES DEPOSITS AND THEIR RESOURCE POTENTIAL

Presentation

Professor Peter Herzig, of the Lehrstuhl fur Lagerstattenlehre Institut fur Mineralogie based in Freiberg/Sachsen, Germany, noted at the beginning of his presentation that it would overlap in part with Professor Rona's presentation, and that his presentation on "Seaflloor massive sulphides deposits and their resource potential" would reflect the point of view of an Economic Geologist. He also informed participants that prior to his fifteen years of experience on seafloor massive sulphides deposits he was a geologist that specialized in land-based massive sulphides deposits.

Utilizing slides, Professor Herzig reiterated some of the points made by Professor Rona, showing, inter alia, the principal morphological features of the modern seafloor: the deep ocean basins with water depths in excess of 5,000m and the occurrence of manganese nodules; sea mount areas of the Pacific and the occurrence of cobalt-rich manganese crusts deposits, and the mid-ocean ridge system, comprised of the Mid-Atlantic Ridge, the Red Sea, the Carlsberg Ridge, the Central Indian Ridge, the Southwest and Southeast Indian Ridges the East Pacific Rise, the Southeast Pacific Rise and the Northeast Pacific Rise.

With regard to the mid-ocean ridge system, Professor Herzig noted that these ridges are to be found across all the major spreading centres of the world's oceans, and that with a total length of 55,000 km, the ridge system is an important morphological feature of the seafloor. He further noted that ridges also define boundaries, places where new oceanic crusts are being continuously formed

In relation to crust formation, Professor Herzig informed participants that rates differed in different parts of the ocean. For example, he noted that the Mid-Atlantic Ridge is a slow spreading ridge with a spreading rate of only a few centimetres per year, while the East Pacific Rise, in particular in it's southern segment is a fast-spreading mid-ocean ridge where crust is being produced at about 20cm per year.

Professor Herzig informed participants that he was aboard the research submersible Alvin in 1979 when the first black smoker was discovered. Once again through the use of slides, Professor Herzig further elaborated on points previously made about the discovery of the first black smoker that was found at about 500 km west of the Mexican coastline, in a water depth of about 2600 m. Referring to the black smokers, Professor Herzig pointed out that after the discovery, scientists involved in the dive conducted temperature measurements and realised that the black smoke jetting out from the chimney had a temperature of about 350˚ C. Later research indicated that seawater was transporting metals from the oceanic crust to the seafloor. At the seafloor, metals are precipitated from the high-temperature hydrothermal fluid as a result of mixing of this hot fluid with the cold ambient seawater, which is about 2˚ C. The smoke, he further pointed out consists of small particles of sulphides, in particular zinc, copper and iron sulphides. These sulphides he said, turn the fluid, which is more or less transparent below the seafloor, into a black cloud. The slope is made of finely dispersed sulphides atop of the chimney feature itself and the underlying sulphides mound.

Utilizing a slide depicting a profile through the East Pacific Rise and South America, Professor Herzig illustrated the process of seafloor spreading and informed participants that a sub axial magma chamber drives the process. Professor Herzig said that the magma chamber at depth is about 3-3.5 km deep and that it is this chamber that produces new oceanic crust that can be seen at the seafloor in the form of pillow lavas. The magma chamber has a temperature of about 1200˚ C and is not only responsible for the formation of new oceanic crusts but is also the driving force for the creation of mineral deposits at the seafloor. He stated that the process of crust formation is intimately related to the formation of metallic mineral deposits at the seafloor. He pointed out that the crust that is produced at the East Pacific Rise, in this case, is consumed at the active continental margin of South America. He also pointed out that part of the crust and some of the sediments are melted, producing intrusions into the Andes mountain range, and that these intrusions are responsible for the big copper deposits that occur in the coastal ranges of South America, Central America and North America.

Professor Herzig provided illustrations of the products of a magma chamber. These included fresh pillow lavas that are manifested at the seafloor and covered with a glass crust due to the cooling of the hot lava by cold seawater, and young pillow lavas that cover older pillow lavas.

Observing that no one has actually witnessed the formation of new oceanic crust at seafloor spreading centres, Professor Herzig said that seafloor spreading is directly related to the formation of polymetallic massive sulphides deposits. Utilizing a slide illustrating a profile of an oceanic spreading centre, Professor Herzig said that at specific locations seawater is able to penetrate into the oceanic crust for one of two reasons: seismicity occurring at a given location due to seafloor spreading that creates channel ways; and, cooling of hot lava at the seafloor that also provides channel ways because of the thermal contraction of the newly formed crust. Professor Herzig also said that at the seafloor and through these channel ways, seawater penetrates into the oceanic crust due to water pressure of about 200-300 bars.

Once the seawater has reached the vicinity of the magma chamber he continued, it is converted into hydrothermal fluid in a high temperature reaction zone. The first change he noted in the conversion process is seawater being heated to temperatures of about 500˚ C. The second change that he also noted is that the pH of seawater, which is about 7.8, is lowered to values as low as 2 to 3 in the high temperature reaction zone. He stated that this is due to a number of chemical processes involving the precipitation of Magnesium and OH-groups from seawater. The third change in the process he further noted is that oxygen contained in seawater, for example in sulphates, is completely removed from it, converting it into a hot, aggressive hydrothermal fluid, that doesn't contain any free oxygen. The hydrothermal fluid reacts with the surrounding rock and up wells to the seafloor. The rocks are leached of metals such as manganese, copper, iron, zinc, gold and silver. Sulphur is also leached from the rocks and is converted to hydrogen sulphide (H_2S). The reduced metals and hydrogen sulphide are then transported in solution to the seafloor, with the precipitation of sulphides taking place below the seafloor.

Professor Herzig said that the spectacular black smokers are the result of this process and that they represented the chimneys of an "ore factory" operating at the seafloor. He emphasized that the important part of the "ore factory" is below the chimneys. Utilizing a slide containing a picture of the TAG mound at the Mid-Atlantic Ridge, Professor Herzig illustrated his point, pointing out the black smoker complex, which has about several dozen high temperature black smokers in a temperature of 360˚ C, on top of a mound feature about the size of the Houston Astrodome, or 200 m in diameter and 50 m high.

With another slide, Professor Herzig showed a picture of a massive sulphides rock that was taken using a TV guided grab from the Galapagos spreading centre. He described this sample as consisting of sphalerite, chalcopyrite, amorphous silica and some other minerals with a geologic age of several hundred years. Using another slide containing a picture of a similar rock, Professor Herzig explained that although this massive sulphides rock is crystallised, its mineralogy is very similar to the picture previously shown.

He informed participants that the difference between the two samples was that while the former picture is of a seafloor massive sulphides rock, the latter is of a sample of ore from a land-based massive sulphides deposit, that is part of the Troodos ophiolites on the island of Cyprus and that are about 80 million years old.

Professor Herzig disclosed that a very close relationship existed between modern hydrothermal system massive sulphides at the seafloor and ancient sulphide deposits on the continents. He illustrated this point with a slide of one of the big Canadian deposits, the Kidd Creek deposit. He noted that the Kidd Creek deposit that is 2.7 billion years old has a total volume of 135 million tonnes of massive sulphides. He referred to indications from other areas that show that hydrothermal processes have been taking place on the bottom of ancient oceans for more than 3 billion years and concluded that this process that is being observed today at the seafloor is more than 3 billion years old.

Professor Herzig informed participants of the distribution of significant massive sulphides mines and deposits in the world. With regard to mineral production from land-based massive sulphide mines, Professor Herzig noted that the contribution from these types of deposits to the global production of base and precious metals is about 50% of world zinc production, 40% of world lead production, 15% of world copper production, 40% of world silver production and 5% of world gold production. He concluded that land-based massive sulphides deposits are an important contributor to the global metal market.

Professor Herzig told participants that after the discovery of the first black smoker at the East Pacific Rise in 1979, international research programmes were launched to study hydrothermal systems and seafloor massive sulphide deposits in the oceans. He pointed out that as a result of these programmes, vessels and equipment have been developed to provide better information on these deposits. In this regard, Professor Herzig showed slides of the German research vessel, the SONNE, and informed participants that the vessel is equipped with the multi-beam echo sounder system that enables researchers to map the seafloor. For detailed mapping and sampling, he stated that submersibles were required. He showed a slide showing the French submersible, Nautile, which has a diving range of 6000 m and that provides berth space for 2 pilots and one scientist.

As a result of the international research programmes since 1979, Professor Herzig stated that 150 sites of hydrothermal activity and massive sulphides deposits on the modern seafloor have been discovered. Of these hydrothermal systems, 35 of them are active and the others are inactive.

With regard to the distribution of known sites of hydrothermal activity and seafloor massive sulphides in the world's oceans, Professor Herzig said that the majority of these sites are located at the Northeast Pacific Rise, the East Pacific Rise and the Southeast Pacific Rise, due mainly to the fact that the first discovery was made in this geographic area at 21° N. He further explained this situation referring to the saying that "if you want to hunt elephants, go to elephant country". As a result, he pointed out the first set of international researching expeditions were carried out north and south of 21° N.

Professor Herzig said that the deposits that have been discovered in the Atlantic Ocean at the Mid-Atlantic Ridge, was in large part due to the work of Russian and the British scientists during their so-called Bridge programme. He stated that in the Indian Ocean two sites have been discovered: the Sonne Field and the Mount Jordan Field. He made the point that the number of deposits at the different mid-ocean ridges is a reflection of the prospecting activity in those areas. He further made the point that increased prospecting activity in the Indian Ocean for example would result in more discoveries.

Professor Herzig noted that two unusual discoveries have been made in the Southwest Pacific. One of these he said is close to 21˚N in the Guayamas Basin in the Gulf of California. This site, Professor Herzig said, is hydrothermally active and the rift to found there is filled with several hundred metres of terrigeneous sediments. Sulphide precipitation in this case he also said, takes place within the sediment and creates a very effective means of concentrating metals without the metals getting lost through the black smokers. He concluded that the presence of the sediments has created a very efficient way of forming a big massive sulphides deposit.

Professor Herzig turned his attention to the metalliferous brines to be found in the Atlantis II Deep in the Red Sea. Noting that this deposit was the earliest discovery of a seafloor massive sulphides deposit (1965), he informed participants that it differed from other seafloor massive sulphides because the hot hydrothermal fluid from the magma chamber mixes with highly saline seawater in the Deep. He further noted that the evaporates that occur in the Red Sea are typical for a young ocean that used to be an intercontinental rift with episodic transgression of seawater. This turn of events, he stated, produced thick salt layers that were moved to the flanks of the Deep where seawater circulates through them. The seawater, as a result, becomes highly saline, producing a metal-rich brine as compared with a metal-rich fluid that jets out of black smoker chimneys. These metal rich brines, he further stated are being deposited in various deeps in the Red Sea.

Professor Herzig reiterated the statement made by Professor Rona that the German Preussag Company under contract with the Saudi-Sudanese Red Sea Commission investigated the Red Sea metalliferous sediments. He noted that these seafloor massive sulphide deposits were the only deposits of this type to have been evaluated according to mining standards, and represent the only seafloor massive sulphides where an indication of the resource potential had been obtained.

Preussag's work he stated reveals that the Atlantis II Deep has a surface of about 30 square kilometres. It contains 94 million tonnes of sulphides, dry and water-free, with an average metal content of 2% zinc, 0.5% copper, 39ppm silver and 0.5ppm gold. Based on these estimates, he concluded that the deposit contained approximately 50 tonnes of gold and about 4,000 tonnes of silver. Noting that the Atlantis II Deep was only one of 21 deeps in the Red Sea, he stated that there was doubt of the significance of the resource potential of these deeps.

Turning to the sizes and tonnages of the other known seafloor massive sulphides, Professor Herzig stated that information in this regard was rather limited. He noted that other than the Atlantis II Deep, information on size and tonnage were available for only three other deposits: Middle Valley on the Juan de Fuca Ridge which is about 200 nautical miles west of Vancouver Island in Canada; a site on the East Pacific Rise located at 13*N, and the TAG mound at the Mid-Atlantic Ridge. Middle Valley, he informed participants, was drilled twice under the Ocean Drilling Programme. Drilling indicates that between 8 and 10 million tonnes of massive sulphides ore covered by sediments are available at this site. This estimate he pointed out has been disputed in some circles and placed at about 80 to 100 million tonnes. At the East Pacific Rise site at 13˚ N, it is estimated that about 5-10 million tonnes of ore grade material are available while drilling of the TAG mound at the Mid-Atlantic Ridge in 1994, indicates about 2.7 million tonnes of sulphides ore at the seafloor and 1.2 million tonnes of sulphide ore below the seafloor, which amounts to approximately 4 million tonnes.

With respect to the mineralogical composition of the samples taken from mid-ocean ridges, Professor Herzig said that their mineralogy is quite simple. The high temperature veins of the deposits are commonly lined by chalcopyrite or isocubanite, which are high temperature copper minerals. The outer parts of the deposits contain sphalerite, which is a zinc sulphide, pyrite an iron sulphide and a couple of other minerals.

Professor Herzig informed participants that in 1987, the area of focus for hydrothermal systems and massive sulphides deposits moved from mid-ocean ridges to back-arc spreading centres of the southwest Pacific. The difference between the two geographic areas he noted is that in the southwest Pacific, mineral deposit formation was at a convergent plane boundary. He said that seafloor spreading in this area, while similar to spreading at the mid-ocean ridge yielded different products because of the rocks that were leached. He pointed out that the rocks in the back-arc environment are usually felsic or intermediate rocks, rhyolites or andesites with different metal contents with respect to the mid-ocean ridge basalt. As a result, the massive sulphides produced in this environment have a different mineralogical composition and, last but not least, different metal grades.

The first discovery of a hydrothermal system and a massive sulphides deposit in the back-arc spreading centres of the southwest Pacific was the spreading centre west of the Mariana Trough that is 11,000 m deep. Subsequent discoveries included the Okinawa spreading centre in the back of the Okinawa Trough, the Manus Basin, the North Fiji Basin and the Lau Basin.

Professor Herzig remarked that the Woodlark Basin that was also discovered during this period is a different situation because it is not a true back-arc spreading centre.

He stated that hydrothermal locations in the southwest Pacific are active, yielding white smokers instead of black. White smokers he went on to say occur at mid-ocean ridges and in back-arc spreading centres. The reason for the white smoke is that some of the metals have already precipitated below the seafloor due to subsurface mixing of the high temperature hydrothermal fluid with seawater and, as a result, only amorphous silica and barite remain in the smoke, creating the white colour. The metals, he reiterated, have been stripped out of the system and are found below the seafloor.

With regard to the mineralogy of massive sulphides from back-arc spreading centres, Professor Herzig described it as quite complex. He informed participants that the first sample from a massive sulphides deposit with a high concentration of gold was taken from the Lau basin. That sample had about 28ppm of gold, or 28g of gold. He said that in general the mineralogical composition of back-arc sulphides differed from mid-ocean ridge sulphides because the rocks, which are leached at back-arc spreading centres have a higher content of lead, arsenic and antimony. The sulphides produced therefore included lead sulphides (galena), some sulphosalts, arsenic sulphides, copper-arsenic-antimony sulphides and gold.

He pointed out the gold found in these deposits is primary gold, hosted in iron-poor sphalerite. He also pointed out that the discovery of gold in these deposits has created interest in the gold potential of seafloor massive sulphide deposits in back-arc areas, resulting in the analysis of a number of previously collected samples from other back- arc areas for their gold content.

With regard to gold grades from different spreading centres, Professor Herzig said that at deposits located at mid-ocean ridges, based on the analysis of 1,200 samples, the typical average grade of gold is about 1ppm. He noted that this average is also typical of the so-called ophiolite-hosted massive sulphides deposits on land. Such deposits he further noted were not typically the deposits mined on land. The important types of massive sulphides for land-based mining are those deposits that occur in felsic to intermediate rocks in a back-arc environment. He said that this is also true for the seafloor where back-arc deposits are the deposits of interest with respect to gold and base metals. In this regard, based on fewer samples, he said that the average grade of gold in back-arc deposits was 30g per tonne, with maximum gold values of 55g per tonne.

Professor Herzig informed participants about a very recent discovery on the Conical Seamount. He said that this deposit is neither a mid-ocean ridge deposit nor a back-arc deposit but a seamount in a fore-arc environment. He also said that from analysing 40 samples taken from this deposit, an average gold grade of 26g per tonne had been established for the deposit. The maximum gold value found in samples taken from this deposit is 230ppm gold or 230g per tonne.

At this point in his presentation, Professor Herzig embarked on the subject of resource assessments of seafloor massive sulphides. In this regard, he informed participants that in addition to information on the average grade of deposits, reliable information was also required on the extent (depth) of these deposits beneath the seafloor along with drill cores in order to make reliable resource assessments. He pointed out that data on the average grade of many of the deposits that he had described were based on samples that had been taken by submersibles, or that were leached, or samples that had been collected with TV-guided grabs. These samples he further elaborated are all from the surface. As regards the depths beneath the seafloor of many of these deposits, he further pointed out that other than the Atlantis II Deep, Middle Valley and the TAG deposits, at present there is no reliable information on this parameter for the other known deposits. He emphasized that drilling is required to obtain representative bulk samples to establish average metal grade, not only from surface samples but representative samples from drill cores to arrive at the average grade of the deposit. In this regard he noted that while the Ocean Drilling Programme had a drill ship, this was not necessarily the best way to proceed. He suggested that a better approach might be to use portable drills that could be deployed on ships of opportunity.

Finally he pointed out that 10 out of 12 of the possible mine sites he earlier identified (Table 6) are located in the Exclusive Economic Zones of various countries and that only 2 are located in international waters.

Professor Herzig listed some critical factors for mining seafloor massive sulphides deposits (Table 10). These were reliable size and tonnage calculations based on drilling and coring; the development and testing of suitable mining techniques and systems, since there is nothing available at the present time that could be used for mining seafloor massive sulphides deposits; economic feasibility studies and analyses, and environmental impact studies. With regard to environmental impact studies, Professor Herzig said that mining of seafloor massive sulphides should be limited to deposits to be found at inactive hydrothermal systems. He described such sites as being devoid of the fauna to be found at active systems.

He stated that if all these critical factors prove favourable for a deposit, then there would be a number of advantages to seafloor massive sulphides mining. The first advantage relating to cost, he said, is that the entire mining system would be portable, easily moved from one location to another. No heavy infrastructure would be required, i.e, roads, railways, airports, towns, etc. He pointed out that about US$350-500 million is required for the development of a middle-sized massive sulphides deposit on land in Canada. He also pointed out that for remote areas in the southwest Pacific this cost could range between US$600-700 million. He suggested that although there would be costs associated with seafloor massive sulphides mining, based on these considerations, he was of the opinion that it would be competitive with land-based mining. He further noted that no shafts or other mine development would be required for seafloor massive sulphides mining and that with regard to the environment, no acid mine drainage would occur at these deposits as was the case on land. Additionally, there would be no overburden to deal with and no waste disposal problems to overcome.

With these considerations, Professor Herzig proposed that a pilot mining site should be identified and used to test the feasibility of seafloor massive sulphides mining. He suggested that such a pilot mining site should have sufficient size and tonnage to make it worth mining, that it should contain attractive base metal and gold grades, that it should be close to land (i.e., within 200nm), at a water depth around 2,000m and at an inactive hydrothermal vent system.

Professor Herzig proposed two possible sites as pilot mining sites: the Vienna Woods and Pacmanus mine site awarded to Nautilus Minerals in the exclusive economic zone of Papua New Guinea near the Island of New Ireland; and a nearby inactive hydrothermal system at a place called Conical Seamount. Professor Herzig characterized the Vienna Woods and Pacmanus sites as definitely prime targets for a pilot mining site. He stated that in addition to meeting all but one of the criteria that he had earlier outlined, the Ocean Drilling Programme would be drilling the Pacmanus deposit in the not too distant future. This would provide aid in assessing the resources of this deposit as well as its extent. The only drawback he saw to this deposit was that it is hydrothermally active. He was of the opinion that while mining could create a problem to the biological community occurring here, the deposit would provide the international community with a good study of what the potential impact would be to the biological communities to be found in this environment from mining.

In relation to Conical Seamount, Professor Herzig described the deposit as being 10 km from the island of Lihir, which is the where that the Ladolam gold deposit is to be found. He described this land-based gold mine as one of the largest epithermal i.e. magmatic gold deposits in the world. The gold content of this deposit he informed participants, is 1,300 tonnes of gold with a daily production of 60 kg. The Conical Seamount he also said is about 25km from the Ladolam mine.

Through the use of a slide, Professor Herzig described the Conical seamount, which he said had a basal diameter of about 2.5 km, is about 600m high, and with an apex at 1,050 m water depth. Through the use of another slide, Professor Herzig provided what he described as an analogy to Conical Seamount, *White Island*. Professor Herzig described *White Island* as an active volcano about 50 km north of New Zealand. The volcano is about 10,000 years old, driven by magmatic fluids instead of seawater and during the past 10,000 years has pumped about 360 and 1 million tonnes of gold and copper respectively into the atmosphere.

He pointed out that White Island, at a water depth of about 1,000 m, would be very similar to Conical Seamount, the only difference being that most of the desirable metals would have been kept in the Conical seamount system.

Professor Herzig informed participants that he along with other scientists has undertaken to explore the Conical seamount in view of its commercial potential. The group had been on two cruises to the deposit to map and collect samples. So far 1,200 kg of rocks had been obtained from the Summit plateau using TV-grabs and a geologic map of the plateau had been constructed.

Professor Herzig revealed that the samples from the Summit plateau of Conical seamount reveal a very complex mineralogy, including vein sulphides in highly altered basaltic rocks with high concentrations of arsenic and antimony, which are indicative of magmatic ore deposits. Their group was of the opinion that this deposit was not formed through the process of hydrothermal fluids from the magma chamber interacting with oxygenated seawater at the seafloor, but rather from a process where hydrothermal fluids interact with magmatic fluids that contained high concentrations of gold.

Based on the samples taken from the surface of the deposit, Professor Herzig provided a summary of the geochemistry of Conical Seamount. The maximum grade of gold he informed participants, is 230g per tonne, with an average of 25ppm based on 40 samples. Base metals values he noted, however, are relatively low and are similar to values being mined at Ladlolam.

The exploration strategy for Conical Seamount is to drill the deposit in order to find out whether it was a deposit with a small gold enrichment at the surface or whether it was indeed a gold deposit. He stated that the research team had submitted a proposal to the Ocean Drilling Programme to drill Conical Seamount just after the drilling operation in the Manus Basin.

Returning to his proposal for a pilot mining site for seafloor massive sulphides, Professor Herzig stated that the advantages of Conical Seamount in this regard were that it is located very close to the island of Lihir, in the EEZ of Papua New Guinea, that there is direct access to a gold processing plant on the Island, that the water is relatively shallow (between 1,050 and 1,650m), that the gold grade of the deposit is high, and that the site is an inactive hydrothermal vent and is also sediment free.

While noting that there is currently no technology available for seafloor massive sulphides mining, Professor Herzig said that the technology currently being used by De Beers for diamonds offshore Namibia could be adapted for this purpose. His thoughts included adapting the rotating cutter heads used in offshore diamond mining for seafloor massive sulphides mining, airlifting of the ore slurry produced from mining the sulphides to the mining vessel and then transferring the slurry by cargo vessel to the oxidation plant at Lihir.

Professor Herzig concluded his presentation by presenting a summary of it. Firstly, he noted that a majority of the potential seafloor massive sulphides deposits are located in the exclusive economic zones of various countries. Secondly, he stated that drilling seafloor massive sulphides deposits is essential to reliably ascertain the amount of suitable ore and the economic feasibility recovering the ore. Thirdly, and perhaps most important, he said that a pilot mining site should be identified to test technology and carry out an environmental impact study. He ended his presentation by saying that that the idea of mining seafloor massive sulphides is not new, and he reminded participants of a passage from Jules Verne's book of 130 years ago, *Twenty Thousand Leagues Under The Sea* where Captain Amos said that in the ocean depths there exists mines of zinc, iron, silver and gold that could be quite easy to exploit.

DISCUSSIONS ON THE SEAFLOOR MASSIVE SULPHIDE DEPOSITS AND THEIR RESOURCES POTENTIAL

The discussions that followed Professor Herzig's presentation focussed on the type of mining system required for seafloor massive sulphides, the possible environmental impacts of firstly, mining in relation to overburden and tailings from the mining operation and secondly at hydrothermal vent systems in general, how the pilot mining proposal could be implemented, the possibility of recovering the enormous thermal energy associated with these deposits while mining, and the geologic history of these deposits.

Mining system

It was pointed out by a participant that Professor Herzig had stated that for evaluation purposes, drilling was required. In this regard, the participant requested information on the proposed mining system pointing out that since the deposit contained a third dimension (depth), either drilling and excavation of the deposit would have to be undertaken or major fracturing and breaking of the rocks that form the deposit would be required.

While acknowledging the need to drill seafloor massive sulphides deposits for evaluation purposes, Professor Herzig stated that geotechnical studies of the rocks recovered from Conical seamount reveal them to be relatively soft because they were highly altered, easy to break, and easy to convert into a gold slurry. In this regard he reiterated that no infrastructure was required to develop these deposits.

Professor Herzig pointed out that Conical Seamount and other arc volcano deposits were commercially interesting for their gold content rather than their base metal content. Given the friability of the rocks that comprise the deposit and with the objective of recovering primarily gold from the deposit, he described a possible mining operation for Conical seamount as one consisting of a process whereby the rocks containing gold in the deposit are crushed and converted into ore slurry, and then pumped onto a mining vessel as part of a continuous system. He rejected the idea of using large grabs to recover the ore, stating that large grabs would be an inefficient way to mine seafloor sulphides. He informed participants that this was the same type of mining operation that was taking place at the Ladlolam mine on Lihir Island.

The operating company for this mine he also informed participants, had a permit from governmental authorities to dispose of overburden from the mine in the Bay of Lihir. With regard to a possible technological configuration, Professor Herzig described a seven-metre cutter head drill developed in Germany for use in offshore diamond mining in Namibia. He said that drills were vertically oriented and used to loosen sediments up to a depth of approximately 0.5 to 1.0 metres, with the sediment and diamond mixture pumped to the surface vessel. Professor Herzig also said that his group envisioned a similar system for mining the Conical Seamount massive sulphides deposit.

Environmental impacts

Questions were raised in relation to disposal sites for the overburden removed during mining and the tailings from the mill after treating the slurry on land. Other questions were raised on the how the slurry would be transported to land.

With regard to the overburden produced from mining, Professor Herzig suggested that in the envisioned configuration, very little overburden would be removed from the deposit. As such, the material that would remain would be sulphide debris that becomes oxidized in the same manner as other sulphides within this marine environment. He emphasized that the vent system at Conical seamount is inactive and therefore mining would not destroy any biological communities. A participant informed the workshop that tailings from the Ladlolam mine were dumped into the sea through a pipeline.

Professor Herzig was of the opinion that a similar arrangement could work for the tailings from the treatment plant for the ore from Conical Seamount. Another participant suggested that the ore slurry from mining could similarly be transported to land through pipes to the island since the distance in question is 10 kms. Professor Herzig responded to this suggestion with the view that since barges were being used to transport the overburden from the Ladlolam mine, these barges could also be used to transport the ore slurry from the Conical seamount deposit.

One participant, observing that the environment in which massive sulphides deposits are formed is toxic, wanted to know what impact could be introduced by mining that would exceed the toxicity of the in situ environment. Another participant was concerned with the possible impact of mining on the fisheries resources in the water column above the deposit.

This participant advocated the need for an environmental impact assessment study, comprising a comparison of an initial baseline study and a post mining test study.

Professor Herzig in agreeing to the need for a baseline study and post mining environmental studies reiterated his proposal for a pilot mining site to be used to clarify environmental issues, test possible technological configurations for mining these deposits and proving the commercial viability of seafloor massive sulphides deposits mining. In relation to the toxicity of the marine environment at active vent systems, another participant pointed out that the observed biological communities at these sites probably had some enzymes and other interesting biochemistry that would prove beneficial to mankind. He suggested that this reasoning by itself made the study of this environment and these organisms worthwhile.

Modalities for the conduct of a pilot mining operation

With regard to the proposed pilot mining site, questions were raised in relation to its probable actors and risk management.

Professor Herzig pointed to the need for industry support in the pilot mining site. He further pointed out that as scientists, his group and other scientists could undertake the required environmental monitoring but that industry support was required to construct the mining system. Another participant pointed out the advantages of using publicly raised financing to undertake the project as compared to the consortium approach.

Finally, questions were raised as to the scale of operation envisioned in the pilot mining site trial. It was agreed that this would be at about one tenth the scale of a commercial enterprise.

Possible recovery of associated thermal energy.

One participant wanted to know whether Professor Herzig's group had thought of attacking the hydrothermal system directly and recovering the thermal energy of the site as a by product of mining. Another participant pointed out that a similar operation was taking lace in the Sultan Sea, where an active geothermal plant had been established with minerals around the deposit being recovered as minor by-products.

Professor Herzig, while pointing out that the Conical Seamount deposit was at an inactive hydrothermal vent site remarked that one of the difficulties with the proposal were that the hydrothermal fluids would boil within the pipes and destroy them. He again reiterated that his objective is to determine the feasibility of mining the Conical Seamount deposit as a gold deposit.

CHAPTER 3

REGIONAL AND LOCAL VARIABILITY IN THE SPATIAL DISTRIBUTION OF COBALT-BEARING FERROMANGANESE CRUSTS IN THE WORLD'S OCEAN

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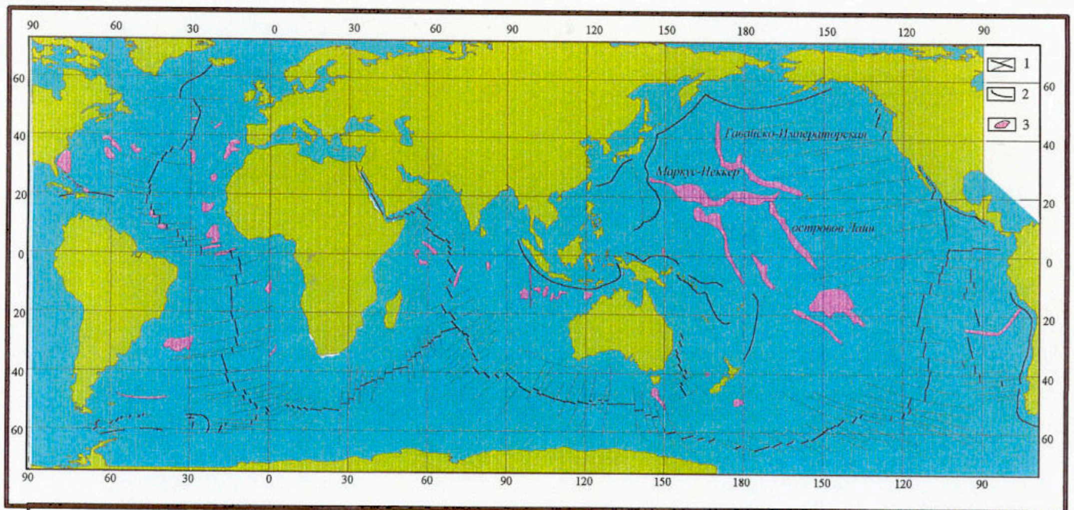
The study of cobalt-bearing ferromanganese crusts, one type of mineral resource of the World Ocean seabed, and the possibility of their commercial exploitation, has reached such a stage that there are grounds to address the problem of their exploration and further exploitation not only theoretically, but practically. Modern knowledge of this type of mineral resource was substantiated by the results of specialized research work that has been actively carried out since the end of the 1970s by various scientific and commercial companies from France, Germany, Japan, Russia and the United States. The high level of existing knowledge helps not only to characterize the extent of these crusts, but to validate criteria for prediction and exploration of cobalt-bearing crust fields, and in some cases, to assess their economic significance.

The first Russian studies concerning cobalt-bearing ferromanganese crusts were carried out on separate guyots of the Marcus-Necker Ridge (the Mid-Pacific Mountains) of the Central Pacific Ocean in 1968, and in 1970 during the 43rd and 48th cruises of RV "Vitiaz" of the Russian Academy of Sciences. Later, as a result of 30 sea cruises of the Academy of Sciences and the Ministry of Natural Resources that were carried out in different regions of the World Oceans much data were obtained about the extent, bedding and features of the structure and composition of ferromanganese crusts which evolved on submarine mountains and uplifts.

Recently, all the acquired and available published data were systematized and a multi-tier graphical database on cobalt-bearing ferromanganese crusts on the ocean floor was created. Currently the database contains parameters on ore abundance from 20 ore provinces and 64 regions where crusts deposits are located This database is based on information obtained from 2217 sample stations (Figure 1).



Province name	Area, thous.sq.km	Station number	Crust resource, Mt
Hawaiian-Emperor	945.4	152	921.4
Line Islands	695.9	91	800.0
Marcus-Necker	1649.0	1723	2906.3

Fig.1. Co-bearing ferromanganese crust provinces of the World Ocean
1 - midoceanic mobile belts; 2 - deep oceanic trenches; 3 - ore provinces

The digital tiers of the database represent different kinds of maps (bathymetric, geological, metallogenic, etc.) of deposits for the different regions of the oceans, based on the size of the deposits. Five classes are distinguished.

- **Metallogenic provinces** that are potential ore-bearing large volcano-tectonic and dome-shaped uplifts of the ocean floor, usually located along the boundaries of the abyssal basins;

- **Metallogenic regions** that are fragments of metallogenic provinces, located within concrete volcanic-tectonic structures and domes with directly proven prospects for ore potential of the crustal type;

- **Metallogenic fields** – fragments of ore regions, confined to individual guyots with abundant cobalt-bearing ferromanganese crusts, studied in great detail, with subsequent assessment of their qualitative and quantitative characteristics;

- **Minerals deposits** – accumulations of cobalt-bearing ferromanganese crusts, whose reserves and quality satisfy the requirements for commercial exploitation;

- **Mineral occurrences**- presumably local accumulations of cobalt-bearing ferromanganese crusts, which were identified as a result of localized observations.

All cobalt-bearing ferromanganese provinces in the World Ocean and the parameters that were included in the database are illustrated in Figure 2.

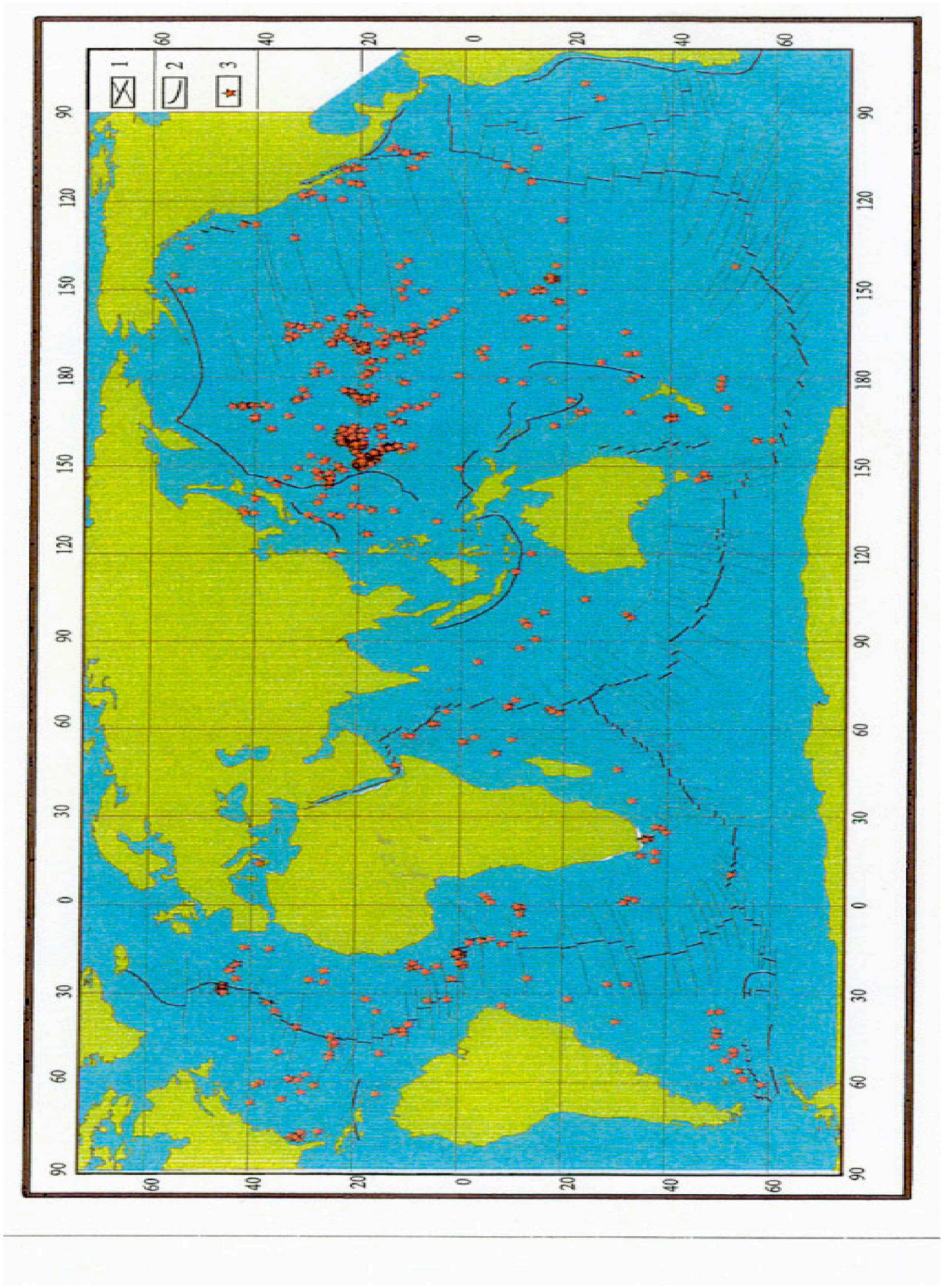
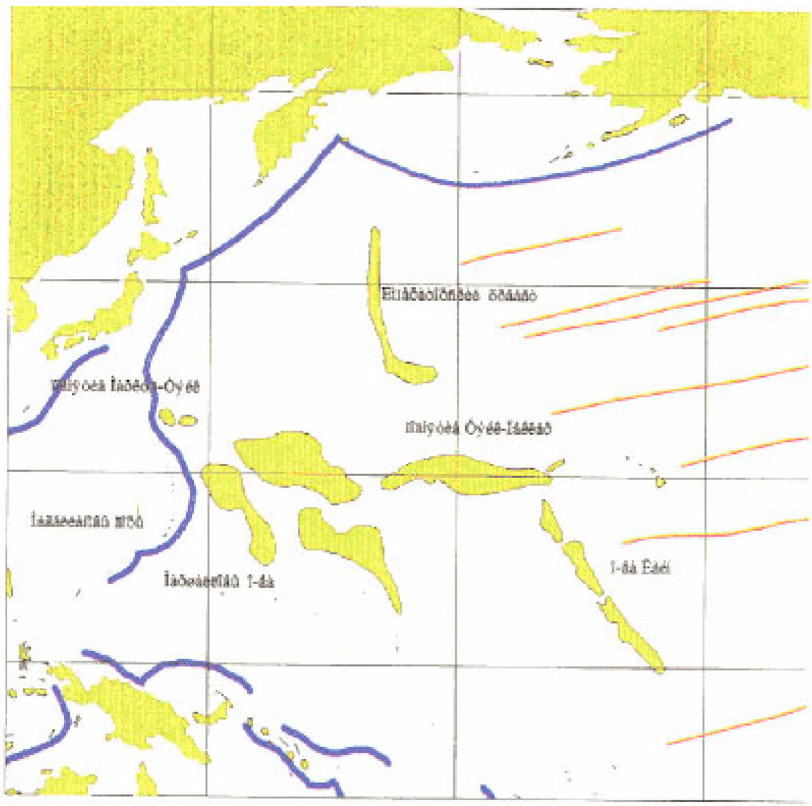


Fig 2. Position of stations with Co-Mn crusts in the World Ocean 1 – midoceanic mobile belts; 2 – deep oceanic trenches; 3 – sampling stations

A digital map of ore-bearing regions was also produced (Figure 3).



Region name	Area, thous.sq.km	Station number	Crust resource, Mt
Emperor ridge	251.80	49	768.0
Wake	706.40	1500	803.4
Magellan seamounts	388.70	1267	1021.4
Marshall seamounts	512.30	92	800.0
Necker	11.33	3	60.0
Line (south part)	177.10	6	400.0
Line (north part)	67.94	18	300.0
Line (central part)	120.60	31	100.0

Fig. 3. Main areas of Co-Mn crusts in the North-West Pacific Ocean

Similar maps for ore fields and for higher classification units cannot yet be produced because of the unsystematic available data, uneven studies carried out in those fields, and often a lack of data concerning methodologies and exploration techniques that were used

However, Russian scientists studied some areas in great detail, and this enabled the creation of an idealized model for an ore field. The model was created for the northeast pre-equatorial part of the Pacific Ocean, where the most prospective provinces of cobalt bearing crusts occur. The provinces are spatially associated with volcano-tectonic uplifts of the ocean floor that are genetically related to Cretaceous basaltic volcanism (Figure 4).

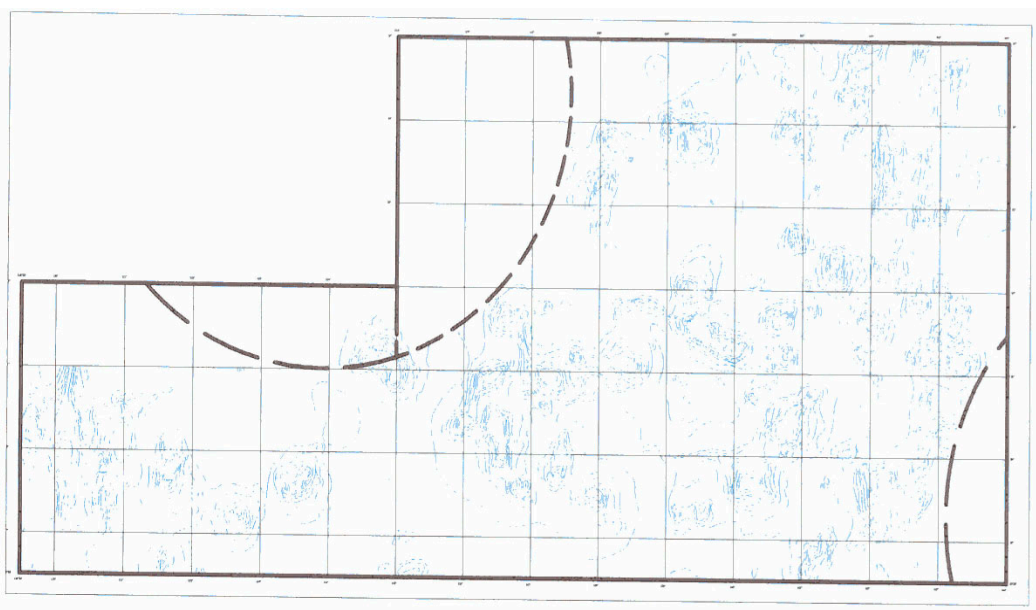


Fig.4. The bathimetric map of the Marcus-Wake underwater rise

A typical ore field can be separately located guyots, whose base is 120 to 80 km. The top is at a depth interval between 1300-1500m, and the slope brow confined to a depth of 1500m. The configuration of the summit plateau is similar to that of the base and has dimensions of 65 to 35 km at a depth of 3000m. The diameter of the structure at this depth is 15km. The average dip of the slopes in between 1500-3000m varies from 20° to 30°, whilst the deeper slopes are more gentle - 5°-10°. In reality slopes have a step-like structure created by a combination of sub-horizontal and gently inclined benches and steep scraps.

As a rule the area covered by crusts is confined to pre-apical zones and slope zones on underwater mountains and its plane has a concentric pattern. Usually, unconsolidated Pliocene-Quaternary sediments with no ores cover the surface of the plateau itself. In our model we have chosen such pattern, though there are cases when the summit plateau is free from sediments and crusts, developed on bedrocks, cover the entire area of the plateau. Very often, nodule fields cover the marginal zones of the summit plateau, gently tilted towards the brow of the slope. The size of nodules varies from 2 to 10cm in diameter and their abundance is not more than 15kgm[2]. Such fields are represented in our model (Figure 5).

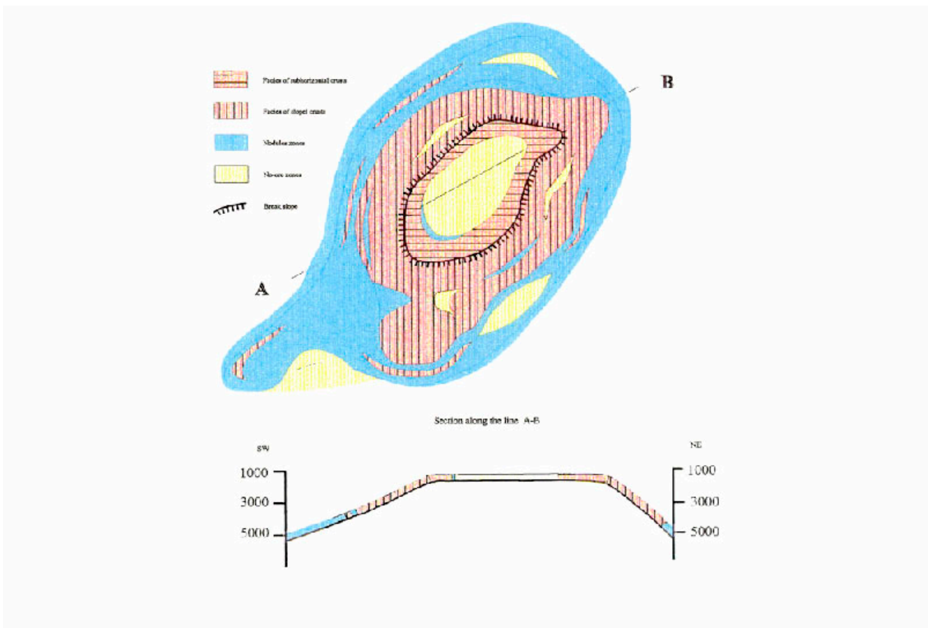


Fig.5. The model of Co-rich manganese deposits of seamounts

Within a concentric zone there are two facies of mineralization. The first can be called a facies of pre-apical sub horizontal surfaces, the second a facies of slopes. The first case is mainly found on the peripheral part of the apical plateau. In our model the depth interval where this facies is developed ranges between 1400–1700m in the area of spurs. Gradients in this area vary from 1.5° to 3°, seldom reaching 5°. In this facies the crusts are typically dense and continuous. The same friable and unconsolidated sediments covering the central parts of the apical plateau usually cover the crusts of this facies. The degree of cover can vary from 20 to 80%, with complete burial of crusts in some areas. Ferromanganese nodules are often associated with the crusts of this facies.

Mineralization of the second facial type is confined to the highly steep upper middle areas of slopes. The upper boundary of crusts of this facies is the slope brown and within the herein presented model this lies at about 1500m. The lower boundary is a break of the slope, below which the slope becomes significantly less steep 5°-7°), which leads to the wide development of sedimentary cover overlaying possible surfaces of crust formation. In the most cases this level is confined to depths around 3000m, though there are cases when the lower boundary of dense and continuous crust mineralization lies as deep as 4000-4500m or as high as 2500m.

The inner structure of the field within the second facial type of ore crusts mainly depends on slope morphology, which as it was already mentioned before has a step-like profile. Accordingly, the main structural elements of fields are narrow but extended bands of crusts confined to gentle areas of steps. Sometimes, such bands can extend along one bathymetric interval of the entire perimeter of a guyot but often only occupy about one third of it. The width of zones can vary within an interval of a few hundred meters to a few kilometres.

Within the area of development of the second facies, the crust surfaces are usually disintegrated to a certain extent. In the upper parts of the slopes, cracking of surfaces and the formation of large blocks represent the process of disintegration. Down slope, a medium level of disintegration can be observed, which is reflected in shifting of formed blocks (i.e. their "peeling" from the substrate with subsequent splitting). At the lower part of facies development there are areas with maximum disintegration of crusts. In such cases the larger sizes of crust fragments are mixed with nodules, fragments of rocks and seabed sediments, actually being a reworked talus.

The thickness of crusts varies over a wide range from a few millimetres to 10-15 cm, and in some cases it can increase up to 24 cm. The zones where crusts are developed with a thickness of 1 cm or less are usually considered ore-free. The thickest crusts were observed in the facies of sub horizontal and gently dipping surfaces, while the thinnest crusts were observed in the facies at the foot of the submarine mountain. As was mentioned above, in the facies of the slopes, thick crusts, steep scraps by thin crusts, cover sub horizontal benches.

A comparison of crusts thickness with water depth suggests that crusts have greater thickness at depths of less than 2500m. There is no relationship between crust thickness and substrate. Thick crusts grow on exposed substrate that is the most favourable condition for crust growth. At the same time, there are limiting factors, in particular the degree of substrate lithification and its age. The older the age of the substrate the greater are the chances of finding thick crusts on it. The lower the degree of lithification, the thinner is the crusts developed on it.

Finally, an important relationship is observed in that thick crusts are confined to scars in the relief. Such conditions are often observed within the spurs crests, complicating positive meso-forms.

Mineralization parameters are controlled by the thickness, structure and composition of crusts. A three-layer structure to the crustal section is very typical of the entire vast region in the northwest pre-equatorial part of the Pacific Ocean. Each of the layers is characterized by a stable individual textural-structure, material features and age (Figure 6).

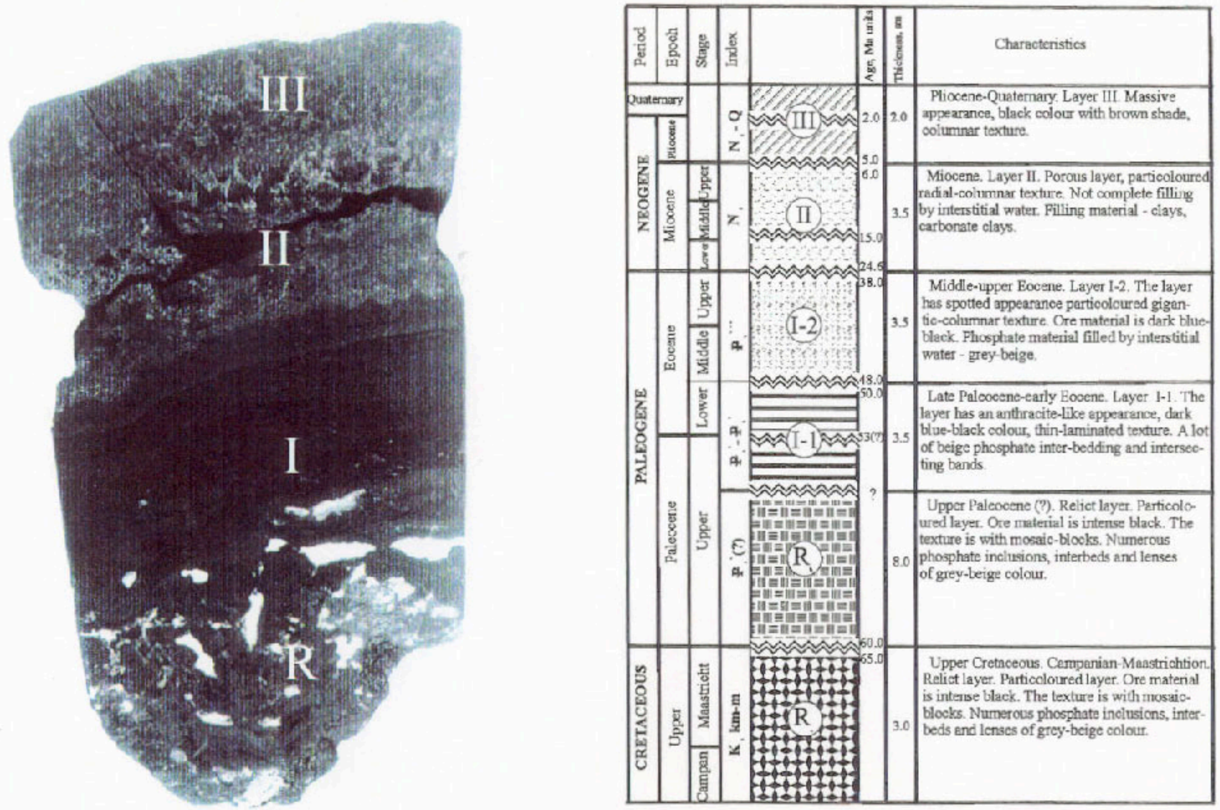


Fig.6 The crust section of Magellan Seamounts and Marcus - Wake underwater rise

Regarding the formation of the first layer, the bedding revealed at the base of the section developed during Late Palaeocene – Late Eocene. The ore matter of this layer has an anthracite-like appearance. The lower half of the layer contains numerous inter-bedding and intersecting by phosphate veins. The mineral composition of this layer is a typical association of vernadite, ferroxigite and apatite. High concentrations of phosphorus and calcium, and low concentrations of metal components due to their impoverishment by phosphate materials are typical of its chemical composition.

The second layer, Layer II, is above Layer I, and is distinguished from this layer by way of a sharp contact. The structure of the ore matter is a radial-columnar pattern. Large pores between columns are partly filled with non-ore typical of its mineral composition. A sharp decrease of phosphate concentrations and high concentrations of metal components are the typical chemical composition of this bed. Its age is Miocene.

The third layer, Layer III, completes the section. This bed can have either a gradual or sharp contract with the underlying layer. The bed has a massive appearance and is of dark brown colour. Its composition is mainly radial-columnar, although thin-laminated varieties are possible. The major mineral associated with this layer is vernadite-ferroxigite-quartz. Its chemical composition is characterized by the maximum concentrations of useful components, firstly manganese and cobalt, and a high metal content. The age of the bed is Pliocene-Quaternary.

Often a section of crust is not complete, and is found with missing layers. In some cases, at the base of the section, there are relicts of ancient crusts from Late Cretaceous to Late Palaeocene, having significant differences in structure and composition from the younger ones (Figure 6).

In order to consider the distribution of valuable metal components in these crusts, it should be noted that these types are mostly concentrated in crusts of the facies found at gently dipping and sub horizontal surfaces. At the same time, on slopes in some localities, high concentrations of manganese and nickel can be observed. Obtaining additional data did not confirm a relationship of metal distribution with depth, as was the assumption in the earlier stages of investigation.

While the majority of researchers support the hypothesis of a hydrogenic-sedimentary origin for cobalt bearing crusts, there is still some debate regarding the genesis of specific formations. Firstly, there is a question concerning the considerable difference between the quantities of the main components of the ore, especially manganese and cobalt, and the possible sources of these metals from the immediate environment surrounding these deposits. According to our assessments, the amount of material coming from this source only represents 10-15% of the mass from predictions.

The second important question concerns the reasons and conditions of enrichment of ore phases by cobalt. In Russian studies, the above-mentioned questions were determined as priority objectives for research at the present time.

SUMMARY OF THE PRESENTATION AND DISCUSSIONS ON THE REGIONAL AND LOCAL VARIABILITY OF SPATIAL DISTRIBUTION OF COBALT-RICH FERROMANGANESE CRUST ACCUMULATION OF THE WORLD OCEAN

In the absence of the authors of the paper on *"The regional and local variability in the spatial distribution of cobalt- rich ferromanganese crusts accumulation of the world's Ocean's*", the paper was neither read nor discussed during the workshop.

CHAPTER 4

HYDROTHERMAL SULPHIDE MINERALISATION OF THE ATLANTIC – RESULTS OF RUSSIAN INVESTIGATIONS, 1985-2000

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Russian studies of the oceanic hydrothermal processes started in mid-60s when the first samples of metalliferous sediments were collected in the Pacific Ocean (Skornyakova, 1964).

During the 1960s and 1970s numerous Russian expeditions studied such low-temperature deposits as metalliferous sediments and hydrothermal crusts as well as hydrothermal anomalies in the near-bottom waters in areas of the mid-ocean ridges in the Pacific and Indian oceans (Lisitsyn et al., 1976; 1979).

The discovery in 1979 of sulphides mineralisation connected with high-temperature vents provided an impulse for these investigations.

In the early 1980s, large-scale investigations of seafloor massive sulphides deposits were launched in the Union of Soviet Socialist Republics. Two Departments were responsible for these expeditions: the Ministry of Natural Resources (MNR) which included scientific bodies such as VNIIOkeangeologia S.E Sevmorgeo, St. Petersburg, and by the Russian Academy of Sciences principally through its P.P. Shirshov Institute of Oceanology (ID RAS, Moscow). While the Shirshov Institute conducted fundamental scientific investigations, the Ministry of Natural Resources concentrated on applied (resource) scientific investigations in an effort to discover these new seafloor deposits and to assess them quantitatively.

The expeditions of the Shirshov Institute were undertaken in submersibles, firstly with the “ Pisces” and then from 1987, with the “Mir”. The investigations during these expeditions were geared to detailed studies of areas of sulphides mineralisation. Fourteen (14) hydrothermal fields were studied in the Pacific and Atlantic Oceans, including the Axial Seamount in the Juan-de-Fuca Ridge, the Guaymas basin in California Bay, some areas in the south-western Pacific Ocean as well as 4 regions on the Mid-Atlantic Ridge (MAR). (Figure 1).

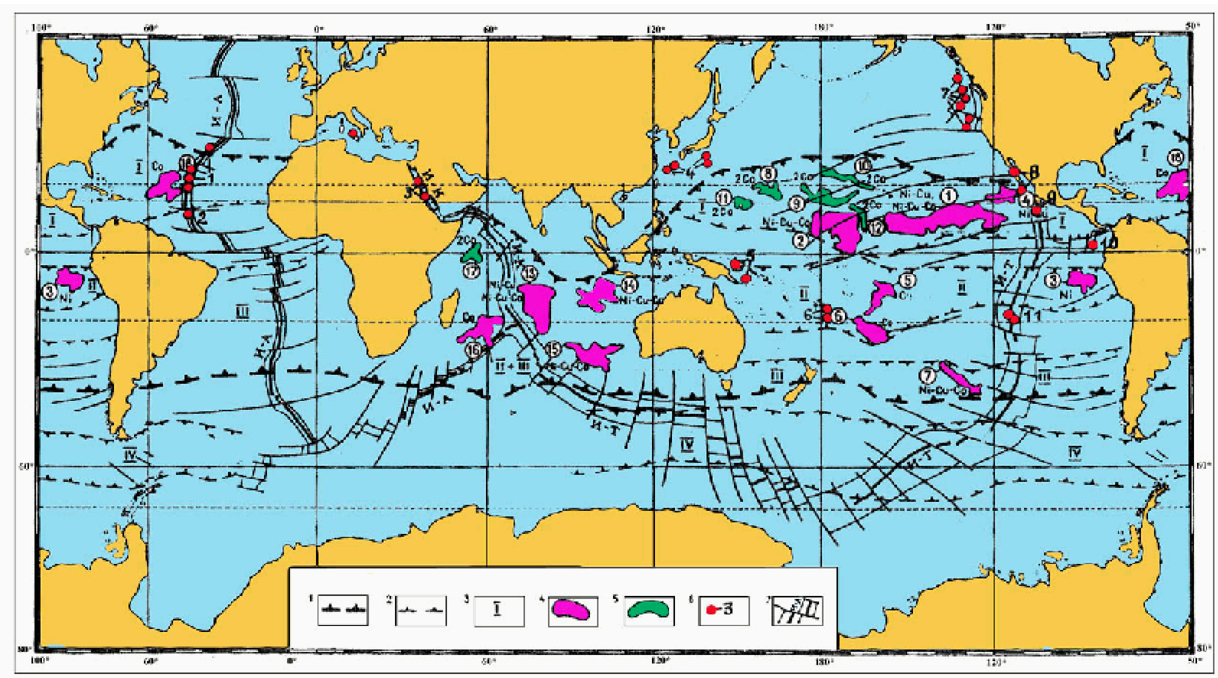


Figure 1. Fe-Mn nodules, Co crusts and massive sulphides distribution in the World Ocean

The first set of data was obtained on the precise position and structure of the largest among the currently known deposits, which was named after the "Mir" submersible (Rona et al., 1993). Recent studies by the Shirshov Institute were conducted in Rainbow, Lucky Strike and Logatchev hydrothermal fields.

Investigations by the Ministry of Natural Resources were initially carried out in the Pacific Ocean. Large segments of the East Pacific Rise (EPR) – from the Equator to 13° N and from 20° to 22° S were mapped as a result of recognition studies. Six (6) new areas of sulphides mineralisation as well as numerous sites of presumed hydrothermal activity were discovered in the northern part of the East Pacific Rise.

Some of the investigations that were began in 1985 in the Mid-Atlantic Ridge are still in progress. Nearly 20 cruises have been organized in this region. Geological and geophysical studies at scales between 1: 1 000 000 and 1: 200 000 were conducted in the course of this period in a 50-100 km band of the axial zone of the Mid-Atlantic Ridge from 12^0 N to 19^0 N and from 21^0 N to 29^0 N. These studies included bathymetric, magnetic, physical and chemical oceanographic studies, side-scan sonar surveys using frequencies of 30 or 100 kHz, as well as video- and photo-profiling and geological sampling.

Ten (10) areas showing promise for new hydrothermal fields that are located at 28°40′ – 28°48′ N, 27°05′-27°10′ N, 25°25′-25°33′ N and 16°07′-16°09′ N were the most significant discoveries by Russian researchers during this period. (Figure 2).

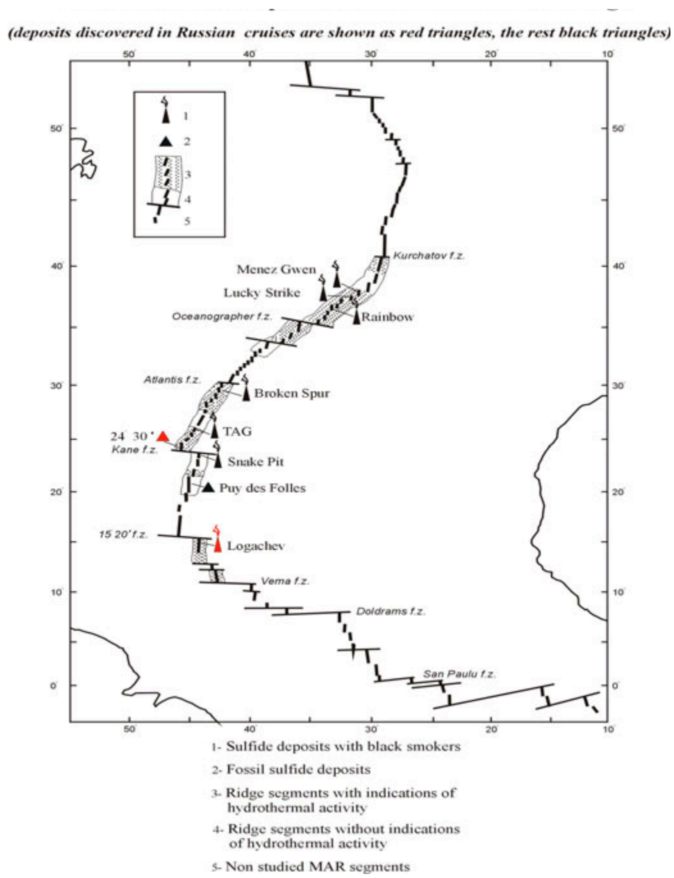


Figure 2: Seafloor massive sulphides deposits at the Mid-Atlantic Ridge

Intensive investigations resulted in the discovery of new hydrothermal sulphides fields; the Logachev - 1 and Logachev – 2 fields, the high-cuprous and high gold content sulphides mineralisation at 24^0 30′N that was photographed and dredged, the MIR hydrothermal mound of the TAG field that was subsequently sampled and studied in detail, as well as the previously known Snake Pit field. (Figure 3). (Krasnov et al., 1995).

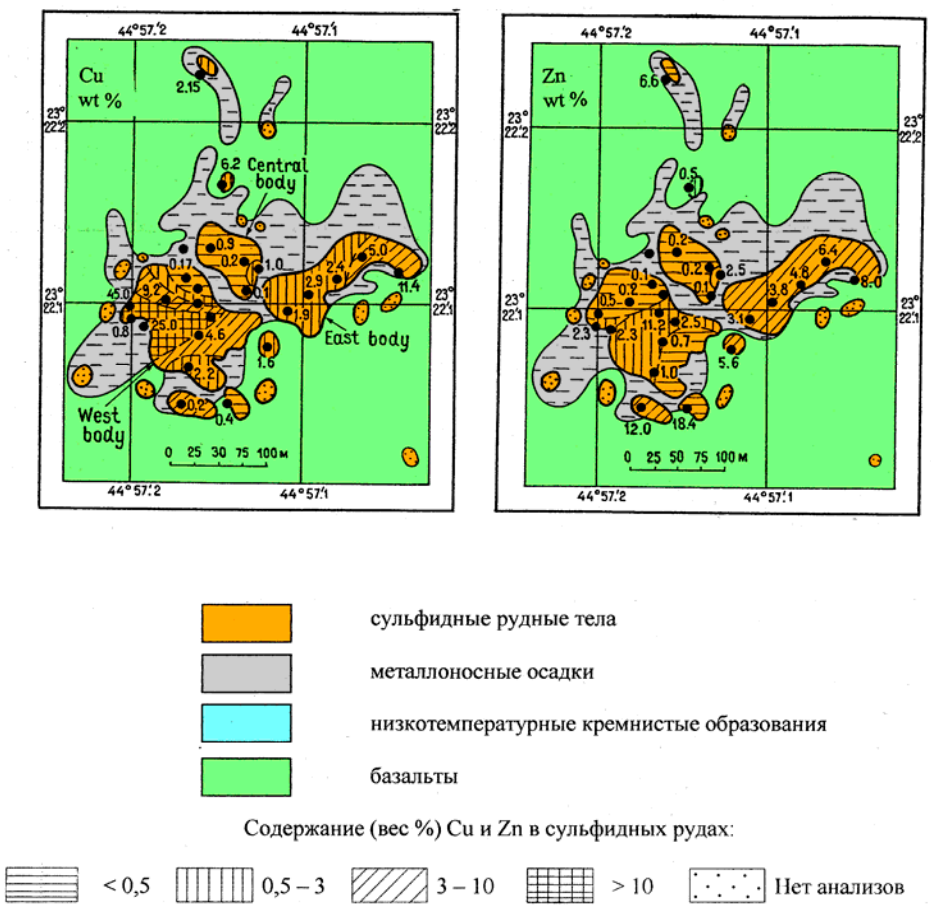


Figure 3 - Snake Pit Field

Logachev –1 hydrothermal field

Anomalies of and manganese concentrations in near-bottom waters indicative of hydrothermal activity have been known for some time above the MAR rift valley segment directly south of the 15^{x}-20^{x} fracture zones (Klinkhammer et al., 1985; Bougault et al., 1990). In addition, objects similar to hydrothermal mounds were photographed at 14^{0} 54' N near the base of the rift valley's eastern wall (Eberhart et al., 1998). The existence of light attenuation, temperature and dissolved Manganese anomalies in the eastern part of the rift valley about 30 km south from the 15*-20* fracture zones was established during the 10th and 12th cruises of the R/V Geolog Fersman in 1991 and 1993.

Between November 1993 and February 1994, the RIFT towed system carrying temperature and spontaneous electrical potential probes, and potentiometer sensors was deployed for detailed studies of the same area during the seventh cruise of the R/V Professor Logachev. The system operates between 30 and 40 m above the seafloor with an interval of 200-500m between tracks. The results of the survey revealed two electric potential and sulphide activity anomalies within a bathymetric step of the eastern wall.

Hydrothermal deposits were discovered during a subsequent TV/photo survey of the sites of these anomalies near 14^{0} 45' N. The deposits are situated on a tectonic step, 7 km to the east of the rift axis at a depth between 2900 – 3050 metres at the base of an ultra-mafic slope with dimensions of 600 x 300 m.

The deposits are 3 large mound- and veneer-like (stratiform) deposits surrounded by the groups of smaller mounds. The mounds are up to 20 metres in height and up to 250 metres in diameter. The apron of metalliferous sediments with more than 0.1% contained copper was sampled. Hydrothermal activity (mainly high- and mid-temperature) is localized within the 3 mounds. Sulphides mineralisation is dominated by copper pyrites, and gold enriched copper and copper-zinc rich ores (Table 1). Mozgova et al (1996) discovered cobalt pentlandite never before observed in ocean sulphides. Widespread are low-temperature crust mineralisation comprising iron-manganese oxides and hydroxides, atakamite, barite and opal crusts that completely overlap the deposits surfaces.

Based on the potential resources contained in these deposits, they are considered to be medium – large, with tonnage estimates between 5 to 50 million tonnes, and with the highest potential in the eastern flanges of the slope of the valley.

The ages of the sulphides samples from the Logachev- 1 site range from about 10-60,000 years (Lalou et al., 1996).

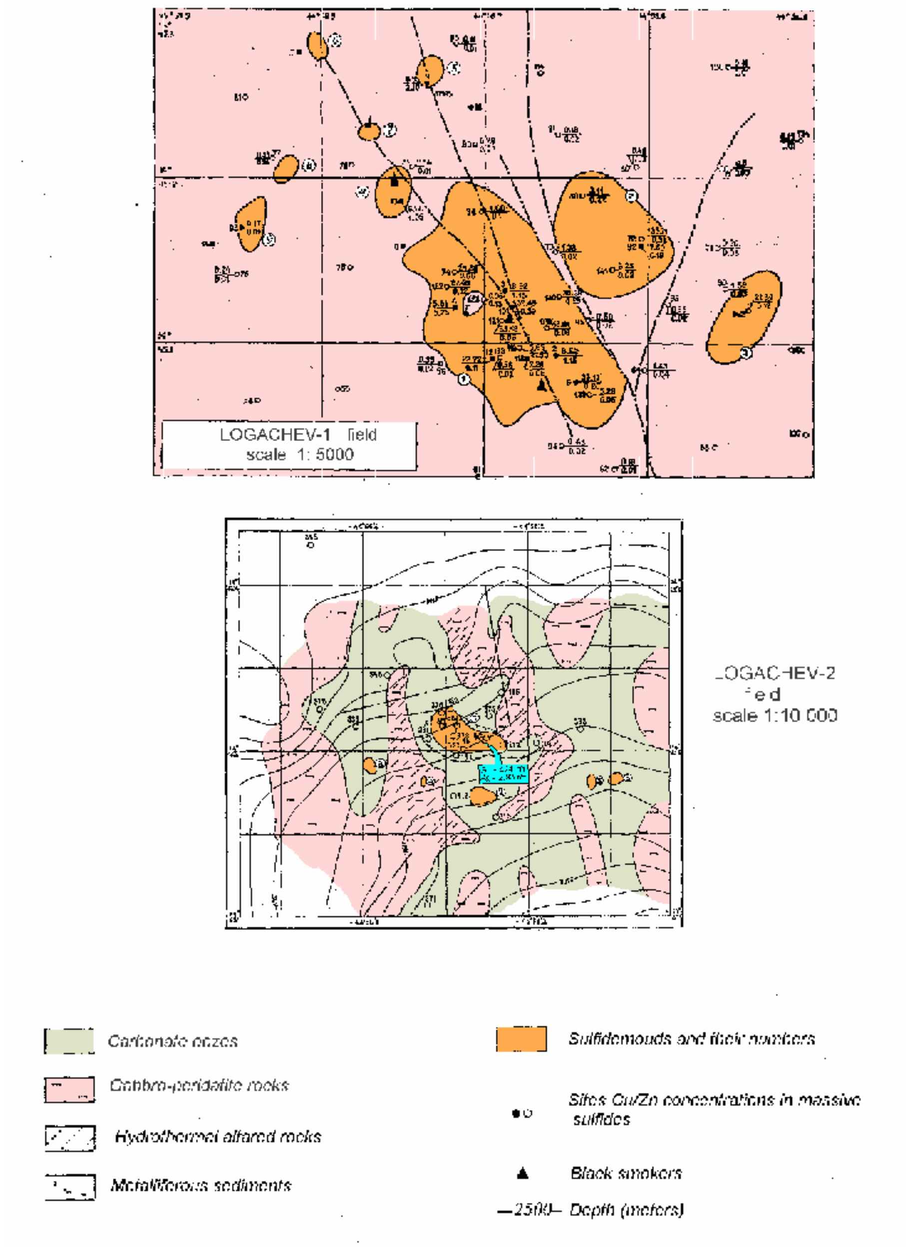
Logachev - hydrothermal field (Figure 4)

The Logachev - 2 hydrothermal field was discovered in 1993-94 at the same time as the Logachev-1 field. The Logachev – 2 field is 5,500 kilometres southwest of it, and was studied in detail during 1996 and 1997 on the 16th cruise of the R/V Professor Logachev.

The field is located between 2660metres and 2700 metres depth in the same geologic setting as Logachev - 1. The host rocks at this deposit are also gabbro-peridotites. Modern volcanic activity is not observed, but 6 sulphides mounds with diameters of up to 120 metres, and surrounded by a field of metalliferous sediments are revealed within its limits. The sulphides contain 7.5 - 22.5% copper, 0.19 - 1.58% zinc and 0.23 - 10.1 g/t gold. Unique for massive sulphides were the contents of valuable components that were recovered in a large bulk sample collected by T/V equipped grab. These included 20.5% copper, 21.2% zinc and 424-ppm gold; in this case the content of gold in particular large-volume samples varies from about 101.1 to 875.1 ppm.

It has been suggested that the mineralisation that has been determined in the Logachev hydrothermal field represents a new type of sulphides mineralisation that differs from the earlier types that have been studied. This mineralisation is characterized by a peculiar composition and genesis that is related to the deep recycling and serpentinisation processes (Bogdanov, 1997).

Cu and Zn distribution in sulfide mounds of the LOGACHEV hydrothermal field



It should be noted that other massive sulphides were also dredged in the immediate vicinity of the Logachev-1 and 2 hydrothermal fields, approximately 30 km to the east of the Mid-Atlantic Ridge (Sharapov and Akimcev, 1993). Currently this is the only find in the Atlantic.

Prediction of a hydrothermal field at 24°30' N?

Massive sulphides in this area of the Mid-Atlantic Ridge were dredged in the course of regional investigations at a scale of 1:1 000 000 - 1: 200 000 in 1987. Five sulphides samples were obtained from a terrace on the eastern slope of a rift valley located between 4000 - 4200 metres depth that is composed of blocks of serpentites and gabbro-peridotites. The massive sulphides debris collected represents the fragments of chimneys and consists mostly of chalcopyrite, bornite, pyrites and marcasite. Very high contents of copper and gold averaging 16.25% and 10.4%, respectively, were found here. The hydrothermal mounds were photographed this year by the deep-towed system of the R/V Professor Logachev.

MIR Sulphide mound of the TAG hydrothermal field

The MIR (Figure 5) mound was discovered by photo profiling in 1985 (Rona et al., 1986) and was first visited by the Mir submersible during the 15th cruise of the R/V Akademik Mstislav Keldysh in 1988 (Lisitsyn et al., 1989). Samples collection along latitudinal and longitudinal profiles was carried out during the dives of the Alvin and the Mir submersibles in 1990 and 1991 respectively (Rona et al., 1993). Detailed photo profiling of the MIR mound and sampling by heavy TV-equipped grabs were performed in 1992-1993 during the 6th cruise of the R/V Professor Logachev. Based on these studies the zonality of the MIR mound was established, large volumes of the deposit were recovered (up to 1.2 tonnes) and the resources of this, the largest sulphide deposit were estimated (Stepanova et al., 1996).

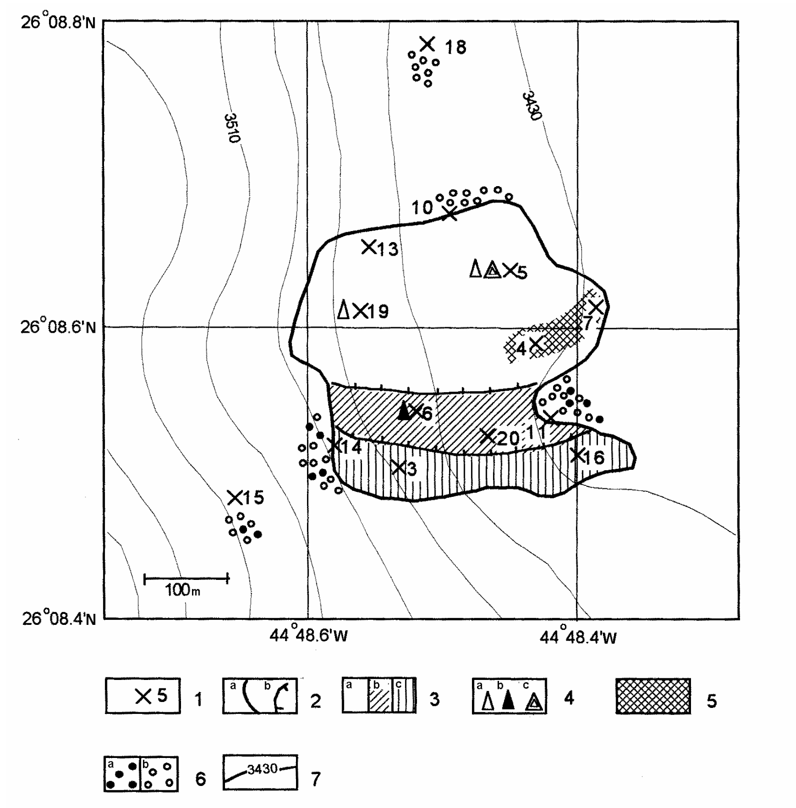


Figure 5: The MIR mound in the TAG hydrothermal field. •1 - station and its number; 2 - the lateral extent of the sulphides mound (a), conventional boundaries between zones (b); 3 - zones: Cu (a), Zn (b), Fe-Si (c); 4 – sulphides chimneys: Py-Cp (a), Sp-Op (b), Bn-Cp-Op (c); 5 – altered sulphides breccias; 6 – oxide mineralisation: Lm-Op (a), OxMn (b); 7 - depth (m).

Metallurgical testing of the 6 large volume samples of the zinc and copper massive sulphides provided the following results:

- Chalcocite-bornite-chalcopyrite sulphides could be metallurgically processed without preliminary enrichment;

- The zinc and copper/zinc sulphides need to be concentrated before metallurgical processing. Depending on the degree of oxidation of the samples, 75-93% of the copper could be extracted, 75-97% for zinc, 32-83% for gold and 68-89% for silver.

Generally, the massive sulphides ores can be profitably reprocessed with the coefficient of complex using 80-87%.

The most ancient sulphides samples, with an age of about 100,000 years were found on the MIR mound (Lalou et al., 1993), suggesting a correlation between the age and dimensions of the sulphides mounds.

In addition to investigations conducted on the Mid-Atlantic Ridge, two other exploration efforts for new hydrothermal fields were conducted in 1996 and 1998 on the northern continuation of the Mid-Atlantic Ridge known as the Knipovich Ridge. In the course of these two international expeditions, onboard the R/V Professor Logachev and the R/V Akademik Mstislav Keldysh respectively, indications of hydrothermal activity were identified and structures that were like hydrothermal mounds were photographed (Cherkashev et al, 1997).

The technologies used by Russian researchers for studying seafloor sulphides deposits included, in addition to conventional methods, a towed geophysical system called RIFT (which was applied during the discovery of the Logachev hydrothermal fields) and a submersible drill to assess the thickness of the sulphides deposits.

SUMMARY OF THE PRESENTATION AND DISCUSSIONS ON HYDROTHERMAL SULPHIDES MINERALIZATION OF THE ATLANTIC – RESULTS OF INVESTIGATIONS 1985-2000

In the absence of Dr. Cherkashev, or any of the authors of the paper, Dr Geoffrey Glasby of the Department of Economic Geology and Geochemistry at the University of Athens read his paper. Apologising for his delivery since he was not familiar with its contents, Dr Glasby's presentation resulted in a discussion of the paper. Unfortunately, these discussions did not have the benefit of responses from Dr Cherkashev.

The discussions focussed on three issues. The fact that gold and silver had been found in massive sulphides deposits at the Mid- Atlantic Ridge whose origins are ultra-mafic rocks rather than ordinary seafloor rocks, the abnormally high values of gold that were reported, and nomenclature problems with the TAG mound.

A number of participants expressed difficulties with the presence of gold and silver in the deposits as reported in the paper. One participant expressed the view that the information that had been provided during the workshop seemed to suggest that the Mid-Atlantic Ridge massive sulphides did not reveal the presence of either gold or silver, let alone the high values reported. Other participants were of the view that at latitude 24˚30′ N, the contents of copper and gold found in the deposit, reported as averaging 16.25% and 10.4% were too high. In particular, with regard to the unit for measuring gold, this participant suggested that maybe the correct unit is parts of gold per million (ppm). Yet other participants suggested a unit of parts per billion (ppb).

With regard to the gold values reported from the Logachev 2 field, another participant requested that one would have to find out about the number of samples analysed and the method that has been used to analyse the gold, because 424ppm, with a maximum of 875ppm is unbelievably high. He stated that based on his experience in analysing seafloor massive sulphides he found these numbers to be unbelievable.

Another participant, however, pointed out that it was very interesting that the deposits at the Logachev field at 14º 45' N, which were discovered on the Mid-Atlantic Ridge are partially hosted in the ultramafic rocks of the upper mantle. He pointed out that the ultramafic rocks provide a suite of metals for leaching by the hydrothermal process that are different from the overlying mafic rocks of the ocean crust. In this instance, he further pointed out; one would expect to find chromium rich and nickel-rich phases in the form of chromate, like the podiform chromite deposit from the Semi ophiolite in Oman. As a result he stated that one would expect a different suite of mineral deposits related to these fields. He also stated that the Russian discoveries open up another dimension to deep ocean mineral deposits, those related to the upper mantle, and that the international scientific community is just beginning to learn about this. He concluded that mankind's understanding of marine mineral deposits continues to expand as we advance in terms of our scientific knowledge of the ocean and the earth.

One of the workshop's participants sought clarification from Dr. Rona on the various references to the TAG mound in Dr. Cherkashev paper. Dr Rona responded that the correct name should be the TAG field, containing the TAG active mound, the MIR inactive mound and the Alvin inactive mound. He pointed out that there are three mounds in the TAG field.

Dr. Rona further pointed out that the TAG hydrothermal field is actually an area about 5km by 5km, encompassing part of the floor and east wall of the rift valley that includes both active and inactive massive sulphides mounds. The mound that was drilled is the active high-temperature mound with the active black smokers at the top; the one that the analogy with the Houston Astrodome is made. The MIR mound which was just described in this paper by Cherkashev and others, is about 2 km to the east of the TAG active mound, on the lower east wall but within the TAG hydrothermal field.

It is one of the inactive massive sulphides mounds and actually it is a very large area, about 1 km in diameter, in contrast to the active mound that is 200m in diameter. He concluded his clarification by further pointing out that there are other active and inactive mounds within that 5 km x 5 km area that has been designated the TAG hydrothermal field.

CHAPTER 5

COBALT-RICH FERROMANGANESE CRUSTS: GLOBAL DISTRIBUTION, COMPOSITION, ORIGIN AND RESEARCH ACTIVITIES

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1. Abstract

Cobalt-rich ferromanganese crusts occur throughout the global ocean on seamounts, ridges, and plateaus where currents have kept the rocks swept clean of sediments for millions of years. Crusts precipitate out of cold ambient seawater onto hard-rock substrates forming pavements up to 250 mm thick. Crusts are important as a potential resource for primarily cobalt, but also for titanium, cerium, nickel, platinum, manganese, thallium, tellurium, and others. Crusts form at water depths of about 400-4000 m, with the thickest and most cobalt-rich crusts occurring at depths of about 800-2500 m, which may vary on a regional scale. Gravity processes, sediment cover, submerged and emergent reefs, and currents control the distribution and thickness of crusts. Crusts occur on a wide-variety of substrate rocks, which makes it difficult to distinguish the crusts from the substrate using remotely sensed data, such as geophysical measurements. However, crusts can be distinguished from the substrates by their much higher gamma radiation levels. The mean dry bulk density of crusts is 1.3 g/cm^3, the mean porosity is 60%, and the mean surface area is extremely high, 300 m^2/g. Crusts generally grow at rates of 1-6 millimetres per million years. Crust surfaces are botryoidal, which may be modified to a variety of forms by current erosion. In cross-section, crusts are generally layered, with individual layers displaying massive, botryoidal, laminated, columnar, or mottled textures; characteristic layering is persistent regionally. Crusts are composed of ferruginous vernadite (δ-MnO_2) and X-ray amorphous iron oxyhydroxide, with moderate amounts of carbonate fluorapatite (CFA) in thick crusts and minor amounts of quartz and feldspar in most crusts. Elements most commonly associated with the vernadite phase include manganese, cobalt,

nickel, cadmium, and molybdenum, and with the iron oxyhydroxide, iron and arsenic. Detrital phases are represented by silicon, aluminium, potassium, titanium, chromium, magnesium, iron, and sodium; the CFA phase by calcium, phosphorus, strontium, yttrium, and carbon dioxide; and a residual biogenic phase by barium, strontium, cerium, copper, vanadium, calcium, and magnesium. Bulk crusts contain cobalt contents up to 1.7%, nickel to 1.1%, and platinum to 1.3 parts per million (ppm), with mean iron/manganese ratios of 0.4 to 1.2. Cobalt, nickel, titanium, and platinum decrease, whereas iron/manganese, silicon, and aluminium increase in continental margin crusts and in crusts with proximity to west Pacific volcanic arcs. Vernadite- and CFA-related elements decrease, whereas iron, copper, and detrital-related elements increase with increasing water depth of crust occurrence. Cobalt, cerium, thallium, and maybe also titanium, lead, tellurium, and platinum are strongly concentrated in crusts over other metals because they are incorporated by oxidation reactions. Total rare-earth elements (REEs) commonly vary between 0.1% and 0.3% and are derived from seawater along with other hydrogenetic elements, cobalt, manganese, nickel, etc. Platinum-group elements are also derived from seawater, except palladium, which is derived from detrital minerals. The older parts of thick crusts were phosphatized during at least two global phosphogenic events during the Tertiary, which mobilized and redistributed elements in those parts of the crusts. Silicon, iron, aluminium, thorium, titanium, cobalt, manganese, lead, and uranium are commonly depleted, whereas nickel, copper, zinc, yttrium, REEs, strontium, and platinum are commonly enriched in phosphatized layers compared to younger non-phosphatized layers. The dominant controls on the concentration of elements in crusts include the concentration of metals in seawater and their ratios, colloid surface charge, types of complexing agents, surface area, and growth rates. Seamounts obstruct the flow of oceanic water masses, thereby creating a wide array of seamount-generated currents of generally enhanced energy relative to flow away from the seamounts. The effects of these currents are strongest at the outer rim of the summit region of seamounts, the area where the thickest crusts are found. Those seamount-specific currents also enhance turbulent mixing and produce up welling, which increases primary productivity. These physical processes also affect seamount biological communities, which vary from seamount to seamount. Seamount communities are characterized by relatively low density and low diversity where the Fe-Mn crusts are thickest and cobalt-rich.

Current patterns, topography, bottom sediment and rock types and coverage, seamount size, water depth, and size and magnitude of the oxygen-minimum zone determine the make-up of the seamount communities, and population density and diversity. Research and development on the technology of mining crusts are only in their infancy. Detailed maps of crust deposits and a better understanding of small-scale seamount topography are required to design the most appropriate mining strategies.

2. Introduction

Cobalt-rich iron-manganese (ferromanganese) oxyhydroxide crusts (see photographs in Appendix 1), hereafter called Fe-Mn crusts, are ubiquitous on hard-rock substrates throughout the ocean basins. They form at the seafloor on the flanks and summits of seamounts, ridges, plateaus, and abyssal hills where the rocks have been swept clean of sediments at least intermittently for millions of years. Crusts form pavements up to 250 mm thick on rock outcrops, or coat talus debris. Fe-Mn crusts form by precipitation from cold ambient bottom waters (hydrogenetic), or by a combination of hydrogenetic and hydrothermal precipitation in regions where hydrothermal venting occurs, such as near oceanic spreading axes, volcanic arcs, and hotspot volcanoes. Fe-Mn crusts contain sub-equal amounts of iron and manganese and are especially enriched in cobalt, manganese, lead, tellurium, bismuth, and platinum relative to their lithospheric and seawater concentrations (Table 1). There are two practical interests in Fe-Mn crusts, the first being their economic potential for cobalt, but also for manganese, nickel, and platinum, and possibly also titanium, rare earth elements (REEs), tellurium, thallium, phosphorus, and others. The second interest is the use of crusts as recorders of the past 60 million years (Ma) of oceanic and climatic history. Besides the high cobalt contents compared to abyssal Fe-Mn nodules, exploitation of crusts was viewed as advantageous because most high quality crusts occur within the Exclusive Economic Zone (EEZ; Fig. 1) of island nations and, therefore, are not subject to some of the perceived problems of recovery of mineral resources occurring in international waters.

2.1. Classification

Up until the late 1970s Fe-Mn crusts were usually not distinguished from abyssal Fe-Mn nodules. If a distinction was made, crusts were called seamount nodules. However, there are distinct differences between Fe-Mn nodules and crusts, other than just morphology (Table 2) (2). Nodules nucleate on small bits of rock, bone, or old nodule fragments on the surface of sediments. Nodules commonly form by both diagenetic (components derived from sediment pore waters) and hydrogenetic precipitation and thus their composition reflect input from both seawater and sediments. However, some nodules form predominantly by either diagenetic or hydrogenetic processes. Nodules have sometimes been referred to as hydrogenous, regardless of their origin; consequently, we use the term hydrogenetic to avoid any confusion about a substrate contribution to crusts--a substrate contribution is not found in Fe-Mn crusts (3). Generally, crusts and nodules have different mineralogical (vernadite versus todorokite and vernadite) and chemical compositions (for example high cobalt versus high copper) because of their genetic differences as well as differences in water depths of formation, although there is much overlap.

Table 1: Contents of manganese, iron, cobalt, nickel, platinum, cerium, copper, and tellurium (wt. %) in marine Fe-Mn crusts compared to contents in and enrichments over seawater and the Earth's crust (lithosphere)

	Seawater	**Lithosphere**	**Fe-Mn Crusts**
Fe/Mn	1.2	57	0.7
Manganese	$5.0x10^{-9}$	0.095	23
Mn/seawater	--	$1.9x10^{7}$	$4.6x10^{9}$
M n/lithosphere	--	--	242
Iron	$6.0x10^{-9}$	5.4	17
Fe/seawater	--	$9.0x10^{8}$	$2.8x10^{9}$
Fe/lithosphere	--	--	3.1
Cobalt	$1.0x10^{-10}$	$2.5x10^{-3}$	0.70
Co/seawater	--	$2.5x10^{6}$	$7.0x10^{8}$
Co/lithosphere	--	--	280
Nickel	$5.0x10^{-8}$	$8.0x10^{-3}$	0.48
Ni/seawater	--	$1.6x10^{5}$	$9.6x10^{6}$
Ni/lithosphere	--	--	60
Platinum	$2.4x10^{-11}$	$4.0x10^{-7}$	$5x10^{-5}$
Pt/seawater	--	$1.7x10^{4}$	$2.1x10^{6}$
Pt/lithosphere	--	--	125
Cerium	$2.8x10^{-10}$	$7.0x10^{-3}$	0.18
Ce/seawater	--	$2.5x10^{7}$	$6.4x10^{8}$
Ce/lithosphere	--	--	26
Copper	$2.5x10^{-8}$	$5.0x10^{-3}$	0.009
Cu/seawater	--	$2.0x10^{5}$	$3.6x10^{6}$
Cu/lithosphere	--	--	18
Tellurium	$1.66x10^{-11}$	$1.0x10^{-6}$	0.005
Te/seawater		$0.6x10^{-5}$	$3.6x10^{8}$
Te/lithosphere			5000

Iron and manganese hydroxides and oxyhydroxides may also form by hydrothermal processes below the seafloor (Table 2). These deposits usually consist of strata bound layers or manganese-cemented volcaniclastic sediments and are distinctly different in texture and composition from hydrogenetic Fe-Mn crusts, especially with regard to the extreme fractionation of manganese and iron (Table 1) and low multiple-trace metal contents in the hydrothermal deposits (4). In the hydrothermal deposits, iron/manganese varies from about 24,000 (up to 58% iron) for hydrothermal ironstones to 0.001 (up to 52% manganese) for hydrothermal strata bound manganese oxides. Many other minor types of iron and manganese mineralisation occur in the ocean basins (Table 2), but this paper is confined to cobalt-rich hydrogenetic Fe-Mn crusts.

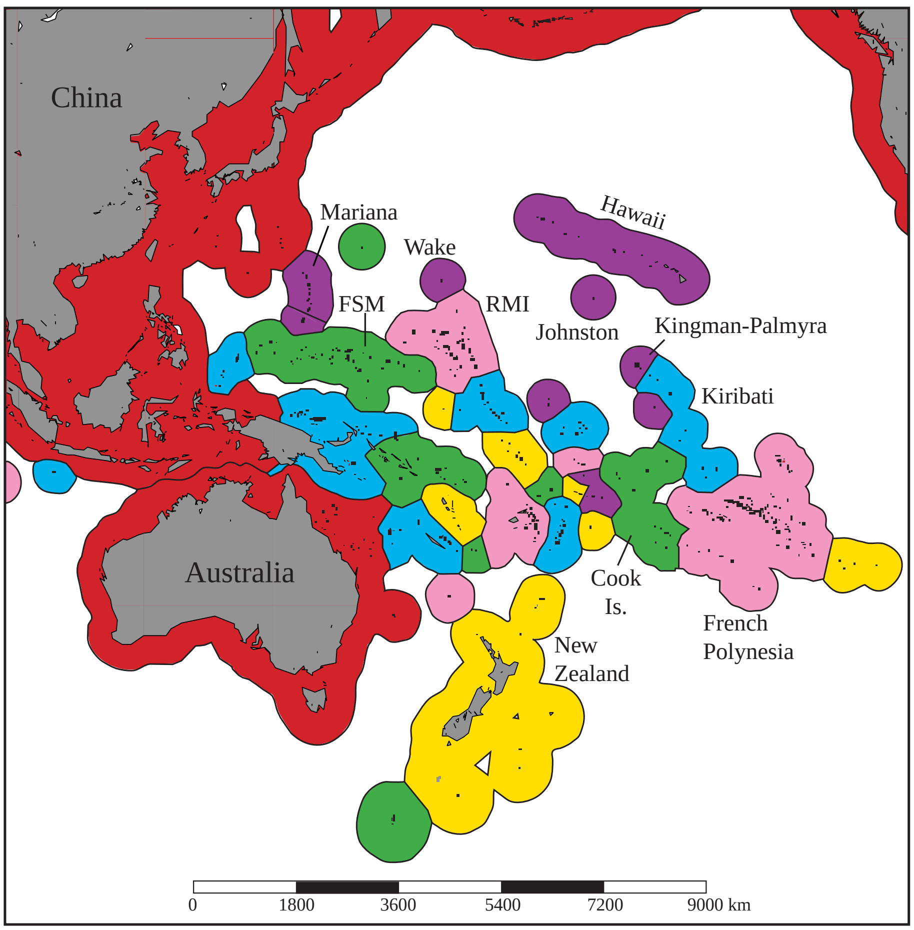


Figure 1. Exclusive Economic Zones (200 nautical mile limits) for island nations within the Pacific, only a few of which are named on this figure; those marked in purple are Territories, Possessions, and Commonwealths of the United States, as well as the State of Hawaii; RMI = Republic of the Marshall Islands; FSM = Federated States of Micronesia; most seamounts in the Pacific are associated with the islands that compose these nations and consequently much of the potential Fe-Mn crust resource occurs within these EEZs (taken and modified from the web site of SOPAC, (www.sopac.org.fj).

Table 2: Classification of marine ferromanganese oxide deposits by form, processes of formation, and environment of formation; most common types in bold, from Hein et al. (1)

	Hydrogenetic	Hydrothermal	Diagenetic	Hydrogenetic and Hydrothermal	Hydrogenetic and Diagenetic	Replacement
Nodules	Abyssal plains, oceanic plateaus, Seamounts[1]	Submerged calderas and fracture zones	Abyssal plains, oceanic plateaus	Submerged calderas	**Abyssal plains, Oceanic plateaus**[1]	All areas (nodule nuclei)
Crusts	**Midplate volcanic edifices**[2]	**Active spreading axes, volcanic arcs**, fracture zones, midplate edifices	---	**Active volcanic arcs, spreading axes**, off axis seamounts, fracture zones	Abyssal hills	Midplate edifices (crust substrate rock)
Sediment-hosted strata bound layers and lenses	---	**Active volcanic arcs, large midplate volcanic edifices**, sediment-covered spreading axes	Continental margins[3]	---	---	Continental margins, volcanic arcs, midplate edifices
Cements	Midplate volcanic edifices[4]	**Active volcanic arcs, large midplate volcanic edifices**[5]	Midplate volcanic edifices[4]	---	Midplate volcanic edifices[4]	Volcanic arcs, midplate edifices
Mounds and Chimneys	---	Back-arc basins, spreading centers, volcanic arcs	---	---	---	---

[1]Less common on ridges, continental slope and shelf; [2]Includes seamounts, guyots, ridges, plateaus; [3]Fe and Mn carbonate lenses and concretions; [4]Mostly fracture and vein fill, cement for volcanic breccia; [5]Mostly cement for breccia, sandstone and siltstone

2.2. Distribution of Fe-Mn Crusts

Fe-Mn crusts have been recovered from seamounts and ridges as far north as the Aleutian Trench in the Pacific and Iceland in the Atlantic and as far south as the Circum-Antarctic Ridge in the Pacific, Atlantic, and Indian Oceans. However, the most detailed studies have concerned seamounts in the equatorial Pacific, mostly from the EEZ (200 nautical miles) of island nations including the Federated States of Micronesia, Marshall Islands, Kiribati, as well as in the EEZ of the USA (Hawaii, Johnston Island), but also from international waters in the Mid-Pacific Mountains. Compared to the estimated 50,000 or so seamounts that occur in the Pacific, the Atlantic and Indian oceans contain fewer seamounts and most Fe-Mn crusts are associated with the spreading ridges. Crusts associated with those spreading ridges usually have a hydrothermal component that may be large near active venting, but which is regionally generally a small (<30%) component of the crusts formed along most of the ridges (5). Those types of hydrogenetic-hydrothermal crusts are also common along the active volcanic arcs in the west Pacific (6), the spreading ridges in back-arc basins of the west and southwest Pacific, spreading centres in the south and east Pacific, and active hotspots in the central (Hawaii) and south (Pitcairn) Pacific. Very few (<15) of the approximate 50,000 seamounts in the Pacific have been mapped and sampled in detail, and none of the larger ones have been so studied, some of which are comparable in size to continental mountain ranges.

Fe-Mn crusts occur at water depths of about 400-4000 m, but most commonly occur at depths from about 1000-3000 m. The most cobalt-rich crusts occur at water depths from 800-2200 m, which mostly encompasses the oxygen minimum zone (OMZ; Fig. 2). In the Pacific, the thickest crusts occur at water depths of 1500-2500 m, which corresponds to the depths of the outer summit area and upper flanks of most Cretaceous seamounts. The water depths of thick high cobalt content crusts vary regionally and are generally shallower in the South Pacific where the OMZ is less well developed; there, the maximum cobalt contents and thickest crusts occur at about 1000-1500 m (7).

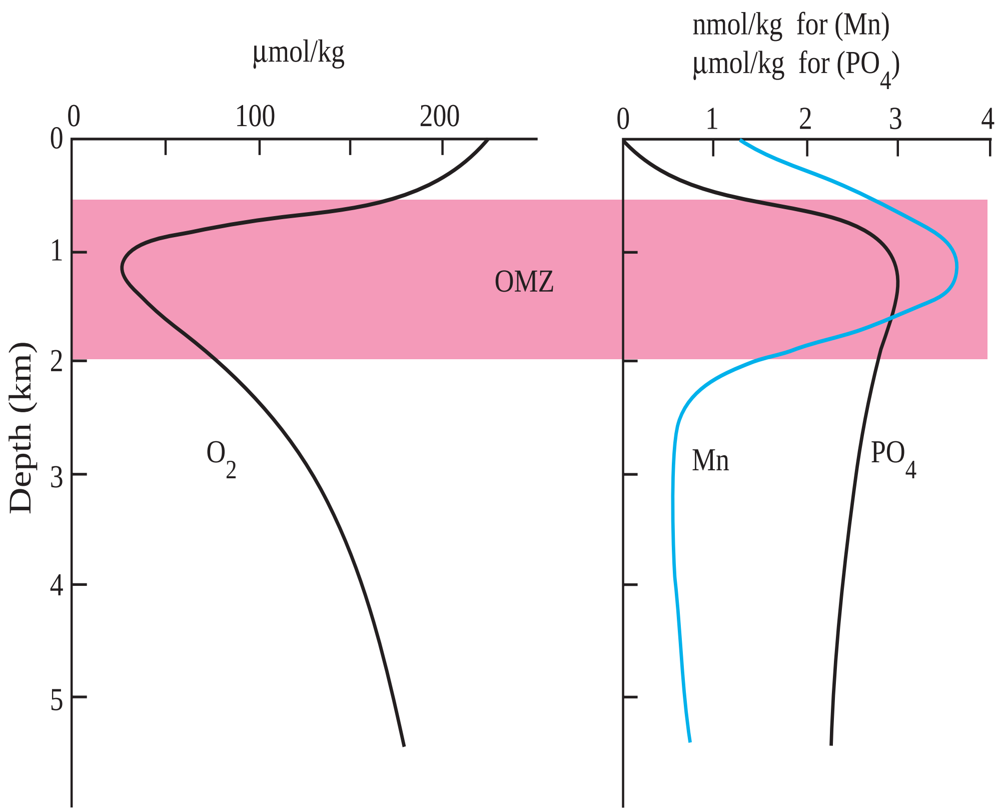


Figure 2. Profiles of dissolved manganese and phosphate compared to oxygen content of seawater over a seamount; low-oxygen seawater (the oxygen minimum zone, OMZ) is a reservoir for high manganese contents.

Crusts become thinner with increasing water depth because of mass movements and reworking of the deposits on the seamount flanks. Most Fe-Mn crusts on the middle and lower seamount flanks consist of encrusted talus rather than encrusted rock outcrop, the latter however typically having thicker crusts (8). Many seamounts and ridges are capped by pelagic sediments and therefore do not support the growth of crusts on the summit. Other volcanic edifices are capped by limestone (drowned reefs), which commonly supports thinner crusts than underlying volcanic and volcaniclastic rocks (9) because of the younger age of the limestones and therefore shorter time for crust growth coupled with the instability and mass wasting of the limestone. Fe-Mn crusts are usually thin down to as much as 3000 m water depth on the submarine flanks of islands and atolls because of the large amounts of debris that are shed down the flanks by gravity processes (10). Reworked crust fragments occur as clasts in breccia, which is one of the most common rock types on seamount flanks (11). Regional mean crust thicknesses mostly fall between 5 and 40 mm. Only rarely are very thick crusts (>80 mm) found, most being from the central Pacific, for which initial growth may approach within 10-30 Ma the age of the Cretaceous substrate rock. Clearly, while most Pacific seamounts are 65-95 Ma old, most crusts collected on those seamounts represent less than 25 Ma of growth because of reworking and episodic sediment cover. Thick crusts are rarely found in the Atlantic and Indian Oceans, with the thickest (up to 125 mm) being recovered from the New England seamount chain (NW Atlantic), and a 72 mm-thick crust being recovered from a seamount in the Central Indian Basin (12).

The distribution of crusts on individual seamounts and ridges is poorly known. Seamounts generally have either a rugged summit with moderately thick to no sediment cover (0-150 m) or a flat summit (guyot) with thick to no sediment cover (0-500 m) (Appendix 2). The outer summit margin and the flanks may be terraced with shallowly dipping terraces headed by steep slopes meters to tens of meters high. Talus piles commonly accumulate at the base of the steep slopes and at the foot of the seamounts; thin sediment layers may blanket the terraces alternately covering and exhuming Fe-Mn crusts. Other seamount flanks may be uniformly steep up to 20°, but most seamount flanks average about 14° (13). The thickest crusts occur on summit outer-rim terraces and on broad saddles on the summits. Estimates of sediment cover on various seamounts range from 15% to 75%, and likely averages about 50%. Crusts are commonly covered by a thin blanket of sediments in the summit region and on flank terraces. It is not known how much sediment can accumulate before crusts stop growing. Crusts have been recovered from under as much as 2 m of sediment without apparent dissolution (14). Based on coring results, Yamazaki (15) estimated that there are 2-5 times more Fe-Mn crust deposits on seamounts than estimates based on exposed crust outcrops because of their coverage by a thin blanket of sediment. Those thinly veiled crusts would be within reach of mining operations.

2.3. Historical Background and Research Investment

The first major advance in the study of oceanic Fe-Mn deposits occurred with the discovery of deep-ocean nodules and crusts by the Challenger Expedition of 1873-6 (16). Dredge hauls collected black Fe-Mn nodules from abyssal depths (4500-6000 m) and coatings, layers, and crusts of iron-manganese oxides from depths as shallow as 370 m. Those samples contained significant minor concentrations of copper, nickel, cobalt, thorium, and thallium (17).

After World War II, it was established that metal scavenging on active catalytic surfaces concentrated metals in manganese oxides in the oceans (18). Most nodules studied were from abyssal depths with 0.30% cobalt or less, whereas a few samples, from ocean spreading axes, had as little as 0.03% cobalt, and samples from seamounts had cobalt contents as high as 0.70%. During the escalation of interest in abyssal Fe-Mn nodules in the 1960s and 1970s, Mero (19) and others (20) noted that topographic highs (seamounts and ridges) in the central Pacific had deposits with the highest mean cobalt contents (1.2%) of any region of the global ocean. During that time, Cronan (21) showed that there is an inverse correlation between water depth and cobalt content of nodules (Fe-Mn crusts) recovered from seamounts. Fe-Mn crusts had begun to be distinguished from nodules in the 1970s (22) and their economic potential was recognized (23). This economic recognition was punctuated by the fact that the price of cobalt had skyrocketed in 1978 (Fig. 3) as the result of the invasion of Zaire by insurgents from Angola and Zambia. Zaire has been the world's largest producer of cobalt, which is a by-product of copper mining in the West African copper belt.

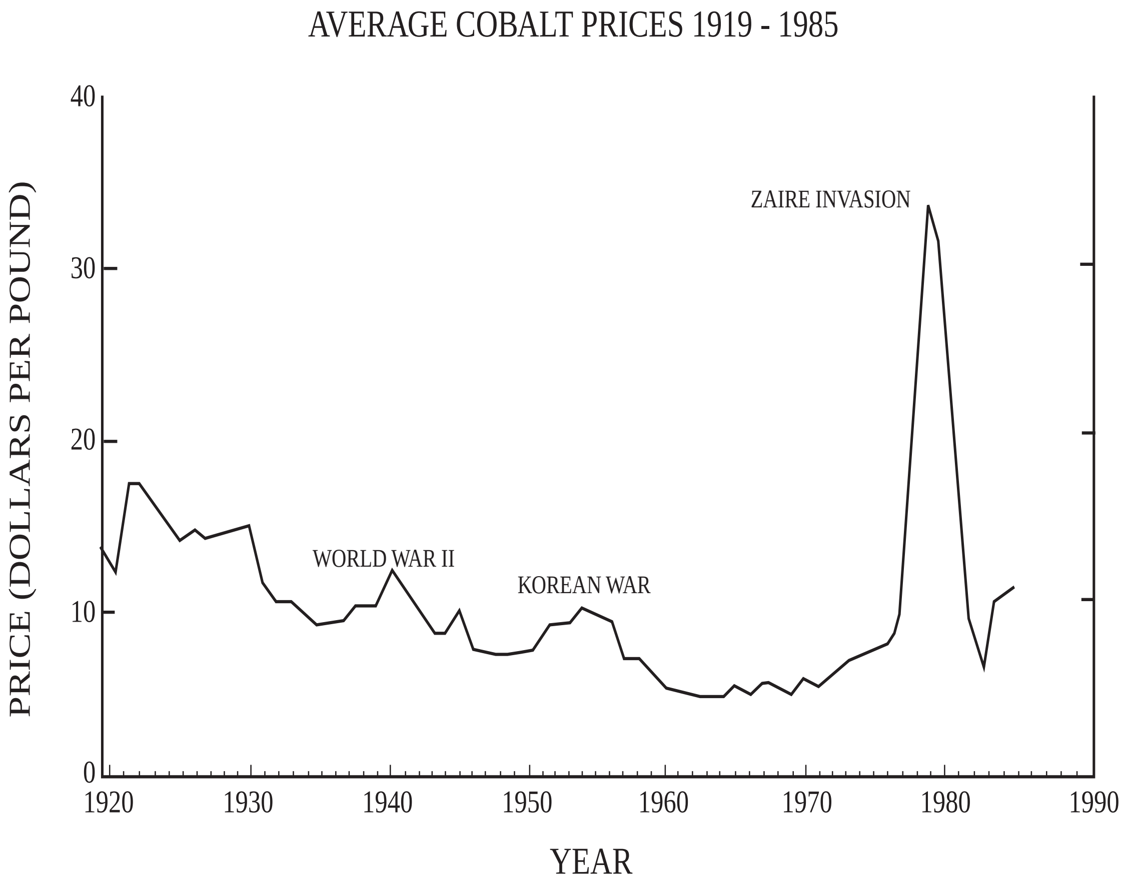


Figure 3. A 66-year record of average cobalt prices, from Manheim (24).

Table 3: Cruises dedicated to the study of Co-rich Fe-Mn crusts, 1981-1999

Ship/Cruise	Year/month	Institution[1]	EEZ/Region
Sonne/SO18	1981/6-7	TUC	US: Johnston, Kingman, Palmyra Is; Kiribati: Line Is
S.P. Lee/L5-83-HW	1983/10-11	USGS	US: Hawaii, Johnston, Palmyra, Kingman Is
Sonne/SO33	1984/7-8	TUC	US: Hawaii, Johnston, Palmyra, Kingman Is
S.P. Lee/L9-84-CP	1984/8	USGS	Marshall Is
Kana Keoki/KK84-04-28-05	1984/6	UH	US: Hawaii
Kana Keoki/KK84-08-24-02	1984/8	UH	US: Hawaii
Sonne/SO37	1985/5-6	TUC	US: Howland, Baker, Johnston Is
Sonne/SO46	1986/11-12	TUC	US: Johnston I; Marshall Is
Farnella/F7-86-HW	1986/11-12	USGS/BOM	US: Johnston I
Jean Charcot/NODCO I	1986	IFREMER	French Polynesia
Tui/Tripartite II	1986	NZOI	Cook Is
Moana Wave/MW-86-02	1986/2-3	UH	Kiribati: Phoenix Is; Tuvalu
Moana Wave/MW-87-02	1987/2	UH	Cook Is; Kiribati: Line Is
?	1987	USSRAS	International: East Mariana basin
Hakurei Maru II/many	1980s-1990s	MMAJ	International waters between Hawaii and Japan
Hakurei Maru II/?	1987	MMAJ	Kiribati: Phoenix Is
Farnella/F7-87-SC	1987/12	USGS	US: California
Hakurei Maru II/?	1988	MMAJ	Tuvalu
Rapuhia	1988/1-2	NZOI	New Zealand
Akademik Nikolai Stakhov	~1988	USSRAS	International: northeast Atlantic
Hakurei Maru II/?	1989	MMAJ	Kiribati: Line Is
Farnell/F10-89-CP	1989/9-10	USGS/KORDI	Marshall Is
Hakurei Maru II/?	1990	MMAJ	Samoa
Farnella/F11-90-CP	1990/10-11	USGS/KORDI	FSM
Farnella/F7-91-WP	1991/7-8	USGS/KORDI	FSM; Palau
Hakurei Maru II/?	1991	MMAJ	Kiribati: Gilbert Is
Vinogradov/91-AV-19/2	1991/6	RAS/USGS	US: Johnston I
Rig Seismic/BMR107	1992/2	AGSO	Australia: Christmas I.
Sonne/SO83	1992/12	FUB	International, NE Atlantic
Rig Seismic/147	1995	AGSO	Australia: Tasmania
Hakurei Maru II/?	1995	MMAJ	Tonga
Hakurei Maru II/?	1996	MMAJ	Marshall Is
Hakurei Maru II/?	1997	MMAJ	FSM
Onnuri/KODOS 97-4	1997/8-9	KORDI/USGS	Marshall Is
Hakurei Maru II/?	1998	MMAJ	FSM; Marshall Is
Onnuri/KODOS 98-3	1998/8	KORDI/USGS	Marshall Is; FSM
Onnuri/KODOS 99-1	1999/5-6	KORDI	Marshall Is

[1]TUC=Technical University of Clausthal, Germany; USGS=United States Geological Survey; UH=University of Hawaii; BOM=United States Bureau of Mines; IFREMER=L'Institut Français pour l'Exploitation de la MER, France; NZOI=New Zealand Oceanographic Institute; USSRAS=USSR Academy of Sciences; MMAJ=Metal Mining Agency of Japan; KORDI=Korean Ocean Research and Development Institute; RAS=Russian Academy of Sciences; AGSO-Australian Geological Survey Organization; FUB=Free University of Berlin; FSM=Federated States of Micronesia

The first systematic investigation of Fe-Mn crusts was carried out in the Line Islands south of Hawaii during the 1981 German Midpac I cruise on the R.V. Sonne, headed by Peter Halbach of the Technical University, Clausthal-Zellerfeld (Table 3). That cruise made breakthrough discoveries using large dredges, seismic profiling, and bottom photography (25). Subsequent German, U.S. Geological Survey (USGS), and University of Hawaii cruises (Table 3; Fig. 4) to submarine edifices in the central Pacific refined our knowledge of Fe-Mn crust distributions and chemical relationships. They showed that crusts were especially enriched in cobalt, iron, cerium, titanium, phosphorus, lead, arsenic, and especially platinum, but relatively lower in manganese, nickel, copper, and zinc compared to nodules (26).

USA activities in Fe-Mn crust studies accelerated as the result of the 1983 proclamation of President Reagan for a 200 nm EEZ, in which he made special mention of cobalt-rich Fe-Mn crust deposits. Subsequent USA research cruises (Table 3) revealed that the most promising Fe-Mn crust deposits occur within the EEZ of the Marshall Islands, Johnston Island (USA), Line Islands (USA and Kiribati), and on Blake Plateau (USA) in the Atlantic.

International complications partly linked to the location of abyssal Fe-Mn nodules in international waters contributed to the withdrawal of commercial consortia from active preparations for nodule mining in the late 1970s. The extensive occurrences of Fe-Mn crusts within the EEZ of coastal nations provided an incentive for mineral interests within areas of national jurisdiction (27). This applied not only to Pacific seamount deposits, but also to Fe-Mn crusts along continental margins (28).

Other systematic iron-manganese minerals investigations during the 1970s, 1980s, and 1990s (Table 3) included a series of cruises by the Japanese Geological Survey, directed mainly toward abyssal nodule deposits (e.g., 29), crust studies centred in the Japanese EEZ (Izu-Bonin arc; see Usui and Someya (30) for compilation of data and references), and in international waters of the Mid-Pacific Mountains. Other Asian nations like Korea and China initiated Fe-Mn crust research with USA and other co-operators (e.g., 31), and, along with Japan and Russia, continue their field efforts in Fe-Mn crust studies today. Field studies by the USA, Germany, UK, and France have largely been discontinued.

A detailed database and review of the chemical composition of crusts based on data up to 1987 was published in 1989 (32), and is also available on NOAA and MMS Marine Minerals CD-ROM, NGDC Data Set #0827, and web site http://www.ngdc.noaa.gov/mgg/geology/ mmdb/. A more recent compilation of mean chemical data was presented by Hein et al. (33) and those data are further updated here.

The list of 37 research cruises in Table 3 is not comprehensive and data for a few cruises completed by the USSR (and later Russia) and China are not available to the author. However, based on an estimated 40 research cruises from 1981 through 1999, it is suggested that minimum expenditures were about US $30 million for ship and associated scientific operations related to field work, and $40 million for shore-based research, for a total investment of about $70 million.

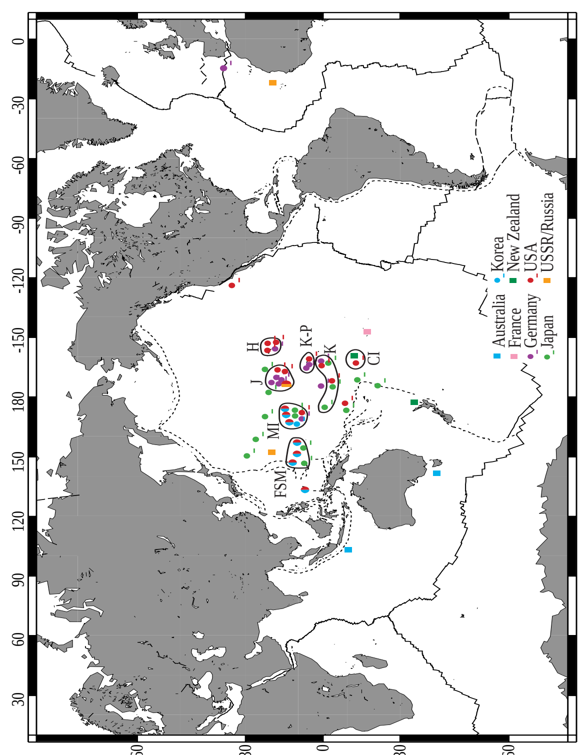


Figure 4. Distribution of research cruises dedicated to the study of cobalt-rich Fe-Mn crusts, 1981-1999 (listed in Table 3); CI = Cook Islands; FSM = Federated States of Micronesia; H = Hawaii; J = Johnston Island (USA); K = Kiribati; K-P = Kingman-Palmyra Islands (USA); MI = Marshall Islands.

3. Fe-Mn Crust Characteristics

3.1. Textures and Physical Properties

Crust surfaces exposed directly to the seafloor are botryoidal, with botryoids varying in size from microbotryoidal (millimetre size) to botryoidal (centimetre size). Fresh growth surfaces are characterized by a fractal distribution of botryoids with extreme surface area. Under conditions of high current flow, the botryoids are modified, either by smoothing or by accentuation of the relief by erosion around the margins of the botryoids, in places producing mushroom-shaped forms. With strong uni-directional flow, the botryoids become polished and fluted. Crusts on the sides of rocks are commonly more protected from current activity and grow at a slower rate thereby acquiring very high cobalt contents; textures of those side crusts are very porous and granular.

Crust profiles vary according to thickness and regional oceanographic conditions. Thin crusts (<40 mm) are usually black and massive, botryoidal, or laminated. Thicker crusts (40-80 mm) commonly have at least two distinct layers, a lower black, massive, dense layer that is phosphatized and an upper black to brown layer that is more porous, with laminated, mottled, botryoidal, and/or columnar textures. The thickest crusts (>80 mm) may have up to 8 distinct macroscopic layers, the lower several layers of which are commonly phosphatized. In polished thin sections, textures consist of alternating laminated, columnar, botryoidal, and mottled textures. Columns range in height from millimetres to 50 mm (34), with detrital grains separating columns and actually promoting columnar growth (35). Mottled layers are the most porous and detritus-rich. The various textures probably reflect bottom-water conditions at the time of precipitation of the oxides. Mottled, columnar, botryoidal, and laminated textures likely represent progressively decreasing energy in the depositional environment (36).

An important consideration in the exploration and exploitation of potential crust resources is the contrast in physical properties between crusts and substrate rocks. Those comparisons are complicated by the fact that crusts grow on a wide variety of substrates including breccia, basalt, phosphorite, limestone, hyaloclastite, and mudstone in that order of abundance.

Phosphorite and fresh basalt are strong, competent rocks and contrast significantly with crusts, which are weak, light-weight, and porous (Table 4); the other rock types, including altered basalt, may not contrast much in physical properties with Fe-Mn crusts. In general, crusts are much more porous (mean 60%) than most substrate rocks and have an extreme amount of specific surface area, which averages about 300 m^2/g (Table 4), similar to the surface area of silica gel. The surface area decreases by up to 20% when measured one month after collection of the crust and up to 40% after two months (45). This clearly shows that many physical properties that are measured a long time after collection of the crusts may not closely approximate *in situ* crust properties. The mean wet bulk density of crusts is 1.90 g/cm^3 and the mean dry bulk density is 1.30 g/cm^3. The P-wave velocity of crusts may be less or more than that of sedimentary substrate rocks, but is generally less than that of basalt. This variable contrast will make it difficult to develop sonic devices for measuring *in situ* crust thicknesses. The most distinctive property of Fe-Mn crusts is their gamma radiation level, which averages 475 net counts/min in contrast to sedimentary rock substrates (101) and basalt substrates (146; Table 4). Gamma radiation may be a useful tool for crust exploration under thin-sediment cover and for measuring crust thicknesses *in situ*.

Table 4. Physical properties of Fe-Mn crusts and substrate rocks, from Hein et al. (37)

Physical Properties	n	Fe-Mn Crusts	n	Sed. Rock substrate	n	Basalt substrate	Ref.
Porosity (volume %)							
Range	13	52-66	8	18-47	2	15-37	38
Mean	13	61	8	39	2	26	38
	-	41-74	-	7-69	-	7-67	39
	-	55	-	35	-	-	40
Wet bulk density (g/cm^3)							
Range	13	1.83-2.04	8	2.04-2.57	2	2.22-2.62	38
Mean	13	1.92	8	2.18	2	2.42	38
Range	18	1.90-2.44	7	1.59-2.68	23	2.06-2.66	41
Mean	18	2.00	7	1.90	23	2.34	41
Dry bulk density (g/cm^3)							
Range	13	1.18-1.48	8	1.56-2.38	2	1.84-2.46	38
Mean	13	1.29	8	1.78	2	2.15	38
	-	1.31	-	-	-	-	40
	-	1.04-2.17	-	1.44-2.92	-	0.78-2.74	39
Grain density (g/cm^3)							
Range	13	3.03-3.87	-	-	-	-	38
Mean	13	3.48	-	-	-	-	38
	-	2.70-3.44	-	2.54-2.81	-	2.32-2.95	42
Specific surface area (m^2/g)							
Range	15	250-381	-	-	-	-	43
Mean	15	323	-	-	-	-	43
Compressive strength (MPa)	-	8.36	-	3.66-32.6	-	-	40
	-	0.5-25.0	36	0.1-52.3	-	0.37-71.0	39
Seawater saturated	-	5.39-8.92	-	1.71-12.4	-	165-219	40
Tensile strength (MPa)	-	1.75	-	4.5	-	-	40
	-	0.1-2.3	-	0.1-4.5	-	0.1-18.9	39
Seawater saturated	-	0.45	-	0.23-0.48	-	11.9	40
Cohesive strength (MPa)	-	2.9	-	7.8	-	-	40
Seawater saturated	-	1.5	-	0.4-2.3	-	26.4	40
Shear strength (MPa)	-	1.26-2.5	-	-	-	-	44
Angle of internal friction	-	42°	-	52°	-	-	40
Seawater saturated	-	76°	-	61°-77°	-	76°	40
Young's modulus (GPa)	-	2.15	-	0.31-10.1	-	-	40
Seawater saturated	-	3.11-4.25	-	0.62-4.76	-	51.3-63.7	40
P-wave velocity (km/s)	-	2.09-3.39	-	1.76-5.86	-	-	39
Range, parallel to bedding	18	2.46-4.19	5	1.80-4.35	23	3.14-5.14	41
Mean, parallel to bedding	18	3.36	5	2.57	23	4.13	41
Range, perpendicular to layers	17	2.07-3.86	4	1.78-4.34	23	3.02-4.93	41
Mean, perpendicular to layers	17	3.16	4	2.56	23	3.99	41
	-	2.26	-	1.01-3.45	-	-	40
Seawater saturated	-	2.72-2.78	-	2.07-2.87	-	5.76-5.80	40
S-wave velocity-saturated (km/s)	-	1.35-1.83	-	1.15-1.67	-	3.46-3.57	40
Gamma radiation (net counts/min)							
Range	18	271-800	6	52-137	23	21-366	41
Mean	18	475	6	101	23	146	

Dash means not reported

3.2. Mineralogy

The mineralogy of bulk crusts is relatively simple compared to hydrothermal and diagenetic iron and manganese deposits. The dominant crystalline phase is iron-rich δ-MnO_2 (ferruginous vernadite (46)); with generally two X-ray reflections at about 1.4 Å and 2.4 Å that vary widely in sharpness as the result of crystallite size and manganese content. δ-MnO_2 generally makes up more than 95% of the X-ray crystalline phases, the remainder being detrital minerals such as quartz, plagioclase, potassium-feldspar, pyroxene, phillipsite, and authigenic carbonate fluorapatite (CFA; Table 5). The older parts of thick crusts are phosphatized and may contain up to 30% CFA in that part of the crust, but CFA is generally less than 10% of thick bulk crusts. Another major phase in crusts is X-ray amorphous iron oxyhydroxide (δ-FeOOH, feroxyhyte; (47)), which is commonly epitaxially intergrown with δ-MnO_2 (48). In about 6% of 640 samples analysed, the feroxyhyte crystallizes as goethite in the older parts of thick crusts. In Pacific crusts, the quartz and part of the plagioclase are eolian, whereas the remainder of the plagioclase and the other volcanogenic minerals derive from local outcrops.

Table 5: Mineralogy of Pacific Fe-Mn crusts

Dominant	Common	Less Common	Uncommon or Uncertain
δ-MnO_2 (Iron-vernadite), Iron oxyhydroxide (Feroxyhyte)	CFA, quartz, plagioclase, smectite	Phillipsite, goethite, todorokite, calcite, K-feldspar, pyroxene, opal-A, barite, amphibole, magnetite, amorphous aluminosilicates	Halite, illite, clinoptilolite, lepidocrocite, manjiroite, manganite, palygorskite, chlorite, dolomite, stevensite, kutnahorite, mordenite, natrojarosite, hematite, manganosite, maghemite, lithiophorite, analcite

CFA = carbonate fluorapatite

Todorokite, which is common in diagenetic Fe-Mn nodules and hydrothermal manganese deposits, is rare in hydrogenetic crusts. Of 640 X-ray diffraction analyses done by the USGS on Pacific crusts, only 5% (2% if offshore California samples are excluded) contain todorokite; 30% of crust samples from offshore California contain todorokite, which, because of very high biological productivity, may reflect the lower oxidation potential of seawater there compared to Pacific sites farther to the west. CFA occurs in 28% of the crust samples analysed, but not in any crusts from the east (offshore California) or far north Pacific; if those crusts are excluded, 34% of central and west Pacific samples contain CFA. Phosphatization of Fe-Mn crusts generally occurred during two periods of time, about 34 Ma and 24 Ma ago (49). Smaller percentages of Atlantic and Indian Ocean crusts contain CFA because those crusts are thinner and younger compared to Pacific crusts.

3.3. Ages and Growth Rates of Fe-Mn Crusts

Hydrogenetic Fe-Mn crusts grow at incredibly slow rates of <1 to about 11 mm/Ma, with the most common rates being from 1-6 mm/Ma (Fig. 5). These slow growth rates allow for the adsorption of large quantities of trace metals by the oxyhydroxides at the crust surface. Growth rates were first measured using either uranium-series or beryllium isotopes, which give reliable ages for the outermost 2 and 20 mm of crusts, respectively, or by radiometric or paleontological dating of the substrate rock and assuming that the substrate age is equivalent to the age of the base of the crust. With both methods, the growth rates and ages of the crusts are extrapolated and do not take into account changes in growth rates, growth hiatuses, or in the later method, the time between formation of the substrate rock and the beginning of growth of the crusts. For equatorial Pacific Cretaceous seamounts, the age of substrate rocks and crusts can vary by as much as 60 Ma, although in rare circumstances the ages of very thick crusts may approach those of the Cretaceous substrates. Beryllium isotope dating is the most reliable and widely used technique today. However, using beryllium isotope techniques requires that the age of the base of crusts thicker than about 20 mm be determined by extrapolation using the growth rate(s) determined for the outer 20 mm.

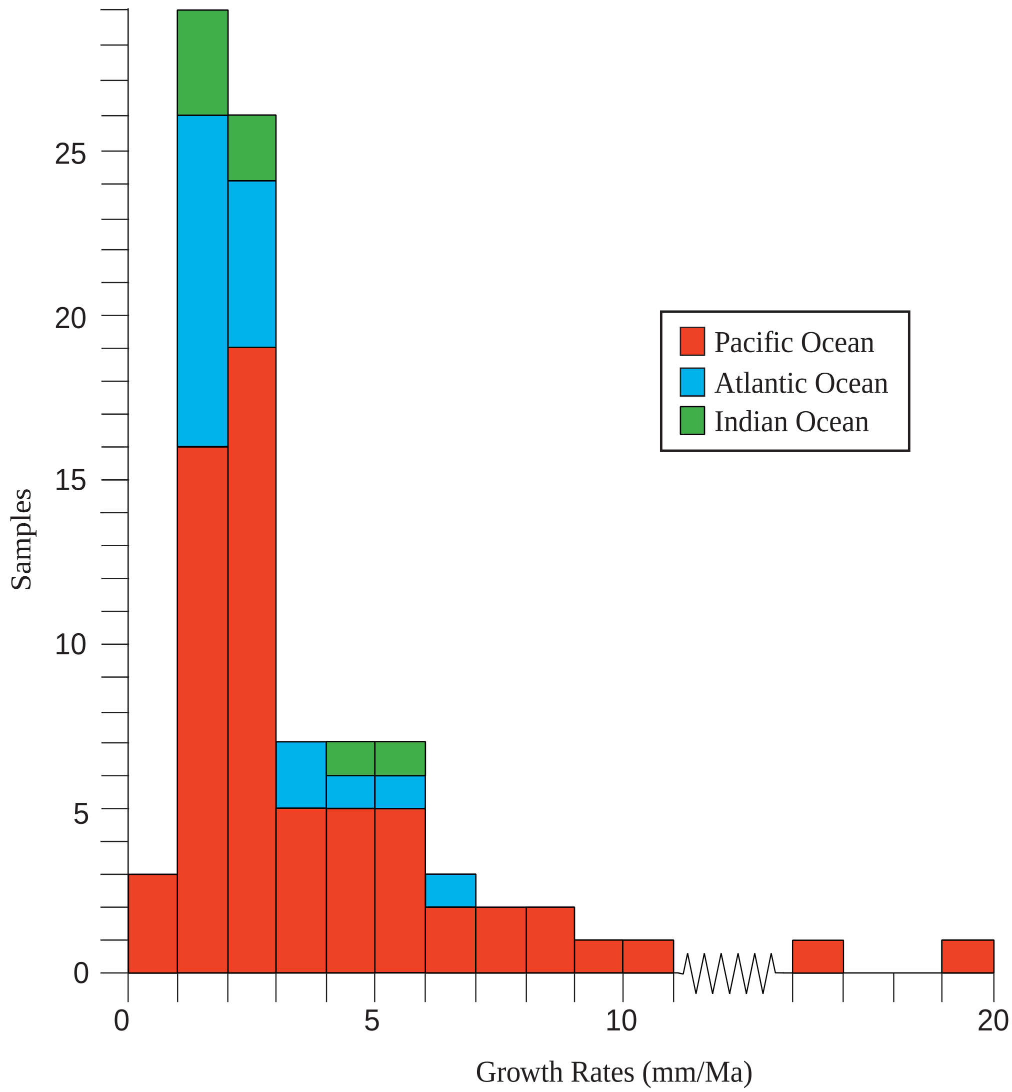


Figure 5. Range of isotopically determined growth rates of hydrogenetic Fe-Mn crusts. A hydrothermal component may exist in the two crusts with the fastest rates; updated (50) from Hein et al. (51).

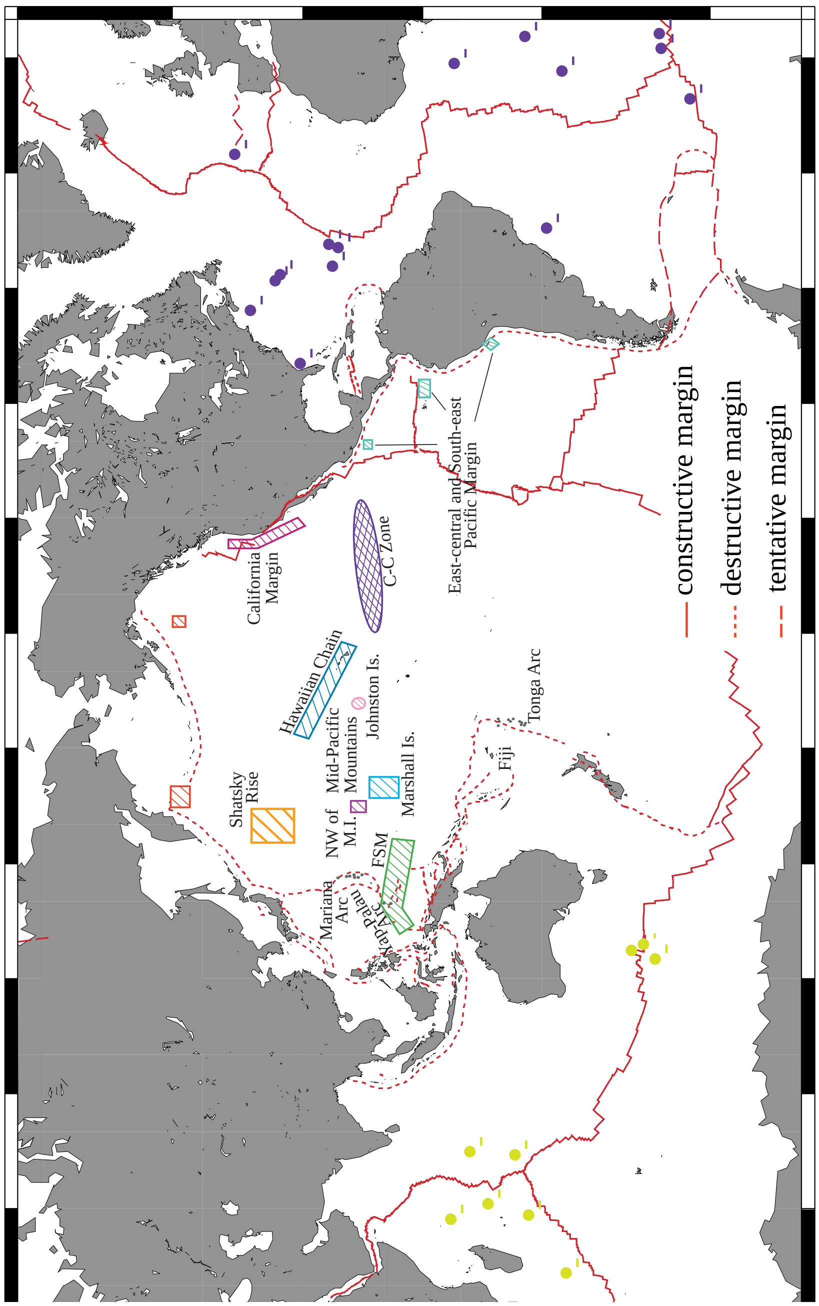
Ratios of osmium isotopes may provide a reliable dating tool for crusts as old as 65 Ma by comparing the ratios in various crust layers with ratios that define the Cenozoic seawater curve (52). However, additional data are required on osmium isotopes in the oceans before that technique can be applied to age date crusts. Nannofossil biostratigraphy has been used to date crusts from impressions and molds of nannofossils left in crust layers after replacement of the carbonate by iron-manganese oxyhydroxides (53). That technique, although reliable, is time consuming to perform and consequently has not been widely used. Recent nannofossil biostratigraphy confirms the crust ages determined from the extrapolation of beryllium isotope-determined growth rates (Puyaeva and Hein, unpublished data, 2000). Finally, empirical equations have been developed to date Fe-Mn crusts (54). Those equations usually give minimum ages for the base of crusts and produce growth rates that are generally faster than those determined from isotopic techniques, although the Manheim and Lane-Bostwick (55) equation does generally produce rates more in line with those determined by isotopic methods (56). It is clear that additional techniques are needed to accurately date thick crusts and the best opportunity may be development of osmium isotope stratigraphy, although argon isotopes, potassium-argon, and paleomagnetic reversal stratigraphy should also be studied. A significant problem with thick crusts is that the inner layers were phosphatized by a diagenetic process that promoted the mobilization of many elements (57). However, the remobilisation of elements apparently did not affect neodymium and lead isotopic ratios (58) and also may not have affected osmium isotopic ratios. No correlation exists in this compiled data set between growth rates of the outermost layer of the crusts and water depth of occurrence.

3.4. Chemical Composition

All USGS chemical data in this report (Table 6) are normalized to zero percent hygroscopic water because that adsorbed water varies markedly depending on analytical conditions. Hygroscopic water can vary up to 30 weight percent (%) and thereby affects the contents of all other elements. Compositions normalized for hygroscopic water can be more meaningfully compared and also more closely represent the grade of the potential ore. Unfortunately, water contents are not provided in many published reports, so we were unable to correct compiled data listed in Table 6. Mean chemical compositions are provided for crusts that occur in the areas marked on Fig. 6, which correspond to the different columns in Table 6.

Hydrogenetic Fe-Mn crusts generally have iron/manganese ratios between 0.4 and 1.2, most commonly 0.7 ± 0.2, whereas mixed hydrogenetic and hydrothermal crusts and continental margin hydrogenetic crusts have ratios between 1 and 3, mostly 1.3-1.8 (from data used to compile Table 6). Cobalt is the metal with the greatest economic potential in crusts and ranges from about 0.05-1.7% (500-17,000 parts per million, ppm) in individual bulk crusts and averages between 0.19% and 0.74% (1900-7400 ppm) for various parts of the global ocean (Table 6). Cobalt is also considered the element most characteristic of hydrogenetic precipitation in crusts (64) and is considered to maintain a constant flux from seawater to Fe-Mn crusts (65), regardless of water depth. Nickel and platinum are also considered of economic importance and range up to 1.1% and 1.3 ppm respectively for individual bulk crusts. Platinum ranges up to 3 ppm for individual crust layers (66). Elements most strongly enriched over abyssal Fe-Mn nodules include iron, cobalt, platinum, lead, arsenic, bismuth, bromine, vanadium, phosphorus, calcium, titanium, strontium, tellurium, and REEs, whereas nodules are more enriched in copper, nickel, zinc, lithium, aluminium, potassium (only Pacific crusts), and cadmium. Fe-Mn crusts are enriched over seawater in all elements except bromine, chlorine, and sodium; enrichments over seawater between 10^8 and 10^{10} times include bismuth, cobalt, manganese, titanium, iron, tellurium, lead, and thorium, and between 10^6 and 10^8 times include tin, hafnium, zirconium, aluminium, yttrium, scandium, thallium, nickel, calcium, niobium, indium, copper, germanium, zinc, tungsten, and tantalum. Crusts are enriched over lithospheric concentrations about five thousand times for tellurium and a hundred to five hundred times for molybdenum, thallium, antimony, cobalt, manganese, bismuth, arsenic, selenium, and lead. Crusts may have an economic potential not only for cobalt, nickel, manganese, and platinum, but also for titanium, cerium, tellurium, thallium, zirconium, and phosphorus.

Elements in crusts have different origins and are associated with different crust mineral phases (67). Generally elements are associated with five phases in crusts, δ-MnO_2, iron oxyhydroxide, detrital (aluminosilicate), CFA, and residual biogenic phases. Manganese, cobalt, nickel, cadmium, and molybdenum are invariably associated with the δ-MnO_2 phase. In addition, in more than 40% of the regions studied, lead, vanadium, zinc, sodium, calcium, strontium, magnesium, and titanium are also associated with that phase. Iron and arsenic are most commonly the only elements associated with the iron oxyhydroxide phase, although less commonly vanadium, copper, lead, yttrium, phosphorus, chromium, beryllium, strontium, titanium, and cerium have also been reported to be associated with that phase. The detrital phase always includes silicon, aluminium, and potassium, and commonly also titanium, chromium, magnesium, iron, sodium, and copper. The CFA phase invariably includes calcium, phosphorus, and carbon dioxide, and also commonly strontium and yttrium; molybdenum, barium, cerium, and zinc may also be associated with the CFA phase in some regions. The residual biogenic phase includes barium, strontium, cerium, copper, vanadium, calcium, and magnesium, and in some regions also iron, arsenic, sodium, molybdenum, yttrium, phosphorus, carbon dioxide, lead, titanium, and nickel. Iron is the most widely distributed element and occurs intermixed in the δ-MnO_2 phase; is the main constituent in the iron oxyhydroxide phase; occurs in the detrital phase in minerals such as pyroxene, amphibole, smectite, magnetite, and spinel; and is in the residual biogenic phase. The strength of correlations between iron and other elements depends on the relative abundance of iron in the various phases (68). The CFA phase only occurs in thick crusts because the inner layers of those crusts have been phosphatized. In thin crusts or the surface scrapes of thick crusts, calcium, phosphorus, and carbon dioxide are associated with the δ-MnO_2 and/or residual biogenic phases. CFA associated elements as well as platinum, rhodium, and iridium generally increase with increasing crust thickness. In contrast, cobalt and elements associated with the detrital phase usually decrease with increasing crust thickness (69).



ined boxes in the Pacific are regions with mean Fe-Mn crust compositional data listed in Table 6; far north Pacific data are from the two nest north; the California margin includes the Oregon margin; the far south Pacific data cover areas mostly offshore New Zealand and stralia; the south Pacific data span most of the area between South America and the west Pacific arcs and between the equator and titude; the crossed hatched oval region is the Clarion-Clipperton prime Fe-Mn nodule zone for comparison; data for all the stations tic and Indian Oceans were averaged for each ocean for Table 6.

REE and yttrium contents in Fe-Mn crusts are very high; 100s of ppm for yttrium and 1000s of ppm for total REE contents (cerium in one bulk crust sample from the Hawaii EEZ is very high, 1.1%--11,000 ppm). Concentrations of the trivalent REEs (includes all REEs except cerium) appear to increase in crusts with increasing water depth of occurrence (70). Irrespective of their specific compositions, Fe-Mn crusts from the major oceans show remarkably similar REE patterns on normalize plots. Shale-normalized REE patterns generally show enrichment of the heavy REEs and commonly show positive anomalies of lanthanum, cerium, europium, and gadolinium, and a negative yttrium anomaly (Fig. 7). The REEs in crusts are derived from seawater, which in turn is supplied with REEs from fluvial and eolian input from continental sources. Except for oxidation-reduction (redox)-sensitive cerium, yttrium and REE distributions in Fe-Mn crusts represent the exchange equilibrium between yttrium and REEs dissolved in seawater and yttrium and REEs absorbed on the surface of iron-manganese oxyhydroxide particles. Cerium is the only REE that in near-surface environments may occur as a tetravalent ion, and the contrasting charge and size of cerium (IV) leads to its decoupling from the other REEs. In the marine environment, cerium uptake by manganese and iron oxyhydroxides is accompanied by cerium oxidation, which is mediated by microbial processes and/or a surface catalysis, a reaction that would otherwise be very sluggish (e.g., 73).

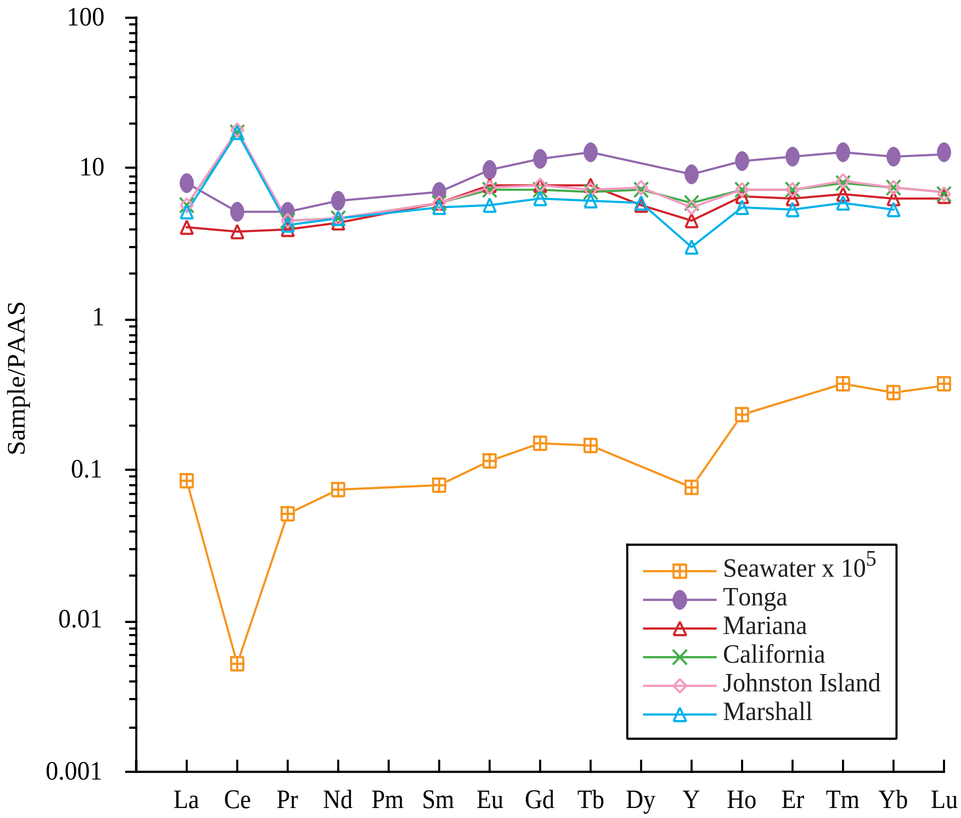


Figure 7. Shale (PAAS, Post-Archean Australian shales; (143)) REE patterns of typical hydrogenetic crusts (Johnston Island, California borderland, and Marshall Islands) and mixed hydrogenetic-hydrothermal crusts (Tonga Arc and Mariana Arc) from the Pacific, compared to the seawater pattern at 1,250 m water depth (145)

Platinum Group Elements (PGEs: platinum, palladium, rhodium, ruthenium, iridium) are highly enriched in Fe-Mn crusts over their abundances in the Earth's crust (with the exception of palladium) and over concentrations in Fe-Mn nodules (Table 6). Platinum has been considered a potential by-product of cobalt mining of crusts and has mean values for different areas of up to 0.8 ppm and individual sample values of up to 3 ppm (74). Rhodium, ruthenium, and iridium contents are up to 124, 32, and 54 parts per billion (ppb), respectively, whereas palladium contents (1-16 ppb) are usually at or just above its mean content in the Earth's crust. Most PGEs have a positive correlation with crust thickness and are concentrated in the inner part of thick crusts. Most PGEs commonly correlate inversely with water depth of occurrence of the crusts (75).

Fe-Mn crusts from the Marshall Islands EEZ, areas in international waters to the north and northwest of the Marshall Islands, and the south Atlantic (Fig. 6) contain the highest PGE contents; crusts from French Polynesia also have high PGE contents. Platinum contents increase markedly in crusts from the west Pacific compared to the central and east Pacific: East Pacific (mean 72 ppb), central Pacific (mean 200 ppb), and west Pacific (mean 600 ppb); then platinum contents decrease again adjacent to the west Pacific arcs (Table 6) (76). Platinum, rhodium, iridium, and in some regions, ruthenium comprise part of the δ-MnO_2 phase, whereas palladium is commonly part of the detrital phase (77). Part of the ruthenium may also be part of the detrital phase and both iridium and ruthenium occur with the residual biogenic phase in some regions. Platinum, iridium, and rhodium are derived predominantly from seawater, whereas palladium and much of the ruthenium are derived from clastic debris, the remainder of the ruthenium being derived from seawater (78). The extraterrestrial component (meteorite debris) in bulk crusts is small. Platinum is a redox-sensitive element and its varying concentration probably reflects changing seawater redox conditions, and diagenesis (maturation of oxide phases and phosphatization) within the older generation of crusts where it is concentrated (79).

Table 6: Mean chemical composition of Fe-Mn crusts from the Pacific, Indian, and Atlantic Oceans compared with C-C and other abyssal Fe-Mn nodules; USGS data (columns 1-5, 8, 9, 10, 13, 14) normalized to 0% H_2O^-

	1 FSM-Palau n=35	2 Marsh-all Is. n=116	3 IW, NW of Marshall Is. n=43	4 Johnst on I. n=103	5 Californi a Margin n=71	6 Mostly IW, NW Pacific n=1478	7 Hawaii n=182	8 IW, Far N Pacific n=6	9 IW, Shatsky Rise n=20	10 IW, EC-SE Pacific Margin n=6	11 IW, S Pacific 0-25° Lat n=228	12 IW, Far S Pacific >25° Lat n=51	13 IW, Atlantic n=25	14 IW, Indian n=14	15 C-C Zone Nodul es n=x	16 Other Abyssal Nodules n=x
Fe/Mn	1.00	0.67	0.76	0.71	1.24	0.68	0.85	0.95	0.93	1.07	0.98	1.14	1.54	1.52	0.27	0.69
Fe wt. %	20.2	15.7	16.6	17.4	19.5	15.1	17.8	20.3	22.5	25.9	21.2	19.0	21.6	23.6	6.9	12.7
Mn	20.1	23.3	21.7	24.4	15.7	22.1	21.0	21.4	24.3	24.1	21.6	16.7	14.0	15.6	25.4	18.5
Si	5.50	2.80	5.38	4.06	10.5	3.7	6.26	4.52	9.45	8.28	4.28	7.14	5.50	7.78	7.6	8.8
Na	2.14	1.57	1.70	1.67	1.81	1.6	1.71	2.04	1.92	1.85	1.76	0.88	2.16	2.24	2.8	2.1
Al	1.31	0.63	1.15	0.81	1.95	1.0	1.69	1.02	1.97	2.10	1.30	3.55	1.54	1.34	2.9	3.0
K	0.55	0.47	0.64	0.55	0.80	0.56	0.65	0.49	0.97	0.81	0.54	0.35	4.39	2.32	1.0	0.93
Mg	1.15	1.05	1.02	1.08	1.14	1.3	1.28	1.14	1.60	1.36	1.31	1.36	1.32	1.72	1.7	1.4
Ca	2.76	5.86	3.57	3.17	1.77	4.1	2.37	2.72	2.61	2.81	2.70	2.22	0.53	0.75	1.7	1.8
Ti	1.009	1.014	1.137	1.216	0.550	0.77	1.329	0.846	1.001	1.029	1.073	0.738	0.948	1.015	0.53	0.78
P	0.47	1.64	0.77	0.61	0.37	1.2	0.43	0.49	0.55	0.54	0.63	0.45	0.78	0.38	0.10A	0.10A
S	0.19	0.27	0.15	0.16	0.10	0.3	--	0.18	0.15	0.1	0.16	--	0.2	0.2	--	--
Cl	0.95	0.92	0.77	0.86	0.85	--	--	1.03	1.11	1.04	1.42	--	1.06	1.39	--	--
H_2O^+	9.2	7.6	8.4	8.5	9.21	--	6.98	--	--	--	10.2	--	28.3	26.2	7.5A	7.5A
H_2O^-	17.2	19.2	24.5	20.4	21.3	--	12.1	14.7	18.0	18.6	18.5	--	11.2	12.8	--	--
CO_2	0.70	1.1	0.65	0.64	0.37	--	0.45	--	--	--	0.83	--	--	--	0.16A	0.16A
LOI	36.9	37.2	49.0	41.8	27.6	--	29.3	31.2	20.3	19.6	37.3	14.6	--	--	--	--
Ag ppm	--	--	--	--	--	0.717	--	--	10.2	--	--	--	--	--	0.10A	0.10A
As	271	212	234	258	246	165	1050	259	210	246	254	544	289	181	159A	159A
B	238	179	177	162	315	115	--	278	326	381	336	--	257	287	273A	273A

Table 6 continued

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Ba	1545	1987	2018	1865	3285	1695	1889	1844	2646	2150	1745	1298	1716	1668	2800	2000
Be	6.9	6.0	4.9	7.5	5.6	--	--	4.9	6.9	8.0	6.9	--	8.4	7.5	4A	4A
Bi	17.5	41.0	59.1	64.3	9.5	--	--	30.7	33.3	12.7	25.4	--	15.3	16.9	21A	21A
Br	32	28	33	25	27	--	--	35	26	18	32	35	36	54	0.05A	0.05A
Cd	2.4	3.7	3.1	3.2	3.1	4.6	5.3	4.8	4.9	3.2	4.1	--	3.7	3.7	12	11
Co	3991	6410	5019	7441	2746	6372	6904	4349	2713	1918	5508	3878	3574	3126	2400	2400
Cr	31	24	17	8	31	22.4	118	31	33	67	35	34	31	33	27	25
Cu	876	963	1310	1059	679	1075	760	298	1270	558	1100	761	774	1254	10200	4200
Ga	30	19	--	11	16	--	--	11	13	27	18	--	16	18	11A	11A
Hf	7	10	7	7	7	7.4	--	7	5	8	7	8	14	12	6A	6A
Li	5	3	4	2	12	63	--	5	12	6	4	--	35	10	160A	160A
Mo	402	504	420	482	329	455	374	794	530	471	470	--	429	330	520	360
Nb	54	51	70	48	32	--	--	34	43	40	62	--	54	74	74A	74A
Ni	3487	4626	3927	4398	2926	5403	3651	3393	3241	2654	4237	3385	2685	2558	12800	6300
Pb	1327	1505	1713	1723	1207	1777	1715	1746	1740	833	1207	1531	1108	1058	450	820
Rb	25	16	--	20	15	--	--	21	19	20	9	--	17	25	15A	15A
Sb	43.3	38.7	49.0	45.1	44.4	24.4	--	48.5	43.0	30.4	40.3	28.5	57.2	43.1	37A	37A
Sc	9.4	6.4	9.8	7.9	10.0	6.4	--	9.1	11.7	8.4	8.1	7.8	17.3	12.3	10A	10A
Se ppm	--	--	--	15	--	0.40	--	10	16	11	15	--	--	9	52A	52A
Sn	5	10	--	12	--	--	--	12	3	5	6	--	13	15	--	--
Sr	1502	1614	1531	1624	1241	1212	864	1619	1539	1399	1521	--	1341	1124	450	700
Te	31.0	60.8	46.8	51.0	8.7	--	--	19.6	25.5	20.9	35.2	--	39.1	32.8	216A	216A
Tl	107	150	226	193	54.0	--	--	127.7	80.0	76.6	190	--	94.5	89.4	169A	169A
Th	11.4	11.2	15.9	13.5	31.1	33.	--	37.2	55.0	19.4	14.9	24.8	51.9	50.3	28A	28A
U	12.5	12.3	13.7	13.6	10.9	9.6	--	15.6	10.8	14.1	13.3	7.4	10.2	9.1	6.8A	6.8A
V	655	650	638	639	556	515	626	768	549	702	710	--	825	624	470	480
W	102	88	135	72	69	93.3	--	120	56	65	110	43	77	78	76A	76A
Y	196	251	225	204	159	166	178	200	178	195	205	--	184	163	133A	133A
Zn	658	719	646	697	620	680	531	535	674	597	688	822	598	533	1400	900
Zr	586	538	678	682	605	172	--	544	602	570	610	--	564	706	350	620
La	365	293	438	345	294	202	361	323	266	184	256	180	277	286	36A	36A

Table 6 continued

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Ce	831	1130	1635	1282	985	--	2354	1570	1742	594	894	868	1430	1481	--	--
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Pr	66.3	49.5	81.0	65.5	67.7	106	87.1	58.7	55.5	35.3	56.6	--	74.6	68.8	158A	158A
Nd	288	219	319	263	270	162	371	298	256	164	237	173	251	248	35A	35A
Sm	57.5	42.9	64.9	54.5	60.1	41.6	74.4	59.3	56.2	33.0	49.5	29.5	61.4	60.2	9A	9A
Eu	14.5	10.0	16.1	14.0	21.4	9.90	18.3	13.0	13.2	8.3	11.4	39.4	10.4	10.8	32A	32A
Gd	67.5	47.7	69.3	61.9	57.6	26	69.2	68.0	63.4	40.3	64.1	--	62.4	62.0	5.4A	5.4A
Tb	10.4	7.2	11.3	9.7	9.3	7.53	12.7	9.4	8.6	6.2	8.4	5.2	10.0	9.0	31A	31A
Dy	61.0	44.2	98.9	59.6	53.6	57.8	62.4	54.9	50.0	38.5	54.6	--	52.9	49.4	4A	4A
Ho	12.5	9.3	13.5	12.4	10.1	6.6	11.4	9.8	8.8	8.2	11.8	--	9.3	9.8	18A	18A
Er	34.6	27.2	37.2	34.8	27.3	31.9	30.1	31.1	26.5	26.1	33.9	--	31.0	26.0	2.3A	2.3A
Tm	4.8	3.9	5.4	5.6	4.1	4.3	4.0	4.3	3.5	3.5	4.93	--	3.6	3.0	20A	20A
Yb	31.6	25.2	32.7	33.8	26.1	17.7	26.0	27.9	23.4	24.8	27.2	18.5	23.8	22.7	1.8A	1.8A
Lu	4.62	4.04	--	4.75	3.61	3.3	3.57	4.28	3.35	4.03	4.03	2.90	4.3	3.46	0.75A	0.75A
Hg ppb	15	9	11	10	39	--	--	1448	38	91	27	--	141	48	0.15A	0.15A
Au	--	107	--	57	26	--	--	30	25	17	30	36	6	31	--	--
Ir	5	16	8	--	2	--	4	3	6	3	2	--	5	8	9.1A	9.1A
Pd	2	4	3	3	4	--	--	5	8	7	8	--	6	7	6.2A	6.2A
Pt	217	489	510	206	69	777	155	157	259	117	286	--	567	348	97A	97A
Rh	15	24	24	19	9	--	10	10	15	10	20	--	37	24	--	--
Ru	19	16	21	--	6	--	12	13	12	12	15	--	18	13	--	--

Columns correspond to areas outlined in Fig. 5; IW=international waters; dash=not analysed; **NW Pacific** data from (59); **Hawaii** from (60); **South Pacific** (61); **Far South Pacific** from (62); **C-C Zone** (Clarion-Clipperton) & other abyssal nodule data from (63). Number of samples (n) that differ from those in the heading are: **column 1**, n=29-34 Al, H_2O^+, CO_2, As, Cr; n=2-16 S, Cl, B, Be, Bi, Br, Ga, Hf, Li, Nb, Rb, Sb, Sc, Sn, Te, Tl, Th, U, W, Zr, REEs, Hg, PGEs; **column 2**, n=75-106 H_2O^+, LOI, Cd, Cr, Y; n=26-45 S, Cl, B, Be, Bi, Br, Ga, Hf, Li, Nb, Sb, Sc, Te, Tl, Th, U, W, Zr, REEs, PGEs; n-2-10 Hg, Au; **column 3**, n=17-18 REEs, PGEs; n=1 Cl, H_2O^+, B, Be, Bi, Br, Hf, Li, Nb, Sb, Sc, Te, Tl, Th, U, W, Zr, Hg; **column 4**, n= 36 LOI; n=24 PGEs, n=15 REEs; n=2 Cl, H_2O^+, B, Be, Bi, Br, Ga, Li, Nb, Sb, Sc, Te, Tl, Th, U, W, Zr, Hg, Au; **column 5**, n=14-15 REEs, PGEs; n=1-8 Cl, H_2O^+, LOI, B, Be, Bi, Br, Ga, Li, Nb, Sb, Sc, Te, Tl, Th, U, W, Zr, Hg, Au; **column 6**, n=1418-1440 Co, Cu, Ni; n=100-370 Si, Na, Al, K, Mg, Ca, Ti, P, As, Ba, Mo, Pb, V, Y, Zn, Pt; n=2-67 Ag, B, Cd, Cr, Hf, Li, Sb, Sc, Se, Th, U, W, REEs; **column 7**, n=83-165 Si, Na, Al, K, Mg, Ca, Ti, P, H_2O^+, H_2O^-, As, Ba, Cd, Cr, Mo, Pb, Sr, V, Y, Zn; n=32-35 REEs, n=2-3 PGEs, Tm; **column 8**, n=1-5 for S, Cl, B, Bi, Br, Cd, Cr, Hf, Nb, Rb, Sb, Se, Sn, Te, Tl, U, W, Zr, REEs, Hg, Au, PGEs; **column 9**, n=15-19 Cd, Hf, Se, Au; n=1-9 Ag, Sn, PGEs; **column 10**, n=1-5 Br, Cd, Li, Se, Sn, W, REEs, Hg, Au, PGEs; **column 11**, n=115-214 Fe, Si, Al, Mg, Ca, Ti, P, Ni, V, Zn; n=46-93 K, Ba, Pb; n=1-37 all other elements except Mn; **column 12**, n=12-34 Si, Na, K, As, Ba, Br, Hf, Pb, Sb, Sc, Th, W, Zn, REEs; n=1-9 Al, Mg, Ti, LOI, Cr, U, Au; **column 13**, n=20-24 As, Bi, Cr, Ga, Te, Tl, Th, Zr, REEs, Hg; n=10-19Cl, H_2O^+, B, Br, Cd, Hf, Sb, Sn, U, W; n=1-9 Rb, Au, PGEs; **Column 14**, n=8-13 S, Cl, As, B, Bi, Cd, Cr, Hf, Li, Rb, Sn, Te, Tl, Th, U, W, Zr, REEs, Hg; n=1-6 Br, Sb, Se, Au, PGEs; **columns 15-16**, n=100-1000 Si, Na, Al, K, Mg, Ca, Ti, Ba, Mo, Sr, V, Cr, Cd, As, P, Ce, Y; n=1000-2000 Zn, Pb; n=2000-4000 Fe, Mn, Ni, Cu, Co; A means for the entire Pacific. A key to the chemical symbols is in Appendix 3.

3.5. Phosphatization of Fe-Mn Crusts

Most thick hydrogenetic Fe-Mn crusts that formed in the open Pacific consist of two growth generations: A phosphatized older generation and a younger non-phosphatized generation. Phosphatization of older crust layers was widespread and is found in crusts from many locations in the central and south Pacific (80). Crusts from relatively deep water (>2800 m), such as from the Teahitia-Mehetia region (81) and from the Tasman Rise (82), show only minor or no phosphatization, which is also demonstrated by a decrease in CFA-associated elements with increasing water depth of crust occurrence (see next section). Phosphatized crusts are also not found in most continental-margin environments, such as in the EEZ off western North America.

Precipitation of the old crust generation began for most crusts between about 55 and 25 Ma ago (e.g., 83) and was interrupted by several Cenozoic phosphogenic events (84). Phosphogenic entailed CFA impregnation of the older crust and formation of phosphorite partings within and at the top of the older generation of some crusts. Phosphatization took place by CFA replacement of calcite infiltered into crust pore spaces, by direct precipitation of CFA in pore space, and by replacement of other crust phases, most commonly iron oxyhydroxide. The thickness of the phosphatized layer can be as large as 12 cm, and calcium and phosphorus concentrations can increase up to 15 wt.% and 5 wt.%, respectively. Growth of the younger crust generation started during the Miocene and continued to the present without interruption by further phosphogenic events.

According to Hein et al. (85), two major and possibly several minor Cenozoic episodes of phosphogenesis were responsible for formation of phosphorite on equatorial Pacific seamounts. Those same phosphogenic events also phosphatized the older generation of Fe-Mn crusts. Crust ages would allow for the major phosphogenic events centred on the Eocene-Oligocene (≈34 Ma) and Oligocene-Miocene boundaries (≈24 Ma), as well as the minor middle Miocene event at about 15 Ma, to have affected growth of Pacific Fe-Mn crusts. Extraction and dating of the CFA from older crust generations support the coeval phosphatization of substrate rocks and crusts (Chan, Hein, Koschinsky unpublished data).

Phosphatization of the older Fe-Mn crust layers caused changes in their chemistry and mineralogy (86). Besides dilution of the primary crust contents by CFA, certain elements were added and others removed. Depletion of elements in the phosphatized crust generation compared to non-phosphatized crust layers occurred in the approximate order silicon>iron≥aluminum≥thorium>titanium≥cobalt>manganese≥lead≥uranium; in contrast, nickel, copper, zinc, yttrium, REEs, strontium, platinum, and commonly barium are enriched in phosphatized crusts (87).

3.6. Local and Regional Variations in Composition

The iron/manganese ratios are lowest in crusts from the central and west-central Pacific and highest for crusts collected in the north Atlantic, Indian, south Atlantic, and near continental margins and volcanic arcs in decreasing magnitude of the ratio. The detrital-associated element (silicon, aluminium) contents increase in crusts with proximity to continental margins (off western North America, far South Pacific) and volcanic arcs in the west Pacific, which have contents equivalent to those found in most crusts from the Atlantic and Indian Oceans (Table 6; Fig. 8A). Within the central Pacific region, detrital-related elements are most abundant in the eastern part, along the Hawaiian and Line Islands. In contrast, cobalt, nickel, and platinum contents are generally highest in crusts from the central and northwest Pacific and lowest in crusts from along the spreading centres in the southeast Pacific, the continental margins, and along the volcanic arcs of the west Pacific (Table 6; Fig. 8B, C) (89). Cobalt contents are low and nickel contents are the lowest for crusts from the Atlantic and Indian Oceans compared to crusts from other regions (Fig. 8B, C). Copper contents generally follow the trend for cobalt, nickel, and platinum, except for the Indian Ocean, where a high mean value (1254 ppm) is found. The reason for those high values is the much greater mean water depth for crusts collected from the Indian Ocean. Shatsky Rise crusts, mid-latitudes of the north Pacific, have a surprisingly high mean copper content, as well as the highest copper value measured in a single bulk crust, 0.4% (4000 ppm). Mean barium content is much higher in northeast Pacific crusts than anywhere else in the global oceans. Those high barium contents are the result of intense up welling and high bio productivity in that region (90), Hein et al., unpublished data). Trends for mean titanium contents do not follow those of aluminium and silicon, but rather follow those of cobalt, nickel, and platinum, which support the idea that much of the titanium in crusts is a hydrogenetic phase (91). Another interesting distribution is seen with phosphorus because it is not most enriched in areas where up welling and bio productivity are greatest (east Pacific, east equatorial Pacific), but rather is highest in crusts from the Marshall Islands and the northwest Pacific (Fig. 8A; see also Hein et al. (92)).

It is not clear why phosphorus does not reflect the high bio productivity in the east Pacific as does barium, or why CFA does not occur in crusts from that region. Phosphorus is relatively high in north Atlantic crusts, where bio productivity is also high. Cerium is generally lower in south Pacific crusts than it is in north Pacific crusts and has moderate contents in Atlantic and Indian Ocean crusts.

Elements concentrated in crusts by oxidation reactions (cobalt, cerium, thallium, and also predicted for lead, titanium, tellurium, and platinum) should be highest in the west Pacific where seawater oxygen contents are the highest. However, that relationship is only clearly defined for platinum and the cerium anomaly (from REE plots), probably because regional patterns are somewhat masked by local conditions where up welling around seamounts mixes various water layers (93).

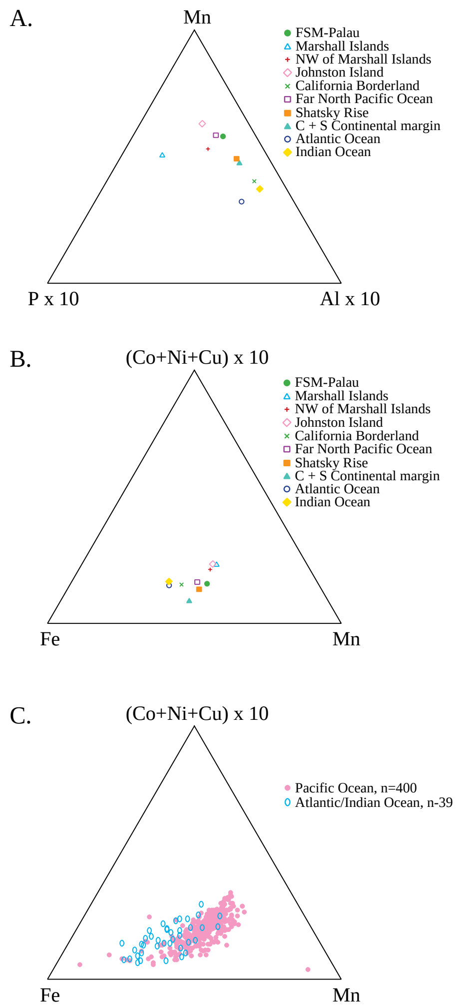


Figure 8. (A) Mn-Px10-Alx10 ternary diagram for mean compositions of USGS data listed in Table 7; note that crusts from all areas except the Marshall Islands have about the same relative amounts of P, but highly variable relative amounts of Al and Mn depending on proximity to continental margins for Al and to the equatorial Pacific for Mn;
(B) Mn-Fe-(Co+Ni+Cu)x10 ternary diagram after Bonatti et al. (146) for data as in (A); Note that crusts in proximity to continental margins and volcanic arcs are relatively enriched in Fe and depleted in trace metals, whereas central Pacific crusts are relatively enriched in Mn and trace metals, with the Johnston Island and Marshall Islands crusts showing the greatest enrichments; (C) Complete data set used in the means in B.

Manganese, manganophile elements (e.g. cobalt, nickel, cadmium, molybdenum), and the iron oxyhydroxide phase generally decrease, whereas detrital phase-related elements (silicon, aluminium, iron, yttrium) increase with increasing latitude (94). The intensification of the OMZ in the equatorial zone of high bio productivity allows for greater amounts of manganese to remain in solution in seawater and slower growth rates of crusts. The increase in iron, silicon, aluminium, and yttrium to the north is partly due to increased supply of detritus by the trade winds. The same trends in manganese and manganophile elements should occur with longitude (increasing to the east) in the equatorial region because regional bio productivity increases in that direction. However, a paucity of seamounts exists between Hawaii and North America, so that trend cannot be confirmed Pacific-wide; regardless, the trend is generally poorly developed regionally (e.g., 95). Contents of manganophile elements in California continental margin crusts are diluted by detrital and biogenic inputs, which ameliorates the increased δ-MnO_2-related elements expected to occur there. The residual biogenic phase elements generally increase with proximity to the equatorial zone of high bio productivity and in the eastern Pacific, where productivity is yet higher (96).

Manganese, manganophile elements, and CFA-related elements decrease, whereas iron, copper, and detrital-related elements increase with increasing water depth of occurrence of crusts (97). Cobalt and other manganophile elements are enriched more than manganese is in shallow water (98). Those relationships have been explained by the increased dissolved manganese in the OMZ (about 300-1500 m water depths; Fig. 2) and an increased supply of detrital phases at greater water depths, which contributed iron, aluminium, and silicon.

4. Iron-Manganese Crust Formation

Even though Fe-Mn crusts form by hydrogenetic precipitation, the exact mechanisms of metal enrichments in the water column and at the crust surface are poorly understood. The ultimate sources of metals to the oceans are river and eolian input, hydrothermal input, weathering of ocean-floor basalts, release of metals from sediments, and extraterrestrial input. Elements in seawater may occur in their elemental form or as inorganic and organic complexes. Those complexes may in turn form colloids that interact with each other and with other dissolved metals (e.g., 99). Thermodynamic, surface-chemical, and colloidal-chemical models show that most hydrogenetic elements in crusts occur as inorganic complexes in seawater (100). Hydrated cations (cobalt, nickel, zinc, lead, cadmium, thallium, etc.) are attracted to the negatively charged surface of manganese oxyhydroxides, whereas anions and elements that form large complexes with low charge-density (vanadium, arsenic, phosphorus, zirconium, hafnium, etc.) are attracted to the slightly positive charge of iron hydroxide surfaces.

Mixed iron and manganese colloids with adsorbed metals precipitate onto hard-rock surfaces as poorly crystalline or amorphous oxyhydroxides, probably through bacterially mediated catalytic processes. Continued crust accretion after precipitation of that first molecular layer is autocatalytic, but is probably enhanced to some degree by bacterial processes (101). Additional metals are incorporated into the deposits either by co-precipitation, or by diffusion of the adsorbed ions into the manganese and iron oxyhydroxide crystal lattices. Cobalt is strongly enriched in hydrogenetic crusts because it is oxidized from cobalt (II) to the less soluble cobalt (III) at the crust surface, possibly through a disproportionate reaction (102). Lead, titanium, tellurium, and thallium, as well as cerium are also highly enriched in hydrogenetic deposits, probably by a similar oxidation mechanism (103).

Concentrations of elements in seawater are generally reflected in their concentrations in crusts, although there are many complicating factors. For example, copper, nickel, and zinc occur in comparable concentrations in seawater (104), yet nickel is much more enriched in crusts than either copper or zinc. Copper contents may be relatively low in hydrogenetic crusts because it occurs mostly in an organically bound form in deep seawater, which is not readily incorporated into iron and manganese metal oxyhydroxides (105). Zinc contents may be relatively low in crusts compared to nickel because little zinc may be adsorbed onto crusts after precipitation of the oxyhydroxides, which follows the order of nickel>cobalt>zinc> copper (106). In contrast, comparable proportions of manganese: iron: cobalt exist in deep seawater (0.5-1.0:1:0.02-0.05; (107)) as exist in Fe-Mn crusts (0.6-1.6:1:0.02-0.05; Tables 1, 6; (108)).

The dominant controls on the concentration of elements in hydrogenetic crusts are the concentration of each element in seawater; element-particle reactivity; element residence times in seawater; the absolute and relative amounts of iron and manganese in the crusts, which in turn are related to their abundance and ratio in colloidal flocs in seawater (109); the colloid surface charge and types of complexing agents, which will determine the amount of scavenging within the water column (110); the degree of oxidation of MnO_2 (oxygen/manganese)--the greater the degree of oxidation the greater the adsorption capacity--which in turn depends on the oxygen content and pH of seawater (111); the amount of surface area available for accretion, which at the surface of growing crusts is extremely large (mean 300 m^2/g), but which decreases with maturation of crusts (112); the amount of dilution by detrital minerals and diagenetic phases; and growth rates. Elements that form carbonate complexes in seawater behave independently from those that form hydroxide complexes, which indicates their different modes of removal from seawater onto crust surfaces (113). Very slow growth rates promote enrichment of minor elements by allowing time for extensive scavenging by the major oxyhydroxides. Accretion of oxyhydroxides will be slower where the OMZ intersects the seafloor than it will be above and below that zone, because manganese is more soluble in low-oxygen seawater (Fig. 2). Crusts exposed at the seafloor may not necessarily be actively accreting oxyhydroxides (114) because of mechanical erosion or, less commonly in the contemporary oceans, because of seawater oxygen contents that are insufficient to permit oxidation of the major metals.

5. Biological Communities and Currents on Seamounts

It is essential to understand the nature of biological communities that inhabit seamounts so that that information can be incorporated into environmental impact recommendations. It is also essential to understand the movement of water masses around seamounts so that appropriate mining equipment and techniques can be developed and dispersal routes of resuspended particles and wastes can be determined. Very few studies have addressed seamount currents and biology, especially the latter. Fe-Mn crusts occur on many different kinds of topographic features throughout the global ocean, but in this section, we concentrate on seamounts of the type that occur in the equatorial Pacific, where the most economically promising Fe-Mn crust deposits occur.

Seamounts obstruct the flow of oceanic water masses, thereby creating a wide array of seamount-generated currents of generally enhanced energy relative to flow away from the seamounts. Seamounts interact simultaneously with large-scale currents, mesoscale jets and eddies, and tidal flows (115), the combined effect of which produces seamount-specific currents. Those seamount-generated currents can include anticyclonic currents (Taylor column), internal waves, trapped waves, vertically propagating vortex-trapped waves, Taylor caps (regions of closed circulation or stagnant water above a seamount), attached counter-rotating mesoscale eddies, and others (e.g., 116). The effects of these currents are strongest at the outer rim of the summit region of seamounts, the area where the thickest crusts are found. However, the seamount-generated currents can be traced for at least several hundred meters above the summit of seamounts. Other water column features produced by the interaction of seamounts and currents are density inversions, isotherm displacement, enhanced turbulent mixing, and up welling; the latter process moves cold, nutrient-rich waters to shallower depths. Up welling increases primary productivity, which in turn increases the size and magnitude of the OMZ, and makes seamounts ideal fishing grounds. Seamount-generated currents also cause erosion of the seamounts (and Fe-Mn crusts) and move surface sediments, which produces sand waves and ripples.

Seamount height, summit size, types of ambient currents, and energy of the tidal currents determine which seamount-specific currents will be generated and their longevity. It is clear that some seamounts in the equatorial Pacific have been swept clean of sediment for most of 60 Ma, because that is the duration of crust growth in those areas, whereas other seamounts may be capped by as much as 500 m of carbonate sediment and therefore lack development of Fe-Mn crusts on the summit.

These physical processes also affect seamount biology. Seamount communities vary from seamount to seamount, even communities from the same water depths on adjacent seamounts. This is partly the result of the varying physical processes in the water column. Most studies of seamount biology have concentrated on seamounts with a sediment cap and on the biological communities living on (epifauna) and in (infauna) that sediment (e.g., 117). Fewer studies have addressed communities dwelling on the rock outcrops, which consist of mostly attached (sessile) organisms. A few studies have looked at the types of organisms that live on the surface of Fe-Mn crusts, which consist predominantly of agglutinated foraminifera (e.g., 118). The bacterial or microbiological processes that may mediate the growth of Fe-Mn crusts and the concentration of trace metals have not been studied.

Seamount biological communities are characterized by relatively low density and low diversity where the Fe-Mn crusts are thickest and cobalt-rich. This occurs because the low oxygen contents in the OMZ decrease the abundance of consumer populations, excludes most tolerant species from seafloor habitats, and can produce steep gradients in seafloor communities (119). Above and below the OMZ, the populations may be greater and more diverse. Levin and Thomas (120) found lower biological activity at the high-energy summit margin (covered by both rock and sediment) of the central-Pacific Horizon Guyot than at sediment-covered summit sites. In contrast, Genin et al. (121) found that antipatharian and gorgonian corals are more abundant in areas of seamount summits where flow acceleration is prominent. Thus, the make-up of the seamount communities and population density and diversity are determined by current patterns, topography, bottom sediment and rock types and coverage, seamount size, water depth, and size and magnitude of the OMZ, which in turn is related to primary productivity.

6. Resource, Technology and Economic Considerations

During the initial stages of exploration for cobalt-rich crusts, the main objectives are to find really extensive, thick, high-grade deposits. Later stages of exploration are dedicated to mapping the precise range of mineable crusts. Consequently, a continuing refinement of detail is obtained for each seamount by successive iterations of sampling and surveying.

Field operations used for exploration include continuous mapping of seamounts using multibeam echo sounder, side-scan sonar, and single- or multi-channel seismic systems; systematic sampling using dredges and corers; bottom video and photography; water column sampling; and laboratory analysis of crusts and substrates for composition and physical properties. Complimentary operations include gravity and magnetic surveys of the seamounts. Operations may also include collecting biological and ecological information that can be used in future environmental impact studies. The typical methodology has been to produce SeaBeam bathymetric maps and derivative backscatter and slope-angle maps, along with seismic profiles, which are used together to select sampling sites; and run geophysical surveys. For reconnaissance work, 15-20 dredge hauls and cores are taken per seamount. Then, video-camera surveys delineate crust, rock, and sediment types and distributions, as well as crust thicknesses if possible. A 1-m-diameter circular chain-bag dredge (Appendix 4) is recommended for seamounts rather than a rectangular box dredge because the latter tends to snag more easily on rock outcrops. These exploration activities require use of a large, well-equipped research vessel because of the large number of bottom acoustic beacons, large towed equipment, and volume of samples collected. During advanced stages of exploration and site-specific surveys, it is suggested to use deep-towed side-scan sonar including swath bathymetry, and tethered remotely operated vehicles (ROVs) for mapping and delineation of small-scale topography. Extensive sampling of deposits will be required by dredging, coring, ROVs, and a device to take a close-spaced sample that has not yet been developed. Gamma-radiation surveys will delineate crust thicknesses and the existence of crusts under thin blankets of sediments. Current-meter moorings will be required to understand the seamount environment and biological sampling and surveys will be necessary.

Based on data collected during the first six years of Fe-Mn crust studies, Hein et al. (122), developed criteria for the exploration for and exploitation of Fe-Mn crusts, which was later expanded (123) to include 12 criteria. Regional Criteria: (1) large volcanic edifices shallower than 1000-1500 m; (2) volcanic edifices older than 20 Ma; (3) volcanic structures not capped by large atolls or reefs; (4) areas of strong and persistent bottom currents; (5) a shallow and well-developed OMZ; and (6) areas isolated from input of abundant fluvial and eolian debris. Site-Specific Criteria: (7) subdued small-scale topography; (8) summit terraces, saddles, and passes; (9) slope stability; (10) absence of local volcanism; (11) average cobalt contents ≥0.8%; and (12) average crust thicknesses ≥40 mm. Depending on the mining systems used, crust thickness may turn out to be more important than grade; if true, then the crust thickness criterion would increase and grade criterion would decrease. That relationship is inevitable because cobalt grade decreases with increasing crust thickness.

6.1. Mining Systems

Crust mining is technologically much more difficult than Fe-Mn nodule mining. Nodule mining concepts developed by mining consortia in the last decades consist of a hydraulic dredge and a slurry lift system (124). Recovery of nodules is relatively easy because they sit on a soft-sediment substrate. In contrast, Fe-Mn crusts are weakly to strongly attached to substrate rock. For successful crust mining, it is essential to recover Fe-Mn crusts without collecting substrate rock, which would significantly dilute the ore grade. Five possible Fe-Mn crust-mining operations include fragmentation, crushing, lifting, pick-up, and separation (125). The proposed method of Fe-Mn crust recovery (126) consists of a bottom-crawling vehicle attached to a surface mining vessel by means of a hydraulic pipe lift system and an electrical umbilical. The mining machine provides its own propulsion and travels at a speed of about 20 cm/s. The miner has articulated cutters that would allow Fe-Mn crusts to be fragmented while minimizing the amount of substrate rock collected (Fig. 9).

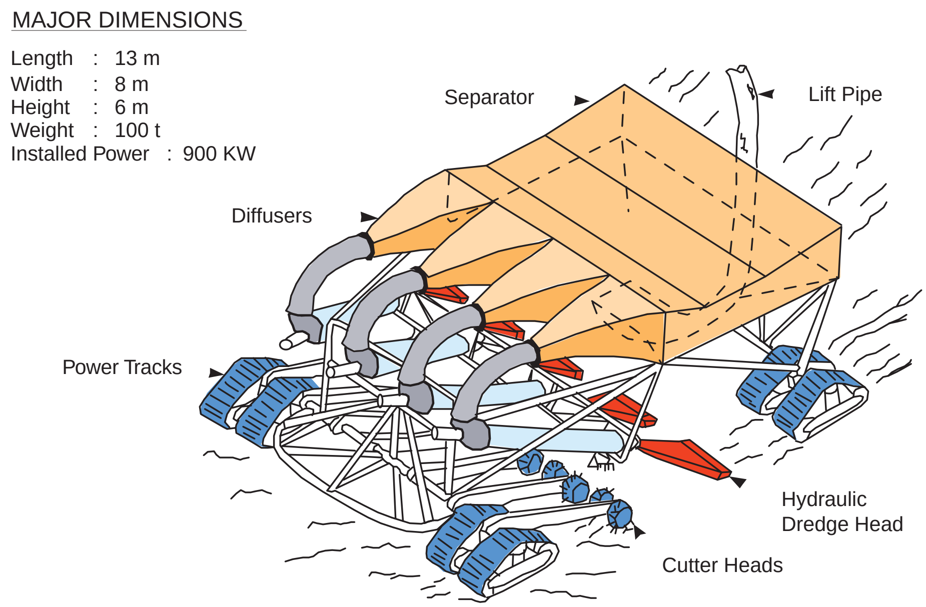


Figure 9. Schematic representation of a deep-sea mining vehicle for Fe-Mn crusts (from DOI-MMS (127); designed by J. E. Halkyard, OTC Corporation)

Hydraulic suction dredges are similar to trailing suction dredge heads commonly used with hopper dredges for sand and gravel mining. About 95% of the fragmented material would be picked up and processed through a gravity separator prior to lifting. Material throughput for the base-case mining scenario (128) is 1,000,000 t/y. That scenario allows 80% fragmentation efficiency and 25% dilution of crust with substrate during fragmentation as reasonable miner capabilities. The net recovery of crusts depends on fragmentation efficiency, pickup efficiency, and separation losses. Fragmentation efficiencies depend on small-scale topography and depth of the cut. Pickup efficiencies also depend on seafloor roughness, but to a lesser extent than fragmentation efficiency, and on the size of fragmented particles and type of pickup device (129).

The Japan Resource Association (130) studied the applicability of a continuous line bucket (CLB) system as a method of crust mining. The CLB could be competitive in an area where crusts are easily separated from substrate rock, or where the substrate is soft enough to be removed by washing (131). While there is some merit in the CLB's simplicity, the most likely commercial crust mining systems will probably use hydraulic lift together with a mechanical fragmentation system attached to a self-propelled collector. That type of system has a better likelihood of efficient crust recovery and substrate separation (132). Some new and innovative systems that have been suggested for Fe-Mn crust mining include water-jet stripping of crusts from the substrate, and *in situ* leaching techniques. Both suggestions offer promise and need to be further developed.

6.2. Economics

The importance of metals contained in Fe-Mn crusts to the world economy is reflected in their patterns of consumption (133). The primary uses of manganese, cobalt, and nickel are in the manufacture of steel to which they provide unique characteristics. Cobalt is also used in the electrical, communications, aerospace, and engine and tool manufacturing industries, as well as its radioisotope in medicine. Nickel is also used in chemical plants, petroleum refineries, electrical appliances, and motor vehicles. Supplies of these metals and other rare metals found in crusts are essential for maintaining the efficiency of modern industrial societies and in improving the standard of living in the 21st century.

Most mineral industry analysts agree that the supply of cobalt is more uncertain than the supply of the other crust metals because most cobalt production comes from politically unstable Zaire (57%) and Zambia (11%) and cobalt is produced as a by-product of copper mining. Consequently, the supply of cobalt is tied to the demand for copper. This is also true for tellurium, which is produced as a by-product of both copper and gold mining. This uncertainty in supply has caused industry to look for alternatives to cobalt and tellurium, resulting in only a modest growth in their markets over the past decade, and consequently relatively low prices. If substantial alternative sources of cobalt and tellurium supply are developed, there should be a greater incentive to reintroduce them back into products and expansion of the markets (e.g., 134).

A preliminary estimate of the economics of crust mining and processing operations for the State of Hawaii (135) indicated that they were not economical, under the circumstances at that time (Table7). The minimum required return on the investment of

Table 7. Fe-Mn crust mining and processing, estimated annual revenues and costs

Commodity	Output (t)	Prices (1985 dollars)	Amount ($ X 10^6)
Pyrometallurgical Process Revenues			
Cobalt	5,710	11.70	133.6
Nickel	2,990	3.29	19.7
Copper	120	0.65	0.2
Fe-Mn	195,000	0.30	117.0
Total Revenues	-	-	207.5
Costs	-	-	-291.0
Net Revenues	-	-	-20.5
Hydrometallurgical Process Revenues			
Cobalt	5,365	11.70	125.5
Nickel	2,900	3.29	19.1
Copper	420	0.65	0.5
Total Revenues	-	-	145.1
Costs	-	-	-204.0
Net Revenues	-	-	-58.9

From DOI-MMS [136]

$750 million in mining and processing is on the order of US $100 million per year. Neither pyrometallurgical nor hydrometallurgical processing options would be commercially viable under the scenario of 700,000 dry t/y of crust production (137). However, it has recently been determined that Fe-Mn crusts contain metals other than manganese, cobalt, nickel, copper, and platinum that may offer additional incentive in recovery (Table 8).

Table 8. Value of metals in one metric ton of Fe-Mn crust from the central-equatorial Pacific

	Mean price of metal (1999 $/Kg)	Mean Content in Crusts (Ppm)*	Value per Metric Ton of Ore ($)
Cobalt	39.60	6899	273.20
Titanium	7.70	12035	92.67
Cerium	28.00	1605	44.94
Zirconium	44.62	618	27.58
Nickel	6.60	4125	27.23
Platinum	13024.00	0.489	6.37
Molybdenum	8.80	445	3.92
Tellurium	44.00	60	2.64
Copper	1.65	896	1.48
Total	--	--	480.03

**Mean of data in Table 6 for columns 2, 4, and 6; ppm is parts per million, which equals micrograms per gram and grams per ton*

For example, titanium has the highest value after cobalt, the rare-earth elements (represented by cerium in Table 8) have a greater value than nickel, zirconium is equivalent to nickel, and tellurium has nearly twice the value of copper. Manganese is not shown in Table 8 as it could be recovered in several different forms depending on demand. This analysis assumes that economic extractive metallurgy can be developed for each of those metals.

Outside of Japan, there has been limited research and development on mining technologies for Fe-Mn crusts and therefore current economic analyses are highly speculative. Despite these uncertainties, China has held discussions with the State of Hawaii about the possibility of placing a plant on the islands for the processing of iron-manganese oxide materials. Over the past decade, at least three companies have expressed interest in Fe-Mn crust mining, including the International Hard Minerals Company, Bluewater Marine, and Oceanx. In addition, the Republic of the Marshall Islands leased its EEZ for minerals exploration, primarily for cobalt-rich crusts. Several evolving circumstances may change the economic environment and promote mining in the oceans, for example land-use priorities, fresh-water issues, and environmental concerns in areas of mining on land.

Based on grade, tonnage, and oceanographic conditions, the central-equatorial Pacific region offers the best potential for Fe-Mn crust mining, particularly the EEZ of Johnston Island (USA), the Marshall Islands, and international waters in the Mid-Pacific Mountains, although the EEZs of French Polynesia, Kiribati, and the Federated States of Micronesia should also be considered. Adding political and international issues to that mix, the EEZ of the Marshall Islands likely offers the best potential for Fe-Mn crust mining in the future, and to date has been the region most extensively studied.

There is a growing recognition that cobalt-rich Fe-Mn crusts are an important potential resource. Accordingly, it is necessary to fill the information gap concerning various aspects of crust mining through research, exploration, and technology development.

7. Recommendations For Research

At the end of the 20th century, 20 years will have gone into studies of cobalt-rich Fe-Mn crusts. However, many questions remain to be answered and it is recommended that research in the 21st century should include:

- Detailed mapping of selected seamounts, including analysis of micro topography
- Development of better dating techniques for crusts
- Determining the oceanographic and geologic conditions that produce very thick crusts
- Determining what controls the concentration of PGEs and other rare elements in crusts
- Determining how much burial by sediment is required to inhibit crust growth; and to what extent crusts occur on seamounts under a thin blanket of sediment
- Determining the role of micro biota in the formation and growth of crusts

- Determining the extent and significance of organic complexing of metals that comprise crusts
- Studying currents, internal tides, and up welling (physical oceanography) around seamounts
- Complete environmental and ecological studies of seamount communities
- Development of new mining technologies and processes of extractive metallurgy

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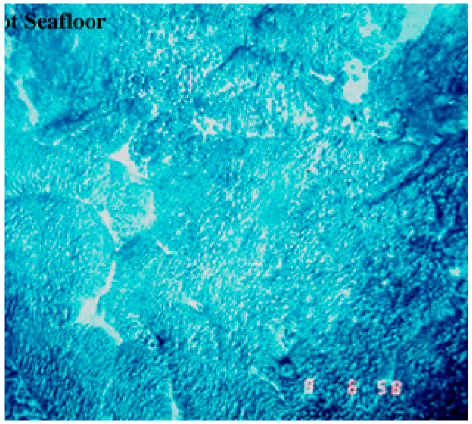
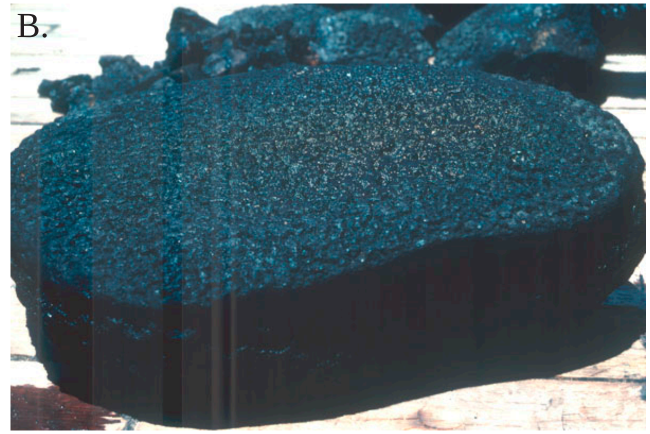
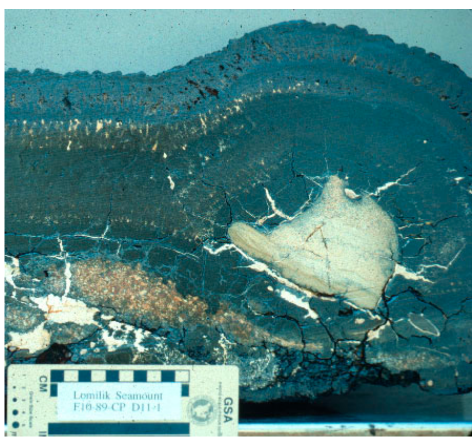
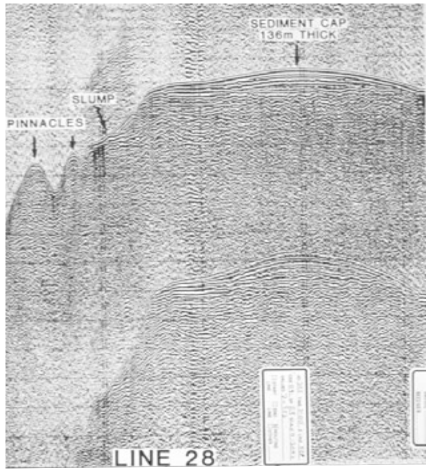
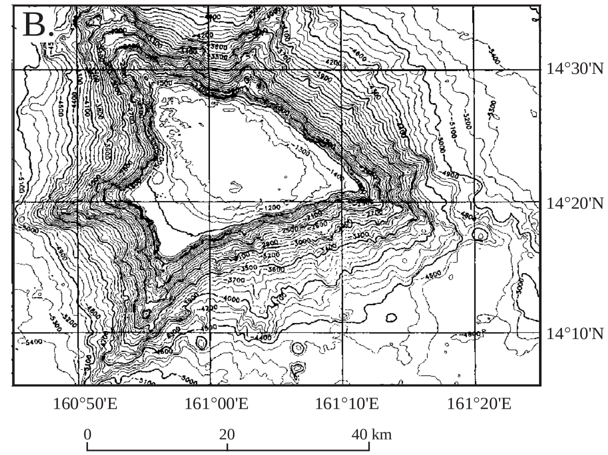


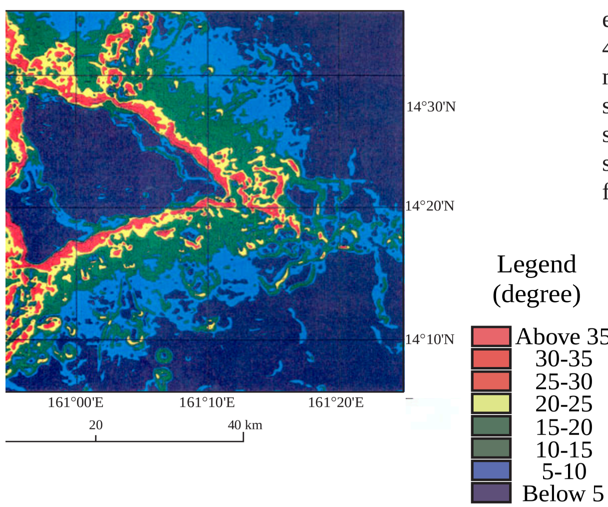




Appendix 1.
A. Fe-Mn crust pavement (~3 x 4m) on the upper flank of Horizon Guyot, Central Pacific; 2000 m water depth. B. Large sample (1.5 x 0.9 x 0.3 m) of cobalt-rich Fe-Mn crust and substrate rock; typical botryoidal surface. C. Same sample as in (B) cut through the long axis. The Fe-Mn crust is about 18 cm thick and shows distinct growth layers. The crust grew on a volcaniclastic substrate rock and growth started 60 Ma ago. A mudstone cobble occurs within the crust on the right side.







Appendix 2.

A. Single-channel, 80 cubic inch, airgun seismic-reflection profile of S.P.Lee Guyot in the Line Islands, Central Pacific; note the large vertical exaggeration; the slope of the flanks is about 14° and the summit is about 4-5°; the water depth at the summit is about 930 m. B. Swath bathymetric map of a Marshall Islands (west-central Pacific) flat-topped (guyot) seamount; the summit is at 1000 m water depth, the summit used is 440 square kilometers and the flanks are 2,700 square kilometers. C. Derivative slope-angle map showing a flat top with less than 5° slope and the steep flanks of more than 35° just below the summit platform (B. and C. from 138).

Appendix 3: .Key to symbols in Table 6

Element	Name	Element	Name
Fe	Iron	Se	Selenium
Mn	Manganese	Sn	Tin
Si	Silicon	Sr	Strontium
Na	Sodium	Te	Tellurium
Al	Aluminium	Tl	Thallium
K	Potassium	Th	Thorium
Mg	Magnesium	U	Uranium
Ca	Calcium	V	Vanadium
Ti	Titanium	W	Tungsten
P	Phosphorus	Y	Yttrium
S	Sulphur	Zn	Zinc
Cl	Chlorine	Zr	Zirconium
H_2O^+	Structural water	La	Lanthanum*
H_2O^-	Hygroscopic water	Ce	Cerium
CO_2	Carbon dioxide	Pr	Praseodymium
LOI	Loss On Ignition	Nd	Neodymium
Ag	Silver	Sm	Samarium
As	Arsenic	Eu	Europium
B	Boron	Gd	Gadolinium
Ba	Barium	Tb	Terbium
Be	Beryllium	Dy	Dysprosium
Bi	Bismuth	Ho	Holmium
Br	Bromine	Er	Erbium
Cd	Cadmium	Tm	Thulium
Co	Cobalt	Yb	Ytterbium
Cr	Chromium	Lu	Lutetium
Cu	Copper	Hg	Mercury
Ga	Gallium	Au	Gold
Hf	Hafnium	Ir	Iridium
Li	Lithium	Pd	Palladium
Mo	Molybdenum	Pt	Platinum
Nb	Niobium	Rh	Rhodium
Ni	Nickel	Ru	Ruthenium
Pb	Lead	Wt%	Weight percent
Rb	Rubidium	Ppm	Parts per million
Sb	Antimony	Ppb	Parts per billion
Sc	Scandium		

* La through Lu are rare-earth elements (REEs); Ir through Ru are Platinum-group elements (PGEs); ppm = grams per ton

Appendix 4.
1-m-diameter circular chain-bag dredge used to sample seamounts.

Summary of Presentation and Discussions on Cobalt-Rich Ferromanganese Crusts: Global Distribution, Composition, Origin and Research Activities

Presentation

Dr James Hein, Senior Geologist at the United States Geological Survey (USGS), Menlo Park, California expressed his gratitude for the opportunity to speak about Ferromanganese cobalt-rich crusts at the workshop. He said that for the past 19 years his work had focussed on this topic. Through a slide, Dr Hein introduced the topic of the very different types of tectonic environments that are involved with the formation of ferromanganese cobalt-rich crusts, polymetallic massive sulphides, and polymetallic nodules. While acknowledging the spectacular images shown in earlier presentations of black and white smokers forming and the dynamic and high-energy environment associated with polymetallic sulphides formation, Dr Hein remarked that a field of ferromanganese crusts could not power a flashlight because crusts form very slowly. Dr Hein said that with time-lapse photography, it would take about 100,000 years to notice the slight difference in colouration on the rock substrate, and about a million years to notice the little film of minerals building up on the crusts.

Participants were informed that ferromanganese (polymetallic) nodules and ferromanganese cobalt-enriched crusts form in different environments; form by different processes and have different compositions. Dr Hein said that until the late 1970s ferromanganese crusts were not distinguished from abyssal ferromanganese nodules. When a distinction was made, crusts were called seamount nodules. Dr Hein however said that nodules commonly form by both diagenetic (components are derived from sediment pore waters) and hydrogenetic precipitation and therefore their composition reflect input from both seawater and sediments. He informed participants that ferromanganese crusts are derived from the slow precipitation of iron, manganese and other metals from cold, ambient seawater (hydrogenetic) or by a combination of hydrogenetic and hydrothermal precipitation in regions where hydrothermal venting occurs. He also informed participants that cobalt is the metal with the greatest economic potential in hydrogenetic ferromanganese crusts and ranges in value in individual bulk crusts from about 0.05 – 1.7 per cent. The average metal value in known crust bearing areas, he also said is between 0.19 and 0.74 per cent for various parts of the world's oceans.

Dr Hein said that ferromanganese crusts are found in all ocean basins that contain hard, sediment- free rocks. Crusts occur on seamounts, ridges and plateaus where currents have kept the rocks swept clean of sediments for millions of years. According to Dr Hein, in the areas where ferromanganese crust formation occurs in part, as a result of hydrothermal precipitation, associated hydrothermal activity tends to dilute the interesting elements that are sought from crusts. With regard to cobalt-rich crusts, Dr Hein said that the best environments are those far removed from areas of hydrothermal venting such as the central equatorial Pacific Ocean. Dr Hein stated that ferromanganese crusts have been discovered in environments that encircle the centre of the Atlantic, the Indian and the eastern part of the Pacific Ocean. However, since these areas are also environments of hydrothermal activity, Dr Hein said that the crusts were not enriched in cobalt. He also said that the same is true of the island arcs of the west Pacific Ocean, the Philippines, Japan, Vanuatu and Tonga. As concerns the mid Atlantic ridge as a whole, Dr Hein told participants that on a regional basis, less than 30% of the crusts that have been found here are the products of hydrothermal precipitation.

In respect of the Atlantic, Indian and Pacific Oceans, Dr Hein pointed out that both the Indian and Atlantic Oceans are dominated by spreading centres and not seamounts like in many parts of the Pacific Ocean that could be described as cobalt-rich crust areas. Additionally, the crusts to be found in these two oceans are also diluted by the amount of detrital material that is brought into their basins from the continents by major rivers. Dr Hein further pointed out that the Atlantic Ocean basin, for example, is much smaller than the Pacific Ocean basin. With the added effect of huge rivers such as the Amazon and Congo discharging detritus containing effluents into the Atlantic Ocean and huge deserts that contribute eolian material into the oceans, a lot of material is introduced into this ocean to dilute the grade of the crusts. Dr Hein observed that the same conditions apply in the continental margins of the Pacific Ocean, which have very similar crust compositions to the crusts in the Atlantic and Indian Oceans. Dr Hein stated that based on this very simple understanding, it can be deduced that the dominant areas of crust occurrence with high cobalt content are not going to be in the Atlantic Ocean nor the Indian ocean nor the continental margins of the Pacific Ocean, but as far as possible from any hydrothermal or detrital source of material. He said this is the reason why most of the research in cobalt-rich ferromanganese crusts has concentrated on areas of the central equatorial pacific. He said that his presentation would therefore focus on this area even though he would present data on the global distribution of crusts.

Using slides illustrating a sixty-six year record of world cobalt prices, Dr. Hein informed participants that the study of cobalt-rich crusts started in the early 80's following the invasion of the copper-cobalt mining region in Zaire in 1978 which led to the highest prices for cobalt ever recorded. As a result, Dr. Hein said that major consumers like the United States of America decided to examine the potential of ferromanganese cobalt-rich crusts that also occurred in the Exclusive Economic Zones of some island nations and the United States of America.

Dr. Hein informed participants that the seamounts in the Pacific Ocean are the largest areas for the occurrence of ferromanganese cobalt-rich crusts. He said that seamounts in the central equatorial Pacific are part of a chain of volcanoes that also form the islands that comprise the countries of the Pacific. He said that these island nations; own through their exclusive economic zones (EEZs) most of the marine areas in the equatorial Pacific Ocean. Among these nations, he singled out the Marshall Islands' EEZ as perhaps having the best potential for crusts mining.

Dr. Hein said that the very first reconnaissance /exploration cruise for crusts deposits was in the Line Islands south of Hawaii during the 1981 German Midpack I cruise on the RV Sonne, headed by Peter Halbach of the Technical University of Clausthal. He noted that the cruise made breakthrough discoveries using large dredges, seismic profiling, and bottom photography. Between 1981 and 1999, Dr. Hein said that there have been at least 37 similar cruises by scientists and institutions from Germany (The Technical University of Clausthal and the Free University of Berlin), the United States (the United States Geological Survey, the United States Bureau of Mines and the University of Hawaii), France (IFREMER), THE New

Zealand Oceanographic Institute, the Russian Federation (the USSR Academy of Sciences and the Russian Academy of Sciences), the Australian Geological Survey Organisation, the Korean Ocean Research and Development Institute, and the Metal Mining Agency of Japan. These subsequent cruises he noted, have helped identify deposits, refine knowledge of ferromanganese crusts distribution and chemical relationships. The cruises have also helped to identify enrichments in these deposits. Dr Hein identified some of these enrichments as cobalt, iron, cerium, titanium, phosphorus, lead, arsenic, platinum, manganese, nickel, copper and zinc.

Dr. Hein said that these cruises helped to establish that some of the most promising crusts deposits are to be found in the EEZ of the Marshall Islands, Johnston Island, Line Islands, and the Blake Plateau. He also said that other areas that have been investigated for their crusts potential include the abyssal nodule province, the Japanese EEZ, the mid-Pacific mountains, areas of the Atlantic and Indian Oceans, and the EEZ off the western coast of the United States.

Dr. Hein said he estimates that the minimum expenditure for these 40 research cruises from 1981 through 1999 was about US $70 millions comprising US$30 millions fro ship and associated scientific operations and US$40 millions for shore-based research.

He informed participants of a detailed database and review of the chemical composition of ferromanganese crusts in the global oceans available through the NOAA of the United States and at their website: http//www.ngdc.noaa.gov/mgg/geology/ mmdb.

Dr. Hein turned his attention to the role of seamounts in the formation of ferromanganese crusts deposits. He said that all of the seamounts in the central Pacific Ocean are extinct volcanoes that have not had volcanism on them for 60 million years, and used this to emphasize the fact that crusts that have been growing on these seamounts for the last tens of millions of years have had nothing to do with the volcanism. Dr. Hein pointed out that the exception is the island of Hawaii, which he described as a hot spot volcano. In a general description of the seamounts of the central Pacific, Dr. Hein that some of these seamounts are the size of continental mountain ranges, some are elongated ridges, some are quite large and some of them have flat tops.

When studying crusts deposits on seamounts, in particular with the objective of finding extensive, thick and high-grade deposits, the first step according to Dr. Hein is to map the seamounts using multi-beam echo sounder and side-scan sonar systems. The typical methodology has been to produce Sea Beam bathymetric maps, derivative backscatter maps, and slope-angle maps. Simultaneously, using single or multi-channel seismic systems, Dr. Hein pointed out that seismic profiles are taken to, *inter alia*, look at the structure of the seamount with depth.

With a cross-section of a seamount, Dr. Hein illustrated slopes of seamounts of about 14 degrees. He also showed areas on the seamount where there is slumping, where the slope of the seamount has undergone mass movement and there is slumping on the slope. He pointed out that the crusts are going to be thinner in those areas where there has been re-working on the slopes of seamounts. He also pointed out that mass wasting is a major problem for the evolution of thick crusts. He informed participants that there is such a tremendous amount of motion of materials down the flanks of seamounts that they constantly destroy crusts. The crusts then have to start growing again. On this subject, Dr. Hein informed participants that there have been very good studies done on the Hawaiian chain on mass wasting. He also informed participants that as part of its research efforts, USGS undertook studies to construct a map on a group of seamounts in the Marshall Islands EEZ to determine the distribution of mass wasting deposits, areas containing sediments and areas containing hard rocks.

Dr. Hein said that seamounts obstruct the flow of oceanic water masses, thereby creating a wide-array of seamount generated currents of generally enhanced energy relative to flow away from the seamount. The effects of these currents are strongest at the outer rim of the summit region of the seamount, the area where the thickest crusts are found. Dr. Hein also said that the seamount-generated currents could be traced for at least several hundred metres above their summits. Other water column features produced by the interaction of seamounts and currents are density inversions, isotherm displacements, enhanced turbulent mixing and up welling. According to Dr. Hein, the up welling process moves cold, nutrient-rich waters to shallower depths. Up welling increases primary productivity, which in turn increases the size and magnitude of the Oxygen Minimum Zone (OMZ), making seamounts ideal fishing grounds.

Returning to the distribution of the crusts in the oceans, Dr. Hein repeated that crusts are to be found essentially everywhere in the ocean basins from the farthest northern parts of the pacific and the Atlantic down to the Antarctic ridge. Dr Hein said that crusts occur in water depths of about 400 to 4000 m, but more commonly at 1000 to 3000 m. He also said that the most cobalt-rich crusts occur between about 800 and 2200 m water depth largely due to a phenomenon in the ocean called the Oxygen Minimum Zone.

Dr. Hein said that the Oxygen Minimum Zone is very important in the formation of cobalt-rich ferromanganese crusts. He described the Oxygen Minimum Zone as a layer of seawater where the oxygen content of the seawater is low relative to the seawater above and below it. He pointed out that an oxygen minimum zone is created because of primary productivity in the surface waters of the oceans. He said that plankton created in the surface waters drift through seawater when they die, and that their protoplasm is oxidized through a reaction with seawater. This process, he also said results in the removal of oxygen from seawater and affects the chemistry of what is going on in seawater. Low oxygen seawater he pointed out acts as a reservoir for a lot of the metals of interest, particularly manganese. Dr. Hein used a slide showing a profile of manganese in the water column, that reveals a dramatic increase in manganese in the oxygen minimum zone. He pointed out that in anoxic conditions, where seawater has no oxygen, crusts would never form. Dr. Hein said that in the central Pacific Ocean all the crusts are composed of a mineral that is the most oxidized form of manganese (Vernadite). He also said that the oxygen minimum zone varies from place to place depending on the intensity of productivity in the area, currents and a number of other factors.

Dr. Hein recalled that he had said that the metals in crusts precipitated under cold, ambient seawater. He described two of the most important factors concerned in this process. He said that the metals in crusts are not floating around in seawater as pure metal but are dissolved in seawater as a complex material combined either as a chloride or a hydroxide. He noted that the iron and the manganese complexes have different surface charges, in other words the surface of the manganese oxy hydroxide in seawater has a negative (-) charge and so attracts positive (+) charged complexes. He pointed out it is his belief that through an oxidation reaction, metals are immobilized from seawater, taken out of it and incorporated in crusts in a manner whereby the metals that are now in crusts cannot be returned to seawater.

Seamount height, summit size, types of ambient currents, and energy of the tidal currents determine which seamount- specific currents will be generated and their longevity. Dr. Hein noted that these physical processes also affect seamount biology. He said that seamount communities vary from seamount to seamount, even communities from the same water depth on adjacent seamounts. Dr. Hein said that most studies of seamount biology have concentrated on seamounts with a sediment cap and on biological communities living on (epifauna) and in (in fauna) that sediment. Fewer studies, he also said have addressed communities dwelling on the rock outcrops, which consist mostly of attached (sessile) organisms. Even fewer studies have looked at the types of organisms that live on the surface of crusts, which consist mostly of agglutinated foraminifera. Dr. Hein noted that seamount biological communities are characterized by relatively low density and low diversity where crusts are thickest and cobalt-rich.

According to Dr. Hein, on the seafloor, ferromanganese crusts exhibit a variety of types of coverage on the summit flanks of seamounts. With photographs, Dr. Hein showed an area of the seafloor entirely covered by ferromanganese crusts and another area where crusts are buried under a very thin layer of sediment. He stated that for the purposes of ore genesis, it is important to know how deeply a crust may be buried under a layer of sediment and still continue to grow. He pointed out that crusts from seamounts have been recovered from under 2 m of sediment with no alteration of the crusts. He said however that he would not recommend such deposits for mining.

With another slide, Dr. Hein showed an area of seafloor entirely covered by ferromanganese crusts. He pointed out how the crusts form pavements on the seamounts, and how extensive they can be, covering square kilometres of the seafloor. Dr. Hein said that the thickest crust that has ever been recovered is 25 cm. He also said that the thickest cobalt-rich crust that has ever been recovered is 18 cm thick. Using slides illustrating conditions at this deposit, and of cross sections of a crust, Dr. Hein informed participants of the chemical composition and processes required for the formation of crusts including the process of phosphatization. Dr. Hein said that crusts deposits cover very, very large areas, and contain a large tonnage of material per sq. m compared to the largest manganese nodule fields.

When searching for thick cobalt-rich crusts, Dr. Hein said that after mapping the prospective area, and obtaining seismic profiles and the other geophysical measurements of the seamount(s), sampling sites are then selected. For sampling, Dr. Hein said that 15-20 dredges and cores are taken per seamount. He pointed out that for ferromanganese crusts the lack of sophistication of dredges is not as critical as it is for polymetallic sulphides, because crusts that are very, very similar can be found over large areas. He reported that both the USGA and KORDI use a relatively inexpensive one metre circular dredge rather than the box type dredge because seamounts are notoriously difficult to dredge. He also reported that many times the dredge gets stuck on outcrops, resulting in losses of the dredge.

Dr Hein informed participants that one of the most difficult aspects of crusts in terms of developing mining equipment, and developing exploration tools is that they occur on a lot of different types of rocks. Dr Hein said that the substrate rock could be a salt, a limestone, sandstone, a mudstone or a lot of different rock types. As a result, Dr. Hein said that sonic equipment could not be used to measure crust thickness because sometimes the sonic velocities of the crust and substrate cannot be distinguished. Dr. Hein did however point out that for all substrate rock types gamma radiation levels are much higher for crusts. This, he said offers an opportunity for measuring in situ crust thicknesses and finding crusts below thin layers of sediment. Dr Hein said that crusts average about 60% porosity, about 1.3 dry bulk density, and that every cubic cm of crust has 300 sq m of surface area.

Regarding improvements required in the future to explore for and mine crusts deposits, Dr. Hein stated that the way seamount crusts have been studied in the past has been mapping the seamounts, sampling 15 or 20 samples per seamount for a reconnaissance type survey and choosing sampling sites based on acquired information. Afterwards, Dr. Hein said that video and still camera surveys are undertaken, and water column work conducted during which oxygen profiles are acquired to find the oxygen minimum zone. Dr. Hein said that once a prospective area is found, new techniques that have not yet been used yet for studying crusts would be required. He pointed to the need for using deep towed side scan sonar and swath bathymetry to map small-scale topography. He also pointed out that during advanced stages of exploration, manned submersibles or remotely operated vehicles may be used for observations and sampling. Finally he said that there is no sampling device that has been invented that is appropriate for the detailed sampling required to evaluate a crusts deposit.

With regard to the chemistry of crusts, in particular metal enrichments in them, Dr. Hein said that an approach is to determine their enrichments relative to the earth's crust, the lithosphere. Using Table 1 of his report, he illustrated enrichments for manganese, iron cobalt, nickel, platinum, cerium, copper and tellurium in seawater, the lithosphere and in crusts. Based on this table, Dr. Hein pointed out that cobalt is enriched relative to the earth's crust about 280 times. He described the enrichment of tellurium in crusts as phenomenal and said that that it is enriched orders of magnitude over any other metal in crusts. He noted that if the tellurium content of the earth's crust is as indicated tellurium is enriched in crusts 50,000 times the content of the lithosphere.

Dr. Hein said that for enrichments between 100 and 1000 times the lithosphere, there is a large group of metals in crusts that may have economic potential besides cobalt, such as nickel and platinum. He also said that while gold and palladium are not enriched in crusts, everything else in the periodic table practically is. He showed maximum values that have been recorded from crusts samples for metals like zirconium, thallium, tungsten, bismuth and platinum.

Dr. Hein reported that after about 6 years of looking at crusts, along with two other scientists, he had developed criteria for exploring for and mining cobalt-rich crusts. He said that these consisted of 6 regional and 6 site-specific criteria. With regard to regional criteria, Dr. Hein said that an explorer should look for: large volcanic edifices (seamounts) that are shallower than 1500 metres, a shallow and well-developed oxygen minimum zone, volcanic edifices that are over 20 million years in age, seamounts that are not capped by atolls or by reefs, areas of strong and persistent bottom currents, and a region that is isolated from fluvial and eolian debris. Once these criteria are met, Dr. Hein recommended the following site-specific criteria: a seamount with summit terraces, saddles and passes where there is no sediment, a seamount with slope stability and subdued small scale topography, a seamount in an area where there is no volcanism, an average cobalt content in excess of 0.8 per cent, and an average crust thickness of at least 40 millimetres.

To conclude, with the use of slides Dr. Hein presented tables 7 and 8 from his paper. Table 7 contains estimates of annual revenues and costs from ferromanganese crusts mining and processing, and table 8 presents the value of metals in one metric ton of ferromanganese crust from the central equatorial Pacific Ocean. Dr. Hein said that he selected a number of the metals to be found in the above crusts deposits, calculated their average content, and then using 1999 data for prices, calculated how much of that metal would be in one metric tonne of crust. He explained that this approach does not amount to much because the extractive metallurgy has not been developed for extracting some of the metals such as platinum from crusts.

SUMMARY OF THE DISCUSSIONS ON COBALT FERROMANGANESE CRUSTS: GLOBAL DISTRIBUTION, COMPOSITION, ORIGIN AND RESEARCH ACTIVITIES

Following Dr. Hein's presentation, a number of questions were put to him. Some of these questions included, *inter alia*, whether it appeared more likely that ferromanganese crusts would be mined before polymetallic nodules, and why the highest contents for cobalt in crusts have been recorded in the central Pacific Ocean. With regard to environmental protection, Dr. Hein was asked whether any microorganisms associated with crusts deposits have been studied, and whether any bio films have been found on the surface of crusts. Dr. Hein was also asked about the prospects for crusts mining in the

Area, taking into account metal prices, the cobalt market, environmental factors and political considerations.

Dr. Hein was asked which mineral, nodules or crusts would be mined first from the Area. He was also asked when he thought crusts mining would occur given land-based reserves of cobalt. He was reminded that he had said that in certain areas, the top part of the crusts was even more enriched in cobalt. In that regard, Dr. Hein was asked where such crusts deposits are to be found and the thickness of the associated crusts.

With regard to the more likely marine mineral to be exploited, Dr. Hein said that based on current metal prices, he was of the opinion that it would have to be cobalt-rich ferromanganese crusts. He noted that in his computation of the value of a tonne of crusts ore, he did not even include the contribution from manganese.

As concerns when crusts mining might occur, given present land-based reserves of cobalt, Dr. Hein said that this was a subject that all interested parties speculate about. He said that in his opinion, all the land use priorities that affect land-based mining, including freshwater and recreational issues, would eventually force mining into marine areas. He also said that politics would play a part in this, together with world market prices, and the development of some new deposits such as the new cobalt-nickel laterites that are being developed in Australia. Dr. Hein said that the cobalt market has been rather unstable in the past, first because of the political stability of the major producers and second because cobalt is a by-product of copper production. He noted that there are no real cobalt mines where the ore is being mined primarily for its cobalt content. He said that recently there was going to be a large cobalt mine developed at Boise Bay in Canada. This mine is now on hold, and he did not know for how long. While the Boise Bay deposit may not be mined for 10 or 20 years, Dr. Hein observed that when it is mined, it would supply a large source of cobalt to world markets. With regard to ferromanganese crusts deposits, while informing participants that there are about 50,000 seamounts in the Pacific Ocean, Dr. Hein said that production from one seamount would supply a proportion of the world's cobalt demand for a long time.

In relation to mining technology, one participant recalled that Dr. Hein had mentioned that the average cobalt grade of the crusts is 0.8%, but that there are deposits where higher cobalt grades are found in the first few millimetres of crusts. This participant wanted to know the thickness of this top layer and where such deposits may be found in crusts bearing areas. The same participant was also interested in the chemical composition of seawater during the past 60 million years. This participant wanted to know whether the phenomena mentioned by Dr. Hein of cobalt and platinum enrichments on the outer and inner sections of crusts leads to the conclusion that 40 million years ago seawater was more platinum enriched than 10 million years ago.

On the question about the distribution of high-grade cobalt-rich deposits, Dr. Hein answered that from a regional oceanography perspective, the highest-grade cobalt deposits that are known are to be found in the central Pacific Ocean within 30 degrees of the equator. He also said that these deposits are found away from the island arcs in the west Pacific. He said that deposits with high contents of platinum and cobalt have been discovered in French Polynesia, for example, but the crusts are quite thin. He reminded participants that the cobalt content of crusts decreases with their thickness. He observed that if the technology existed to mine crusts that were 1 cm thick, one could find an ocean crusts deposit averaging over 1% cobalt content.

With regard to the question on the enrichment of platinum and cobalt in crusts and a relationship to seawater composition during the past 50 million years, Dr. Hein said that the phenomena takes place as a result of phosphatization. He noted that in very thick crusts that are not phosphatized, in the inner part the platinum is not enriched.

Microorganisms associated with crusts deposits.

Dr. Hein was asked about current knowledge of microorganisms that are associated with crusts deposits. He was also asked if any bio films have formed on the cobalt bearing rocks.

Apologizing for not presenting “the biology of seamounts” part of his paper, Dr. Hein remarked that this subject is an exciting area of research that needs more study, since very few studies have addressed seamount biology.

Dr. Hein said that he has not seen an organic film on the surface of crusts deposits but thinks that the oxidation of the metals and their incorporation into crusts has to be aided by a bacterial process. He said that he suspects that it is a biochemical (microbiological) catalyst that creates the first molecular layer. After this layer is formed, Dr. Hein said that the process becomes autocatalytic, alternating between oxidation and reduction reactions.

Dr. Hein said that the only study that has been conducted in relation to microorganisms is on the benthic foraminifera that live on the surface of crusts. He said that while scientists have learnt that these communities can cover up to 30 per cent of the crust surface, he also said that the role of these communities in inhibiting or enhancing the growth of crusts has not been determined. He suggested that a study should be conducted on the protoplasm of communities that are living in the oxygen minimum zone, and on crusts that have 200 parts per million each of thallium, arsenic and other toxic metals. Dr. Hein said that because of the interaction of the oxygen minimum zone and crusts deposits, on seamounts in general the population density and the diversity are low.

Crusts exploration and mining in the Area

Recalling that in another presentation on polymetallic massive sulphides deposits participants had been informed that thirteen of the fifteen prime sites presently known are in the EEZ's of some states, this participant asked for the number of prime areas for crusts mining in the Area. In view of the lesser degree of environmental damage from crusts mining, another participant who was of this opinion wanted to know whether the metallurgical processing of platinum from crusts had been established.

Another participant wanted to know the source of the gamma radiation used to measure crusts thickness. Dr. Hein was asked to comment on the nature of the mining technology required for crusts mining. It was pointed out that because the crusts had to torn apart and fragmented, the technology required would of necessity be more complex. Comments and opinions were expressed about the market for cobalt; the politics that have guided the various search efforts, and the work of the International Seabed Authority.

On the most promising sites for crusts deposits and their grouping by geographic region, i.e., EEZs and Area, Dr. Hein stated that studies within EEZ's have been emphasized over international waters. He said that in international waters, Japan has done significant work but has kept all of its data proprietary. In terms of the two most promising EEZ's, Dr. Hein said that these are Johnston Island in the EEZ of the United States and Marshall Islands, a trust territory of the United States. He also said that the best regional cobalt contents are in the EEZ of Johnston Island with average cobalt contents in excess of 0.8 per cent.

One participant, recalling Dr. Hein's comments on determining crusts thickness asked if there is any other method for determining thickness without recourse to gamma radiation. This participant also wanted to know the source of the radiation. In response, Dr. Hein said that multi-frequency sound techniques have been used to try to distinguish between crusts and substrate. Noting the variability of the substrate and how in a large are there could be several different types of substrate material, Dr. Hein said that many types of techniques are not very successful. He said that he didn't know the source of the gamma radiation but it is one technique he has seen work without some kind of mechanical device that penetrates the crust.

A participant made a comment on manganese nodule mining vs. crust mining. He said that a major advantage of crust mining is that no sediments would be generated. He noted that mining manganese nodules would result in the creation of sediment plumes that will be a big environmental problem. He said that he recalled a time that the big problem with crusts became the high contents of platinum that were discovered in them. He therefore wanted to know whether the metallurgical process for the recovery of platinum is in place.

Dr. Hein said that he is aware of two efforts in this regard. He said that the German firm, Preussag, had tried to extract platinum from crusts without good results. He also said that he sent large quantities of samples to Mintech in South Africa. This company, he said was to try to develop the required extractive metallurgy but after looking at the grades thought it wasn't worthwhile. Dr. Hein therefore said that there are a lot of other metals in crusts that will make more money than platinum.

Regarding the complexity of crusts mining machinery versus nodule mining machinery, Dr. Hein noted that Japan has done more to develop crusts mining technology than anyone else. He said that it appeared to him that the crusts have to be fragmented. He said that the crusts are fairly delicate and can be broken up and fragmented.

Political and economic considerations.

A comment was made about the relative paucity of crusts deposits in the Area as compared to the numbers to be found in exclusive economic zones. It was said that the cobalt crust and massive sulphides deposits research programmes were launched at the end of the 70's when there was less political incentive to go to the deep sea. The question was asked whether or not this did not account for the existing situation.

Dr Hein acknowledged that there were a lot of aspects to the question. He said that one reason for looking at the EEZ of the Marshall Islands is because they are a trust territory of the United States. Dr. Hein said that the US programme started in Hawaii and in Johnston Island that are part of the US and then moved to the former trust territories.

Dr. Hein said that as it turned out, the Marshall Islands were the most interesting from a scientific and economic standpoint. Dr. Hein said that the US programme looked at a lot of other areas in a really superficial reconnaissance way and that these areas bore out their thinking. This included the fact that most of the places in Kiribati for example are large atolls, extremely large atolls, with very thin crusts. While noting that the Marshall Islands also have some large atolls Dr. Hein said that in between their large atolls they have a lot of isolated seamounts. He said that these are some of the reasons why the programme ended up there.

In view of the good and large cobalt-rich crusts deposits to be found in some EEZs, Dr. Hein was asked what the International Seabed should do to encourage crusts mining in the Area.

In addition to the International Seabed Authority disseminating information about crusts deposits in the Area, Dr. Hein said it was a matter of competition. As an example, he used the Marshall Islands that according to him is extremely interested in having their crusts developed. He said that the Government of the Marshall Islands have offered to put up a processing plant on the islands without the energy source necessary to run it. He asked if the International Seabed Authority could match or beat the deal offered by this government for mining a deposit in international waters right next door.

CHAPTER 6

IMPACT OF THE DEVELOPMENT OF SEAFLOOR MASSIVE SULPHIDES ON THE VENT ECOSYSTEM

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Abstract

The discovery of chemosynthetic-based ecosystems at hydrothermal vents in the deep ocean was arguably one of the most important biological findings of the 20th century. Nearly 500 new animal species have been described from this environment, most of which are endemic. Unusual, highly-evolved symbioses between invertebrates and chemolithoautotrophic bacteria are common at vents, and can produce concentrations of biomass that rival the most productive ecosystems on Earth. The abundance of ancient, extremophilic microbes in hydrothermal vent waters has stimulated new theories of the origin of life on Earth. It has also prompted astrobiologists to seriously consider underwater volcanoes as a likely source of energy for biosynthesis and maintenance of carbon-based life forms on other worlds. Hydrothermal vent science is now in its third decade of discovery. More than 100 vent fields have been documented along the 60,000km global mid-ocean ridge system. Species conservation and environmental stewardship are becoming issues of particular concern to vent scientists. Hydrothermal faunal communities occupy very small areas of the seafloor and many sites contain animal species found nowhere else. As vent sites become the focus of mineral exploration and deep-sea mining, oversight organisations will need to develop mitigative measures to avoid significant loss of habitat or extinction of populations. This paper will provide a brief overview of vent biology and ecology, and attempt to identify issues critical to the evaluation of the potential impact of mining operations on the productivity and biodiversity of vent communities.

1. Introduction

Plant life is impossible in the total darkness of the deep sea and food resources are consequently rare. Most deep-sea food chains are nourished by organic debris that sediments down from surface waters where phytoplankton carry out photosynthesis. Only a very small fraction (1% or less) of this surface productivity reaches the deep ocean floor. As a result, animal life is very scarce. The discovery of luxuriant oases of giant worms, clams and mussels clustering around hydrothermal vents >2000m deep came as a complete surprise to biologists who scrambled to identify the food source for this unusual ecosystem. Vent faunal biomass, measured as kg tissue/m^2, can be 500 to 1000 times that of the surrounding deep sea, and rivals values in the most productive marine ecosystems such as shellfish cultures[1]. Another surprise to biologists was the novel nature of the vent organisms, most previously unknown to science and many exhibiting unusual adaptations to the severe, potentially toxic nature of hydrothermal fluids. High animal density and the presence of unusual species are now known to be common characteristics of deep-sea hydrothermal vents all over the globe, with the composition of the fauna varying between sites and regions.

The presence of hydrogen sulphide in hydrothermal fluids and an abundance of sulphide-oxidizing bacteria were the first clues that led to the development of the hypothesis whereby biological productivity at hydrothermal vents is sustained not by photosynthetic products arriving from the sunlit surface ocean, but rather by the chemosynthesis of organic matter by vent microorganisms[2], using energy from chemical oxidations to produce organic matter from CO_2 and mineral nutrients. Hydrogen sulphide and other reducing substances present in hydrothermal fluids provide the 'fuel' for organic matter synthesis (Fig. 1).

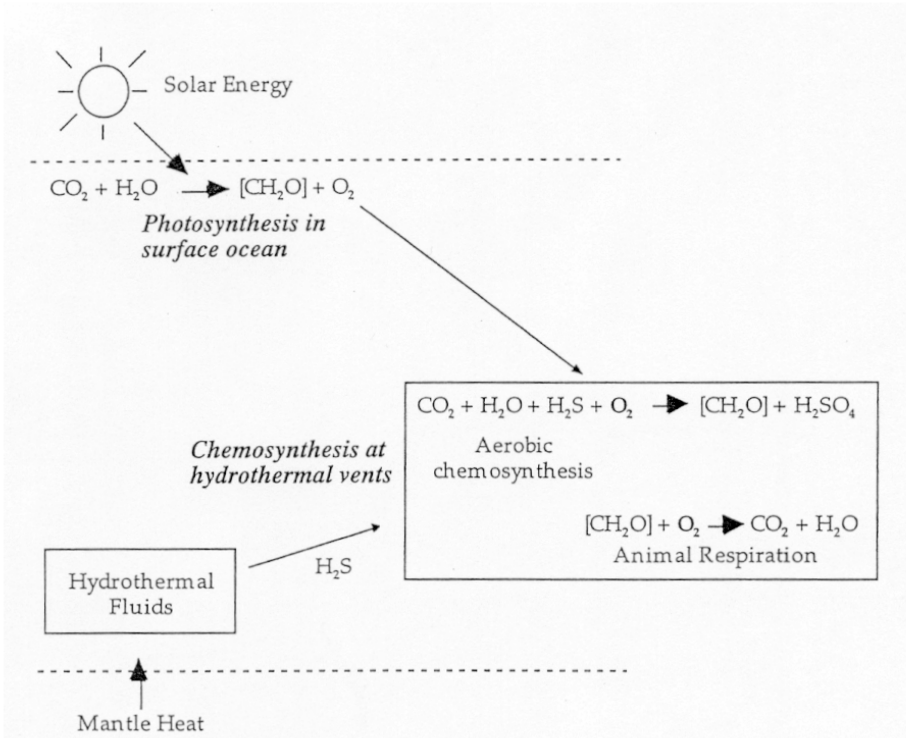

Figure1: Schematic representation of the biogeochemical relationship between the photosynthetic production of organic matter in the surface ocean and the chemosynthesis of organic matter at deep-sea hydrothermal vents. In photosynthesis, solar energy is used to fix CO_2 into organic material while microbes at vents use energy derived from the oxidation of hydrogen sulphide (H_2S) for the same purpose.

Since hydrothermal fluids are formed by reaction of seawater with hot rock, researchers quickly realized that vent ecosystems were ultimately powered by heat from the earth's mantle. This was a startling conceptual challenge to the long held view that all of our planet's ecosystems require sunlight and photosynthesis to create new biomass and nourish animal food chains.

Vent ecosystems are not completely independent of sunlight. All animals and many microorganisms at vents require dissolved oxygen for their metabolism (Table 1).

Table 1 Potential microbial metabolic processes at deep-sea hydrothermal vents. Processes involved in the chemosynthetic production of new organic matter (primary production) are given in italics. Hetrotrophic metabolism also occurs in hydrothermal systems, and involves the decomposition of organic matter produced at vents or imported from the surrounding ocean. Organisms representative of most of these forms of metabolism have been isolated and cultured from vent samples but the quantitative importance of the various electron donor and acceptor pathways in overall ecosystem metabolism is poorly understood. Table adapted from Karl (1995).

Conditions	**Electron (energy) donor**	**Electron acceptor**	**C source**	**Metabolic process**
	H_2	O_2	CO_2	*H oxidation*
Aerobic	*HS- S°,* $S2O_3$	O_2	CO_2	*S oxidation*
	Fe^{2+}	O_2	CO_2	*Fe oxidation*
	Mn^{2+}	O_2	*?*	*Fe oxidation*
	CH_4 *(and other*	O_2	CH_4, CO_2,	*Methane(C-1)*
	C-1 compounds)		*CO*	*oxidation*
	Organic	O_2		Heterotrophic
	compounds		*Organic*	metabolism
	H_2	CO_2	*compounds*	*Methanogenesis*
	H_2	*S°,* $S2O_4$	CO_2	*S and sulphide reduction*
Anaerobic	Organic	NO_3	CO_2	*H oxidation*
	compounds	NO_3	CO_2	*Denitrification*
	Organic	O_2	*Organic*	
	compounds	*S°,* $S2O_4$	*Organic*	*S and sulphide reduction*
	Organic		*Organic*	
	compounds	Organic	compounds	Fermentation
		compounds	Organic	
			compounds	

Since dissolved oxygen in the world's oceans is a by-product of photosynthesis, there is a critical biogeochemical link between the vent ecosystems and the photosynthetic ecosystems in the upper layers of the sea and on land. Had photosynthesis not evolved on earth, hydrothermal vents would only be populated by micro-organisms that do not require dissolved oxygen - such as methanogens that derive energy for growth by converting hydrogen into methane using CO_2 as an oxidant.

2. Vent Productivity

At vent openings, local ecosystems are nourished by microbial growth that is coupled to the oxidation of H_2S, CH_4, H_2, Fe, Mn and other reducing substances. A recent thermodynamic modelling study[3] identifies hydrogen sulphide (H_2S) as the most important potential energy source for microbial growth in seafloor hydrothermal systems. Since both H_2S and dissolved oxygen are usually available in the mixing zone around vent openings, it is not surprising that the most visibly dominant forms of microbial growth around vent openings are dependent on hydrogen sulphide oxidation. What is unusual is the diversity of sources and locations of chemosynthetic activity within the hydrothermal system.

2.1 Symbiotic and free-living chemosynthesis

Seafloor vents

At vent openings, some chemosynthetic microorganisms live in symbiotic associations within the tissues of giant worms and bivalves[4], converting CO_2 into organic matter to nourish themselves and their hosts. Others grow freely as bio films and filamentous mats on mineral and animal surfaces, providing food for grazing and deposit feeding animals. Predators and scavengers - some vent specialists, others attracted from the surrounding deep sea - complete the food web (Fig. 2). It is likely that at least some biological productivity from seafloor vents is exported to the surrounding deep sea through predation and advection of organic detritus but this food pathway has not been quantified (Fig. 2).

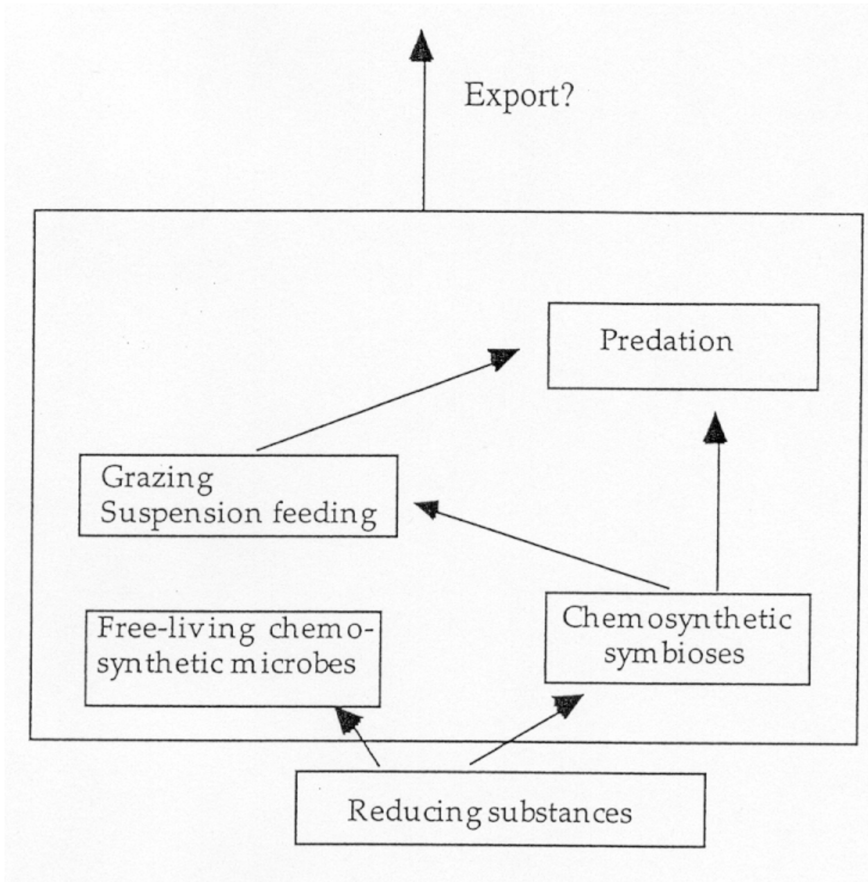

Figure 2 Simplified representation of major components involved in the production and consumption of organic matter in hydrothermal vent ecosystems. A food chain is based on organic matter produced by free-living and chemosynthetic microbes. Some food may be exported to the surrounding deep sea.

Other hydrothermal habitats

Microbial chemosynthesis also occurs in subsurface hydrothermal conduits[5], and in the plumes[6] that overlie vent fields, but faunal exploitation of microbial biomass produced in these two environments has not been extensively examined. Interaction between biological and geochemical processes has been most clearly documented in hydrothermal plumes. For example, recent studies show that oxidation of dissolved manganese in hydrothermal plumes is mostly microbial mediated[6, 7]. High concentrations of zooplankton at the upper boundary of hydrothermal plumes in the northeast Pacific indicate that plume productivity may feed plankton food chains in the water column[8]; this remains to be quantified.

3 Vent Ecosystems

Mid-ocean ridges reveal an astonishing diversity of styles of seafloor spreading and associated geology and biology. One of the key variables that affect spreading style is the plate divergence rate: slow spreading ridges have very different characteristics from fast spreading ridges. Readers are referred to a theoretical paper[9] for detailed consideration of the relation between seafloor spreading rate, vent habitat frequency and vent faunal diversity. This section will briefly compare vent ecosystems on two parts of the ridge system that have formed the basis of much of our understanding: the East Pacific Rise (EPR), between 8° 30′ N and 13° 30′ N, which is spreading at approximately 100 mm/yr; and the Mid-Atlantic Ridge (MAR) between 33° N and 38° N, which is spreading at about a quarter of that rate.

3.1 EPR Vent Ecosystems

A schematic representation of the general appearance of vent ecosystems on the northern EPR is shown in Figure 3.

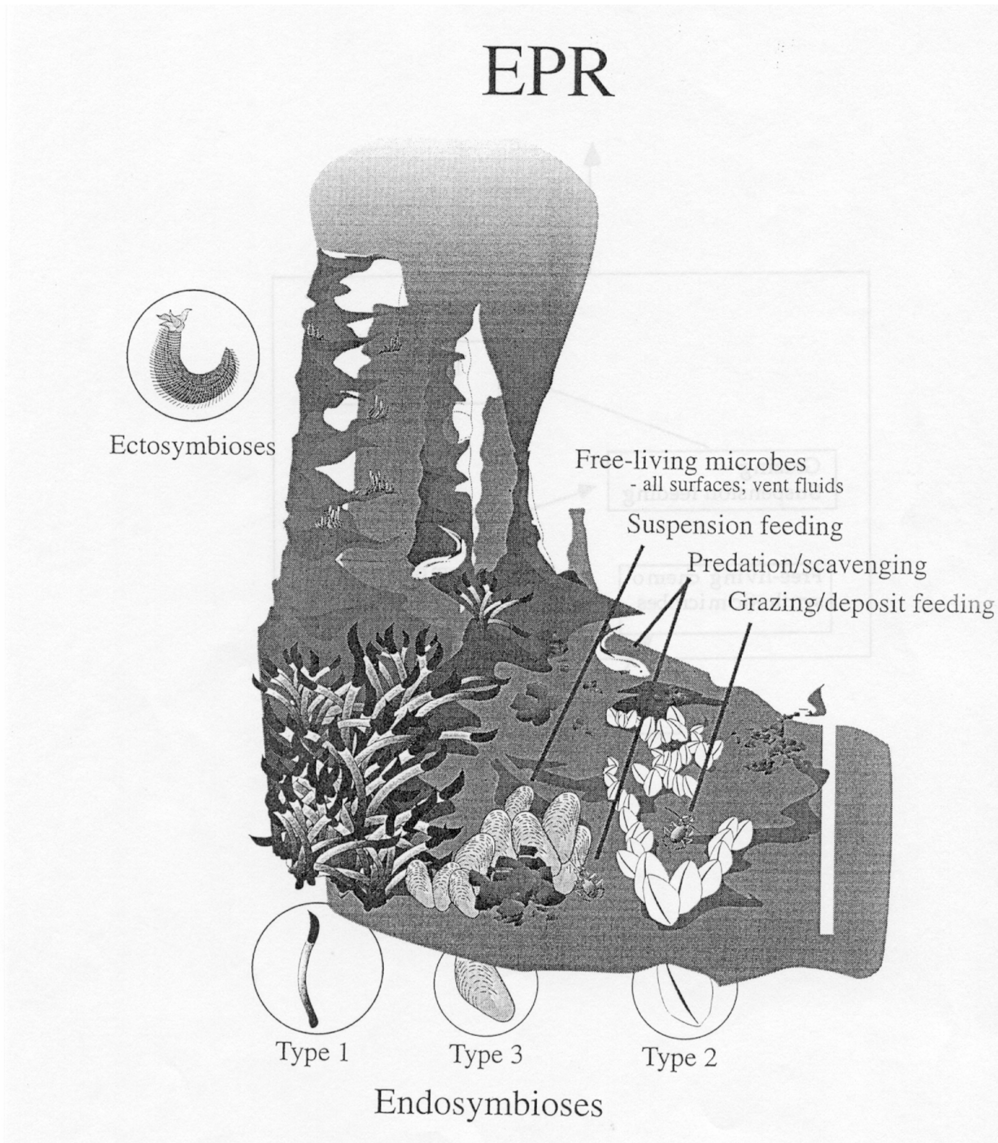

Figure 3 Major components of a generic vent ecosystem on the northern East Pacific Rise (EPR). See text for explanation.

More vent species are known from sites on the northern EPR than from any other spreading ridge on the planet. This may in part be due to the longer history of research in the area, but there are legitimate theoretical arguments that relate this greater biodiversity to the history of seafloor spreading and the abundance of vent habitat along the northern EPR[9, 10]. Chemosynthetic microbial growth provides the primary production of biomass, and occurs in three distinctly different habitats: endosymbioses, ectosymbioses, and free-living on animal and mineral surfaces.

Endosymbioses

There are three general models for the functioning of the most common forms of host-symbiont associations at EPR vents: vestimentiferan worms, clams and mussels. Microbial symbionts directly nourish their hosts through lysis (digestion of symbionts within host cells) or through secretion of organic matter that is subsequently absorbed by host tissues[4].

Type 1 - The most evolved symbiosis occurs in the vestimentiferan tubeworms - which have no mouth or digestive system, and are entirely reliant on their symbiotic bacteria for nutrition. In the tubeworms the symbiotic bacteria are housed in a specialized organ known as the trophosome. Substrates for microbial metabolism (HS^-, CO_2, O_2, etc) are taken up at the gills and transported to the trophosome by the worm's blood[4]. Physiological and biochemical aspects of this symbiosis have been extensively studied in the vestimentiferan *Riftia pachytila*[4].

Type 2 - Vesicomyid clams found at vent sites are filter-feeding animals, but their digestive tract is highly reduced and experiments have shown that they are unable to survive without a supply of hydrogen sulphide for their symbionts. They host their symbionts in the tissue of their large modified gills. CO_2 and O_2 diffuse directly into the gills from the external environment, while the clams take up H_2S into their blood through their foot, which they extend into fractures, or sediments where there is diffuse hydrothermal flow[4]. The large size attained by the giant vent clam *Calyptogena magnifica* attests to the productive nature of this symbiosis.

Type 3 - Like the clams, the EPR vent mussel *Bathymodiolus thermophylus* also houses its symbionts in gill tissue, is a filter feeder and has a functional digestive system. Unlike the clams, filtration of particles of organic matter from the surrounding water appears to provide a significant supplement to the mussel's nutrition. When experimentally moved away from active venting these mussels do survive, although considerable weight loss occurs. The mussel blood lacks specific proteins for the binding and transport of sulphide and oxygen that are found in the vestimentifera and clams[4].

Ectosymbioses

The EPR Pompei worm *Alvinella pompejana* represented in Figure 3, has specialized structures on its dorsal surface that are colonised by a diverse community of bacteria, including large filamentous forms visible to the naked eye. While described as the most highly evolved epibiotic association among all marine invertebrates, the functional role of the Pompeii worm’s bacteria remains uncertain. They may serve as a source of nutrition for the worm or in detoxifying the microenvironment within the worm’s tube[11]. The worm does have a functional digestive system and exhibits deposit-feeding behaviour. Since at least some of the epibiotic bacteria are know to be chemosynthetic, and are probably sulphide oxidizers, they could both provide a supplementary food source for *A. pompejana* and act as a barrier against the diffusion of hydrogen sulphide into the worm’s tissues.

Free-living microbial growth

Microorganisms can also grow abundantly on animal and mineral surfaces that are exposed to hydrothermal fluids[12, 13]. Filamentous bacteria often produce dense aggregations that are visible to the naked eye as fluffy tufts and mats. These surface-growing bacteria are a potential food source for grazing and deposit-feeding animals such as snails, limpets and worms. These same microbial films can be detached from surfaces by turbulence, and either consumed by filter or suspension feeding animals around the vent or exported to the surrounding deep sea.

3.2 MAR Vent Ecosystems

The visually spectacular vestimentiferan tubeworms, the archetypal organisms of vents in the eastern Pacific, are conspicuously absent from known vent sites on the Mid-Atlantic Ridge.

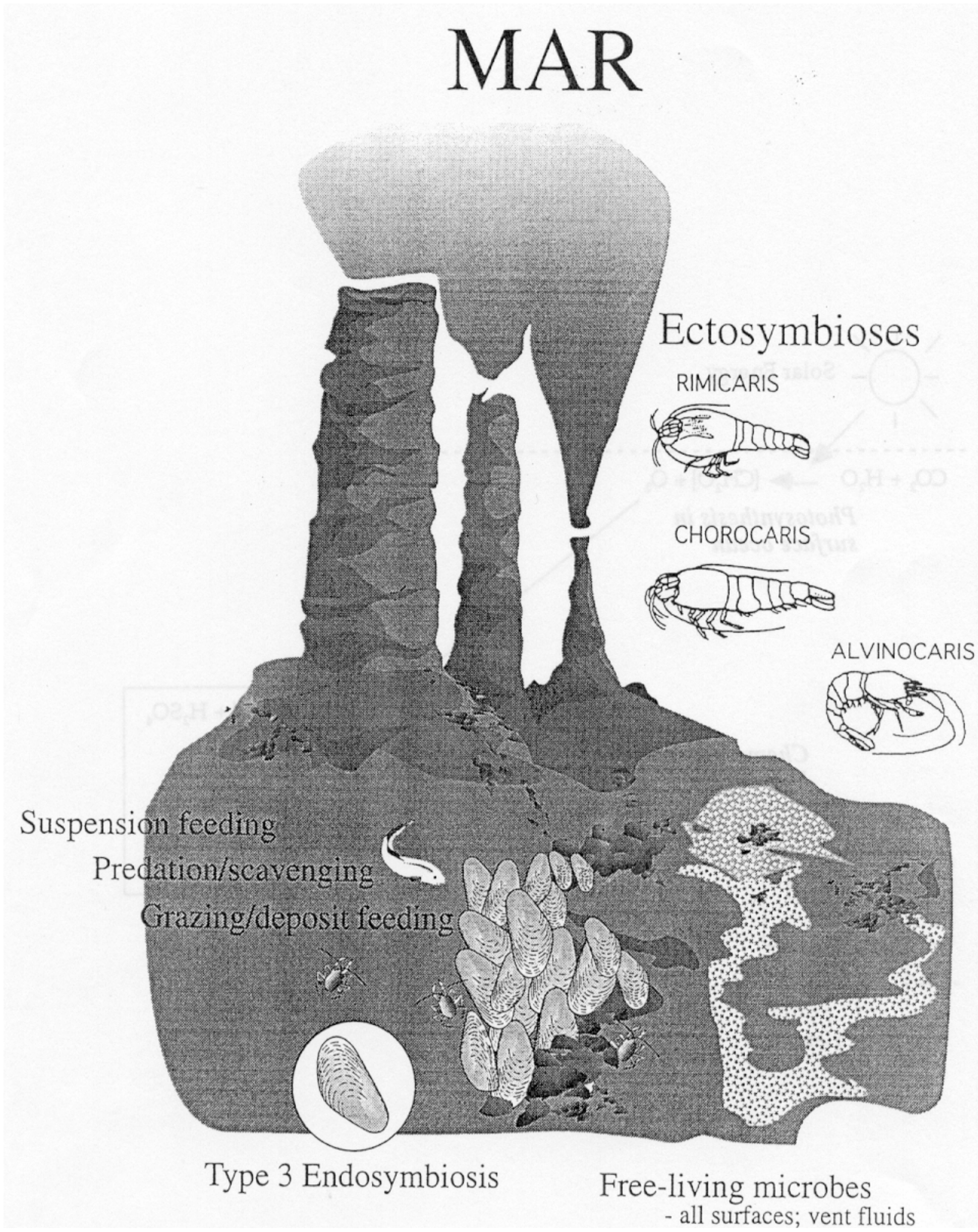

Figure 4 Major components of a generic vent ecosystem on the Mid-Atlantic Ridge (MAR). See text for explanation.

Reasons for this do not appear to be strictly related to the geographic separation of the Atlantic and Pacific oceans, since tubeworms are abundant at cold seeps in the Gulf of Mexico.

Endosymbioses

Only mussel endosymbioses are known from vents on the Mid-Atlantic Ridge. The mussels are similar to the EPR species although some have been found to harbour methane-oxidizing bacteria in their gills[14]. Other vent mussels from the MAR host a dual symbiosis, containing both sulphide oxidising and methane oxidising bacteria in their gills[15]. This is a highly unusual condition in multicellular animals.

Ectosymbioses

Swarms of shrimp bearing ectosymbiotic bacteria on their legs and in specialised branchial (gill) cavities occur on hydrothermally active sulphide deposits on the MAR. Different shrimp species occupy different habitats and there are at least two distinctive forms of ectosymbionts. The ectosymbiosis is most prominent in *Rimicaris exoculata,* which has an enlarged gill chamber housing a dense flora of bacterial filaments[16]. Two other common MAR shrimp species, *Alvinocaris markensis* and *Chorocaris chacei*, also carry some bacterial filaments on their carapace and appendages but these associations are much less developed compared to *Rimicaris exoculata*[16]. As in the case of the EPR alvinellid worms, the nutritional or detoxifying roles of these ectosymbioses remain uncertain. All shrimp can be observed to actively feed on chimney surfaces, and guts of collected specimens usually contain abundant mineral particles[16]. In addition, the two larger shrimp species (*Alvinocaris markensis* and *Chorocaris chacei)* are listed among the predators of the smaller *Rimicaris exoculata*[17].

Free-Living Microbial Growth

As on the EPR, microorganisms grow abundantly on mineral surfaces that are exposed to hydrothermal fluids[18]. Filamentous bacteria often produce dense aggregations that are visible to the naked eye as fluffy tufts and mats.

These bacteria are a potential food source for grazing and deposit-feeding animals.

4. Gene Flow Along the Global Ridge System

From the time of the first discovery of hydrothermal vent communities biologists have been asking how vent animals manage to persist in this ephemeral and spatially discontinuous habitat. How are new vents colonized? Why do we find the same species at vents hundreds and thousands of km apart? Why do other species have very restricted distributions? These questions lead to a fundamental point about how genetic information is transmitted along the global ridge system. Most hydrothermal vent species colonize new sites by producing larvae that have some swimming ability but, as for most marine larvae, are primarily transported by ocean currents. If there are barriers to the movement of larvae between different areas of the ridge crest, their species compositions will eventually begin to differentiate as a result of natural mutations or local extinctions. If gene flow is maintained through the exchange of larvae, then the populations and assemblages of species will continue to resemble each other.

Part of the answer to questions about gene flow along ridges has come from sampling of vents around the world and comparing species inventories between geographic locations[19]. New techniques in molecular biology are also being applied to this problem, both to confirm differences between morphological species and to compare populations of the same species in order to quantify the rate of genetic exchange along the ridge axis. While published data are few and sampling of the global ridge system is still very incomplete, several interesting observations and hypotheses have emerged regarding the relationship between ridge crest processes and gene flow within the global vent fauna. First is a finding that species distribution along present day ridges is related to tectonic plate history. One model suggests that the global distribution of vent species and groups of species can be explained on the basis of a radiation away from an ancestral source on the mid-Tertiary ridges in the eastern Pacific. The entire global ridge fauna has ancestral ties to the eastern Pacific vent fauna, through shared species, genera and families, and can be seen as a subset of it since the greatest number of vent species is found on the northern EPR. When comparing the vent faunas of different regions, one study pointed out that taxonomic similarities reflect distance along the ridge system rather than shortest oceanic distance, implying a primarily along-ridge flow of genetic information[10]. These authors also showed that some present day relationships between vent faunas separated by major discontinuities in the global ridge system can be explained on the basis of past connections between ridges such as the northern EPR and the northeast Pacific ridges, and between the northeast Pacific ridges and the back-arc basins of the western Pacific[10].

At the scale of individual ridge systems, studies of the influence of distance and discontinuities on gene flow are indicating that high levels of long distance gene flow may be a pre-requisite for success of vent species. However, molecular work is also showing that the ability of species to move along and between segments can vary considerably. Eastern Pacific tubeworms are very good at dispersing their genes along ridge axes although neighbouring populations are more similar than more distant ones, producing a quantifiable effect of along-axis geographic distance on gene flow[20, 21]. Discontinuities between ridge axes can also have a measurable effect on gene flow, as has been shown by comparison of populations of the same species on either side of transform faults of different length. For the northeast Pacific tubeworm, *Ridgeia piscesae*, no detectable genetic differentiation was found across the 160km offset between the Juan de Fuca and Explorer Ridges, while populations on either side of the 360km offset between the Juan de Fuca and Gorda Ridges had significant genetic differences[21]. Depth discontinuities may also act as a barrier to gene dispersal and confound interpretation of genetic differences between sites. Vertical mixing is limited in the deep sea so that water mass and larval transport tend to be horizontal. Mussel populations at the Snake Pit and Lucky Strike sites on the MAR show distinct genetic differences that may reflect their separation by transform faults but may also be influenced by depth differences between the two sites (3489m vs. 1650m)[22]. A clearer example of a likely depth effect is that of the amphipod crustacean *Ventiella sulfuris* in the eastern Pacific. The species shows low divergence along the EPR, even across the 240km Rivera Fracture Zone, while the 5000m deep, 50km wide Hess Deep between the Galapagos spreading center and the EPR separates populations with major genetic differences[23].

5. Response to Perturbations

Recent observations of the biological consequences of seafloor volcanic eruptions and the growth of hydrothermal sulphide chimneys and larger multi-chimney edifices provide new insight into the ability of vent communities to colonise newly-created habitat, to recover from major perturbations and to adapt to local-scale changes in habitat conditions.

5.1 Seafloor eruptions

Information on the effects of eruptions on vent fauna comes from time series observations at 9° 45' - 9° 52' N on the East Pacific Rise that followed the serendipitous discovery of a very new lava flow, and from similar studies on the Juan de Fuca and Gorda Ridges in the northeast Pacific. While the characteristics of the eruptions and the suites of observations made vary between sites, the post-eruptive periods have a number of consistent features that reveal the interconnection of magmatic, hydrothermal and biological processes.

Seafloor eruptions provoke rapid and significant changes in the location and style of venting. Widespread diffuse venting is usually observed soon after the event, with new vents being created in areas where there was no previous venting[24]. The biological consequences of this perturbation of the hydrothermal system are considerable. Existing vent communities can be destroyed by lava flows or as a result of the re-organization of hydrothermal venting. Both the 9° N and CoAxial eruptions initiated intense bursts of biological activity as organisms colonized new vents. Most immediate were blooms of free-living microorganisms. The ubiquity of microorganisms of most metabolic types in seawater and their ability to grow rapidly under favourable conditions result in their being the first life forms to exploit the new energy source. In the first few weeks after the eruptions, observers[24, 25] reported the outpouring of particulate microbial material from the subsurface through "snow blower" vents and the massive accumulation of filamentous bacterial mats and flocculent microbial waste on the seafloor in areas of diffuse flow. The discharge of biogenic particulates from snow blower vents can be sustained for several months[24, 25], suggesting continuous microbial production in the subsurface. Post-eruptive diffuse venting can initially be very widespread, supporting microbial growth over large areas of the seafloor. For example, following the 1993 CoAxial eruption there was a 21 ha. zone of microbial growth on new lava flows[26].

Post-eruptive colonization or recolonization by the vent fauna proceeds more slowly than the microbial response because most recruits must arrive as larvae that settle and grow into adult organisms. Some mobile predators and scavengers may recruit as adults from nearby hydrothermal sites if they survive the eruption[25]. Nevertheless, the rapidity with which faunal communities develop around new vents is astonishing. Within one year of the 9°N and CoAxial eruptions tube worm communities had appeared, requiring growth at several 10's of centimetres per year[24, 27], the highest growth rates ever reported for multicellular animals. These observations bespeak the extent to which vent communities have adapted to exploit this ephemeral but energy-rich habitat through their capacities for reproduction, dispersal, colonization and growth. At CoAxial, one third of the regional pool of vent species had become established at the new vents within 2 years of the eruption[24].

5.2 Local habitat evolution

Active hydrothermal vents are extremely dynamic environments and studies of how vent communities respond to local environmental change provide an appreciation of their capacity to recover from human perturbation. Studies at 13˚N on the East Pacific Rise and on the Juan de Fuca Ridge[28, 29] found that alvinellid worms adapted quickly to sulphide chimney growth and were able to colonise new areas of chimney as they were formed. A more extensive, 4-year study of habitat and faunal community dynamics on a hydrothermal sulphide edifice on the Juan de Fuca Ridge showed that the composition of entire communities could be very plastic, shifting with fluid flow regimes at time scales of weeks to months[30]. These adaptations involve both recolonizations by more tolerant organisms where hydrothermal conditions become too severe for the previous community, as well as the progress colonisation of cooling surfaces by species less tolerant of severe conditions. All such observations contribute to an emerging picture of a fauna that is well adapted to the ever-changing habitat of active sulphide edifices. This capacity to keep up with environmental change is dependent on a ready supply of adults and larvae to recolonise disturbed or gradually changing surfaces.

6. Potential Mining Impacts

6.1 Nature of mining-related perturbations

Mining activities in the coming decades are likely to be concentrated in very limited areas where polymetallic sulphide deposits of commercial size are known to occur. At these locations, extracting ore will result in removal of the substratum and production of a particulate plume. Some organisms will be directly killed by mining machinery, while others nearby risk smothering by material settling from the particulate plume. Individuals surviving these perturbations would be subject to a radical change in habitat conditions with hard substrata being replaced by soft particulates settling from the mining plume. These particulates could also clog hydrothermal conduits, depriving established vent communities of their vital fluid supply. At sedimented hydrothermal sites, where much of the ore body lies within a sediment overburden, digging out the deposit would produce a much more extensive plume that could completely eradicate the local vent fauna.

6.2 Important biological considerations

The global hydrothermal vent fauna is one of the most unusually adapted assemblages of organisms found in the oceans, in terms of tolerance of extreme physical-chemical conditions and exploitation of chemosynthetic food sources. This high degree of uniqueness, together with the facts that most vent species do not occur outside of the hydrothermal environment and that many have restricted distributions along the global ridge system are important issues to be considered in developing strategies and regulations for the mining of seafloor polymetallic sulphide deposits. In contrast, microorganisms colonising hydrothermal sites are generally assumed to be drawn from a globally distributed gene pool and therefore little threatened by localised mining activities. The biogeography of marine microbes has been little studied and the present view of their global distribution may eventually change.

Studies of the rapid colonisation of new vents following seafloor eruptions demonstrate the ability of the vent communities to re-establish at a severely disturbed site, as long there are hydrothermal emissions to support microbial chemosynthesis. While time scales for the establishment of mature, multi-species communities remain uncertain, high biomass and faunal density levels are attained within a few years after eruptions. Observations of local shifting of vent species to adapt to changes in fluid flow reinforce this notion of resilience. While it may be tempting to apply the resilience argument to considerations of mining impact, it is important to point out that the mother populations that permit repopulation after perturbation are themselves particularly vulnerable to mining. There is some evidence that biodiversity within a given region is greatest at larger, longer-lived hydrothermal sites[9, 31]. This is in keeping with what has been observed in other ecosystems on Earth. Long-lived 'mother populations' may be critical to the maintenance of vent species biodiversity within a region. These same long-lived hydrothermal sites are also the most likely locations for accumulation of large sulphide deposits and therefore will be prime targets for mining (see papers by P. Rona and P. Herzig, this volume). As well, many localised species many not have a nearby mother population or they may be unable to recolonise the altered substratum after mining. In the latter case, only the establishment of protected areas would prevent eradication of species.

Some large, seafloor polymetallic sulphide deposits are hydrothermally inactive and provide no habitat for a specialised vent fauna. There are some observations of the colonisation of inactive deposits by 'normal' deep-sea organisms. This would suggest that mining would pose little threat to the survival of individual species since its fauna is drawn from the surrounding deep sea. However, inactive sites have received little attention from biologists and more extensive sampling is required to establish that the nature of their fauna. Mining will effectively eliminate the habitat formed by extinct deposits, so it is important to confirm that they host only background deep-sea species.

Arguments for the conservation of vent species can be developed from the same sources that have led to the present global interest in the preservation of biodiversity. In addition, cutting edge biological science has become an important stakeholder in this resource and millions of research dollars are annually directed to laboratory and field studies of vent organisms. Vent biology, in its brief history, has made major contributions to the development of basic models of life processes. Most recent editions of university textbooks in biology and ecology now use examples from hydrothermal vents to illustrate points on symbiosis, detoxification, adaptation to extreme conditions and ecosystem function. The visually spectacular and extreme nature of vent communities also makes them popular subjects for the science media and science education sectors. Several of the world's leading natural history museums feature new exhibits on hydrothermal vents. While few of the novel species discovered at vents may be edible or of any immediate material value, any one may hold a priceless message of fundamental importance to basic science.

6.3 Development of guidelines and regulations

Any guidelines aimed at protection of vent species will require provision for site-specific issues such as whether mining will occur on active or inactive hydrothermal sites and the geographic range of the affected vent species. Standard criteria used in environmental assessment in other marine habitats will also have to be taken into account. These include:

i) *Characterisation of the type of disturbance* – in particular the destruction of the substratum and associated organisms, and the creation of particulate plumes that could bury or stress organisms in areas directly adjacent to mining activities.

ii) *Estimation of the percent loss of seafloor vent habitats* – most vent fields include several types of habitat that host different assemblages of organisms. Managing the impact of mining on individual species will thus require specific information on the fraction of individual types of habitat that remain undisturbed, as well as an estimation of the total disturbance

iii) *Identification of affected seafloor organisms* – this information is critical to evaluating the impact of mining activities on the survival of species. Species with a broad geographic range are less likely to be endangered by mining, which is expected to be very localised. On the other hand, sites containing species with restricted distribution will require more careful management to assure maintenance of biodiversity.

iv) *Dose-response characteristics of plume fallout* – many vent species are sessile or capable of little locomotion. Some feed by filtering particles from surrounding seawater. In both cases, the presence of particulate plumes or sediment fallout from adjacent mining could have adverse affects on their survival even if they are not directly disturbed by mineral extraction machinery. There is no published information on dose-response characteristics of vent organisms in relation to particulate plumes. Test or pilot mining operations would provide opportunities to conduct this type of study prior to full-scale mining operations. Such studies need not be site specific since much useful general information can be derived from monitoring burial of vent organisms or their food supply and particulate fouling of suspension feeders.

Development of management plans for individual mining sites will require baseline information on their biological characteristics. These include:

i) *Distribution of habitat within the affected area* – Hydrothermal emissions are often correlated with seafloor relief features. Sidescan or pencil-beam sonars provide detailed topographic information that can be used to develop a base map. Submersible video surveys or digital photography can then be used for "ground truthing" sonar maps to relate relief and textural information to hydrothermal activity, occurrence of mineral deposits and presence/absence of visually distinct faunal assemblages.

ii) *Species composition and community structure* – complete information on species composition can only come from sampling. This information is vital to questions regarding the geographic range of the affected species. Since extensive sampling is costly and time-consuming, an approach that combines synoptic habitat mapping (see above) with targeted sampling will likely be the best strategy.

iii) Basic biology of species – key here is information concerning the feeding mode of individual species (i.e. how they will be affected by particulate plumes) and an understanding of their ability to recolonise a disturbed site (reproductive cycles, recolonization potential).

There is no imminent threat to the entire global vent fauna from mining or any other human activity. Concentration of mining activities in areas such as the southwest Pacific back arc spreading centres will, however, produce local and even regional effects on vent organism abundance, to the point where the survival of some species could become an issue. The challenge to regulators, vent biologists and miners will be to use existing knowledge to develop strategies for managing these effects. A realistic overall goal for management could be the maintenance of biodiversity throughout the period of mineral extraction so that exploited sites could be repopulated. This may require managed protection of breeding populations within colonisable range of the affected site. Identification of a potential source of colonists for all affected species in nearby areas unaffected by mining operations would obviate the need for formal protection.

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SUMMARY OF THE PRESENTATION AND DISCUSSIONS ON THE IMPACT OF THE DEVELOPMENT OF POLYMETALLIC MASSIVE SULPHIDES ON DEEP-SEA HYDROTHERMAL VENT ECOSYSTEMS

Dr. S Kim Juniper, of GEOTOP Research Centre, University of Quebec in Montreal prefaced his presentation by informing participants that the mining industry is not the first industry interested in studying massive sulphides at vent areas. He said that in fact basic biology is one of the major stakeholders in this area. He said that through scientific research, new discoveries in biology are discovered by studying this environment. In addition to informing participants about how the different types of biodiversity are formed and sustained, Dr. Juniper said that he would address the question of environmental assessment and the potential impact from mining and what needs to be done to prepare for mining.

Dr. Juniper placed the discovery of biodiversity at vent sites in context by describing the normal situation in the abyssal plains of the deep sea that he said is the largest ecological region on earth, covering something like 59% of the planet surface, and under 2km of water.

Using slides, he said that the animals that live on the seafloor, such as a sea cucumber crawling around in mud that he showed, depend entirely on what is happening 2000 metres above them in the photic zone for food. He explained that in the photic zone where there is light, there is plankton carrying out photosynthesis and leaking particles of organic matter that eventually trickle down and get to the seafloor. For most seafloor animals in the abyssal plains, this is the source of food.

Dr. Juniper described the abyssal plains as a biological desert because species of individual animals are rare. He also said that if one considered the entire abyssal plains, one could find several million species living in it although one would also find that it's a long way from one individual to the next. Recalling earlier presentations on hydrothermal vent environments, in particular the parts on hot fluids full of chemicals coming out onto the seafloor, he described this environment as toxic. He said that any animal living in this environment has to be a specialist. Dr. Juniper said that hydrogen sulphide and other substances that for many other species of animals would be toxic is actually the source of energy for many of these specialist animals. He said that microbes that are found in this environment use a process called chemosynthesis to take the chemicals, transform them, derive energy for their metabolism from them, and use this energy to turn carbon dioxide into sugar. He said that the sugar that is produced is the food for the rest of the food chain.

He described the situation at vent sites as unusual, with many bacteria living inside the tissues of animals. He said that the bacteria are not just growing on the seafloor and being gobbled up, but that to make the system even more productive they are living in symbiosis within the tissues of some of these very specialized animals that exist only in hydrothermal vent environments.

To illustrate the high degree of evolution that has gone into creating the symbiosis, Dr. Juniper used the example of the giant tubeworm that is found on the east Pacific Rise all the way from the gulf of Northern California all the way to near Easter Island in the South Pacific.

Dr. Juniper described the discovery as interesting because there has never been anything found like it in the entire history of biology. He said the discovery has been classified as one of the major biological findings of the 20th century.

He pointed out that there are also many animals found at hydrothermal vent sites that do not have bacteria living in their tissue. He said that these animals live off free-living bacteria. He also said that free-living bacteria grow on animal surfaces and on water surfaces, being born out in the hydrothermal fluid. He showed participants some white material that he said came out from below the seafloor in the vents. He described this material as bacterial particles, individual cells that have come together. He showed participants a slide of a large field of tubeworms including two giant spider crabs that he said lived off the site. Dr. Juniper said that samples taken from this area usually consist of clumps of intertwined tubeworms held together with mucus that is secreted by a number of different organisms. Dr. Juniper said that the tubeworms feed the mass growing on the animal surfaces and then predators feed on the tubeworms. He apologized for not being in a position to describe some of the other symbiotic relationships at vent ecosystems but said these include a number of shellfish (clams and mussels) which also have special bacteria living inside their tissues, and which are also suspension or deposit feeders. He also said that some of the predators are octopus that love the clams and fish and like to hang around the hydrothermal vents in some areas.

Dr. Juniper however noted that there are major differences between the Eastern Pacific vents, the mid-Atlantic ridge vents and the Western Pacific vents.

He said that hydrothermal vents fauna at the Western Pacific Ridge seem to be something of an intermediary between fauna at the Eastern Pacific and the Mid-Atlantic Ridges. He also said that what probably happened is that back in Geological time the hydrothermal vents fauna originated from somewhere in the Eastern Pacific and had spread out by producing larvae. He said that the animals colonize other sites by sending up larvae which are fertilized eggs with arms and legs and that swim a bit, often with a little sack on their back for eating. He noted however that the larvae have a very limited life span. Dr. Juniper showed participants an area on the Eastern Pacific Ridge and informed them that fauna were taken from this area and compared with fauna 300km down the axis. He said that the fauna were found to be very similar. He said that 3000km away the fauna were found to be very different because these communities have been isolated for tens of thousands of years since genetic information was not flowing back and forth. Dr. Juniper said that in the last 10 years or scientists have witnessed several volcanic eruptions on the seafloor and watched the recolonisation of the site afterwards. He stated that the speed of recolonisation is surprising. He said that within a couple of years an established and recognizable community is established where everything was as it was 2 years before. In relation to mining therefore, Dr. Juniper said that one could cautiously say that there is a tremendous capacity for recolonization if there is a source of larvae to make this possible. He emphasized that recolonization has to be from a breeding population that is not disturbed.

Dr. Juniper also emphasized the need to be pragmatic. He pointed out that because a few species may be lost, decisions would have to be made about the uniqueness of the gene pool to be disturbed. Whether the gene pool is consists of just another worm that eats dirt or if it consists of animals that some day medical science may want to exploit. He noted that currently the scientific community does not have answers to all these questions.

Dr. Juniper concluded his presentation saying that the longer-lived hydrothermal sites are obviously going to be one of the more attractive sites for mining because that's where venting has been going on the longest and where more sulphides have accumulated. He also expressed concern that these sites are also the ones that have the highest biodiversity because they've been a stable habitat for tens of thousands of years like the Amazon Rainforest.

DISCUSSIONS.

In relation to bacteria producing gold and silver in an oxygen-free environment, Dr. Juniper was asked whether this was at the 2,000 – 3,000 metres depth. He was also asked how species diversity at hydrothermal vents compares with species diversity at coral reefs and at tropical rainforests. Finally, Dr. Juniper was asked if the species to be found at vent ecosystems have a commercial value.

With the regard to the question as to where in the deposit bacteria produce gold and silver, Dr. Juniper said that while bacteria attack the massive sulphides deposits, breaking them in order to get at the sulphides, there are some fundamental differences in the conditions. Firstly, Dr. Juniper said that when bacteria are degrading the deposits there is no longer hydrothermal activity so there is oxygen available. In the most likely cases it would be in bottom seawater that has dissolved oxygen in it. Dr. Juniper said that because the seawater is such a good pH buffer and does not get acidic like a typical acid mine leaching situation, it looks like another group of bacteria which are adapted to decomposing sulphides. He said that under close to neutral ph conditions, it would be very interesting to exploit these bacteria because perhaps they could be used to leach the deposit without the acidity problem in land-based mines.

With regard to the question on the comparison of species diversity at vent sites, at coral reefs and at tropical rainforests, Dr. Juniper said that the total number of species globally is very narrow about 500 at a single site. He said that the latest study at the Endeavour segment, undertaken for a week identified 77 species in that area. He pointed out that before that only 34 species had been identified. 34. He also pointed out that what is being discovered is that the very small creatures known as meiofauna that are only a few mm long, exhibit a tremendous amount of diversity. He said that in the old days, the meiofauna that was collected in samples used to be discarded. He said that in past few years, biologists have been much more careful about keeping the sample intact.

Finally in relation to the question on the possible commercial value of vent species, Dr. Juniper said that they have an economic value to the scientific research industry because there many people studying them. He also said that there is real interest from the bio-technology industry in some of these bacteria which are specialized to do things at high temperature. He said that there is a lot of bio-prospecting going on by European and North American prospectors. Dr. Juniper said that there is few enzymes on the market that come from high temperature vent bacteria but progress is slow like it is in any other type of bio prospecting. In terms of the animals, Dr. Juniper said that their initial value is discovering biological processes that mankind never knew existed before. He concluded by saying that these elaborate symbiosis, these adaptations to living in a toxic environment may eventually allow mankind to deal with toxic situations on land. He pointed out that presently it is very basic research that is taking place. He also said that while he could not put a dollar value on it today, massive sulphides would definitely be a mine for genetic information.

CHAPTER 7

TECHNICAL REQUIREMENTS FOR THE EXPLORATION AND MINING OF SEAFLOOR MASSIVE SULPHIDES DEPOSITS AND COBALT-RICH FERROMANGANESE CRUSTS

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During the past decade, marine mineral exploration programmes have been significantly enhanced through the development and availability of state-of-the-art exploration tools and equipment. Today, multi-purpose research vessels with swath mapping capabilities, deep-towed camera and video systems, TV-guided grab samplers, as well as deep-diving submersibles and remotely operated vehicles (ROVs) are almost routinely used. A first order technical requirement for a new era of scientific research and resource assessment of polymetallic massive sulphides deposits is the availability of portable seafloor drilling and coring devices which can be deployed from a research vessel rather than a specifically designed drill ship. So far, most research results and resource assessments are based on surface samples only and thus are not sufficiently reliable. The development of mining systems for massive sulphides and precious metal deposits needs to focus on continuous recovery through rotating cutter heads and airlift of an ore slurry to the mining vessel. Recovery technologies for cobalt-rich ferromanganese including hydro jet and heavy-duty rollers need to be tested in order to demonstrate that the crusts can be efficiently separated from the substrate rock.

1. Introduction

Since the discovery of black smokers, massive sulphides and vent biota in 1979[1], numerous academic and government institutions carry out exploration for seafloor massive sulphides deposits at oceanic spreading centres worldwide. Leading countries in this field are the United States, France, Germany, the United Kingdom, Japan, Canada, Russia, and Australia (cf., Table 1). In some countries, such as Portugal and Italy, marine exploration programs for massive sulphides have newly been developed over the past few years. Cobalt-rich ferromanganese crusts in the Pacific Ocean have been the focus of exploration and evaluation since the mid 1980s led by the United States, Germany, and Japan[2]. Technical developments in marine research and exploration equipment that paralleled geological research programmes were critical factors in advancing scientific and resource-oriented studies of hydrothermal systems and cobalt crusts. Today, a large number of different tools and systems are available for the efficient search and evaluation of marine mineral deposits as a whole. State-of-the-art equipment includes modern multi-purpose research vessels with multibeam swath mapping systems and DGPS-navigation, side-scan sonar devices, deep-towed camera and video systems with on-line capability, TV-guided grabs for controlled large-scale geological sampling, shallow and deep-diving research submersibles, and remotely operated vehicles (ROVs). In the future, autonomous underwater vehicles (AUVs) will become available on a routine basis. Recently, a first generation of portable drilling and coring devices for shallow drilling at the seafloor has been developed but needs significant improvement with respect to drilling depth and core recovery in order to reveal reliable information on the third dimension of polymetallic massive sulphides deposits. Mining tools for massive sulphides so far have not been specifically designed but may be adapted from the offshore diamond mining industry. For cobalt-rich ferromanganese crusts, two different mining systems (hydro jet and roller) have been designed but not yet fully tested.

Table 1: Selected Research Programmes for Seafloor Massive Sulphides Deposits 1980-2000

Program	Countries	Ocean Area
FAMOUS	France/USA	Mid-Atlantic
TAG	USA/France	Mid-Atlantic Ridge, 26°N
FARA	France/USA	Mid-Atlantic Ridge, Azores
DIVA	France/USA	Mid-Atlantic Ridge, Azores
BRIDGE	United Kingdom	Mid-Atlantic Ridge
CYAMEX	France/USA	East Pacific Rise, 21°N
GEOMETEP	Germany	East Pacific Rise, South
GARIMAS	Germany	Galapagos Rift, 86°W
HYDROTRACE	Germany/Canada	Juan de Fuca Ridge, Axial Seamount
VENTS	USA/Canada	Juan de Fuca Ridge
GEMINO	Germany	Central Indian Ridge
HIFIFLUX	Germany	Southwest Pacific, North Fiji Basin
STARMER	France/Japan	Southwest Pacific, North Fiji Basin
PACMANUS	Australia/Canada	Southwest Pacific, Manus Basin
PACLARK	Australia/Canada	Southwest Pacific, Woodlark Basin
NAUTILAU	France/Germany	Southwest Pacific, Lau Basin
EDISON	Germany/Canada	Southwest Pacific, Tabar-Feni Arc

2. Exploration Tools and Systems

Marine mineral exploration programmes for massive sulphides and cobalt-rich ferromanganese crusts require state-of-the-art multi-purpose research vessels that allow time and cost efficient exploration of large areas. A prerequisite is a permanently installed multibeam swath mapping system (up to 121 beams) which is capable of mapping the seafloor down to several thousand meters depth. Modern systems are able to map a swath width of more than 3 times the water depth along the ships track. On-board computer processing usually produces a coloured or even 3D bathymetric map to 5 m contour intervals. In addition, ship-mounted sediment echo sounders are being routinely used to determine the thickness and nature of the upper part of the sedimentary column, whereas seismic reflection surveys reveal information about the deeper part of the sedimentary pile. Side-scan sonar systems that are towed behind the ship obtain information about tectonic features at the seafloor. Gravity, magnetic, and heat flow surveys are also routinely run.

On-line real-time observation of the seafloor in the search for hydrothermal sulphides at oceanic spreading ridges or for cobalt-rich ferromanganese crusts at seamount flanks is achieved by using deep-towed camera-systems (rated up to 5.000 m depth) which are equipped with lamps and flashes in combination with high-resolution colour video cameras and still cameras for up to 700 colour slides. The data transfer from the seafloor to the ship is achieved via a fibre optic cable while the energy for cameras, lamps and flashes is transmitted via a co-axial cable.

Basic sampling devices include various corers (spade, piston and gravity) and dredges (barrel, box and chain-bag) as well as free-fall grabs known from manganese nodule exploration. An excellent development is that of TV-guided grab systems (rated up to 5.000 m depth) for precise large- scale (up to about 3 tonnes) sampling of rocks, massive sulphides or cobalt crusts. Due to a high-resolution video camera and several lights mounted in the centre of the grab, the system can be used for small scale mapping of the seafloor as well as for sample selection and finally sampling. If the sample is not sufficient, the grab can be reopened and closed several times before the batteries are exhausted and need to be recharged. TV-grabs are usually also operated on a fibre optic cable to enhance the camera signal and to trigger the closing and opening mechanism of the grab. The power necessary to close and open the claws, however, is provided by deep-sea batteries.

For water sampling in the search for geochemical signals (methane, manganese, helium isotopes) of active hydrothermal vents, several CTD (conductivity-temperature-depth) and rosette sampler systems with up to 24 bottles are in use. Each bottle can be closed remotely at a certain water depth. Chemical analyses of the water samples are usually performed on board ship with only limited time delays. In recent years, geochemical scanners (e.g., **SUAVE**: NOAA/USA; **ZAPS**: Oregon State University/USA; **ALCHEMIST**: IFREMER/France) have become available, and are used in the towed mode to provide continuous (on-line) registration of various pathfinder elements for active hydrothermal vents. The advantage over conventional hydro cast surveys is obvious as large areas can be covered in a reconnaissance mode in relatively short periods of time.

3. Submersibles And ROVs

For detailed mapping of particular seafloor sites ("ground truthing"), for precise small-scale sampling, and in particular for direct sampling of hydrothermal fluids at active black smoker chimneys, manned research submersibles and/or remotely operated vehicles (ROVs) are required. There are currently several research submersibles available that have operational depths of 400-6,500 m. These submersibles have the ability to withstand water pressures of 40-650 bars or 4-65 MPa. The submersibles commonly seat two pilots and one scientist, and are launched from a mother ship. Individual dives last about 8-10 hours in total; however, dives whose duration is more than 16 hours have been reported. Most submersibles are equipped with two 5 to 7-function manipulators for sampling and measurements. Remotely operated vehicles (ROVs) have several advantages over manned submersibles including (i) longer bottom time (up to a week and more), (ii) reduced cost, (iii) no risk for pilots and scientists. ROVs are equipped with camera/video systems that transfer video images via fibre-optic cable to the ship. This enables a larger group of scientists to participate in a dive and to discuss the selection of sampling locations etc. Similar to submersibles, ROVs are also fitted with two robot arms for manipulations at the seafloor. Currently, the Canadian **ROPOS** (Remotely Operated Platform for Ocean Sciences) operated by the Canadian Scientific Submersible Facility, the American **JASON** operated by Woods Hole Oceanographic Institution, and the French **VICTOR** operated by IFREMER, are leading in this field together with the Japanese **KAIKO** which has a maximum depth range of 11,000 m (Table 2).

Table 2: Research Submersibles and Remotely Operated Vehicles

Name	Organization	Country	Depth Capability
ALVIN	WHOI	USA	4,500m
NAUTILE	IFREMER	France	6,000m
CYANA	IFREMER	France	3,000m
MIR 1 & 2	Shirshov Institute	Russia	6,000m
SHINKAI 6500	JAMSTEC	Japan	6,500m
SHINKAI 2000	JAMSTEC	Japan	2,000m
PISCES IV & V	SOEST	USA	2,000m
PISCES	-	Russia	2,000m
JAGO	MPI Seewiesen	Germany	400 m
ROPOS (ROV)	CSSF	Canada	6,000m
JASON (ROV)	WHOI	USA	6,000m
VICTOR (ROV)	IFREMER	France	6,000m
ROBIN (ROV)	IFREMER	France	3,000m
DOLPHIN 3K (ROV)	JAMSTEC	Japan	3,300m
KAIKO (ROV)	JAMSTEC	Japan	11,000 m

Seafloor Drilling and Coring Devices

Drilling of seafloor polymetallic sulphides deposits is essential to obtain samples and information from the interior of hydrothermal mounds and chimney complexes. The drilling vessel JOIDES RESOLUTION which is operated by the Ocean Drilling Program at Texas A&M University, USA, has carried out scientific drilling at the Middle Valley sulphides deposit on the Juan de Fuca Ridge off-shore Canada during Legs 139 and 169, and at the active TAG hydrothermal mound at the Mid-Atlantic Ridge 26°N (Leg 158). A further drilling leg is planned for 2000/2001 (Leg 193) in the eastern Manus Basin offshore Papua New Guinea to explore the third dimension of the Pacmanus hydrothermal field.

In addition to drilling vessels such as the **JOIDES RESOLUTION**, a first generation of portable seafloor drilling and coring systems (Table 3) is available including the **PROD** (Portable Remotely Operated Drill), which was jointly developed and constructed by the US/Australian group of Benthic GeoTech Pty. Ltd., Williamson and Associates. Inc., and the University of Sydney. Performance specifications for PROD include a maximum penetration of 100 m at an operating depth of up to 2,000 m, and a rock core diameter of 40 mm with individual core lengths of 2.2 m. So far, however, the drill has not yet been fully tested and longer cores have not been retrieved. A second drill, the **BMS** (Benthic Multicoring System) was built by Williamson and Ass. Inc. for the Metal Mining Agency of Japan (MMAJ) in 1996 and is presently installed on the research vessel Hakurei Maru No. 2. The **BMS** uses conventional diamond rotary-rock and soil sampling tools and can be operated from ships-of-opportunity at water depths of up to 6,000 m. Individual cores have a diameter of 44 mm at a maximum coring depth of 20 m. The system has been successfully used by the MMAJ to drill in the submarine caldera of Suiyo Seamount at the Izu-Bonin Arc at a depth of 9.8 m achieving a core recovery of 26%[3].

Table 3: Available Seafloor Drilling and Coring Devices

System	Depth	Coring Depth	Core Diameter
PROD[1]	2,000 m	100 m	40 mm
1. Portable Remotely Operated Drill, Australia/USA			
BMS[2]	6,000 m	20 m	44 mm
2. Benthic Multicoring System, Japan/USA			

4. Technical Requirements

For research and resource assessment of polymetallic massive sulphides deposits, technological advances are a critical factor. In the present state of research and commercialisation, information on the depth extent and therefore the size of the deposit, and the type of mineralisation and alteration are extremely important. Drilling by the Ocean Drilling Program Leg 158 at the active TAG hydrothermal mound at the Mid-Atlantic Ridge[4] has indicated a total tonnage of 2.7 million tonnes of sulphides above, and 1.2 million tonnes below the seafloor[5]. It was also found that high concentrations of base and precious metals are confined to the upper few meters of the mound. The mound itself consists of breccias with varying proportions of pyrites, silica, and anhydrites that would not be economically recoverable. Initially, it was thought that the entire mound consists of polymetallic massive sulphides.

Except for the TAG mound, the Middle Valley site at the Juan de Fuca Ridge, and the Atlantis II Deep in the Red Sea, depth information is not available for any of the known seafloor sulphides deposits. Research and resource assessments of these deposits rely on surface samples only. As drilling of hydrothermal systems by the Ocean Drilling Program will be the exception rather than the rule, reliable portable drilling and coring devices are required for research and industry. It has to be demonstrated that these systems are actually capable of supporting drilling and coring several tens of meters of massive sulphides and rock at the seafloor. The available technology is an encouraging start but needs to be further developed in order for drilling at the seafloor to depths of 50-100 m a routine operation by any research vessel, and to reveal reliable information on the depth extent of mound and chimney complexes (Table 4).

Table 4: Technical Requirements for Resource Assessment and Mining of Seafloor Sulphides

- Portable seafloor drilling and coring systems with depth capability of 50-100m and core recovery of >50% to be used from ships-of-opportunity
- Continuous mining techniques with flexible drill string and airlift/hydraulic pumping of ore slurry to mining vessel

After the resource potential of a massive sulphides deposit has been adequately established by grid drilling similar to land-based operations, exploitation and recovery will be the next challenges. Selective mining using large TV-controlled grabs similar to those used for exploration are an option, however, continuous mining appears to be the only economic alternative. It appears that the continuous mining systems used by De Beers Marine, offshore Namibia, for the recovery of diamonds from water depths of about 100-150 m could be converted for massive sulphides mining. These systems consist of large (7 m diameter) rotating cutter heads that are attached to a flexible drill string through which the diamond-bearing sediment is airlifted onto the ship for further processing. The redesign of such a system for massive sulphides and/or altered gold-bearing rocks seems possible. A weight on head of several tens of tonnes controlled by the ships drill rig in combination with a heave compensator would allow crushing sulphides and altered rock *in situ* and converting them to a slurry. The slurry could then be airlifted to the mining vessel from which the ore slurry would be transferred to a cargo freighter for transport to a processing plant. There is no question that the design and construction of suitable seafloor mining systems for polymetallic massive sulphides and gold-rich rocks are major tasks for research institutions and the offshore industry. These needs ought to be met within the next few years.

5. Processing Technologies

The physical properties of seafloor sulphides deposits are an important consideration for future evaluation of their mine ability and the recoverability of their contained metals. The bulk dry density of sulphides chimneys, hydrothermal crusts, and sediments from the outer surface of the deposits are very low. Sulphides chimneys from the East Pacific Rise 21°N have a dry density of only 1-2 gm/cm^3 and an *in situ* water content of 25-50 per cent[6]. Higher densities due to compaction, open-space filling, and hydrothermal re-crystallisation of the sulphides can be expected in the interiors of the mounds. Most recovered samples are fine-grained, complex intergrowths of sulphides minerals and gangue (silica, barite, anhydrite). Their fine-grained nature is partly a consequence of the manner in which the sulphides are precipitated from the hydrothermal fluids. Rapid quenching of the solutions as they mix with seawater results in poor nucleation of minerals and limited growth of large crystals. Particle size analysis of sulphides chimneys from the East Pacific Rise 21°N, crushed to their individual grains, shows that 93% of the material is in the 10 micron-to-1 millimetre range (silt-to-sand sized particles)[7]. Analyses of samples from the East Pacific Rise 11°N and Southern Explorer Ridge also indicate a range of grain sizes for pyrite, sphalerite and chalcopyrite from 1-600 microns with averages of 22-37 microns; 90-95 per cent of the particles in the -400 mesh range (smaller than 37 microns) are free of interlocking[7]. Some degree of natural coarsening of the sulphides may occur in large deposits, where early-formed minerals are continuously re-crystallised by hydrothermal reworking.

The technology for treating fine-grained ores is poorly developed, and fine grinding of the kind required to liberate individual grains of pyrite, sphalerite, and chalcopyrite is energy intensive. Significant losses of the ultra-fine fraction (particles <10 microns in size) are commonly encountered in processing of fine-grained ores from land-based deposits. Some deposits are economic only because re-concentration of metals during structural deformation and thermal metamorphism has upgraded the ore and increased the grain size of the minerals of interest to a range amenable to processing. Flotation is the most important method in current use for the production of sulphide concentrates at base metal mines on land, but there are also serious limitations to the effectiveness of this technique in separating fine-grained particles (<10 microns). Ultra-fine particle flotation with seawater has been tested to produce a bulk sulphides concentrate from the Red Sea muds[8, 9], but other novel methods of mineral processing may be warranted. Fine grinding and high inductance magnetic separation of seafloor massive sulphides has proved to yield a suitable copper and zinc concentrate with a recovery rate of 81%[7]. This technique could be used at sea to produce a pre-concentration that could be easily shipped to shore at reduced costs[10]. The complex polymetallic nature of the sulphides may require developments in extractive metallurgy before they could be adequately treated (e.g., hydrometallurgical processes such as oxidative pressure leaching).

Gold and silver are recovered as by-products of base metal mining on land, most commonly during the smelting of copper, zinc, and lead concentrates. The recovery of silver depends largely on its mineralogical siting in the ore, usually as a trace constituent in galena, chalcopyrite, or sulphosalts such as tetrahedrite. Gold is recovered as free grains of native metal or electrum and usually reports to the copper concentrate during flotation. Current milling practices, however, recover only a fraction of the total contained gold in most massive sulphides ores (as little as 60 per cent in some cases). This poor recovery is a consequence of the uniformly small grain size of gold particles (typically <10 microns) that are not adequately liberated by conventional methods of mineral processing. In primary (i.e., not oxidized, not re-crystallized) sulphides from the seafloor, coarse-grained gold has been documented in only a few deposits. The recovery of fine-grained gold from massive sulphides without compromising the recovery of copper and zinc and at a reasonable cost (determined by energy requirements for fine-grinding) represents a major challenge to mineral processors and metallurgists and will be an important consideration in the possible development of seafloor polymetallic sulphides as a precious metal resource

6. Cobalt-Bearing Ferromanganese Crusts

In contrast to polymetallic massive sulphides, which occur at or within volcanic rocks or sediments at oceanic rifts such as mid-ocean ridges and back-arc spreading centres, cobalt-bearing ferromanganese crusts form on the flanks of seamounts at water depths of 800-2,500 m. Cobalt-bearing crusts grow on substrate rocks because of metal precipitation from cold ambient seawater close to the oxygen minimum zone[2]. Relative to ferromanganese nodules, the crusts contain elevated concentrations of cobalt (up to more than 2.0 wt. per cent) and Platinum (up to 3 ppm). Research on cobalt-bearing ferromanganese crusts has largely been carried out in the 1980s by the United States, Germany and Japan[2]. It was found that economic grade crusts should be at least 4 cm thick and contain >one wt. per cent cobalt on average[11]. The majority of the crust fields are found in the Exclusive Economic Zones of Micronesia, Marshall Islands, Kiribati, and the USA, as well as in the international waters of the Central Pacific Mountains.

Mining of crusts fields involves the efficient fragmentation and *in situ* separation of the crusts from the substrate rock to avoid dilution of the crusts metal grade, a problem which has still not been sufficiently resolved (Table 5). However, hydro jet systems and heavy-duty roller combined with suction and hydraulic pipe lift or airlift devices have been designed but not yet fully tested. Any mining system needs to be capable of mining at least 1 million tonnes per year. This scenario allows for 80 % separation efficiency and 25% dilution by substrate rock fragments[2]. As the interest in ferromanganese crusts mining is currently, relatively low, new technical developments of mining equipment such as advanced trench cutters have not taken place. This is also true for metallurgical processing which needs to focus on the efficient recovery not only of the cobalt but also of the platinum, which has been a major problem in the past.

Table 5: Mining Ferromanganese Crusts

Efficient separation of crust from substrate rock by rollers	hydro jet system heavy-duty
Both systems need further development and full testing	

7. Conclusions

First order technical requirements for polymetallic massive sulphides exploration include portable drilling and coring devices to be operated from ships-of-opportunity. These systems need to be capable of drilling several tens of meters into the seafloor with more than 50 per cent core recovery. For mining massive sulphides at and just below the seafloor, continuous operating devices with large-scale cutter heads in combination with airlift or hydraulic pumps need to be developed (Table 6). Exploration tools for cobalt-bearing ferromanganese crusts such as deep-towed cameras, side-scan sonar, and TV-guided grabs are available. The problem of the efficient separation of the crusts from the substrate rock by suitable mining tools (hydro jet, rollers) has not been resolved and needs further consideration.

Table 6: Continuous Mining of Seafloor Massive Sulphides Deposits

-	Rotating cutter heads (7-10 m diameter)
-	Airlift or hydraulic pumping of ore slurry to mining vessel
-	Transfer of ore from mining vessel to cargo freighter

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SUMMARY OF THE PRESENTATION AND DISCUSSIONS ON TECHNICAL REQUIREMENTS FOR EXPLORATION FOR, AND MINING OF SEAFLOOR MASSIVE SULPHIDES AND COBALT-RICH FERROMANGANESE CRUSTS DEPOSITS

Summary of the presentation

Dr. Peter Herzig made a second presentation to the workshop, on the technical requirements for exploring for and mining seafloor massive sulphides and cobalt-rich ferromanganese crusts deposits using slides and a video presentation. He informed participants that his presentation would comprise an overview of existing technology and future developments that he felt were required to make progress in exploration and research. He pointed out that his presentation would focus on massive sulphides deposits. Dr. Herzig said that since the first black smokers were discovered at the East Pacific Rise in 1979 a number of international research programmes have been initiated. He pointed out that these programmes have led to the development of new techniques and systems for research and for the exploration for massive sulphides and cobalt-rich ferromanganese crusts deposits.

Dr. Herzig illustrated some of the systems that are available to marine geologists and researchers for exploring for seafloor massive sulphides and cobalt-rich ferromanganese crusts deposits. His presentation followed the general principles used in searching for mineral resources, namely, the appraisal of large regions to select those areas favourable for the occurrence of these two types of deposits, followed by reconnaissance of the favourable regions in search of target areas. Target areas are defined as those areas with the characteristics required for the formation of the mineral deposit. Once targets areas are found, detailed investigations of the target areas takes place. Detailed investigations are normally first conducted on the surface, and then, if warranted, by three-dimensional physical sampling such as drilling. Because both types of deposits occur at depth and in deep-sea, the first requirement is a platform.

Dr. Herzig informed participants that for appraisal of large seabed areas, the system required is a research vessel with a multi beam echo sounder system for mapping the sea floor and producing a bathymetric map. He described the bathymetric map as a basic requirement for future work because such a map is the basis for further detailed study including sampling and mapping small areas.

Dr. Herzig said that modern multi-beam echo sounding systems are able to map the seafloor down to several thousand metres depth. The systems are also able to map a swath width of more than three times the water depth along the vessel's track. Computers on the vessel are able to print maps of the seafloor at 5 m contour intervals. In addition, Dr. Herzig said that there are several ways to display the data, including display a three-dimensional view of bathymetry.

Dr. Herzig said that a side scan sonar system used with the echo sounder system provides information about the reflectivity of the seafloor. The echo sounder system as described by Dr. Herzig, helps researchers to identify sediment areas, and to distinguish between larva flows (hard reflector) and sediment ponds (soft reflector). Dr. Herzig said that reflectivity information could be translated into tectonic maps that help investigators to find, for example, fractures and other features at the seafloor. Dr. Herzig showed an illustration of a deep towed video camera system that he said provides online observations of the seafloor. These systems, he pointed out, are attached to the research vessel with coaxial or fibre optic cables. He also illustrated several TV guided grabs, which he described as excellent mapping and sampling tools. Dr. Herzig introduced participants to a CTD (conductivity, temperature and depth) system and told them that other water samplers could be added to it.

Dr Herzig showed participants some pictures of German oceanographic research vessels. These included the R.V.Sonne, the Meteor and Polarstein. He described the RV Sonne, equipped with the Hydrosweep system (a multibeam hydrographic surveying system) as the flagship of the German fleet. Previously used in polymetallic nodule prospecting and exploration, Dr. Herzig informed participants that this vessel would be decommissioned in 2008.

With regard to the Meteor research vessel, Dr. Herzig told the workshop that it is also equipped with the Hydro sweep system to map the seafloor. Finally, with regard to the Polarstein, Dr. Herzig said that it is a German icebreaker used primarily for research in the Antarctic region. This vessel, according to Dr. Herzig is equipped with the Hydrosweep system as well.

With a picture of the British ocean survey side scan sonar, GLORIA, Dr. Herzig told participants how this system, developed nearly thirty years ago has been instrumental in mapping ocean ridges. He said that the system could map 20,000 sq/km per day.

Starting with the rosette water sampler, Dr. Herzig explained how the appraisal of large regions of the seabed could be undertaken using different techniques and tools to identify hydrothermal vent sites.

The rosette water samplers described by Dr. Herzig, is equipped with 24 thirty-litre bottles with a probe for measuring conductivity, temperature, depth and pressure. He said that other sensors could be attached to it. As an example, he said that an oxygen sensor attached to it could be used to map the oxygen minimum zone. Because the bottles can be closed individually, Dr. Herzig said that the water column could be sampled at different depths. He explained that this capability of the system is invaluable since a major tool in the search for hydrothermal vents is through the measurement of trace metals in the water column. Dr. Herzig said that the two most useful elements are manganese and methane.

Dr. Herzig said that the most powerful pathfinder element for finding hydrothermal vents is manganese because it provides the largest halo around hydrothermal sites, and therefore around black smoker complexes. Dr. Herzig said that the other powerful pathfinder component for hydrothermal vents is methane. He explained that black smokers emit methane and that methane remains in seawater and thus the water column. He also explained that methane, like manganese, provides a large halo and is therefore another excellent pathfinder element for searching for active hydrothermal sites. Dr. Herzig described manganese and methane as direct geochemical signals in the search for sites of hydrothermal venting. Since methane is also emitted at faults, and by hydrothermal alteration (serpentinization), Dr. Herzig stressed the need for a correlation between manganese and methane. He used an example from the Indian Ocean to highlight the need.

In addition to these two elements, Dr. Herzig said that isotopes such as helium are also good pathfinder elements. However, while manganese and methane can be analyzed on the vessel, helium and the other isotopes have to be analyzed in a land-based laboratory.

Dr. Herzig said that temperature anomalies are also used in the search. The towed CTD devices are excellent for this purpose he said, because very little time is wasted lowering and raising the system.

Dr. Herzig said that recently, geochemical scanners have been developed and are being used. He showed participants pictures of two such systems, the ZAPS system that was developed by Oregon State University, and the SAUVE system that was developed by the United States NOAA. Dr. Herzig said that ZAPS is towed by the vessel and is able to record the density of metal particles from black smokers in the water column. The SUAVE system, also towed by the research vessel, was presented by Dr Herzig and shown mounted on a video camera system. Dr. Herzig said that the SUAVE system could analyse Fe^{2+}, Fe^{3+}, Manganese and Hydrogen sulphide (H2S). He said that the data obtained by this system are stored on a recorder within the instrument, retrieved later, and correlated with time. Dr. Herzig said that time on the vessel is positioned, so when correlated with position, researchers are able to go back to areas where anomalies have been identified.

Dr. Herzig said that both systems could be equipped with a CTD system. He also said that both systems could analyse the concentration of manganese photo-chemically and also measure bio-phosphorescence. The data collected by the system are stored on a recorder, and subsequently related to the vessel's position. He said that an obvious advantage of this system is the large area that it could cover. He described the system as a time saving method of acquiring the relevant information.

Dr. Herzig informed participants of techniques and tools for taking samples of sediment and hard rocks in prospective areas.

Among other things, he said that information obtained through sediments could be used to determine the proximity of hydrothermal sites. He pointed out the many ways of taking sediment samples; piston corers, spade corers, box corers etc.

For collecting rock (non-sediment) samples, Dr. Herzig suggested two methods. These were dredging and TV guided grabs.

In relation to dredging, Dr. Herzig recalled Dr. Hein's presentation and said that the range of dredges included barrel dredges, box dredges, and chain bag dredges for various purposes. He showed participants how a conventional chain bag dredge is configured and used to recover either rocks or massive sulphides.

Dr. Herzig however said that the more elegant approach to sampling is with the TV guided grab. He informed participants that this system was developed by PREUSSAG a few years ago, for the Galapagos Rift Exploration Programme for massive sulphides.

Through slides, Dr. Herzig demonstrated how the system operates and the advantages that it provides the researcher/explorer in the search for hydrothermal vent sites. Dr. Herzig said that the grab shown in the slide could hold up to 3 tonnes of sulphides or rocks. At the centre of the grab, Dr. Herzig showed a TV camera and a number of lights. He explained that with this system, as the grab is lowered to the seafloor with open claws, small areas of the seafloor could be mapped in detail.

Dr. Herzig informed the participants of the flexibility of this system for selecting samples. He said that a sample could be selected and rejected from the control room of the vessel because the claws of the grab could be opened and closed depending on the life of the deep-sea batteries used in this mechanism. He described the TV guided grab as an excellent system for sampling, for the selection of samples and for mapping. With regard to the claw type dredge, Dr. Herzig said that an entire chimney had been recovered with such a grab. In addition to the claw type grab, Dr. Herzig described two others. One, he said was developed for sampling the Red Sea metalliferous sediments and the other was developed to sample rocks and sulphides without taking any sediment with the samples. He said that researchers still used the grab developed for the metalliferous sediments because it is quite robust and has turned out to be a good tool for sulphides and rock sampling.

Following the appraisal of large regions of the seabed, grassroots exploration work as Dr. Herzig described it, he said that economic geologists and geochemists still required other data and information on, *inter alia*, the composition, grades of contained metals, the content of reduced sulphur and other characteristics of the hot fluid coming out of the chimneys. To obtain these data and information, Dr. Herzig said that the normal process is to take samples of the fluid with titanium bottles at the vent. He pointed out that this cannot be done from a research vessel, but has to be from a submersible or by using a remotely operated vehicle (ROV). In addition, he said that for "ground truthing" or detailed mapping of particular seafloor sites and deposits, for precise small scale sampling, including sampling of hydrothermal fluids at active black smoker chimneys, manned research submersibles and remotely operated vehicles are required.

He identified twelve research submersibles with operational depths of between 400 and 6,500 metres, from five countries as being equal to the task. He also identified six remotely operated vehicles (ROVs) with depth capabilities ranging between 3,300 and 11,000 metres, from four countries that could also do this work.

Research Submersibles

With regard to research submersibles, Dr. Herzig said that they normally accommodate two pilots and one scientist, are generally equipped with two 5 to 7 function manipulators for sampling and measurements, and are launched from a mother ship.

He described the German submersible, JAGO that can accommodate a pilot and a scientist as an excellent mini submersible that is easy to use, and that has very good handling capabilities up to a water depth of about 400m.

He said that the JAGO has only one pilot operated mechanical manipulator. A major advantage of JAGO according to Dr. Herzig is the big window that it has. Dr Herzig said that it was like sitting in a helicopter close to a hydrothermal vent with a magnificent view of the action.

Dr. Herzig then briefly described the Russian PISCES submersibles with a diving capability of 2000 m, and able to accommodate one pilot and two observers. He said that Russia has two deep diving submersibles with 6000 metres diving capability on one ship, the Academic Mstislav Keldysh. The two submersibles are the MIR submersibles, MIR 1 on one side and MIR 2 on the other side. He described the two submersibles set-up as an excellent arrangement and also said that the MIR submersibles have been instrumental in significant discoveries and research work on hydrothermal systems worldwide.

Describing the United States submersible ALVIN, Dr. Herzig told participants that with respect to black smokers and hydrothermal systems discoveries during the past few decades it is the submersible that has been the most successful. Dr. Herzig said that ALVIN, operated by Woods Hole Oceanographic Institution, has a diving capability of 4500 metres and can accommodate two pilots and a scientist.

Dr. Herzig also described the submersible NAUTILE that belongs to France and is operated by IFREMER. He informed participants that the NAUTILE has a diving capability of 6,000 metres, accommodates two pilots and one scientist, and has two manipulators for sampling and other measurements. He said that typically a dive to a depth of 3000 metres in this submersible lasts for about two hours.

Finally, Dr Herzig described the Japanese SHINKAI 6500 and SHINKAI 2000 submersibles operated by JAMSTEC of Japan. He said that the SHINKAI 6500 has a diving capability of 6500 metres, and the SHINKAI 2000 a diving capability of 2000 metres.

Remotely operated vehicles (ROVs)

Dr. Herzig briefly explained the principles of using a remotely operated vehicle (ROV). He said that the ROV usually sits in a cage connected to a ship through a fibre optic cable. He said that the cage is lowered to a distance of about 10 metres from the sea floor. The ROV moves from the cage on a tether of about 200-300 metres in length. He also said that the ROV is equipped with electro-hydraulic arms and with video eyes, and can do the same operations as a submersible. He noted the need for transponders at the seafloor to better navigate the ROV from the ship.

Dr. Herzig described the six ROVS presently in use. These, he informed participants are the Remotely Operated Platform for Ocean Sciences (ROPOS) operated by the Canadian Scientific Submersible Facility, the United States JASON operated by Woods Hole Oceanographic Institution, France's VICTOR and ROBIN that are operated by IFREMER, and the DOLPHIN 3K and KAIKO of Japan that are operated by JAMSTEC.

Dr. Herzig showed illustrations of the Canadian Remotely Operated Platform for Ocean Sciences (ROPOS), a remotely operated vehicle (ROV) which he said had stayed at the seafloor for about a week. He said ROPOS, with a depth capability of 6,000 metres, is equipped with video cameras, still cameras and two electro-hydraulic arms. There is a control room on deck with a video screen. Dr. Herzig said that these illustrations were in the context of the German-Canadian cooperative research programme (HYDROTRACE), to the Axial Seamount on the Juan de Fuca Ridge.

He also showed illustrations of VICTOR, the French ROV. He said that VICTOR is a recent development in France, designed and constructed by IFREMER, and has a depth capability of 6000metres.

Submersibles and ROVs

In comparing submersibles to remotely operated vehicles (ROVs) for exploring for hydrothermal vents and seafloor massive sulphides deposits, Dr. Herzig said that there are a number of advantages in using ROVs. He said that although there are technical problems during most dives, the unlimited time on the seafloor from the use of a ROV is an asset. He also said that the operating costs of a ROV compared to a submersible, and the elimination of risks to pilots and scientists by using an ROV were added advantages. On the other hand, he pointed out that what one sees on a video screen on the vessel is not the same as images from a submersible. In this regard, he said that the submersible provides a much better appreciation of the environment at the seafloor.

Seafloor drilling

Dr. Herzig said that once surface sampling of the massive sulphides deposit has been completed, a major issue for both researchers and explorers is drilling the deposit to ascertain the quantity of possible ore material.

Dr. Herzig informed participants of massive sulphides deposits that have been drilled under the auspices of the Ocean Drilling Programme (ODP) and some of the results that have been obtained. He also described the first generation of portable seafloor drilling and coring systems, and the success of these systems in drilling other deposits.

Dr. Herzig told participants that the Ocean Drilling Programme is an international scientific drilling programme that operates a specially equipped deep-sea drilling ship, the JOIDES Resolution (SEDCO/BP 471), which contains state-of-the-art laboratories, equipment, and computers. The ship is 471 feet (144 metres) long, is 70 feet (64 metres) wide, and has a displacement of 18,600 short tons. Her derrick towers system stabilizes the ship over a specific location while drilling in water depths up to 8,230 metres. Its drilling system collects cores from beneath the seafloor with a derrick and draw works that can handle 30,000 feet (9,144 metres) of drill pipe. Dr. Herzig said that this international activity is probably the most successful international earth science programme. Dr. Herzig said that the JOIDES Resolution was a former oil drill ship that has been converted to a ship that is capable of drilling hard rocks.

Through slides, Dr. Herzig explained how the technology on board the ship operates. This included the computer controlled eleven thrusters that are required to make sure that the ship's position over a drill hole is maintained. He said that at the seafloor, sedimented areas could be directly drilled, but that where there is only a slight sediment cover and hard rock, a so-called re-entry core is required.

In addition, for hard rock drilling Dr. Herzig said that a so-called hard rock guide base cemented to the seafloor has to be assembled together with the re-entry core. He described this assembly as a routine operation for the ODP.

Dr. Herzig informed participants that in 1994, he was part of a team of scientists that conducted a drilling project at the (Trans-Atlantic Geotraverse) TAG active hydrothermal mound. To illustrate the absolute need for drilling in order to know what to expect at mounds, Dr. Herzig volunteered to share the results of this Leg of the ODP with participants. Dr. Herzig showed a slide containing a bathymetric map of the TAG mound. He pointed out the locations of the black and white smoker complexes, and the Kremlin area. He said that 17 holes were drilled in five areas in 2 months. The areas included a high-temperature (363 deg C) black-smoker complex, characterized by chalcopyrite and anhydrite deposits, and a low-temperature (260-300 deg C), sphalerite-dominated white smoker vent field. Dr. Herzig said that total penetration from the 17 drill holes was almost 600 metres, the total core interval 435 m, the total core recovery out of the cored interval 51 m or about 12%, and that the maximum penetration achieved was 125.7 m. He also said that at the beginning of the project a maximum penetration of about 500 metres was expected. He said that the problems encountered were related to the cuttings that were produce while drilling the massive sulphides. He said that cuttings are usually flushed out of the drill holes with seawater but that in this case the cuttings were relatively dense and heavy. As he result, he said that the drill string got caught in the cuttings, necessitating the use of explosives to free the drill string.

Dr. Herzig said that through drilling it was discovered that most of the base and precious metals are concentrated in the upper few meters of the mound within massive pyrite, and pyrite breccias underlain by pyrite anhydrite breccias. Based on this discovery, Dr. Herzig said that the new hypothesis is that most of the metals that were precipitated during the growth of the mound were later mobilized by hydrothermal fluids, transported to the seafloor and were redeposited in a small horizon on top of the mound. He said that the mound contains only a small amount of metal resources confined to the upper 5 metres. He also said that while this may be not typical for all massive sulphide deposits in hydrothermal systems, the message made it clear that the contrary situation is not universal.

Dr. Herzig said that the other information obtained through drilling is the tonnage of the deposit. From drilling, he said that it is estimated that the mound contains about 2.7 million tonnes of sulphides above the seafloor and 1.2 million tonnes of sulphides below the seafloor or a grand total of 3.9 million tonnes of sulphides.

Dr. Herzig said that later during the year, the ODP will be drilling the Manus Basin in the area that Nautilus has its exploration licenses.

Dr. Herzig pointed out however that the drilling of massive sulphides deposits and hydrothermal vent systems by the Ocean Drilling Programme is the exception rather than the rule. For research and resource assessment, Dr. Herzig said that seafloor drills need to be developed. In this regard, he said that two currently available systems for use on ships of opportunity or ordinary research vessels are the PROD-drill (Portable Remotely Operated Drill) and the Benthic Multicoring System (BMS).

Dr. Herzig said that the PROD drill was built in Australia with the help of the US group Williamson and Associates, Inc. It has a depth capability of 2000 metres, core index 100 metres in series and a core diameter of 40 millimetres.

Dr. Herzig said that the BMS system (Benthic Multicoring System) was built in 1996 by Williamson and Associates, Inc. for the Metal Mining Agency of Japan (MMAJ). It is installed on the Metal Mining Agency's research ship Hakurei Maru No 2. The BMS system has a depth rating of 6,000metres, core depth of 20 metres, a core diameter of 44 millimetres, and a cable length of 12,000 metres.

Dr. Herzig summarized the technical requirements for the resource assessment and mining of seafloor massive sulphides as consisting of the need for portable seafloor drilling and coring systems that can be used on ships of opportunity, and that have depth capabilities of between 50 to 100 metres and core recoveries of more than 50 per cent. He said that with these basic requirements, there would be major advances in research and in resource assessment. With respect to mining, Dr. Herzig said that since nothing had been tried, mining technology needed to be developed.

With regard to the exploration and mining technology for cobalt-rich crusts, Dr. Herzig said that the exploration technology is very similar to the exploration technology for massive sulphides deposits. Mining however he said would be different. Using a slide that depicted a crusts deposit, Dr. Herzig pointed out how the crusts form on a substrate rock. He said that this situation is an important issue for mining because of the need to efficiently separate the crusts from the substrate rock. He said that there have been experiments to mine such deposits with hydro jet systems and to use heavy-duty rollers to crack the crusts into fragments, and to separate them from substrate rock. Dr. Herzig said that both systems need further development and full testing. He also said that hey have not been tested because there is no industry push right now.

In relation to economic sizes of mining operations, Dr. Herzig said that recently a report was published that indicated mining at least 1 million tonnes of crusts per year. This mining capacity assumes a separation efficiency of 80 per cent, and substrate rock dilution of 20 per cent. Dr. Herzig therefore pointed out that large crusts deposits would have to be mined in conjunction with favourable metal prices. With regard to crusts mining technology, Dr. Herzig described the situation as very similar to that of massive sulphides.

SUMMARY OF THE DISCUSSIONS

Following Dr. Herzig's presentation the discussions focussed on four matters: the relationship between hydrothermal activity in the mound and base and precious metals distribution within the mound, the economic prospects for “ white smokers”, data confidentiality issues concerning the Ocean Drilling Programme’s project to drill the Manus Basin that is now under an exploration license, and known problems with potable drills.

Based on the results reported by Dr. Herzig on drilling the active TAG hydrothermal field, in particular that the base and precious metals are concentrated in the upper few metres of the mound, Dr. Herzig was asked whether the mounds are still building up and whether there are land-based analogues of this geological setting.

Dr. Herzig said that as the mound continued to grow, as hydrothermal fluids circulate through the mound, metals from below would be absorbed into the fluids and would be precipitated at the sulphide/ seawater interface. He did say however, that no relics or former enrichment zones were found during drilling. He also said that core recovery was only 12 per cent, suggesting that a lot of information was lost. With regard to land-based analogues, Dr. Herzig said that such analogues are not often found. When found, the sulphides in the upper five metres cover an extensive area and are able to support a viable mine. He said that the setting that was discovered could have developed because of either the age of the system or because of differences in the source rocks.

Dr. Herzig was asked whether “white smokers” produce base and precious metal sulphides, and if so, at what depth such deposits are to be found. He was also asked if these deposits would contain the same metals as found in “black smokers”. Dr. Herzig said that “white smokers” would indeed generate sulphides deposits but that these would occur at several dozens of metres depth. Dr. Herzig described the process whereby sulphides would be deposited in a white smoker system, referring to it as shallow mixing.

In relation to the statement made in Dr. Herzig’s presentation that the Ocean Drilling Programme will be drilling the massive sulphides deposit in the Manus basin (Leg 193), he was asked how this could be done since that deposit is part of the exploration license covered in the agreement between Nautilus and the Government of Papua New Guinea. It was pointed out that normally the approved targets of ODP drilling are scientific and not commercial. Since confidentiality of data and information differs depending on whether the activity is marine scientific research or exploration, it was asked how the acquired data and information would be treated.

Indicating that he was not in a position to address these issues, Dr. Herzig asked Mr. Julian Malnic, the Chief Executive Officer of Nautilus Minerals and Mr James Wanjik, Acting Director of Papua New Guinea's Department of Mining for any light that they could shed on the matter.

For his part, Mr. Malnic said that the position of Nautilus Minerals has always been clear. He said that since the company's creation is the result of marine scientific research, nothing that it does should sterilize the activity of researchers. He said that the company got in touch with a few such marine scientific researching organisations and following a short meeting with the ODP, an agreement was reached as to how results would be handled. He pointed out that if Nautilus Minerals were a public company the arrangements would have had to be different.

It was pointed out that while the disadvantage to Nautilus Minerals might be that the data acquired would be published, Nautilus would benefit because the drilling done free of cost. Mr. Malnic said that while drilling would be free of cost, it would not take place at the locations in the deposit that the company felt was needed to for resource evaluation.

Mr. Wanjik said that under the arrangements with the ODP, the information sought by researchers would have been provided to the Government of Papua New Guinea. Whether or not Nautilus Minerals or any other potential investor has a license or not, Mr. Wanjik said that any other potential investor in this particular area would be entitled to that information through the government agency concerned. He also said that since the license to Nautilus was issued, JAMSTEC of Japan and IFREMER of France have conducted cruises through the area. He commented that he did not understand why the ODP drilling project should be construed as a problem

Another participant said that in a recent cruise by the Metal Mining Agency of Japan (MMAJ), scientists tried to use a portable drill. This participant said that for technical reasons it did not work. Dr. Herzig was asked how soon he expected reliable portable drills to be made available to researchers and explorers.

Dr. Herzig observed that under the circumstances where the cost of the JOIDES RESOLUTION is US$180,000.00 per day, portable drills are indeed a big issue that need to be urgently addressed.

CHAPTER 8

FACTORS IN FINANCING EXPLORATION FOR SEAFLOOR MASSIVE SULPHIDES DEPOSITS

Julian Malnic, Chief Executive Officer
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1. Introduction

With exploration for Seafloor Massive Sulphides (SMS)* deposits barely half a decade old, there are not statistically sound generalizations that can be drawn from the financing experience so far. Furthermore, because of the normal confidentiality that surrounds corporate activity, knowledge of industry experience does not extend far beyond our own group. However, it is evident that the capital raising process will be similar to either terrestrial mineral exploration, or maybe even to dot.com style, companies.

As the first pioneer into this new field starting in 1994, Nautilus has a unique experience base that I will attempt to share with you in this presentation. I hope that my comments here today are illustrative and inform our workshop about life in this exciting new sector of mining

The reason that we are here is to promote a broad understanding of the challenges we are facing and to give people from all sectors a feel for the sort of people we are and the things that motivate us.

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*The term Seafloor Massive Sulphides (SMS) has been proposed to create a distinguishing label for this new marine variant of a class of deposits normally referred to as Volcanogenic Massive Sulphides. SMS deposits differ markedly in that they are still forming, or have recently stopped forming, and that they will require very different commercial and engineering solutions to VMS in their mining. The term polymetallic is strongly discouraged in labelling or describing SMS deposits (and manganese nodule deposits) because virtually all ores are 'polymetallic' before they are processed and thus the word confuses rather than distinguishes.

So working from the traditional capital-raising model, I will make extensive comments on the distinguishing factors, the factors that are unique to, the capital raising for exploring for seafloor massive sulphides.

Before I outline some the spectacular differences in financing SMS exploration, a quick reminder of the traditional structure:

1. Seed Capital – Committed and visionary individuals galvanise the play from a relatively low capital base by forming the company applying for rights and bringing together their key skills and personalities that will create success.

2. Mezzanine Capital – This interim capital uses thoroughly prepared presentational material to solicit capital off-market from individuals or organizations that usually have other investments. Groups incoming at this stage are still quite courageous but they will mostly likely have laid before them an 'exit strategy' which limits the time their investment will be exposed to risk before they can sell out – perhaps following a public company Initial Public Offering (IPO).

3. Project Capital – this is the lowest risk stage where the largest sum of capital is sought. Accordingly, a detailed prospectus of some type accompanies the investment proposal usually presenting a wide array of direct public equity participation or public participation through joint venture or consortia partnership companies.

2. Defining the purpose of the investment?

The most basic rule of capital raising is that one should be able to say what the money is to be used for in a clear and detailed way. So this can be an early Catch 22.

The traditional project stages that we use in terrestrial mining are:

Reconnaissance exploration
Target definition
Resource definition
Pre-feasibility study
Feasibility study
Decision to mine
Construct and commission
Operate and sell metals

Through centuries of experience, on land, we know exactly what to do. In the marine environment where things are being done for the first time, it is difficult to project for example how much ship time will be required to explore 5000 km^2 of the Bismarck Sea to a satisfactory reconnaissance level.

The other difficult area is to define the reward to the investor. What business is the investing party becoming part of? An engineering firm may want to invest solely in the technologies and intellectual property assets while a major mining house will want to invest only in the mineral deposits and the concentrate streams that will flow from them. A regional bank might only want to invest in Papua New Guinea.

This is why I refer to Nautilus as 'a group'. It is an international group of companies that holds rights to different regions and different elements.

I mentioned some of the different types of investors above. Each of these will require a different structure. An individual speculator will want to be able to trade in and out of your company and would like to see it listed on a stock exchange. In contrast a major engineering firm will want a joint venture of direct equity position that avoids the complications and overheads of running a public company.

There is a lot to understand and to a lot of structuring to do before an exploration company can accept investment.

3. Understanding the Motive of the Investor

There is only one ultimate measure of the success of an investment and that is the return. But the human element plays a very big part of any decision.

In December 1997, Nautilus made its first press release headlined *Nautilus Granted World-first Licences over High-grade Marine Sulphide Deposits.* We were nearly bowled over by the response. Nearly every major newspaper in the world ran something on it. We were on the front page of the *New York Times* on *Channel 4 ITV News* in Britain, the *Minneapolis Star Tribune*, PNG's *Post Courier* – you name it.

From this we learned that there is a deep human interest in mining the sea. It is seen by the media and the public as an adventure, as pioneering. This is one of our greatest assets. Once an investment proposal is planned, structured and budgeted correctly, it is still important that the investor goes ahead and makes the decision to invest. This is where appeal is critically important.

In the *New York Times*, science writer Bill Broad said 'Mining experts familiar with the New Guinea project say it could mark a turning point in the art of metal extraction, especially as growing red tape curbs some terrestrial digs around the world.' Nigel Hawkes from *The Times* in London said 'Mining companies are about to follow the oil giants to the bottom of the sea.' This ground swell of public interest has been very important in raising the private capital that we have raised so far and will be an important driver for Nautilus and its competitors in the future.

4. The Importance of Grade

Mining higher grades means processing less rock. Grade is the fundamental difference between manganese nodules and crusts and SMS deposits. SMS deposits such as the TAG deposit on the Mid-Atlantic Ridge have been known and studied for a long time but did not excite a lot of interest because of their low grades of commercial minerals. The discoveries during the last five years have been that within this broad family of deposits, there is a subset that forms in specific geological environments where contained metal values routinely exceed US$500/t.

It is this discovery of high-grade deposits that is the key draw card for the investor. It is also the reason why there is commercial interest in SMS deposits and not in manganese nodule deposits.

The new class of high-grade SMS deposits such as those of the PACMANUS Basin have high zinc, copper and gold and will probably also yield silver and barite. Even during times of depressed gold prices such as now, there is a lot of investor focus on the high gold values even though the yellow metal comes a clear third in the tally and will be sold off in a zinc or copper concentrate. Nonetheless the gold grades of 15-21 grams per tonne are a multiple of those mined in typical terrestrial mines and always attract attention.

Both copper and zinc are seen as metals with a special role to play in our future and demand is expected to continue to grow in the coming decades.

If as we suspect those shown in the table below for the Manus Basin are sustainable, mining may also be about to enter a new era where the amount of waste products is sharply reduced. I will say more about this later on when I talk about processing cost environmental benefits.

Factoring in the iron and sulphur levels that occur in the primary economic sulphides present, chalcopyrite and sphalerite, around 80% the volume of the mineralised rock is accounted for the economic sulphides minerals. A 1.1 tonne chuck of SMS mineralization recovered in April from Nautilus' PACMANUS Field in Exploration Licence 1196 assayed 51% zinc. Many zinc concentrates traded on the world market assay 55% zinc.

	Suzette	PACMANUS
No Samples	24	59
Cu%	15.3	9.9
Zn%%	3.4	25.6
Fe%	18.6	14.7
Pb%	0.24	1.5
Au ppm	21	15
Ag ppm	130	200

5. Why no Rush by the Major Mining Houses?

Since our beginnings, Nautilus has had intimate discussions with perhaps 10 major mining houses and while all of them have expressed admiration, none have committed. With hindsight, Nautilus spent far more time in discussions with them than it should have.

Through the process, we did however learn a great deal about the paradigm that the major companies have been thrust into over the last five years. Leading up to mid-1999, metal prices steadily eroded due to a generally slow world economy outside of the US. The economic 'meltdown' of Asia added to considerable gloom. The technology stocks were starting to fly and the mining houses were slashing exploration budgets by as much as 80% in some cases.

This was coincident with another major mining house phenomenon that from within was inexplicable. The discovery of new mineral deposits was eluding them. Somehow they had lost the core skill of mineral discovery. Recent figures compiled by leading exploration veteran David Lowell show that the unit cost of discovery shot up 3-4 fold during the late 80s and 90s. In a desperate bid to prop up share prices, now-unjustifiable exploration budgets were slashed as management turned to mergers and acquisitions as a means of competing for the attention of investors. The markets were mostly only interested in dotcom and technology stocks.

The major mining houses have changed forever and seem to expect future discoveries to come from small companies. They are not the bold risk takers they were when the manganese nodules boom of the early 80s bloomed. Lowell is predicting a serious 'ore shortage' to emerge in the next two years or so as the strong world economy consumes stocks. But for now, the majors have lost their exploration skills and are out of the equation. It has become a sector with a deep-seated fear of being first. A cost-cutting mentality has lead to no job being secure and in this climate no one is prepared to stick their neck out. Corporate cultures have become dominated by negativity.

On one occasion, the high-ranking exploration manager of a major company with which we were in advance discussions lost his job as the result of his company being taken over.

We remain in touch with the many major mining houses but do not expect investment to come from that sector until marine mining emerge as a threat to existing businesses.

6. Packaging by Concept

In our earlier experiences, we tended more to present our group to investors as a single entity with many purposes, and with many different potential dividends. Recently, as we move further into the development capital stage, we have found it far more effective to present the project in two groups. One group that owns the titles and applications to minerals and the second being a technology company owning intellectual property and a service contract to develop and supply exploration and mining technology and services to the minerals arm. This is actually how we are structured.

In seeking development capital as we now are, we find that the people we approach are more interested in minerals ownership or technology but not both. Each has a large potential but at this stage they each attract different players. Some see the minerals as the place to be and others see the technology and know-how as the key.

So what are these attractive areas of technology? Exploration technology including the *Rapid Exploration System* we have drafted will create a lot of value by surveying large areas, finding new plumes and locating the SMS deposits. The design of the mining machine that can break, load, crush and lift the sulphides by pumping them up a riser will be the most critical factor in making SMS lower cost than terrestrial mining. The largest item is the topside production plant such as the Floating Production Storage Offtake (FPSO), the pre shuttling craft and the refinery (if any). Here ships-of-opportunity and existing systems will be modified and combined.

For the people with knowledge of the state of marine technology, the development of these technologies is simply an extension of what is already being done in the deep-sea environment by the oil & gas, military and communications sectors. To them, marine mining is not only possible but is a logical extension of land-based mining. Clearly marine technologists and engineering groups will be much more inclined to invest than say a major mining house that knows nothing about the sea. This has certainly been our experience and flags for you the direction we are taking.

The possibility of developing a SMS mining system is highly attractive to the marine engineer because it offers a clear road to lucrative mining contracts and early returns.

Despite the fact that manganese nodules were effectively mined from the abyssal plans of the East Pacific rise in nearly 5km of water nearly 20 years ago, the media, the public and investors generally remains quire unaware of the state of marine technology.

The question 'Will it be possible to mine SMS deposits?' is frequently asked. Nautilus puts a lot of effect into communicating well-illustrated answers to these groups.

7. Why SMS Mines will be Lower Cost

Ask any terrestrial mining company what their greatest issues and problems are, and the chances are they will give you a long list of factors that are appear as advantages in the Nautilus vision for SMS mining. Current market metal prices are determined largely by the efficiency of supply from the current terrestrial mines. The chart presented below forms represents the core arguments that we see will lead to SMS mining out competing terrestrial metals in the production of zinc, copper and gold. These are the fundamental logical factors that we see transcending the elements of romance and public interest and that will attract investors to SMS mining for centuries to come.

The advantage of SMS mining relative to terrestrial mining

1. Lower discovery costs – live geochemical signatures, visible deposits
2. Shorter development lead-time – ease of sampling, access
3. No landowner disturbance and compensation costs
4. Exposed deposits – no prestripping or shaft/drive development costs/delays
5. Cheaper beneficiation – superior metallurgy indicated, less grinding
6. No pit-to-port infrastructure – a major capital cost in terrestrial mines
7. Cheaper plant and transport – mobilised from ship year to site
8. FPSO vessel leaseable – not conventional "mine life economics"
9. Metal price responsive – high zinc or high-copper areas targeted
10. One "mine plant" can work many deposits around the world
11. Little waste – costly to produce and a major environmental liability

Cumulative benefit – low capital and operating costs

The oil and gas sector moved offshore in the late 70s and 80s and is a valuable example of what to expect for the evolutionary course of SMS mining. In the oil and Gas sector it took less than a decade for offshore production to move from the sheltered Gulf of Mexico and water depths of 20m to Bass Strait in Australia and the wild conditions of Britain's North Sea. In Minerals, things tend to move in booms. By April 2000, the fabrication yards around the Gulf of Mexico had built 5,500 platforms for exploration and production.

The manganese nodule boom was short-lived and driven by geopolitical forces stemming largely from the Cold War. The 70s nickel boom and the severe prices spike it creased has also gave nickel a commercial status it has not enjoyed since. Personally I believe manganese nodules will not be economic for centuries to come because of their inferior grade and the water depths they are found in. Some of the shallower manganese crusts and perched nodule fields may be commercialised sooner.

Looking to what I see as a current analogy for SMS mining, the runaway success of the Namssol alluvial diamond mining off the west coast of southern Africa is generating intense interest. I have just inspected two new mining systems that are to be deployed there.

Today, the greatest threats terrestrial mining faces are most likely land access problems due to indigenous peoples issues, the increasing (over) population of the Earth, and the decreasing liberty with which tailings and mine waste can be disposed. On all points, marine mining will get the inside running.

Sovereign risk factors are also making terrestrial mining investors nervous. While less developed countries are seen as being increasingly unstable, regulation and intense environmental pressure in the developed nations is also closing mines. In Fiji and the Solomon Islands coups and succession moves have recently impacted on mining operations there. In the United States, mining has been all but outlawed in many areas through overly tough legislation despite booming consumption there.

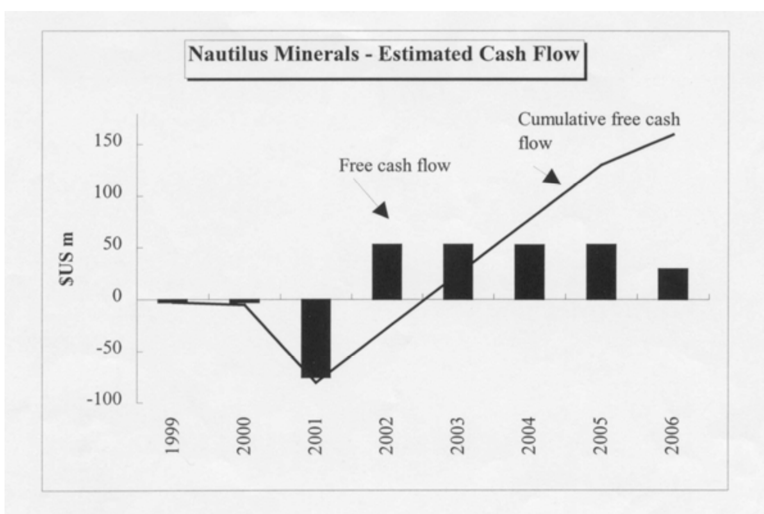
The offshore environment is attractive to resource developers. Apart from offering magnificent transport, excellent equipment availability and convenient topography-free working environment, it has isolation from population pressures and the risks they bring. The 1999 decision by Shell to spend US$8.0 billion in offshore petroleum exploration and production preceded the countries first democratic election for some time by three weeks. The offshore environment presents a large comfort factor for investors concerned about sovereign risk issues.

8. Modelling

SMS mining offers scope for a highly compressed development cycle. The time between first identifying a plume and tracking down a deposit, and the time of mining the deposit can be very short, a factor that will also carry considerable economic advantage. 'With the mobility of the production vessel, test mining can be conducted within a matter of weeks of a discovery. On land, the definition drilling required to justify the cost of a test shaft will typically take two years and then test shaft will take additional time. By lowering such development threshold, the feasibility costs are also expected to be significantly lower than for terrestrial mines.

Using very basic assumptions and calculations about the most likely system we will use, Nautilus has performed some very useful spreadsheet models for a proposed Manus Basin mining operation.

We regard these models as proprietary assets so I do not intend to present them here. But for the sake of illustration, one base case involved an arbitrary mine size of 1.5Mt and at the rate of 1000tpd, the mine life will be 4.5 years. The following chart shows the summary of net cash flow and cumulative net cash flow for this scenario. Capex costs include the acquisition of a ship for US$50m.



9. The Environment Issues and Benefits

Proposals to mine zinc, copper and gold from SMS deposits are driven by investor belief that this type of mining will be more profitable that terrestrial mining. Similarly, there is a belief that they may also be competitive in terms of environmental impact.

Modern man's diet of metals and a wide range of other materials such as diamonds, mineral and building sands, and aggregates have already shown the ability to substitute marine sources for terrestrial sources. To this extent, mining has already started in the marine environment and learning about its impact has already advanced. In a holistic view, substituting marine sources for terrestrial sources may offer a way to limit the net environment impact of winning these materials.

SMS mining can reasonably be expected to have at least two major environmental advantages. First, high grades mean a low proportion of waste will be produced. Terrestrial mines, the alternative source of the metals, produce increasingly high proportions of waste and by far the greatest amount of liability faced by terrestrial miners is the result of tailings related disasters, and acid mine drainage from waste dumps.

Secondly, in active SMS deposits, it has been shown that hundreds of tonnes of mineralization are likely to be generated every year in the wake of mining. As long as the heat and fluid emissions continue to provide an oasis in this cold dark world, life will return to it. The more that we understand deep vent fauna; the more we see that they depend primarily on the presence of heat, H_2S and fluid emissions alone. The spatial and temporal discontinuity of the production of these life-sustaining nutrients has made vent fauna voracious survivors.

Perhaps only the cold and relatively lifeless deposits will be economically attractive. With every year comes new discoveries adding to our growing archive of active vent sites and the perception that these are a far more frequent marine environment than was once imagined.

Because exhalative SMS deposits are not covered by sediment, any fine sediment produced in mining will be comprised mostly of sulphide. Density will aid rapid settling of silt particles reducing. Compared with mining manganese nodules that will require vast areas to be disturbed, SMS mining operations can be expected to be highly focused, simplifying the job of monitoring and remediation. SMS mines are expected to operate in less than 40% the water depth of manganese nodule operations, again simplifying the tasks.

Greenhouse advantages may be recognized. Terrestrial mining operations are great consumers of fossil fuels and are already under pressure to cut emissions from the Greenhouse lobby and from the prospect of a carbon tax. Australia's WMC has done some number crunching with respect to this matter and based on an assumed $30 per tonne carbon tax found it will be up for $100 million per year, off the bottom line. BHP has gone through a similar exercise and my understanding is that their number is about $1 billion.

10. Nautilus' Proposal of a Code for Environmental Management

The emerging marine minerals exploration and mining industry is currently focused mainly on the technical elements for its success such as developing exploration and mining technologies. However, in one sense, the technical challenges are quite soluble whereas those arising in the fields of the environment and public opinion could present this new generation of miners with problems that are far more difficult to overcome.

One need only look at the issues currently faced by mining projects on land to see how powerful the new forces of so-called 'civil society' are in, stopping mineral developments in many countries. From the geographic viewpoint, there are many countries but there is just one ocean, so the impacts experienced by any one operation are likely to have pervasive repercussions throughout the industry. A well-oiled NGO development protest lobby will see leverage in resisting this new industry and will seize on the single-ocean angle.

The Australian Minerals Industry has established a voluntary *Code for Environmental Management* that provides an active and valuable model for satisfying the 'court of public opinion' and in delivering economic results to an industry that are in current jargon, *sustainable*. An explanation of the *Code for Environmental Management*, and the reasons behind 44 companies representing more than 300 operations and 85% of Australia's sizeable mineral production being signatory to it will be given. Participants see it as a means to future shareholder wealth.

The Importance of Biological Resources

11. Competition with Marine Scientific Research

National aspirations and the need for guidelines and legislation.

The role of the International Seabed Authority, South Pacific Applied Geosciences Commission (SOPAC) and governments –which is to serve the needs of island nations.

12. Managing Success

The role of the entrepreneur – and ingredient approach
People and Management factors
The skunkworks and Ship of Gold and the Deep Blue Sea model.

While conditions in the Bismarck Sea are generally benign, exploration and production vessels will have protected anchorages where they might weather out severe weather events with only moorings remaining on station.

SUMMARY OF THE PRESENTATION AND DISCUSSIONS ON FINANCING EXPLORATION FOR SEAFLOOR MASSIVE SULPHIDES DEPOSITS

Summary of the presentation.

Mr. Malnic said that when he was asked to speak about critical factors in financing seafloor massive sulphides exploration, initially it sounded a little bit difficult but fairly soon he realized that it was actually very easy because he only had to dig through Nautilus' experience. He said that his presentation would try and touch on a very wide range of aspects involved in financing massive sulphides exploration. He added that many of the factors are non-technical and that they relate to the kind of information that investors look for, the kind of returns that investors are seeking, and why some investors want to put money into mineral deposits such as seafloor massive sulphides. He said that Nautilus Minerals Company has been seeking financing from public and private investors and institutions. In this regard, Mr. Malnic pointed out the range of different types of capital and said that the purposes of each type of capital vary.

Mr. Malnic said that with exploration for seafloor massive sulphides barely half a decade old, there are no good statistical models for raising exploration finance for such deposits. Mr. Malnic said that whilst raising exploration financing for seafloor massive sulphides has a lot in common with traditional capital raising for land-based deposits there are some significant differences. Mr. Malnic said that when established in 1994 as a pioneer in this field, Nautilus Minerals had no idea of what to expect. Recalling the sequence of events, he said that the company's first act was to apply for mineral licences in the waters of Papua New Guinea. When the licenses were granted, Mr. Malnic said that the whole world took off for the company. He also said that there was a large media interest.

He said that one of the options being considered by the company is whether to offer shares of the company to the public. He noted that with this approach, Nautilus would be required to offer the titles for the deposits as security for the transaction. He said that the project capital being sought would be to build the mine. He also said that traditionally mines are fixed to a country, and are very expensive to build. He said that it was the considered opinion of his group that although the capital requirements to build the seafloor mine at PACMANUS would be in the range of US$150 – 200 million, this would be far less than a typical terrestrial mine and that the " seafloor mine" could also be transported.

Mr. Malnic said that Nautilus' task is to explain to investors why the seafloor deposit is attractive. In this regard, Mr. Malnic said that a lot of work has had to be done to structure a package for proposals to investors. He emphasized that a basic rule for raising capital is that the use of capital should be presented in a clear and detailed way, noting however that this could be an early catch 22 for this type of mining that has no precedents.

Mr. Malnic pointed out that for traditional land-based exploration the steps involved in development included reconnaissance exploration, target identification and resource definition. He also pointed out that for land-based exploration, it is difficult to accurately cost these stages. He said that in their efforts to raise capital, potential investors expect to see the project described in this format. With no model to follow, Mr. Malnic said that Nautilus has therefore had to overcome this difficulty and to invent new descriptions that reflect these stages.

Dr. Malnic used as an example, the difficulty in projecting how much ship time would be required to effectively explore 5,000 square kilometres of the Bismarck Sea. He pointed out that once plumes are discovered, their origins have to be tracked down. He also pointed out that the length of time required to meet this objective is unknown. Whatever cost estimates are used, Mr. Malnic said that there isn't an experience base to underwrite those projections.

Mr. Malnic said that Nautilus has also had to describe to potential investors the nature of the business for which it seeks investment and noted wide differences in potential interest in Nautilus. In this regard, he pointed out that some Engineering Firms want to invest solely in technology development and intellectual property assets, while major mining houses want to own the mineral deposits and the stream of concentrates that would flow to the metal markets. He also pointed out that a regional bank might only want, for example, to invest in Nautilus' activities in Papua New Guinea, while an individual speculator would want to be able to trade in the company and to see a listing on a stock exchange. For this reason, Mr. Malnic said that Nautilus viewed itself as an international group of companies that holds rights to different regions and differing technology and real estate elements. As concerns structure therefore, Mr. Malnic said that it has had to be such that it could entertain all kinds of investors and be able to give them something that addresses their needs.

With slides, Mr. Malnic identified the marine three areas for which Nautilus had submitted applications to the Government of Papua New Guinea. He pointed out the Conical seamount and Lihir Island deposits previously referred to by Dr. Peter Herzig. He also said that most of the planned marine scientific research activity is to be concentrated in this area. He recalled that in December 1997, Nautilus had issued its first press release headlined "Nautilus granted world's first licences over high grade marine sulphides deposits". He further recalled the tremendous coverage that the issuance of the licenses had received in the world's press and media, including the New York Times, ITV news in Britain, the Minneapolis Star Tribune, the PNG Post Courier and magazines such as the Arkansas Democrat Gazette. Based on this experience, Mr. Malnic said that anyone engaged in an effort to undertake marine mining should put a significant effort into leveraging the associated media coverage and public entertainment as a driver for fundraising. He also said that the media and public see marine mining as a pioneering adventure, and suggested that this element of romance should be used to create the excitement that makes investors want to sign up and be part of the project. Compared to land, Mr. Malnic said that there are a large number of seafloor massive sulphides deposits to be claimed, and that these deposits are going to be the low-cost mines of the future.

Pointing out indications of copper in samples of massive sulphides ore, Mr. Malnic stated that the larger proportion of the rock is made up of economic minerals. He also said that mining high grades of economic mineral material means processing less rock. He emphasized that grade is the fundamental difference between manganese nodules, and cobalt-rich ferromanganese crusts and SMS deposits.

Mr. Malnic told participants that because most of the metal bearing ores of the seabed are polymetallic, the Nautilus group is not keen on using the word "polymetallic" to describe massive sulphides, and that the term SMS deposits or 'seafloor massive sulphides' is for the group, the preferred terminology. Mr. Malnic also said that this term distinguishes the deposits from land-based volcanic massive sulphides deposits that are the well-known fossil versions of the seafloor massive sulphides. He said that the new class of high-grade SMS deposits such as those in the Pacmanus Basin have zinc, copper and gold and may be able to yield silver and barite. As a result, he said that even during times of depressed gold prices, such as now, there is a lot of investor focus on the high gold values.

Mr. Malnic said that from Nautilus' operations, it is expected that the commodities to be sold will be zinc and copper concentrates. He pointed out that gold in the zinc concentrate fetches less than from a copper concentrate. He also pointed out that the price that would be realized from the sale of these concentrates is about half of the contained metal value. Therefore, from concentrate containing approximately $600/tonne of contained metal, Mr. Malnic said that Nautilus' obtained price would be about $300/tonne.

Mr. Malnic showed illustrations of various samples of massive sulphides materials. These included a sample from the Roman ruins deposit containing 51 per cent zinc, and another from the KODOS cruise of Korea in 1999 also rich in Zinc. Mr. Malnic said that a typical tradable concentrate grade for zinc is about 55 percent, indicating the small amount of waste that would be generated from mining a sulphides deposit.

With regard to the impact of the world economy on land-based mining activities, Mr. Malnic said that up until mid 1999, metal prices steadily eroded due to a generally slow world economy outside of the United States. Mr. Malnic said that since the major mining companies have not made any significant discoveries during the past ten years, and have had to compete with technology stocks, many of them have had to slash their exploration budgets. He said that these companies have changed forever and they are not the big risk takers as they were in the manganese nodule boom. He stated that David Lowell, a major veteran mineral explorer is predicting a serious ore shortage in the next couple of years. In relation to interest in seafloor massive sulphides, Mr. Malnic made the statement that Lowell's prediction would be interesting to watch.

Mr. Malnic said that Nautilus' activities have progressed to the point where as development capital is sought, it has found it far more effective to present its proposed massive sulphides mining project as two streams of activity. Within these two streams, one group of investors owns the titles in mineral applications and the second owns the technology and intellectual property rights. He said that this framework has come about because potential investors that have been approached are either interested in mining technology or in mineral deposits, but not in both.

For exploration for massive sulphides deposits in Nautilus' license areas, Mr. Malnic showed an illustration of the "Rapid Exploration System". Mr. Malnic said that Nautilus has received a proposal for the system.

Mr. Malnic said that the design of mining equipment for massive sulphides deposits is an area in which many potential investors are interested. In this regard, Mr. Malnic said that a floating production off-take vessel and a mill are elements of technology that could actually be pieced together from existing technology.

Mr. Malnic said that because plumes associated with massive sulphides deposits are a live source, they represent very reliable geochemical targets. With dredging, therefore, Mr. Malnic said that sulphides could be recovered and mining targets quickly identified. Compared to what happens on land, Mr. Malnic described this process as rapid. He said that being able to a small sample through to a few tonnes of material and eventually bringing the mining ship to the mining target for a trial pilot run would as quickly would shorten the lead-time to production considerably. He also said that for land-based deposits, landowner disturbances are a critical factor, with indigenous landowners around the world increasing their vigilance over intruders. He referred to the integrated benefits package that was given to land owners at Lihir, and described it a very serious cost to that project.

In relation to materials handling at a seafloor massive sulphides deposit, Mr. Malnic said that the wastes generated are very much reduced by the fact that the grade is high. He said that the high sulphides content of the ore means that grinding would be a low cost activity and that benefits would be quickly realized through froth floatation because these deposits have not yet been liquefied. He noted that for every base metal mine in the world, this aspect of mining is costly.

Mr. Malnic compared some of the items that have to be financed in land-based mine development to similar items required for the development of Nautilus' seafloor massive sulphides deposits. The first comparison that he made was with respect to the two mines, the land-based mine and the seafloor massive sulphides mine, once reserves have been established. Thereafter, he informed participants about the inherent flexibility of a seafloor massive sulphides mining operation, making comparisons with the costs and financing of similar stages in land-based mining operations.

Mr. Malnic described a land-based mining plant as a plant that is bolted on to a country, in a remote location and most probably in a mountain range, and to which all the equipment required to assemble the plant have to be transported. He described the proposed seafloor massive sulphides mining plant as one that would be assembled in a shipyard at lower cost, and moved at a single mobilization cost to the location where it is to be deployed. He said that the floating nature of the plant would probably mean that the vessel could be written off on a lease basis, which is significantly different to the traditional, terrestrial, mine. He said that during mining operations, high zinc or copper areas could be mined in response to prices. He compared this situation to an underground land-based mining operation that required the operator had to burrow his/her way everywhere through the mine without much flexibility. He also said that without the need to demonstrate the mine-life of a seafloor massive sulphides deposit, potential investors would find this operation more attractive because of lower front-end costs, and returns on investment. He said that for the Lihir mining operation it took almost 10 years and $160 millions to demonstrate how long the prospective mine plant would be in operation for, and a further $760 millions to build the plant. On the one hand, Mr. Malnic said that for a seafloor massive sulphides deposit plant, without the need to demonstrate an entire mine life before mining starts, the operation could take place on a more tentative basis and confidence could be built up without taking massive financial risks.

Mr. Malnic described waste products as the cause of 90 percent of environmental disasters around mining operations on land. He said that at Bougainville, the tailings were a huge issue. By offering a mining investment that generated a much reduced volume of tailings, Mr. Malnic said that seafloor massive sulphides deposits mining would have an advantage over terrestrial mining.

With a slide, Mr. Malnic showed a picture of environmental problems involving effluents from a copper and gold mine in west Irian formerly called Irian Jaya in Indonesia. The picture showed tailings from the mine emptying into a nearby river. While noting that the situation could have been worse, Mr. Malnic said that the discovery of this practice drew a lot of attention to the operator's environmental protection procedures, including generating legal issues. Therefore, in Nautilus' efforts to promote the mining of its seafloor massive sulphides deposit, Mr. Malnic said that the possible environmental impacts from this operation are offset against the kind of damage that would be created from the recovery of the same metals in a terrestrial environment.

Mr. Malnic recalled an earlier statement that he had made that high-grade ore means a low proportion of waste products. He said that terrestrial mines, the alternative source of the metals that are found in seafloor massive sulphides produce increasingly high proportions of waste as grades of ore decline. He also said that the greatest amount of liability faced by operators of these mines is related to tailings, especially acid mine drainage. He said that at active seafloor massive sulphides deposits hundreds of tonnes of mineralisation is likely to regenerate every year in the wake of mining. He said that as long as the heat and fluid emissions at these sites continue to provide an oasis in this environment, life would return to it. He pointed out that the key environmental factors are the heat and hydrogen sulphide (H_2S) emissions as opposed to the presence of the large volume of sulphides that is ready to be fossilized. With the example of coal, Mr. Malnic said that such deposits were created through chilling the carbon compounds because the hot waters that were part of their formation have ceased to exist. Mr. Malnic pointed out that around massive sulphides deposits, a rim of dead individuals could be found, explaining that the life forms down there are extremely good at shifting. Mr. Malnic described the dead fauna as sacrificial, stating that the focus of life continues to move on at vent sites.

Mr Malnic said that because sulphides ore is soft and easy to grind due to the ore's high porosity, metallurgical tests for recovering the metals of economic interest have been very successful. He added that flotation tests have yielded very good results.

With regard to the sulphides mining plant that Nautilus envisioned, Mr. Malnic said that it has been designed around deposits with reserves of 1.5 million tonnes of ore, and a production rate of 1,000 tonnes a day using idealized grades because the deposits have not yet been drill tested. The operation would purchase a vessel for $50 millions. He said that the other elements of the operation include ore recovery using grabs, and transportation to land using barges.

With slides, Mr. Malnic showed participants a mine in New South Wales called North Parks. Another slide contained a newspaper headline that read that this mine is the lowest cost underground mine in Australia. In describing this mine, Mr. Malnic said mining operations were based on remotely controlled machines that hauled broken rock from a large block caving operation to a shaft. He suggested the evolution of similar technology for seafloor massive sulphides, and described this as a natural convergence that would take place between terrestrial mining and marine mining.

With regard to the actual mining technology in Nautilus' mine plan, Mr. Malnic said that a similarity in rock type has been established with Ezena Cauldron. He informed participants that Nautilus has been using information on the rock properties of this deposits to design equipment. He also informed participants that because of the proprietary nature of the information, he was not in a position to divulge it. He however informed participants that the porosity of the rocks at the two areas is the key to them being so easy to break and grind up. He described the sulphides rocks at Nautilus' deposits as of ideal consistency for mining.

Based on this and other considerations, Mr. Malnic said that engineers were asked what equipment should be used to mine the deposits. Mr. Malnic revealed that a grab would be used. This would be deployed from a vessel.

Mr. Malnic said that he is often asked the question – "When will mining commence?" He indicated that he routinely gave the response that as more of these deposits are found, when the known 20 million tonnes of this material on the seafloor increases to over 200 million tonnes, and a spark is lit, then seafloor massive sulphides would generate enormous interest.

Dr. Malnic pointed out that within a decade, the petroleum industry moved from the shallow waters of the Gulf of Mexico to the Bass Strait at the southern end of Australia and then to the North Sea. He said that once these offshore deposits were discovered engineers caught up very quickly, developing cost effective technologies for mining these resources. He also said that twenty-five years later petroleum exploitation has moved from the land end of the sea to 5,500 metres offshore platforms. He said that in his opinion this would happen for seafloor massive sulphides deposits.

Mr. Malnic said that every year there are more discoveries of mineral deposits being made in the deep sea. He pointed out that these discoveries are not because of commercial exploration. He said that these discoveries are because of research driven exploration that finds something that is interesting to commercial operators. He said that he believed that this trend would continue.

With further regard to environmental concerns, Mr. Malnic noted that terrestrial mining operations, great consumers of fossil fuels, are under pressure to cut emissions from the Greenhouse lobby and also face the prospect of a carbon tax in Australia. He said that in Australia's western mining province, a group has made some calculations on this matter and estimates that based on an assumed $30 a tonne carbon tax, some companies could pay up to $300 million per year in taxes. He also said that one such company, BHP had gone through a similar exercise and estimated that it could pay up to $1 billion per year in respect of its operations. Mr Malnic spoke about a proposal that Nautilus had made in respect of environmental protection at a meeting of the Underwater Mining Institute earlier in the year.

He said that in Australia the mining industry has adopted a 'Code for Environmental Management that is a voluntary code. He said that the Australian minerals industry wanted to win back the sort of initiative it had in conducting the environmental debate. It was convinced of its own motive with regard to the environment but was tired of having other groups running away with the story and always trying to polarize the situation into a good guy/bad guy relationship.

Mr. Malnic said that the code has attracted 44 companies that represent 85 percent of Australia's mineral production and that 29 of them have now gone to the next stage which is to self regulate. He said that every year the companies go out, audit their environmental improvement achievements, and make them known in a published report.

In concluding his presentation, Mr. Malnic again pointed out that the marine areas in which their licenses are to be found are the subject of a lot of marine scientific research. He pointed out that Nautilus owes its existence to marine scientific research. Mr. Malnic said that while many scientists come back to the area to conduct research, one of the conditions that is not being met is to make the results of their work available to Papua New Guinea. In some cases, Mr. Malnic said that the permissions of Nautilus and the Government of Papua New Guinea were not obtained.

SUMMARY OF THE DISCUSSIONS

The discussions that followed Mr. Malnic's presentation focussed on the plant envisioned by Nautilus at its site. One participant pointed out that based on a daily production rate of 1000 tonnes as indicated by Mr. Malnic, the price of the mining vessel of $50 millions and a price of product of $300.00/tonne, the return on investment would be very high. The same participant said that based on these figures, in a year and a half the entire investment would have been recovered. This participant wanted to know whether or not the daily production target was reasonable.

Mr. Malnic said that the mining operation would be very close to shore. He also said that the model is based on having a small operation on a nearby island, and utilizing a low-cost mill for grinding. He pointed out that there was no need for a plant that is even vaguely similar to a typical terrestrial mine. With regard to the ship, Mr. Malnic said that cost estimates are based on a ship in position in Papua New Guinea. Mr. Malnic said that the cost for barges is based on hiring them from local barge firms. He said that the grab to be used on the ship is to be contracted.

In reaction to Mr Malnic's statement that ore grades are declining at land-based deposits, another participant was of the view that grades have not been declining over the years and that it is the opposite that has taken place. This participant said that the largest VMS deposits in Calamares in Cyprus would not have been economical at all to mine today. He also said that the grades in a VMS deposit today have to be much higher than they were 10 or 20 years ago.

Mr. Malnic used the grades of newly established copper mines that he said were decreasing each year to register his disagreement. He however said that the point is the capacity of seafloor massive sulphides to compete against land-based deposits. In this regard, he said that there is an advantage in every area from energy consumption to capital expenditure, and that seafloor massive sulphides deposits to are better placed to respond to the ongoing decline in metal prices.

Another participant, noting that Mr. Malnic had said that it was relatively easy to find high-grade massive sulphides wanted to know how this is done.

Mr. Malnic said that the process is to follow the large plumes of smoke. He said that a single plume could cover up to 100 square kilometres of the area. Once the plume is found, Mr. Malnic said that it is followed back to a topographic source that looks structurally right.

CHAPTER 9

STATUS REPORT ON THE DATA AND REPORTING REQUIREMENTS OF PAPUA NEW GUINEA'S POLYMETALLIC MASSIVE SULPHIDES DEPOSITS

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Abstract

Prospecting and exploration for polymetallic massive sulphides deposits is a relatively new activity that is unlike marine scientific research on these deposits. Any commercial mining in the future is dependent on the extent of resources being identified and more importantly such resources being converted to reserves.

A prospecting and exploration obligation hence data and information reporting requirement ought to be first geared towards identifying resources and proving reserves. Given this necessity consideration should be given to encouraging both prospecting and exploration on one hand and marine scientific research on the other.

Other information relating to the oceanic environment, the surrounding life-forms, and exploration and mining technology will be useful for trial and actual mining phases which are still way off yet.

Introduction

Offshore mineral prospecting and exploration is a relatively new phenomenon particularly in respect of polymetallic massive sulphides (PMS) in Papua New Guinea (PNG) and indeed the world.

Polymetallic Massive Sulphides are types of mineral deposits that occur deep in the ocean where volcanic vents are active. Unlike polymetallic nodules that are found in the deep-seabed, PMS types of deposits occur in relatively shallow waters and contain high grades of copper, zinc, nickel, gold and silver. Except for volcanically active vents that have a trail of black smoke, hence the term "black smokers", it is not easy to locate these mineral deposits though scientific knowledge and technological improvements assist mankind to conquer this frontier in the near future.

Papua New Guinea has been in the process of developing its offshore mineral policy that was largely driven by three factors.

First, Papua New Guinea ratified the *United Nations Convention on the Law of Sea* (UNCLOS) 1982 on 14 January 1997 hence it was required to meet its obligations and to take advantage of the benefits offered there under.

Secondly, Papua New Guinea's *Mining Act 1992* was largely intended for activities onshore rather than in the offshore. In light of UNCLOS, this legislation required review and, where appropriate, updating of existing laws or promulgation of a new Offshore Minerals Act.

Thirdly, in spite of the deficiencies in the *Mining Act 1992* regarding the regulation of offshore mineral exploration and mining, two offshore exploration licences were granted to Nautilus Corporation of Australia pursuant to that Act. The particular type of deposits this licensee was interested in are the Polymetallic Massive Sulphides within Papua New Guinea's archipelagic waters where the existing *Mining Act 1992* was applicable but not necessarily appropriate.

In this paper it is intended to provide a brief status report on the data and reporting requirements for Polymetallic Massive Sulphides deposits under existing *Mining Act 1992* and under the proposed Offshore Minerals Policy and subsequent legislation.

1. Regulatory Framework for Offshore Mineral Prospecting and Exploration

1.1. Mining Act 1992

The key domestic legislation regulating all mineral exploration and mining in Papua New Guinea is the *Mining Act 1992* though the Panguna and

Ok Tedi Copper Mines have separate legislation respectively. Nonetheless, the *Mining Act* this is quite deficient as regards offshore exploration and mining though the statutory reporting requirements on the exploration licence holders having tenements within the territorial sea would be bound by this legislation.

Generally, no mineral exploration or mining can take place in the country without the express authority of the State except for small alluvial mining by a landholder utilising traditional artisanal tools on his own land. An authorisation is granted through various licences under the *Mining Act*.

Licences that may be issued under the Act include exploration licence, mining lease, special mining lease, alluvial mining lease, lease for mining purposes, and mining easement.

For purpose of this paper the exploration licence is the key tenement that will be discussed. Table 1 illustrates the typical terms of an exploration licence under the *Mining Act*.

A holder of exploration licence has the right to search for and find mineral resources. Among its other obligations, the licensee is obligated to report its findings on a biannual and annual basis.

Table 1: Exploration Licence Terms

Initial Term:	2 years
Extension:	2 year tranches
Area:	750 sub-block or 2 539.2 Km2
Acreage Relinquishment:	50 % at end of first term
Exclusivity:	Exclusive right to occupy land and explore for minerals specified
Work Programme:	Required as a condition
Reporting Requirements:	Biannual and Annual Reports
Minimum Expenditure:	Sliding scale and dependent on term of licence

2.2. Major Features of the Draft Offshore Mining Policy

Under Papua New Guinea's *Constitution*, no international treaty that PNG is a signatory to is binding on it until such treaty is given domestic legal force. In this instance either the *Mining Act 1992* may be amended or a new legislation for offshore mineral exploration and mining may be promulgated. The final form of legislation will be dependent on the outcome of the Offshore Minerals Policy. Currently, it is on hold pending engagement of a consultant under the World Bank Institutional Strengthening Project to review and finalise the policy including its enabling legislation.

For the purposes of this paper the major features of the draft policy are enumerated for ease of reference.

2.2.1. Diverse Offshore Resources

The draft policy is open to accommodate different offshore resources (excluding fish and other marine resources) that may be found in the offshore. In general terms the developed and potential mineral deposits are diverse and include sand, gravel, diamonds, black sands, oil, naturally occurring hydrocarbons, manganese nodules, manganese crusts and PMS. They are poorly explored and have a wide range of issues impacting on their development including inadequate governing policy and legislation, need for new and improved technology for exploitation, lack of assured economic potential, numerous environmental impacts and other as yet unquantified stakeholder interests.

Of these offshore mineral resources deep ocean manganese nodules are by far the most studied by researchers and the private sector while the PMS that occur within several nations' exclusive economic zones are rapidly assuming more importance in terms of research and private sector interest.

2.2.2. Licences and Licensing

The exploration cost in the offshore may be high if costs for scientific cruises are any indication. One scientific cruise on average costs anything in the order of US$20, 000 plus. Add to this the lack or infant status of offshore exploration and mining technology, and the usual terrestrial licensing arrangements may not be applicable. For the offshore, the licensing regime will be modified to take account of different oceanographic and environmental conditions.

Based on the application of known terrestrial licensing procedures and their effectiveness, it is proposed that there be 5 different types of tenements to be issued for offshore mining. These are: Prospector's Right, Exploration Licence, Mining Lease, Lease for Mining Purpose (LMP) and Mining Easement. In addition, it is proposed that a prospector's right licence be granted under special circumstances for offshore mining. Table 2 shows likely terms for the licences or permits as the case may be.

2.2.3. Marine Scientific Research

It is perhaps worth noting that it is not entirely clear what is marine scientific research (MSR) and what is exploration under the UNCLOS. By introducing prospector's right as a form of licence separate from exploration, it is hoped that the confusion may be clarified though not eliminated.

Incidentally MSR by itself may not be exciting but when one hears of potential industrial and pharmaceutical applications of biogenic materials found around the hydrothermal vents for instance it does. And so it must as this industry is estimated to be worth billions of dollars. Obviously MSR will require regulation and closer scrutiny if Papua New Guinea is to benefit from scientific and industrial information generated from sources within its jurisdiction.

2.2.4. Offshore Fiscal Regime

There are a lot of unknown variables like extent of offshore mineral resources, available offshore exploration and mining technology and the cost of such technology. Consequently, the fiscal regime is not definitive though as a minimum the current regime is highlighted to guide the investor or potential investor in offshore exploration to make an investment decision to invest.

As a general principle the fiscal package attempts to be flexible, simple, transparent and applicable to the issues involved in offshore mining. It is accepted that certain unique aspects of deep ocean resources warrant a deviation from the onshore fiscal package. These include the anticipated long period of time required for exploration and technology development, the unique environment under which mining takes place, high risks associated with a pioneering endeavour and the uncertainty surrounding the economic viability of deposits. With this in mind flexibility may mean that overall lower front-end rates with respect to royalty and income tax may be balanced by an Additional Profits Tax that comes into place at a lower profit threshold rate than onshore.

In addition it is anticipated that some of the recently introduced taxes such as mining levy, and interest withholding tax might not be applicable to offshore mineral operations

Table 2: Likely Offshore Licensing Terms

Licence/ Permit	Term	Area	Nature of Right	Rights
Prospector's Right	3 yrs initially Renewal 3 yrs	Unrestricted	Non exclusive	Prospecting
Exploration Licence (EL)	5 yrs initially Renewal 5 yrs	1000 sub blocks (3410 sq km) 20% reduction	Exclusive	Exploration
Pilot Mining Test	Part of EL	Part of EL	As for EL	Test mining technology and system
Mining Lease	Negotiable	Less than for EL	Exclusive	Mining
Lease for Mining Purpose	Need Dependent	Need Dependent	Exclusive	Installation of facilities for mining purposes
Mining Easement	Need Dependent	Need Dependent	Non exclusive	Use of structures like pipes, special access ways

2.2.5. Offshore Environmental Regime

Mining projects including offshore mineral resource development will have unavoidable environmental impacts. In addition, offshore areas contain living organisms unique to the marine environment that may be of industrial and medicinal significance. Consequently, proponents of such ventures will need to obtain and show evidence of necessary environmental approvals prior to granting of exploration or mining tenements. Furthermore, mineral exploration and mining companies will be required to undertake their activities consistent with the requirements of the environment related laws and regulations operating in Papua New Guinea.

2.2.6. Benefits Distribution Mechanisms

Benefits distribution is important in the light of Papua New Guinea enacting the new *Organic Law on Provincial Governments and Local level Governments* and the ratification of the UNCLOS. Under the former, the State is not only required to consult with affected provinces and local communities but also it is required to share some of the benefits derived from mineral projects. As to the latter, the International Seabed Authority established under the UNCLOS and the 1994 Implementation Agreement relating to Part XIII of the UNCLOS will be entitled to share with a coastal state revenues derived from resource exploitation within the additional continental shelf area i.e., additional 150 nautical miles from the usual 200 nautical miles limit.

It is further proposed that the State may consider cooperative development arrangement such as joint development with the ISA in areas that are beyond normal 200 nautical miles. This will save time, effort and cost for delimiting the outer continental shelf of the State.

Talking about stakeholders I want to say something about the controversial but necessary subject of "landowners" or indigenous peoples' rights. During my committee's deliberations and at the Madang regional workshop sentiments were expressed that we might have a break with that issue in the offshore.

I think the issue is not as simple as that. In PNG we have the *Fisheries Act* that recognises traditional fishing rights and reef claims of coastal and island communities. That obviously will be an issue. Their positions as well as that of the relevant Provincial Governments are further reinforced under the *Organic Law on Provincial Governments and Local level Governments*. I guess we have not decided how far they should stake any claim- by distance, depth, or whatever? There is though a suggestion, in fact a recommendation from the Madang regional workshop that, island states consider declaring offshore areas beyond say 3 nautical miles from the coastline as "common heritage of the nation".

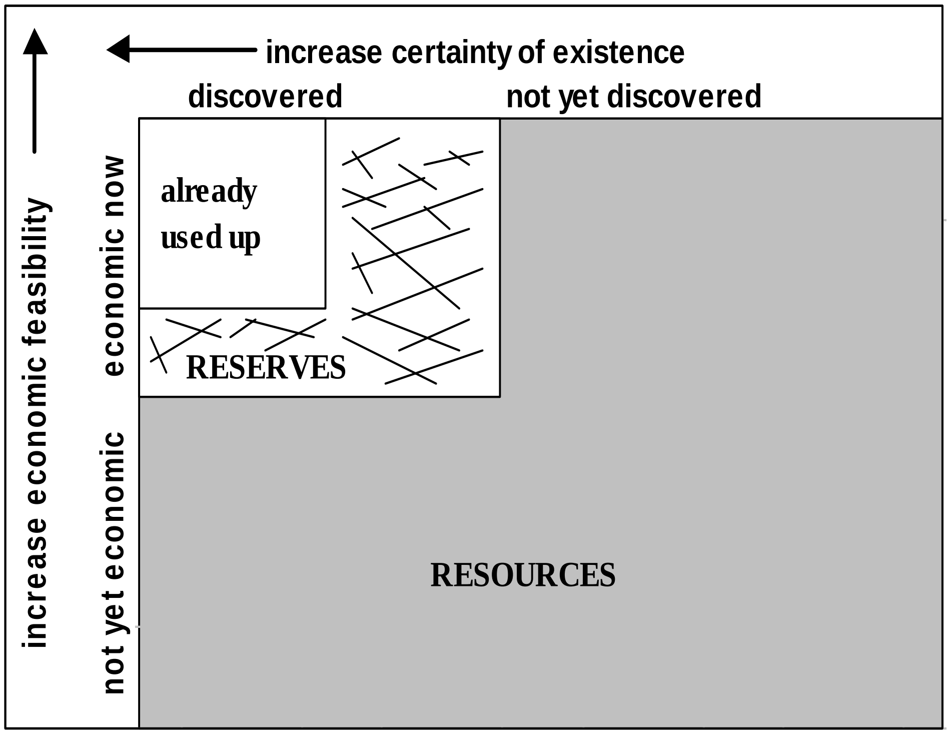
2. Data and Information Requirements of Prospectors And Explorers

2.1. Requirements under the Mining Act 1992

Under the *Mining Act 1992* no distinction is made between prospecting and exploration as separate activities. It follows that there are no separate licences or permits for these activities. Indeed under the current licensing regime, an exploration licence entails prospecting i.e. searching for minerals to taking samples, drilling and even doing pre-feasibility and full feasibility studies.

In terms of data and information requirements of prospectors and explorers they were expected to report on all matters falling within the definition of exploration. Some of the specific matters include: geological mapping, geochemistry, geophysics, drilling, bulk sampling, specialist geological studies, and pre-feasibility and feasibility studies.

The core consideration in exploration is to ensure that resources were located and added to the total resource of the nation. As resources *in situ* are useless, economically they need to be defined further to reserves that can be economically and legally exploited. This relationship between resources and reserves is succinctly expressed in Figure 1.



Reproduced from David A Rothery, Geology, Chicago: NTC Publishing Group; 1997, p139

Figure 1: Relationship between physical resources and reserves

3. Requirements under the draft offshore minerals policy

As the offshore minerals policy has not been approved and given legislative force yet, any data and information reporting requirements of offshore prospectors and explorers of polymetallic massive sulphides under the draft policy are not binding. Nonetheless, it is important to point out some of these requirements under the proposed policy per Table 3 below.

Table 3: Data and information requirements of offshore prospectors and explorers

Factor	**Status**	**Requirements & Justifications**
Resource	Largely unknown although some data and information are now available through the activities of the Marine Scientific Researchers.	More data and information is required to ascertain the extent of the resource and to convert such resource to mineable reserves. Any future commercial exploitation of offshore minerals will be dependent on the amount of mineral reserves that can be economically and legally exploited.
Environment	The deep ocean environment where polymetallic massive sulphides occur varies from the ocean surface environment. Advances have been made to study and understand the unique offshore environment principally by Marine Scientific Researchers.	Data and information on deep sea environment relating to factors such as salinity, pressure, chemistry, deep sea currents, benthic flora and fauna and their habitats will enable appropriate design or modification of exploration and mining technology. In addition such data and information will provide sound basis for Environmental Impact Assessment Statement to be prepared if one proceeds to the trial mining or actual mining phase.
Technology	Offshore technology for polymetallic massive sulphides is still in its infant stages unlike those for the manganese nodules.	Data and information on its innovation and development was essential for development planning purposes. Commercially, this is a sensitive matter as the application of data and information may not be necessarily limited to offshore mineral exploration and mining.

4. Utilisation of Data and Information by the Government

The data and information generated serve a number of useful purposes.

First, the data and information are used to ascertain degree of compliance by the licensee with the licence conditions. This ensures licensees do not hold on to acreage without doing agreed work programme.

Secondly, the data and information are used to ascertain location of the resource, extent of the resource, and further work required for proving up the reserves for potential commercial exploitation.

Thirdly, the data and information may form the basis for additional conditions to be imposed on the licensee at renewal of such licence.

Fourthly, the data and information may be relied on to invite additional or new participant into the industry.

Finally, in the case of biogenetic resources associated with the polymetallic massive sulphide deposits, the government may enter into alliances with explorers and researchers to share in the benefits of potential commercial utilisation of such resources. In fact PNG through the BIONET already has an access agreement with the Commonwealth Scientific Industrial Research Organisation (CSIRO). Similar arrangements are anticipated with other international researchers and research entities.

In a nutshell, the data and information generated are important for policy-making, planning, and compliance monitoring of activities associated with polymetallic massive sulphides prospecting and exploration.

5. Compliance with The Data and Information Reporting Requirements

Generally, tenement holders under the *Mining Act 1992* comply with the data and reporting requirements. However, there are instances where licence holders either delay the reporting or have forgotten to report. In the former case a reminder notice is sent out that usually get a favourable response while the latter may result in the licence being terminated or not renewed.

A major difficulty confronting the Government is not so much with reporting but auditing the report and the actual work undertaken during the term of an exploration licence. An audit will assist the Government to determine how much money was actually spent on exploration and how much on other expenses including overheads.

Currently there is deficiency in the capacity to undertake this auditing task. As a consequence, a consultant is anticipated to be engaged to fill this capacity gap and to transfer the know-how under the Institutional Strengthening Project to be funded by the World Bank in the next few years.

As regards data and information reporting requirements in the offshore there are only two licences held by the same company. While the reporting requirement is governed by the *Mining Act 1992* for the time being it is really a dilemma to ascertain what constitutes exploration in the offshore. As these two licences are in the process of renewal , no more could be said at this stage.

However, it would be noted that the situation will become clearer if there were clear definitions of marine mineral exploration and marine scientific research as most of the resource data generated to date are from MSR. Unfortunately no help can be found in the UNCLOS. Perhaps as a passing remark this may be an aspect that the Legal and Technical Committee of the International Seabed Authority may wish to take up in the near future.

6. Conclusion

Offshore prospecting and exploration are relatively difficult given the unique ocean environment. It follows that conventional data and information reporting requirements may not necessarily apply.

However, the full extent of the offshore reporting requirements will only be known when the offshore minerals policy is finalised, legislation put in place, and potential investors granted prospecting and exploration licences.

It is very obvious that the data and information are required for various purposes including ascertaining availability and extent of the mineral resource, monitoring compliance, and potential economic exploitation of offshore minerals in particular polymetallic massive sulphide deposits in the future should circumstances permit.

As the extent of resources hence reserves is a key requirement if there is to be a marine mining project involving polymetallic massive sulphides deposits, in the future both MSR and offshore mineral prospecting and exploration will be encouraged under the proposed Offshore Mining Policy for PNG.

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SUMMARY OF THE PRESENTATION AND DISCUSSIONS ON A STATUS REPORT ON THE DATA AND REPORTING REQUIREMENTS OF PAPUA NEW GUINEA'S SEAFLOOR MASSIVE SULPHIDE DEPOSITS

Summary of the presentation.

Mr. Wanjik, Acting Director of the Mining Division of Papua New Guinea's Department of Mining informed participants that his presentation would focus on the regulatory regime being developed by the Government of Papua New Guinea for offshore minerals, and the data and information requirements contained in it. He pointed out that until now, Papua New Guinea's mineral policy has been oriented to land-based deposits and has been deficient with regard to marine mineral resources. He said that the two exploration licenses that have been issued for seafloor massive sulphides deposits in Papua New Guinea's archipelagic waters were granted based on the country's Terrestrial Mining Act.

With regard to exploration licenses granted for the development of land-based deposits, Mr. Wanjik said that in Papua New Guinea, the exploration license includes prospecting and exploration. He said that for the two licensed marine areas under the provisions of the Terrestrial Act, the initial term of the license is two years, and is renewable for two-year periods, subject to compliance with the terms. He said that the maximum exploration area comprises 750 sub- blocks, or up to 3000 sq km. Mr. Wanjik told participants that the Act contains a requirement for acreage relinquishment, and that after two years 50% of the acreage has to be relinquished. Mr. Wanjik said that an exploration license provides its holder with exclusive exploration rights. He also said that a work-programme is a condition of the license, and that the license holder is required to submit biannual and annual reports on the activities that it has undertaken during the period, along with information on how much was spent on those activities.

Mr. Wanjik said that there is a provision for minimum expenditures under the license. These expenditures he said are on a sliding scale., Mr. Wanjik said that the rationale for this approach is based on the idea that the longer an area is held, more information should have been acquired on it on it to facilitate a decision on whether or not to establish a mine.

In relation to the development of an offshore mining policy, Mr. Wanjik said that the Government was considering the different features of the land-based and marine environments. In this regard, he pointed out that the ocean and what is above and below it are all different resources. He also said that Papua New Guinea requires regulations and a policy for marine mineral resources in order to encourage further investments to develop these resources.

Exploration license

Mr. Wanjik said that the draft Offshore Mining Policy of Papua New Guinea foresees five different types of tenements under the offshore licensing regime. These are Prospector's Right, Exploration License, Mining Lease, Lease for Mining Purposes and Mining Easement. He said he would limit his presentation to the Prospector's Right and the Exploration License.

As concerns Prospectors' right, Mr. Wanjik said that it is being suggested that the term should be for three years and renewable for another three-year term. Mr. Wanjik said that depending on the application, the area under the license would be unrestricted. He said that the applicant would have to demonstrate its capability to undertake and finance the work under the application. Mr. Wanjik also said that no exclusivity is provided with this license because of the size of area, and because no drilling is envisaged. He said that when drilling is carried out this would normally occur under an exploration license.

In relation to an Exploration License, Mr. Wanjik said that under the draft Offshore Mining Policy, instead of a two-year license for exploration that is renewable for two-year periods, it has been proposed that the term of the license should be for five years, and should be renewable for five-year periods. In addition, he said that it has been proposed that the maximum size of an exploration area should be 1000 sub-blocks or about 3,500 square kilometres.

He pointed out that these provisions would ensure flexibility for the license holder in the search for the minerals provided for under the license. He also said that the exclusive rights granted the license holder would ensure once it had found a viable deposit, it would have the first right to develop that deposit. Mr. Wanjik said that another important innovation in the proposed regulations concerns the pilot mining test. In this regard, he said that under the proposed regulations, when an exploration license holder finds enough minerals and is ready to test mining or processing technology, a work-programme may be submitted. When approved, the license holder may test the mining and or processing technology. Thereafter, following an application to mine, Mr. Wanjik said that that a negotiable mining lease may be entered into for periods starting from 5 years.

Mr. Wanjik said that the exploration license for marine areas would make it beneficial to develop marine minerals resources. He pointed out however that since Papua New Guinea is a mining producer and mineral exporter, it is wary of providing too many incentives.

Marine scientific research

With regard to marine scientific research, Mr. Wanjik pointed out that whilst the Government of Papua New Guinea wishes to encourage prospecting and exploration, it also wishes to ensure that marine-scientific research in areas under its jurisdiction continues. He noted that as parties to the Law of the Sea Convention, Papua New Guinea has an obligation to encourage marine-scientific research for the benefit of mankind. He also noted the need to protect the marine environment and its associated biological communities.

Mr. Wanjik made the point that marine scientific research is the source of Papua New Guinea's information on its marine mineral resources. He also pointed out that the distinction between marine scientific research and marine mineral exploration is unclear. In this respect, he said that while developing the draft policy, it was realized that there are potential industrial and pharmaceutical applications from properties of vent biota. Observing that no expert at the workshop had placed a value on such applications, Mr. Wanjik said that he is aware that some countries have applied for patents for enzymes from the deep sea. One group of enzymes Mr. Wanjik said, are coral enzymes that are thought to have medicinal qualities for cancer treatment. Mr. Wanjik said that under the draft policy, regulations for biological prospecting are being considered. Mr Wanjik said that a network of various groups who work together to look at the prospects for bio prospecting has been formed in Papua New Guinea under the an institution known as PNG BIONET. He said that any request to conduct marine scientific research on biodiversity in Papua New Guinea's marine areas has to be cleared by PNG BIONET. Mr. Wanjik informed participants that Papua New Guinea has a standing arrangement with Australia's scientific research organization, CSIRO, on the commercial utilization of such resources.

Benefits distribution

With regard to the benefits distribution scheme from land-based mining, Mr. Wanjik said that all benefits are shared between the province in which the mining project takes place, the landowners and the indigenous people.

In the draft Offshore Mining Policy, Mr. Wanjik said that the emphasis is on a distribution scheme wherein resources found in the ocean will be developed for the entire country rather than to be distributed to a province or landowners.

SUMMARY OF THE DISCUSSIONS

The discussions following Mr. Wanjik's presentation focussed on the distinction between marine scientific research and mineral exploration. One participant, noting that Mr. Wanjik had raised this matter in his presentation said that in his country their scientists normally advised the government on these matters. In this regard, this participant said that he had been informed that scientific research involved studies on the natural phenomena of the sea including the seabed. He said that the emphasis placed on this activity was the study of natural phenomena. He had also been informed that prospecting is an effort to find out whether or not there are resources in that natural set-up, to identify these resources and determine their location. The participant said that he had been informed that the purpose of exploration, that followed the discovery of and determination of the location of this resource is to identify, study, and determine whether the resources are commercially exploitable. This participant asked whether this advice is reliable.

Another participant, recalling Mr. Wanjik's comment about exploration and scientific research, said that there is more than one reason to study the grade and tonnage of mineral deposits. This participant said that scientists are interested in the geo-chemical balance of the oceans, so it is important to study the quantity of minerals and the deposits and what they are composed of, without having necessarily any economic interest whatsoever.

Another participant made the observation that although scientific research can be done under exploration, if a researcher proposes generating scientific information on resources to be found in the marine environment in the common interest of mankind that is scientific research. This participant said that the moment a conversion component is introduced, then the activity transforms to exploration.

Responding to these questions, Mr. Wanjik stated that from the regulatory point of view, in terms of activity, the distinction is not a problem. As an example, he said that although drilling is considered an exploration activity, drilling is also undertaken by marine scientific researchers. He therefore asked where the distinction should be made.

A participant made the point that exploration comprises the activities under an exploration license and marine scientific research comprises the activities undertaken with a permit for scientific research. This participant therefore said that with exclusive rights under an exploration license the two activities could co-exist.

Mr. Wanjik concluded the session noting that under the draft Offshore Mining Policy, marine scientific research is encouraged. Where interest in developing marine mineral resources is generated, the Prospector's Rights and Exploration License tenements are then available.

CHAPTER 10

NATIONAL AND INTERNATIONAL PROGRAMMES FOR THE INVESTIGATION OF SEAFLOOR HYDROTHERMAL ACTIVITY: THE CURRENT INTERNATIONAL STATE-OF-THE ART

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This paper summarises the work currently undertaken by national and international programmes to continue the search for new fields of hydrothermal activity along mid-ocean ridges throughout the world's deep-oceans; to understand the geological processes which control the distribution of these vent-sites through the world's ocean basins; and to determine their role in maintaining the global vent ecosystem. First, I provide a brief overview of the nature of hydrothermal venting. Next, I discuss the likely geologic processes which can determine where hydrothermal massive sulphide deposits are formed, their likely contribution to the formation of large versus small deposits, and the principal international expeditions which are to be conducted in the coming years, informed by these considerations. In the following sections I described the theory and currently adopted "best-practice" methods of prospecting for new sites of hydrothermal activity, followed by a discussion of some novel low-cost approaches that one could follow to achieve some simple but fairly reliable first-order value-judgements concerning the likely resource potential of any new hydrothermal fields. Finally, I close with a brief warning of the limitations of the (academically-driven) best-practices described throughout this paper which should not be of significant concern to those interested in the search for polymetallic massive sulphide deposits along mid-ocean ridges throughout much of the Area, but which are likely of greater relevance to those interested in searching for similar deposits not only within individual member states' exclusive economic zones (EEZ) but also within certain extensions to legal continental shelves (ELCS).

1. Introduction

Hydrothermal Activity at Mid-Ocean Ridges represents one of the fundamental processes that control the exchange of thermal energy and materials from the Earth's interior to the oceans. Thus, hydrothermal interactions profoundly influence the composition of the ocean crust and seawater. In addition, hydrothermal vent areas support diverse and unique biological populations by means of microbiological communities which link the transfer of thermal and chemical energy from the Earth to the production of organic carbon. It was during an expedition in 1977 to the Galapagos Spreading Centre that low-temperature (10-30°C) hydrothermal activity was first discovered (Corliss et al., 1979). That was followed by a further French-American expedition in 1981 that discovered high-temperature (350°C) hydrothermal activity for the first time, on the East Pacific Rise (Spiess et al. 1980). Since then, more than 100 different new sites of active high-temperature hydrothermal venting have been found, around the world's oceans - yet more than 50% of the total 60,000km of globe-encircling ridge crest remains unexplored for hydrothermal activity. This paper summarises the work currently undertaken by national and international programmes to continue this exploratory work, to understand the geological processes which control the distribution of hydrothermal venting throughout the world's ocean basins and to determine their role in maintaining the global vent ecosystem.

2. Background: Hydrothermal Vents, What are they? How do they work?

The pattern of hydrothermal circulation is one in which seawater percolates downward through the fractured seafloor towards the base of the oceanic crust and, in some cases, close to molten magma. In these hot rocks, the seawater is progressively heated and undergoes chemical reaction with the surrounding host basalt. As it is heated, the water expands and its viscosity reduces. If these processes occurred on land, at atmospheric pressure, catastrophic explosions would occur as temperatures would rise above 100°C and the water would turn to steam. However, because mid-ocean ridges typically lie under 2000-4000m of seawater, at pressures 200-400 times greater than atmospheric pressure, the reacting seawater reaches temperatures up to 350-400°C without boiling. At these temperatures the altered fluids *do* become extremely buoyant, however, with densities only ~2/3 that of the down welling seawater, so that they rise rapidly back to the ocean/seafloor interface as hydrothermal fluids. The movement of the fluid through the rock is such that, whilst the original downward flow proceeded by gradual percolation over a wide area, the consequent upflow is often much more rapid and tends to be focussed into natural channels emerging at "vents" on the seafloor.

Beneath the seafloor, the reactions between seawater and fresh basalt remove the dissolved Mg^{2+} and SO_4^{2-} ions that are typically abundant in seawater and lead to precipitation of a number of sulphate and clay minerals. As the water seeps lower into the crust and the temperature rises, metals, silica and sulphide are all leached from the rock to replace the original Mg^{2+} and SO_4^{2-} ions. The hot and by now metal-rich and sulphide-bearing fluids then ascend rapidly through the ocean crust to the seafloor. When they begin to mix with the ambient cold, alkaline, well-oxygenated deep ocean waters; the result is instantaneous precipitation of a cloud of tiny metal-rich sulphide and oxide mineral grains. These rise within the ascending columns of hot water giving the impression of smoke. Precipitation around the mouths of the vents over time builds chimneys through which the smoke pours giving rise to the term "black smokers"; hot water gushes out of these tall chimney-like sulphide spires at temperatures of ~350°C and at velocities of 1-5 m/sec. Upon eruption, this hydrothermal fluid continues to rise several hundred metres above the seabed, mixing with ordinary seawater all the time, in a buoyant turbulent plume (Figure 1).

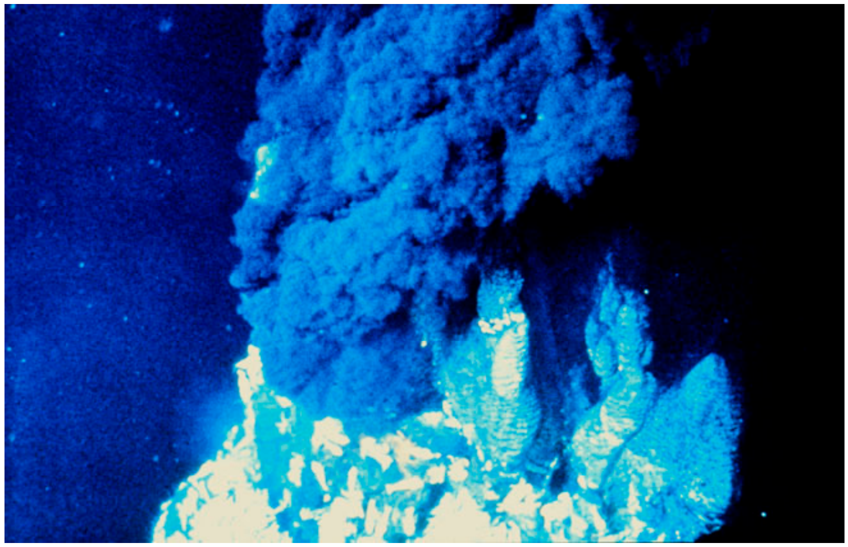

Figure 1: A high-temperature "black smoker" hydrothermal vent emitting super-heated vent fluid at approximately 350°C from the floor of the Mid-Atlantic Ridge.

Individual high temperature vents at mid-ocean ridges may only be ~10cm in diameter at their mouth, yet over time, growing like stalagmites from the sea floor, they can form chimneys anywhere from 1m to 30m tall. A typical vent-field might comprise several such chimney structures spread out over an area ~100m across. Throughout this area, there may also be a number of lower temperature vents emitting hot shimmering water from the seabed. Even these vents are as hot as 10-30°C that is notably warmer than typical deep ocean water (2-3°C). It is near these warm and more diffuse emissions that the majority of vent-specific biota is most abundant.

3. The Global Distribution of Seafloor Hydrothermal Venting

3.1 The influence of spreading rate for seafloor hydrothermal venting

Although the global mid-ocean ridge extends as a near-continuous 60,000km volcanic chain that girdles the entire planet (Fig.2), it does not exhibit the same activity everywhere.

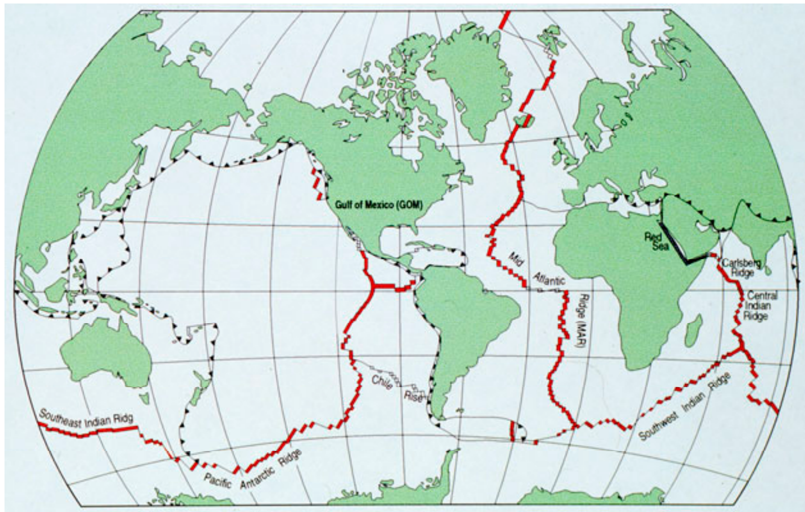

Fig. 2 Schematic diagram showing the location of the global mid-ocean ridge crest (coloured red) that measures ca 60,000km in extent – the largest single geological feature on the earth.

Instead, the rate of plate spreading is fastest (hence, the rate of fresh magma supply is greatest) across much of the Pacific Ocean (typically 10-20cm/yr) with intermediate spreading rates in the Eastern and Central Indian Ocean and the North Eastern Pacific Ocean (5-7cm/yr). Spreading rates are much slower in the Atlantic Ocean (2-3cm/yr) and along the South West Indian and Arctic Ridges (<2cm/yr). It is perhaps no coincidence, therefore, that the first seafloor hydrothermal vents were discovered along the fast spreading East Pacific Rise (Spiess et al., 1980). By contrast, it took almost a decade of further research to find the first "black smoker" site on the slow-spreading Mid-Atlantic Ridge (Rona et al., 1986). Indeed, for some years, one line of thought was that hydrothermal activity could not occur at ridges that exhibited less than some (undefined) threshold-spreading rate. This has since been disproved, however, with the discovery of hydrothermal vent signals even along the SW Indian Ridge, one the world's very slowest-spreading ridge crests (German et al., 1998). What remains the case, however, is that the abundance of hydrothermal venting along the global ridge-crest does seem to correlate, to a first approximation, with spreading rate (e.g. Baker et al., 1986). Thus, hydrothermal activity is most abundant along the Southern EPR followed by the Northern East Pacific Rise, the Juan de Fuca Ridge (North

East Pacific Ocean), Central Mid-Atlantic Ridge and South West Indian Ridge (Figure 3).

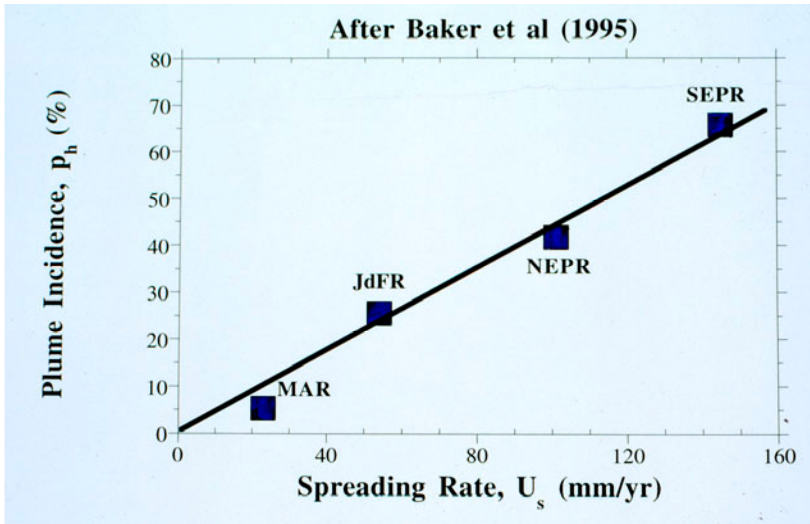

Figure 3. Plot of incidence of hydrothermal plume activity (i.e. what proportion of any mid-ocean ridge section is overlain by a detectable neutrally-buoyant hydrothermal plume) versus full spreading rate for all of: the central Mid-Atlantic Ridge (MAR); the Juan de Fuca Ridge (JdF), the North East Pacific Rise (NEPR) and the South East Pacific Rise (SEPR). After Baker et al. [4, 28].

3.2 Secondary effects: Ridge Segmentation and Hot Spots

Although spreading rate can account for much of the variability seen in the abundance of hydrothermal venting worldwide, it cannot explain everything. In recent work, we have studied the incidence of hydrothermal activity along three different sections of the Mid-Atlantic Ridge between Iceland and the equator, which exhibit markedly different abundances of venting, all at the same spreading rate. The first section, between approximately 15°N and 30°N exhibits approximately one vent site every 100-150km along axis, consistent with the predictions from spreading rate alone (Figure 4).

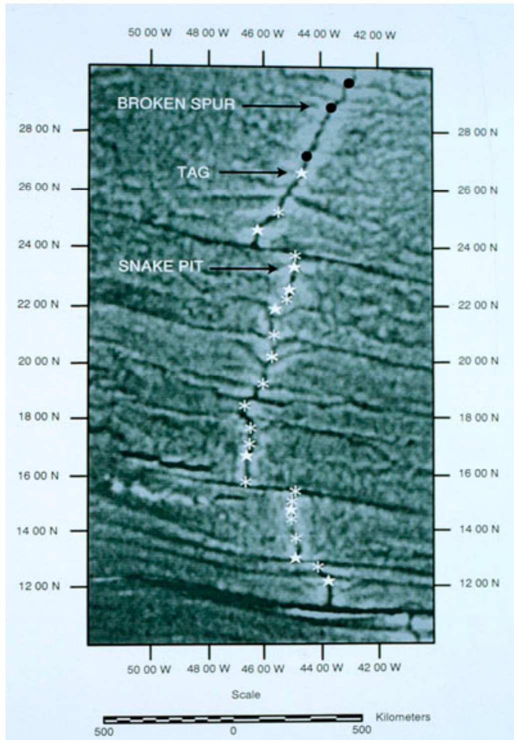

Figure. 4: Distributions of hydrothermal activity detected along the central Mid-Atlantic Ridge (15°N-30°N) superimposed upon the pseudo-bathymetry derived from satellite altimetry by Sandwell & Smith [29].

By contrast, a survey of the 600km of the Reykjanes Ridge south of the Iceland hot spot revealed evidence for only one hydrothermal system (German et al., 1994) despite the increased magmatic budget that occurs as the Mid-Atlantic Ridge and this underlying mantle plume coincide (Figure 5).

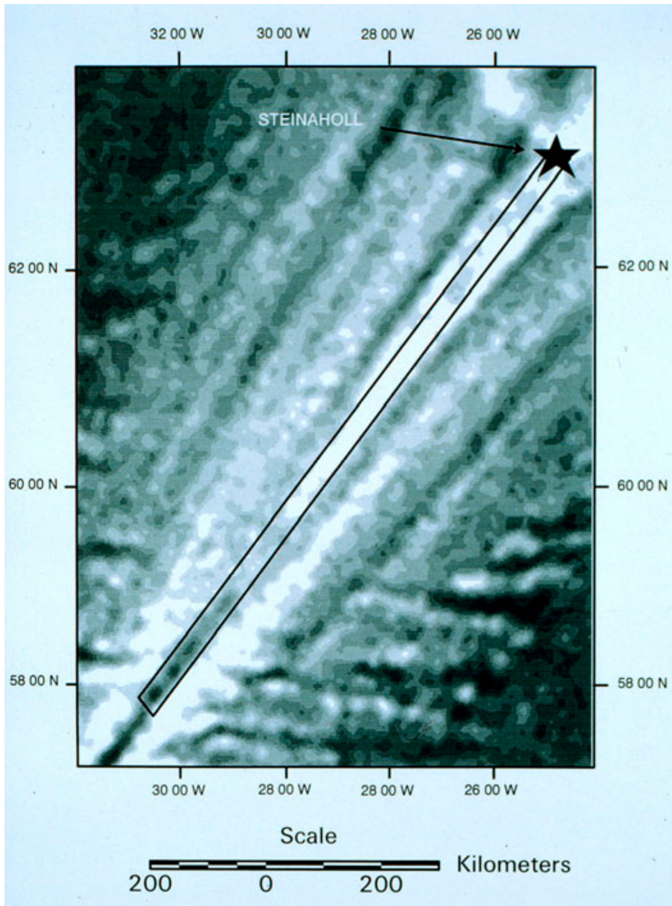

Figure. 5: Distributions of hydrothermal activity detected along the Reykjanes Ridge superimposed upon the pseudo-bathymetry derived from satellite altimetry by Sandwell & Smith [29].

The same is not the case near the Azores islands however, where another plume-ridge interaction has occurred. In that case, much higher than predicted activity occurs (Figure 6) with hydrothermal plumes arising approximately every 20km along axis (German et al., 1996).

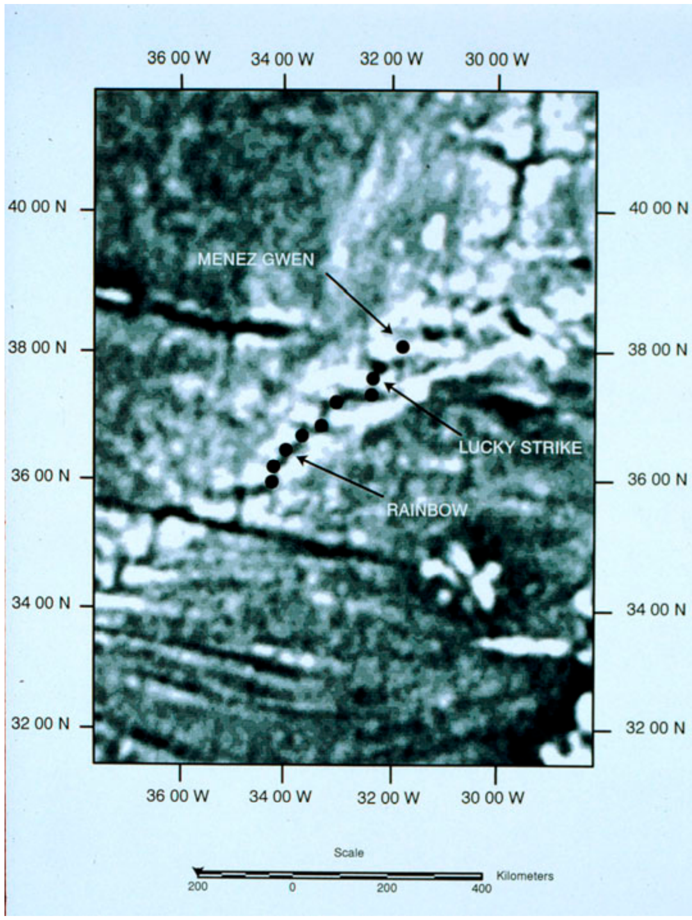

Figure 6: Distributions of hydrothermal activity detected along the central Mid-Atlantic Ridge near the Azores Triple Junction (35°N-40°N) superimposed upon the pseudo-bathymetry derived from satellite altimetry by Sandwell & Smith [29].

One of these sites has been studied in detail - the Rainbow hydrothermal field, which lists among the few largest massive sulphide deposits yet located in the North Atlantic Ocean (Fouquet et al., 1997). Intriguingly, this deposit is also located in an entirely new geological setting. It does not occur where freshest lava out-pouring have occurred, at the centre of a ridge segment but, instead, is found at the intersection between a segment of ridge axis and the offset or fracture zone that connects that segment of the

Mid Atlantic Rise crest to the next one (German & Parson, 1998). In fact, of the seven different hydrothermal fields located as part of our Azores hydrothermal study, four including Rainbow were found in this novel geologic setting (Figure 7).

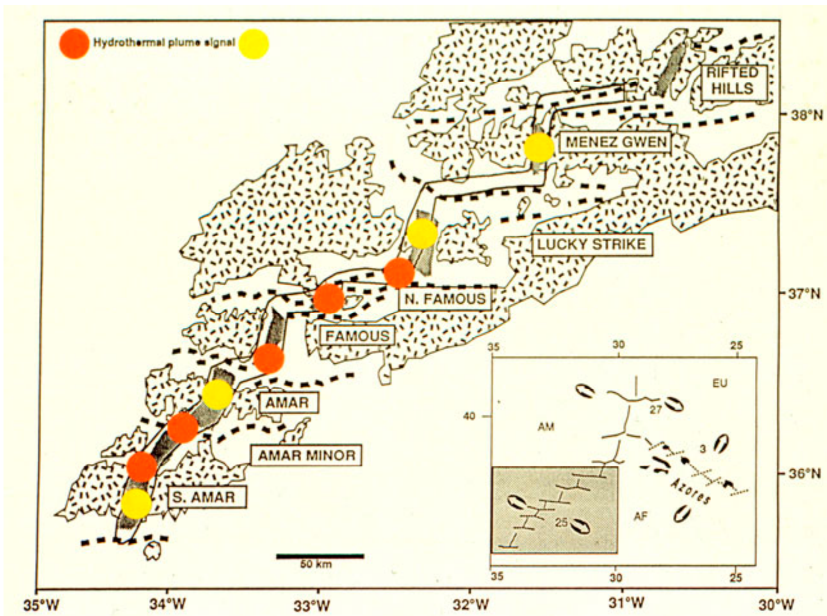

Figure 7: Line drawn map of the MAR near the Azores Triple Junction. Locations of detected hydrothermal plume signals and/or active vent sites are shown by coloured circles. Yellow: "conventional" volcanically hosted systems. Orange: novel fault-controlled environments within non-transform ridge discontinuities [7, 9,10].

What is clearly the case, therefore, is that one does not simply require a fresh volcanic eruption (heat source) to establish seafloor hydrothermal circulation. If one includes the Reykjanes Ridge and Azores Triple Junction data in our previous plot, we now find that a range of different vent abundances can arise at constant spreading rate (Figure 8).

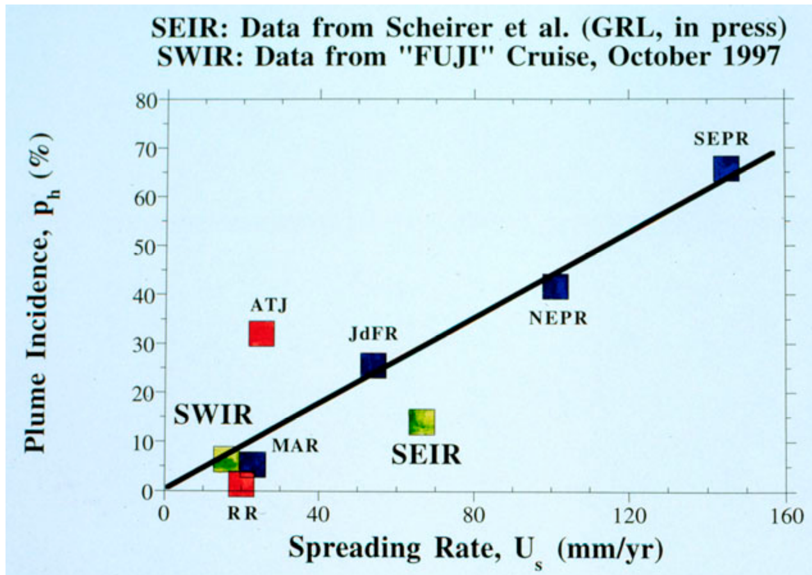

Figure.8: Plot of incidence of hydrothermal plume activity versus full spreading rate (cf. Fig.3) but now also including the Reykjanes Ridge (RR) and the mid-Atlantic Ridge near the Azores Triple Junction (ATJ), both coloured red, and the SW Indian Ridge (SWIR) and the SE Indian Ridge (SEIR), both coloured green.

Further, we do not believe this to be a purely random distribution. Recently, Cannat et al. (1999) have shown that the Azores Triple Junction was extremely volcanically active approximately 10 million years (Ma) ago. At that time, the ridge topography around the Rainbow area would have been very similar to that seen along the Reykjanes Ridge today. It seems highly plausible; therefore, that it is precisely because this "swollen" ridge crest has subsequently cooled, subsided, and become so extensively cracked/faulted, that the abundant ridge-crest hydrothermal circulation now observed has been developed. Along the Reykjanes Ridge by contrast, continuing high levels of melt generation, subsurface, continue to warm and buoy up the overlying crust which remains ductile, not brittle, thereby reducing the efficiency of hydrothermal cooling and circulation through this section of ridge crest (German & Parson, 1998). If this hypothesis is correct then it may also explain why the only other study of hydrothermal activity near a fresh and active hot-spot -near the Amsterdam-St. Paul's plateau of the South East Indian Ridge (Scheirer et al., 1998) - also shows an anomalously low incidence of hydrothermal venting for its measured spreading rate (*cf* the Juan de Fuca Ridge; (Figure 7).

3.3 The significance of slow-spreading ridges

Whilst the long-term impact of hot-spot effects may remain speculative for now, however, what is undeniable is that deep penetrating faults which allow seawater to penetrate deep beneath the seafloor, and not just fresh outpourings of lava onto the seafloor - can lead to high-temperature circulation. Further, whilst volcanically hosted systems have a finite supply of heat and, hence, a finite lifetime during which high-temperature circulation can be established, the cross-cutting fault structures at segment ends have great potential to both a) focus hydrothermal up-flow at a single point on the seafloor and b) continuously reactivate themselves through movement along the fault zone, reopening cracks and propagating into fresh unreacted ridge-crust. It is these latter structures, therefore, which might be most productive in terms of seafloor massive sulphide production and, again, it is probably no coincidence that both the TAG and Rainbow hydrothermal fields host large fault-controlled massive sulphide deposits distant from any fresh neovolcanic activity (German & Parson, 1998).

Thus, although the majority of currently active hydrothermal fields in the modern ocean may occur along fast spreading ridges, it may well be that the most economically interesting (i.e. largest) concentrations of polymetallic sulphides are actually produced in fault-controlled hydrothermal systems along slow spreading ridges. And if faulting can play an important part in controlling the distribution of hydrothermal venting at ridge crests, as well as fresh volcanism, then the scope exists for there to be important hydrothermal circulation systems throughout all the world's ocean ridge systems and not just along the fast spreading ridges - which only make up a minority of the total 60,000km of global ridge-crest.

Spurred on by this finding, we have already located the first evidence for hydrothermal activity along part of the South West Indian Ridge (German et al., 1998) - one of the two very slowest spreading ridge crests on Earth. Thanks to a combination of French and US research programmes already scheduled for the coming 2000/2001 Austral summer, a preliminary evaluation of this entire ridge will be completed by Spring 2001. In parallel, new international research promises to investigate and evaluate the importance of hydrothermal activity on the slowest and most remote of all ridge sections, the Arctic ridges, over the same time frame. Autumn 2000 will see the first expedition to the Knipovich Ridge, north of Iceland and immediately south of Spitsbergen, to search for hydrothermal activity. The expedition is a joint Japanese-Russian research programme with additional participation from US, UK and other European researchers. In Autumn 2001 and even more ambitious 2-icebreaker expedition is proposed, using the new US Icebreaker "Healy" and Germany's R/V "Polarstern" to investigate the presence and abundance of hydrothermal venting along the Gakkel Ridge which extends north of Spitsbergen, directly across the floor of the ice-covered Arctic Ocean basin.

4. Searching for hydrothermal vents.

4.1 Background - hydrothermal plumes

When "black-smoker" type hydrothermal fluids erupt from the seafloor they mix turbulently with the surrounding ocean to generate a buoyant mineral-laden plume. This plume continues to ascend, becoming progressively diluted with ambient seawater as it rises, until a stage is reached at which the plume is no longer buoyant and can rise no further but, instead, is disperse laterally by the prevailing deep-ocean currents at that depth (Speer & Rona, 1989). A simple and commonplace analogy is the effect seen by the smoke rising above a factory chimney on a windy day. Initially the smoke rises near-vertically but, increasingly, it is seen to be bent-over by the prevailing wind direction as it rises.

Typically, in the deep-ocean, the height-of-rise achieved by a black smoker hydrothermal plume is of the order of 100-300m, the time taken to rise this far is short (approx. 1 hour) and the dilution factor of vent-fluid: ambient seawater is typically ca. 10,000:1. While such pronounced dilution is sufficient to obliterate (or at least confuse) and primary physical (e.g. temperature, heat) anomalies from the original vent-fluid, a range of chemicals are typically at least one million-fold enriched over seawater in vent-fluids meaning that, even at the top of the rising hydrothermal plume, they are still 100 times more concentrated than normal seawater. Prime examples of this are: iron (Fe), manganese (Mn), methane (CH4) and a particular isotope of helium (He-3). Strong potential exists to prospect for enrichments of any or all of these tracers in the deep water column above ridge crests, therefore, to detect evidence for new sites of hydrothermal activity.

4.2. Chemical Prospecting

From a "purist" point of view, the ideal tracer is helium (He_3) because it is geochemically inert once it has erupted from a vent-field and therefore its trace in the water column can persist over very long distances - for example one plume from the South Pacific could be detected at constant latitude over 2000km West, away from the ridge-crest (Lupton & Craig, 1981). In practice, however, dissolved helium (He_3) measurements in seawater require a systematic water-sampling programme at sea followed by laborious analysis in a specialist noble gas mass spectrometry laboratory on shore - which means, typically, that any evidence for a new hydrothermal site could not be found until 6-12 months after the survey was completed! This is far from ideal. Dissolved Manganese (Mn) and methane (CH_4), by contrast, offer much greater promise. Although one can sample for these tracers, as for helium (He_3), for subsequent shore based analysis it is also possible to routinely take the necessary laboratory instrumentation for dissolved Mn and (CH_4) analyses to sea. Thus, sampling equipment can be lowered to the seafloor beneath a survey vessel, a series of samples from different (near-bottom) water depths can be collected in the order of an hour or two, and a complete analysis of those samples can be expected within a matter of hours, rather than months, of the samples arriving on deck, greatly accelerating the survey potential of a research cruise (see e.g. Klinkhammer et al., 1986; Charlou et al., 1988; Gamo et al., 1996). Perhaps the simplest and most elegant tracer that can be exploited, however, is Iron (Fe). The dissolved Fe erupted from a hydrothermal vent does not remain in solution. Instead, it is quantitatively precipitated out before it reaches the top of a buoyant hydrothermal plume as a combination of sulphide and oxide mineral particles. Because they are so very fine-grained, however, these particles do not immediately sink to the seabed but, instead, are dispersed within the neutrally-buoyant hydrothermal plume which, therefore, has the characteristic of being optically much more cloudy than the remainder of the (both underlying and overlying) deep-ocean (Figure 9).

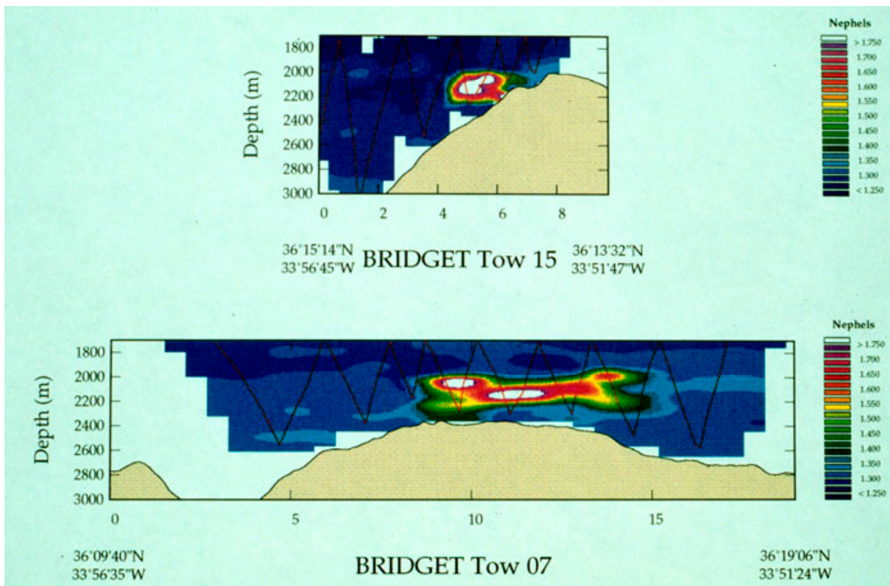

Figure 9 Examples of nephelometry (optical back-scatter) cross-sections detected from a deep-sea hydrothermal plume at the Rainbow vent-site, 36°N, MAR

This characteristic of hydrothermal plumes was first demonstrated by Nelsen et al (1997) who used an *in situ* optical back-scatter instrument (a nephelometer) connected to a standard water-sampling instrument package to show a linear correlation with shipboard dissolved Mn analysis of the water samples taken - but with the added advantage that the nephelometer data were obtained both continuously and in real-time. For obvious reasons, use of *in situ* optical sensors has subsequently become a staple method or preliminary investigation for seafloor hydrothermal circulation.

4.3 Modern instruments of choice

The most popular current method for locating new sites of hydrothermal activity is to use an integrated geophysical and geochemical approach. First, one requires a pre-collected multibeam swath bathymetric map of the given work area, to navigate by. Once that is obtained, an optimal approach is to deploy a deep-tow sidescan sonar instrument (this author has experience with both the WHOI DSL 120 system, USA and the SOC TOBI 30kHz system, UK) equipped with *in situ* real-time continuous optical backscatter sensors. Towed at 100-300m above the seafloor, these instruments are, thus, poised at exactly the right height off-bottom to intercept particle-laden "black-smoker" type hydrothermal plumes that may exist and, whenever such signals are intercepted, can also provide a detailed geological sidescan sonar image of the immediately underlying seafloor which hosts the high-temperature hydrothermal field. Our experience has shown that, allowing for a double-pass along any section of ridge crest, a one-month unit of ship time devoted to these operations should be able to provide 100% survey coverage of ca. 200km of ridge-crest with a return of ca. 6 new potential sites of high-temperature hydrothermal activity (German et al., 1996, 1998, 2000).

This first survey of a ridge area will not take you immediately to an active area of venting, however. More likely is that it will narrow down an area of search from approximately 200km of previously unexplored ridge-crest to an area 2-5km across within which the source field lies. To more precisely locate the active site of venting requires detailed systematic lowering of a conventional CTD-system along a grid-like pattern (e.g. Klinkhammer et al., 1986) or, better, a tow-yo survey using (e.g.) the purpose-built BRIDGET instrument, developed at Southampton Oceanography Centre, that can both map out and sample a hydrothermal plume in 3-dimensions (Rudnicki et al., 1995). Following identification of the Rainbow hydrothermal plume from TOBI in 1996 (Fig.10) (7) a further 7 days of survey with BRIDGET in 1997 were sufficient to both i) map out the far-field dispersion of this plume over 20-30km downstream and ii) identify the source of venting for this pronounced hydrothermal field to within ±100m on the seabed (Figure 11) (21).

Figure 10: The Southampton Oceanography Centre's deep-tow sidescan sonar instrument TOBI being prepared for launch from the RRS Charles Darwin at the Mid-Atlantic Ridge

Figure 11: The Southampton Oceanography Centre's deep-tow hydrothermal plume instrument BRIDGET being prepared for launch from the RRS Charles Darwin at the Mid-Atlantic Ridge

The latter achievement was particularly important because it meant that the first active investigation of chimneys at the vent-site could commence on the very first research dive with a manned submersible to that site, later in that same summer. A more typical experience, previously, had been that researchers would waste valuable time at new vent-sites diving blindly across the seafloor in search of the actual site of venting.

5. Resource Evaluation

Once a new hydrothermal site has been located, as described above, the problem of evaluation of that deposit's resource potential must commence. In many cases, this will typically be initiated through investigation by either tethered or manned deep-ocean vehicles. For example, a deep-towed camera system may be used to complete a thorough gridded over-flight survey to provide a 100% coverage image determining the full extent of the sulphides deposit (at least in 2-D). Alternately either a manned submersible or a tethered ROV (remotely operated vehicle) may be lowered to the seabed to conduct both detailed sampling and mapping of the seafloor exposures of the sulphides deposit. Any further characterization of the 3-dimensional nature and/or extent of such a structure can also be conducted, albeit at considerable cost.

In the future, it is to be anticipated that full-ocean depth AUV's (Autonomous Underwater Vehicles) will also be able to complete this work extremely efficiently. Such systems could be equipped with *in situ* optical and chemical instruments to first map out the 3-dimensional distribution of a neutrally-buoyant plume to locate fresh vent-sites, to conduct detailed imaging of the seafloor using a combination of digital photography and/or co-registered hi-resolution side-scan sonar and multi-beam bathymetry, and perhaps also to use high-resolution 3-component magnetometer measurements to determine constraints on the subsurface structure/extent of the located massive sulphides body.

In the meantime, simple analysis of plume characteristics of any new hydrothermal field may also provide important and inexpensive first-order information concerning the nature of the hydrothermal fluids erupting at depth that, in turn, exhibit a pronounced influence upon the particles collected from hydrothermal plumes overlying an extensive section of the northern East Pacific Rise. Feely et al. [22] used the simple measure of (Iron) Fe: (Sulphur) S: (Copper) Cu to accurately predict the relative proportions of oxide material, polymetallic sulphides material and biogenic material being erupted from a range of vent-sites between 9°N, and 11°N, whose actual vent-fluid characteristics were only subsequently confirmed, at much greater cost, following a dedicated series of sampling dives conducted by the deep submersible research vehicle “Alvin”. Thus, careful, but reasonably straightforward analysis of hydrothermal material collected as part of any surface-ship investigation of a new hydrothermal field can provide important and potentially insightful information concerning the nature of the sulphides deposit forming at depth, at relatively little additional research cost.

Another key aspect of initial data gathering that can provide important information is a regional (5-10km) scale side-scan sonar image of the area hosting the detected hydrothermal source. I have described, previously, the difference between volcanically-hosted and fault-hosted hydrothermal systems and the likelihood that the latter should give rise to larger massive sulphides deposits focussed at a single location whereas the former more probably generate a series of much smaller sulphides deposits dispersed across a wider area of the ocean floor within a mid-ocean ridge rift valley. However, simple chemical analysis of a hydrothermal plume’s characteristics would provide no such information that would allow one to distinguished such obvious differences in resource potential. Nor, strikingly, would hull-mounted swath bathymetry collected from a surface ship survey – as was demonstrated by the erroneous early identification of the non-transform discontinuity between the AMAR and S. AMAR segments as an additional volcanically active ridge segment. These important differences can readily be discerned by co-registered collection of water column hydrothermal plume data, however, together with sidescan sonar images of the underlying seafloor. Figure 12 shows a portion of a typical volcanically active segment centre from the Mid-Atlantic Ridge rift valley that might be expected to host a short-lived (ca 10-100 yrs) hydrothermal system linked to the most recent episode of volcanic eruption and measuring only some tens of metres in diameter.

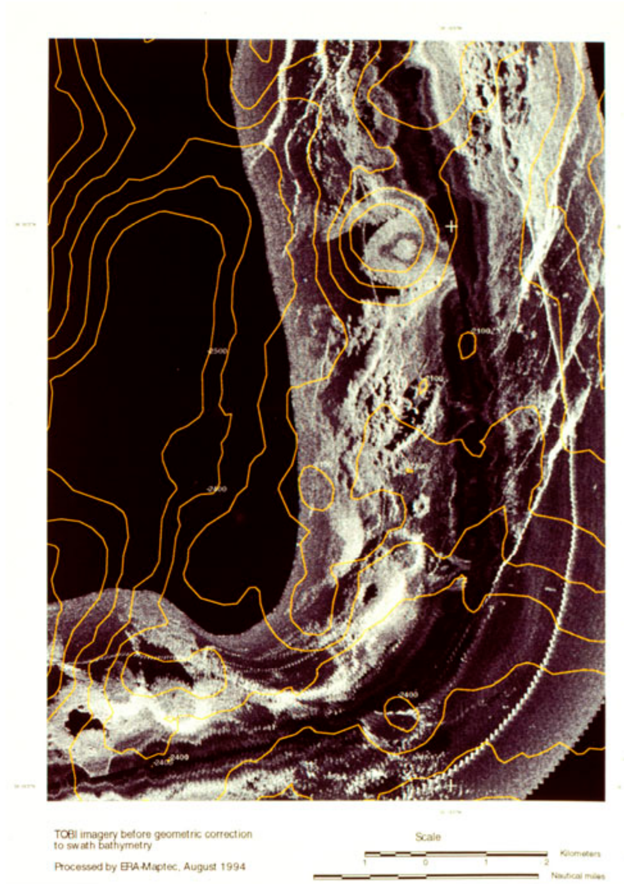

Figure 12: TOBI sidescan sonar image of a volcanically active segment centre on the Mid-Atlantic Ridge at approximately 38 degrees North, near the Azores Triple Junction.

By contrast, Figure 13 shows the intensely fractured seafloor which hosts the Rainbow hydrothermal field at 36°15′N, a deposit that extends approximately 100m x 300m across the seabed and which, best recent estimates indicate, has been maintaining its current rate of hydrothermal discharge (the single largest source of hydrothermal activity currently known throughout the North Atlantic Ocean) throughout the past 18,000 years [23]. Clearly, such markedly different sidescan images may prove that hydrothermal plume signals may be expected to host respectively small or large individual seafloor hydrothermal sulphides deposits.

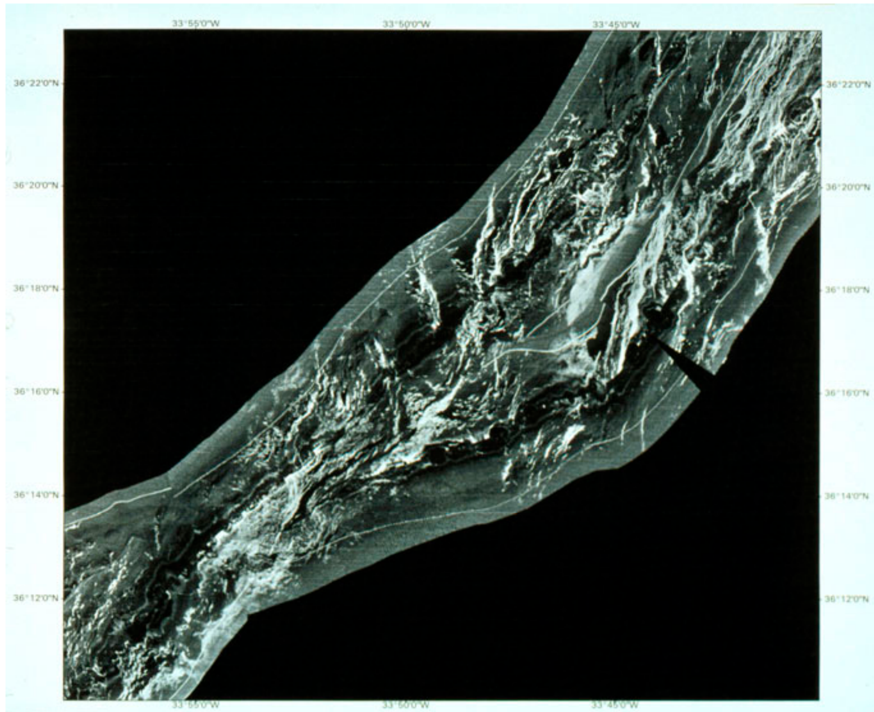

Figure 13: TOBI sidescan sonar image of the highly tectonic non-transform discontinuity which offsets two adjacent segment centres on the Mid-Atlantic Ridge and hosts the pronounced Rainbow massive sulphides hydrothermal deposit at approximately 36 degrees North, near the Azores Triple Junction.

6. Limitations to the Current Approach

A limitation to the majority of the investigative processes described above is that they focus primarily on "black-smoker" type hydrothermal sources, the typical sulphides-forming systems throughout the deep mid-ocean ridges of the Area. By their very nature, however, these systems can be seen to be rather inefficient in terms of generation of massive sulphides deposits because a substantial proportion of the metal-rich mineral precipitates formed are not deposited and, instead, are dispersed widely to the surrounding seafloor as sediments by hydrothermal plumes. There are unusual systems, however, where this does not occur and, instead, relatively "spent", clear; metal-free fluids are erupted from the seabed. Although such plumes would not be detected using *in situ* optical sensors, they can nevertheless be detected by relying on chemical indicators of dissolved volatiles/gases, most notably methane, which has led to the detection of both the Steinaholl and Menez Gwenn hydrothermal areas on the shallow Reykjanes Ridge and the shallow Mid Atlantic Ridge near the Azores Triple Junction, respectively [6, 24].

The first mechanism by which such clear fluids might be formed is through a process called "phase separation". In much of the deep ocean the pressure and temperature conditions encountered at and below the seafloor are such that, despite the high temperature achieved, vent-fluids remains as a single liquid phase because of the confining pressure (typically 200-300 times atmospheric pressure). In sufficiently shallow systems, however, the confining pressure is reduced such that, at depths below approximately 1800-1700m a two-phase stability field for seawater-like fluids is encountered leading to separation into i) a dense, metal-laden brine-like fluid which is retained within the ocean crust and ii) a vapour phase, close to fresh, distilled-water in composition enriched in many of the dissolved gases initially present in the original vent-fluid. It is this latter "vapour-phase" fluid which is erupted from the seabed (examples are Axial Volcano, Juan de Fuca Ridge; Steinaholl, Reykjanes Ridge; Menez Gwen and parts of Lucky Strike, and the Mid-Atlantic Ridge near the Azores Triple Junction). In such cases, it is anticipated that the conjugate metal-laden brine phase is retained within the ocean crust where saturated solutions may be formed leading to extensive solid-phase sulphides precipitation. No such systems have yet been positively identified in the geological record, however, and the potential for recovery – from what would almost certainly be a rock hosted hydrothermal system – would appear to be highly problematic.

Following the above approach we have been able to demonstrate that with only on the order of 30 days of scientific ship time it is possible to both conduct a preliminary broad-brush survey, locating all likely hydrothermal sources along a 200 km length of mid-ocean ridge crest, and to complete the near-filed follow-up survey work required, in at least one area, to more precisely locate the exact source of venting for more detailed seafloor investigations. Such investigations include camera surveys, manned or unmanned research for active polymetallic sulphides deposits along all the mid-ocean ridges that span the deep ocean basins throughout the Area.

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SUMMARY OF PRESENTATION AND DISCUSSIONS ON CURRENT NATIONAL AND INTERNATIONAL PROGRAMMES OF EXPLORATION FOR SEAFLOOR MASSIVE SULPHIDES DEPOSITS AND STATE-OF-THE-ART TECHNIQUES AND OPERATIONS IN EXPLORATION

Presentation

Dr Chris German of the Challenger Division for Seafloor Processes of Southampton Oceanography Centre expressed his appreciation for having the opportunity to address the workshop. He introduced himself as a member of an organization called Inter Ridge that he described as an organization made up of scientists from about 20 different nations who have decided to agree to collaborate on an academic level on those aspects of mid-ocean ridge research, which are most difficult to address on an individual or single nation basis. He pointed out that both Dr Kim Juniper (Canada) and Dr Peter Herzig (Germany) who were participating in the workshop are also members of this organization. He said based on the above considerations, a large part of Inter Ridge's work tends to be focussed on the most remote parts of the world's mid-ocean ridge system. Dr German explained that the organization is divided into about half a dozen different working groups on particular issues. He said that within Inter Ridge, he is Chairman of the Working Group on "Understanding the Global Distribution of Hydrothermal Activity." He also said that the group's function is to coordinate international research on the mid-ocean ridge, to look at hydrothermal activity there, and to identify where it occurs.

Dr German informed participants that his presentation on " Current national and international programmes of exploration for seafloor massive sulphides and state-of the-art techniques and operations in exploration " would contain some information on the working group's functions starting with images of black smokers, information on the geological controls that determine where hydrothermal vents occur around the world's ridge crest, information on whether or not hydrothermal vents are evenly distributed, and how one actually goes to a new part of the ocean that nobody has looked at before, and conducts a search for hydrothermal activity. Following this, Dr German said that his presentation would describe how one assesses the resource potential of hydrothermal sites, and the type of baseline information that may be gathered during a preliminary survey of an area.

With regard to hydrothermal vents in the deep sea, particularly in the Area, Dr German said that they are to be found typically at depths of a few thousand metres. He described the phenomenon of a hydrothermal vent as comprising seawater circulating down through fractured seafloor towards the oceanic crust where it reacts with fresh volcanic lava, expanding and suffering a loss in viscosity. At temperatures of 350 to 400 degrees centigrade, the clear hydrothermal fluid formed in the reaction rises to the seafloor and erupts as sulphides chimneys. Dr German described the fluid as very hot and very acidic and saturated with metals. When the fluid comes to the seafloor and begins to mix with ordinary seawater, it is first cooled, quenching the fluid and thus precipitating sulphide minerals, and with oxygen contained in ordinary seawater, produces reactions that result in smoke that is manifested as black and white "smokers".

From an academic point of view, Dr German said that one of the reasons for looking at hydrothermal activity around the world's oceans is to obtain an understanding of the life forms around them. He said that in the Pacific at these sites, the life forms are actually living in simmering water. He showed pictures of tubeworms that are characteristic of the Pacific Ocean which grow up to eight feet long, and which are actually drawing on the dissolved hydrogen sulphide coming out of hydrothermal systems and cultivating sulphide oxidising bacteria inside their plume. He further stated that the tubeworms draw hydrogen sulphide (H_2S) through red plumes; the red colour coming from the haemoglobin, the same as found in human blood. Effectively, he continued, the tubeworms draw hydrogen sulphide into their gut where they have colonies of bacteria that react with carbon dioxide to fix organic carbon, producing foodstuffs for them to live on.

Dr German pointed out that no one expected to find these life forms when they were first discovered in the 1970s in the Pacific Ocean. Their significance he also said is that they actually produce a base of a food chain on the seafloor that is independent of sunlight. In the Atlantic Ocean, he referred to shrimp that are found at black smoker hydrothermal fields. He said that each shrimp is about as long as a finger, maybe just a few centimetres long, but because the shrimp are found in large quantities, it's a different way of accumulating huge biomass at any one site. At any hydrothermal field, he noted there is very low biodiversity. He emphasized that at any field, while there isn't a huge range of species there are species that have adapted and that cope with these environments, proliferating in their present state in huge abundances.

Turning his attention to the mid-ocean ridges, Dr German said that the mid-ocean ridges were the driving forces of plate tectonics in every major ocean basin. The whole chain, he noted, starts in the Arctic Ocean and extends through the Atlantic Ocean, the Indian Ocean out to the Pacific Ocean, about 60,000 kilometres of almost one continuous geologic feature. He also said that the mid-ocean ridge system is not only the largest single geologic feature on the earth but that it might also be the largest ecosystem. Through biogeography he further noted, while scientists can determine that different species live in different parts of the system, they still do not know what lives in most of the world's ocean basins and hydrothermal sites, because they haven't been to these areas to look for the associated biodiversity.

Dr German informed participants that when he started working in this field there were only two known hydrothermal sites: the site at the northern-east Pacific rise and the site at the Galapagos rift. He also informed participants that the prevailing scientific theory until the early 1980s was that hydrothermal activity occurred only on fast spreading ridges. In this regard, he pointed out that not all the world's ridges spread at the same rate. The east Pacific rise for example spreads pretty fast, at about 10 centimetres a year and rising to about 20 centimetres a year in certain areas. On the other hand, the entire ridge system of the Atlantic Ocean only spreads at about 2-3 centimetres per year. Based on this hypothesis, if one ridge is spreading 10 times faster, it means that it is having 10 times as much volcanic activity at any one time, so the amount of heat that is being produced is 10 times greater.

With regard to the larger numbers of hydrothermal vent sites that have been discovered in the Pacific Ocean as compared to discoveries in the Atlantic and Indian Oceans, Dr German suggested that in addition to the hypothesis regarding hydrothermal activity and faster spreading ridges, the proximity of hydrothermal sites in the north Pacific Ocean to research bases in the United States and Canada, could not be overlooked. He said that the dearth of research to discover hydrothermal sites in mid-ocean ridges south of the equator has created a huge gap in the international community's knowledge of possible hydrothermal activity on ridges in this region. He noted that because of concerted efforts by a combination of US and Japanese researchers in the southeast Pacific rise since the latter part of the 1990s, new hydrothermal fields had been found in this region. In addition to these efforts, Dr German mentioned the efforts undertaken in this regard by Inter Ridge's Working Group on " Understanding the Global Distribution of Hydrothermal Activity" in fulfilling one of its missions, that of addressing all other ocean basins, the southern half of the Atlantic, the entire Indian Ocean and large parts of the south Pacific, that remain unexplored.

Dr German outlined the scope of Inter Ridge's work in this subject area since the mid-1990s when the Working Group was established. He informed participants that upon its establishment, the Working Group, based on the hypothesis that hydrothermal activity is favourable only on the fastest spreading ridges, tried to determine how often hydrothermal vents occur along a ridge crest and the spacing between these sites. He informed participants that different ways were found to determine the location of vents on a ridge crest. With this information, the group tried to determine whether or not there was a direct correlation with the spreading rates of four mid-ocean ridges. These were the southeastern Pacific rise, the northeastern Pacific rise, Juan de Fuca ridge and the mid-Atlantic ridge.

In relation to spreading rates at various ridges, Dr German pointed out that based on data obtained from the North American and Japanese collaboration on the south eastern Pacific rise in the 1990s, it has been determined that this is the fastest spreading ridge presently known. The next fastest spreading ridge he said is the northeastern Pacific Rise, followed by the Juan de Fuca Ridge, and then the Mid-Atlantic Ridge. Based on the hypothesis, he said that as a first approximation, if you knew what the spreading rate of a given ridge is, then you could predict whether you would have hydrothermal activity on it. From another perspective, if you could only have abundant hydrothermal activity on the fastest ridges, then large parts of the world's ocean basins are places that you could immediately then turn around and decide were uninteresting with respect to hydrothermal activity. Because of their studies, it has been revealed that this is not necessarily the case.

With slides, Dr German illustrated their findings with respect to vent sites and spreading rates in three areas. In an area of the mid-Atlantic ridge between 10 degrees and 30 degrees north, there was evidence of hydrothermal activity at a spacing of 150 kilometres. In an area just south of Iceland on the Reykjanes Ridge with exactly the same spreading rate as at the mid-Atlantic ridge above, Dr German stated that very little hydrothermal activity was found. Finally, in a third area just south of the Azores amidst significant faulting of the seafloor, Dr German showed many sites of hydrothermal venting.

He pointed out that in the central Atlantic a vent site was found about every 150 kilometres, that on the Reykjanes Ridge one vent site was found every 600 or 700 kilometres and that near the Azores the frequency was every 20 kilometres or so.

Dr German said that the Working Group was of the opinion that the incidence of higher hydrothermal activity on the mid-Atlantic ridge was because of fracture zones found along it that are not characteristic of fast spreading ridges. He described these fractures as deep-seated cracks that cause breaks in the ocean crust, which is still quite hot. As the seawater, percolates through these cracks Dr German said that it strips minerals back out of the rocks and causes hydrothermal circulation.

He therefore described these areas on the mid-Atlantic ridge as new settings away from volcanic activity that had not been previously anticipated as areas of hydrothermal activity. As a result of this discovery, he said that there are now two ways known for seafloor hydrothermal venting to occur: one related to fresh volcanic reaction (volcanically-hosted hydrothermal systems), and the second related to ridges cooling down, cracking up and forming fractures following volcanic activity. He also said that the fractures enable seawater to re-enter the earth's crust, stripping minerals from rocks and causing hydrothermal circulation (fault-hosted hydrothermal activity). Noting that the basic rock type in this reaction is very similar to the original rock type and that the seawater is the same, he pointed out that it would be the same kind of compositional material arriving at the sea floor and producing sulphides deposits. The process he further noted is very interesting because at these places even larger sulphides deposits may evolve.

As support for this theory, Dr German offered as examples the Rainbow field and TAG hydrothermal deposits on the mid-Atlantic ridge that are both products of fault controlled systems. He said that to his knowledge, both deposits are substantially larger than most of the other sulphides deposits found elsewhere on the world's mid-ocean ridges. Dr. German re-emphasised the findings of the Working Group firstly: that at faster spreading ridges the more hydrothermal signals and individual hydrothermal vent sites are to be found along the ridge crest. In this regard, he used as an example the southeastern Pacific rise. Secondly, he emphasised the effect of secondary controls such as fracturing that occurs at some of the vents in the mid-Atlantic ridge, in particular places like the Azores. He said that what appears to be happening there is that the ridge never cools down long enough to start cracking and the venting is on one single line, but that as one moves through the rest of the world's ridge crests this line basically broadens out into some big fan through the fractures formed at the slower spreading ridges. He postulated that it could be that all slower spreading ridges have quite a lot of hydrothermal activity. He noted however that most of the slower spreading ridges are in ridiculously remote places, which require some international coordination to actually get to go to them and to do the preliminary investigation.

In this regard, Dr German described international collaboration that has been planned in the Artic basin this year and next year. Based on a combination of French and American research programmes scheduled for the summers of 2000 and 2001, Dr German said that a preliminary evaluation a stretch of mid-ocean ridge from the Bouvet Triple Junction in the South Atlantic to the Rodrigues Triple Junction in the Central Indian Ocean basin will completed by Spring 2001. In parallel, he also said, an expedition by Japanese, Russian, American, British and other European researchers to the Knipovich Ridge that is north of Iceland and immediately south of Spitsbergen will be undertaken to search for hydrothermal activity. Finally, in the fall of 2001, an even more ambitious two-icebreaker expedition is proposed, using the new US icebreaker "Healy" and the German R/V "Polarstern" to investigate the presence and abundance of hydrothermal venting along the Gakkel Ridge.

Dr. German turned his attention to the properties of plumes that can assist prospectors in their search for hydrothermal activity and ultimately massive sulphides deposits. He recalled that high temperature hydrothermal plumes or high temperature hydrothermal vents produce hot fluids that rise out of chimneys that percolate up from the sea floor. With regard to the available technology for viewing this phenomenon, Dr. German pointed out that from a submersible, in general one can probably only see about 10 metres in any direction at best. In this regard, he informed participants that one of the properties of plumes that have been utilized to obtain a visualization of them from a greater distance in a submersible is their acoustic property. Dr. German said that the plume rises because the water that initially comes out of the vent is so hot that it actually has different acoustic characteristics from ordinary deep ocean water. He informed participants that Professor Rona and his colleagues had developed a technique to develop an acoustic image of the plume from these characteristics, allowing the plume to be detected from hundreds of metres away.

In relation to the rising plume, Dr. German pointed out that the plume does not rise forever and that at a point in its ascent, it loses it's buoyancy and flattens out. He drew an analogy with the smoke coming out of a factory chimney on a windy day. He pointed out that when the smoke first comes out of a chimney, it is very hot; it starts rising up and then it slows down. As it slows down, if there is any wind (current) blowing on a given day, it bends the smoke (plume) over, and disburses it downstream. The level at which the plume is no longer buoyant, according to Dr. German is called the level of neutral buoyancy. Depending on which way the current is moving; the plume is transported in that direction. Dr. German said that typically, plumes rise somewhere between a hundred and 300 metres above the sea floor as they are diluting themselves. He also said that this dilution factor tends to be about 10,000 to 1, making it very difficult to find any temperature or heat anomalies in the water column associated with them. On the other hand, he said that although the plumes have been diluted 10,000 fold, since the fluid itself was a million fold enriched in the first place, the material that rises and starts being blown away by deep ocean currents, is still a hundred times richer in all kinds of different chemicals than ordinary seawater. It is this characteristic that is employed in prospecting for manifestations of hydrothermal activity and thus associated massive sulphides deposits. Dr German identified four chemical anomalies commonly used in this search. These are helium, methane, manganese and iron.

Starting with helium Dr. German said that it is a noble gas; whose most common form is He_4 isotope, which is produced from radioactive decay. He said that there is also He_3 that is trapped inside the interior of the earth coming out where volcanoes erupt. One of the prime places it can therefore be found is in association with smokers from hydrothermal vents, and ultimately the plumes that they produce. Dr. German informed participants that helium in this form is inert and through measurements of its concentrations, one obtains an excellent tracer for hydrothermal activity.

According to Dr. German, the drawback with this prospecting method is the need to analyse samples with a noble gas mass spectrometer, which is a specialist piece of equipment not available on research vessels. This means that all samples have to be analysed at a land-based facility resulting in the loss of valuable ship time, and a delay in determining the precise location of a given anomaly. He noted that it could take up to six months to obtain the results of analysis and for the search to continue. To facilitate better use of resources and to know whether or not the station that a sample was taken from is close to or far from a potential hydrothermal field, Dr. German said that methane and manganese, which are also about a million-fold enriched in hydrothermal fluids, are being used as trace chemicals.

Dr. German said that the advantage of using methane and manganese as chemical tracers in the search for hydrothermal venting at mid-ocean ridges is that the necessary laboratory instrumentation for analysing dissolved methane and manganese in seawater can be carried out to sea. As a result, sampling equipment can be lowered to the seafloor, a series of samples from different near bottom water depths can be collected in about an hour or two, and a complete analysis of those samples can be expected within a matter of hours rather than months, greatly accelerating the survey potential of a research cruise.

With regard to iron, Dr. German described it as perhaps the simplest and most elegant tracer that can be exploited. He said that the dissolved iron erupted from a hydrothermal vent does not remain in solution and is precipitated out as a combination of sulphide and oxide mineral particles before it reaches the top of a buoyant plume. Because the particles are so finely grained however, they are dispersed within the plume and give the plume the characteristic of being optically more cloudy that the surrounding seawater. Using optical sensors, Dr. German said that that the iron in the disbursed plume can be detected very easily, much more simply than doing any kind of chemical analysis just by looking at the optical clarity of the seawater. The optical sensors are used to measure the light backscatter. A light source and a light detector are used. The light is shone out into the sea, and in the very clear seawater water, the light doesn't bounce off anything and the light disappears. If any iron particles are present in the seawater, light will bounce off those particles back to the detector and the measuring instrument will show a higher voltage reading. The voltage reading provides an indication of whether the iron particles are present, and whether or not the seawater is getting cloudier or lighter. Dr. German pointed out that this process is used as a directional aid and that if the measurements are taken continuously they provide real time data as the vessel moves along. Dr. German described this method of searching for hydrothermal venting as the method of choice in chemical prospecting.

Dr. German proceeded to describe integrated methods that can be used to locate new sites of hydrothermal activity. He said that these methods were a combination of geophysical and geochemical methods. He indicated that a good starting point is a multibeam swath bathymetric map of the proposed area. The map he said serves as a navigational tool. At the prospective area, he said that a deep-tow sidescan sonar instrument equipped with an *in situ* real-time continuous optical backscatter sensor should be deployed. Towed at between 100 and 300 metres above the seafloor, Dr. German said that these instruments were then optimally configured to intercept particle laden black smoker type hydrothermal plumes that may exist.

Dr. German showed slides of the Woods Hole Oceanographic Institution's deep tow survey system (TOSS) that is equipped with video and electronic still cameras, a dual frequency side scan sonar, acoustic current profiler, sub-bottom profiler, conductivity, pressure and temperature sensors, transmissometer, optical backscatter and hydrophones. He also showed slides of the Southampton Oceanography Centre's deep towed platform called BRIDGET, purposely built for the detection, investigation and sampling of hydrothermal plumes. Dr. German said that BRIDGET was conceived and designed by engineers and scientists from Southampton and the Department of Earth Sciences of the University of Cambridge. The vehicle deploys an array of sensors to 6,000 metres depth. The vehicle can be towed by a ship's conducting cable at speeds up to 2 knots. The basic suite of sensors carried is an FSI, micro-CTD, Nephelometer, Transmissometer, Niskin bottle water sampler, pumped filter systems and chemical sensors.

Dr. German described some of the intricacies of the work involved and insisted that because the plume did not disperse in a predetermined or systematic fashion, upon detection of the anomaly, some knowledge of the local physical oceanography is required.

Once a site is found, Dr. German suggested a number of ways to evaluate the site. One way that he suggested is the use of, for example, Woods Hole Oceanographic Institution's ARGO Deep Tow Camera system to determine the size of the site. Thereafter, Dr. German suggested the use of

ROVS, AUVs or submersibles to produce three-dimensional, photo mosaics of the sulphide deposit, and to sample the deposit.

Dr. German concluded his presentation with comments on prospecting for white smoker type hydrothermal systems and the knowledge gained in drilling feeder/ stockwork zones of seafloor massive sulphides.

Dr. German said that the investigative processes that he had described focus primarily on "black-smoker" type hydrothermal sources, the typical sulphides forming systems throughout the mid-ocean ridges of the Area. He noted however that these systems by their very nature are inefficient in terms of the generation of massive sulphides deposits because a substantial portion of the metal-rich precipitates formed are not deposited and, instead are dispersed widely to the surrounding seafloor and by the associated hydrothermal plumes. He described "white-smoker" type hydrothermal systems as much more efficient systems for the generation of massive sulphides deposits because much more of the metal-rich brine phase is retained within the ocean crust, where saturated solutions may be formed leading to extensive solid-phase sulphides precipitation. According to Dr German, the first mechanism by which these clear fluids are formed is through a process called phase separation. In this regard, Dr. German pointed out that in much of the deep ocean, the pressure and temperature conditions that are encountered at and below the seafloor are such that despite the high-temperatures, vent fluids remain as a single liquid phase because of the confining pressure that is typically 200 to 300 times atmospheric pressure. In sufficiently shallower systems at depths of 1800 to 1700 however, Dr. German said that a two-phase stability field for seawater-like fluids is encountered leading to separation into a dense metal-laden brine-like fluid that is retained in the ocean crust, and a vapour phase enriched in any dissolved gases initially present in the original vent fluid. Dr. German said that the vapour phase fluid is erupted from the seabed as a "white smoker". The vapour phase he also said is metal-free. Therefore, while the plume from such systems can be detected by relying on chemical indicators of dissolved gases, notably methane, they cannot be detected using in situ optical sensors. Dr. German concluded by pointing out that the white smoker type deposits should not be of much concern to the Authority since for the most part they occur in the exclusive economic zones of states and not in the Area.

SUMMARY OF THE DISCUSSIONS ON NATIONAL AND INTERNATIONAL PROGRAMMES FOR THE INVESTIGATION OF SEAFLOOR HYDROTHERMAL ACTIVITY

The discussions following Dr. German's presentation focussed on spreading rates and associated subduction zones, the mineral composition of deposits that originate from fault-controlled and volcanically-controlled hydrothermal systems, and the possible benefits to be derived from the Argo Programme of the Global Ocean Observing System (GOOS) in the search for areas of hydrothermal venting.

Dr. German was asked how seafloor spreading in the Red Sea compares with seafloor spreading at the West Indian Rise that he had described as the slowest spreading centre rate (1.5cm/year) in the world. Dr. German said that the Red Sea is an area where a mid-ocean ridge is just beginning to develop. A statement was made in support of Dr. German and it was said that the spreading rate in the in the northern part of the Red Sea is less than one centimetre while in the southern part of the Red Sea it is 1.5 centimetres.

One participant reminded Dr. German that he had said that the southeast Pacific rise is the fastest spreading centre, with a rate approaching 20 cm/yr. This participant wanted to know whether there was a subduction area to accommodate this rate of spreading or if the Earth is expanding. Dr. German said that there is subduction underneath South America on the Chilean Rise, but that most of the material from the southeast Pacific rise is accommodated on the other side of the Pacific Ocean in the south-west Pacific basins, surrounding the Indonesian and the island arcs through the lower basin in the Marianas. He however said that the earth is not expanding and that its size remains the same.

Dr. German was asked if he would expect the mineral compositions of deposits at fault controlled hydrothermal systems and at volcanically controlled hydrothermal systems to differ. Dr. German said that he might have oversimplified the case in his presentation. He said that in reality there is probably a continuum between the two. He pointed out that a very interesting site is the Rainbow hydrothermal site that has been studied in detail. He said that at the fault to be found here, the ocean crust has been displaced by about one kilometre and that some of the rocks that are exposed where the black smokers occur are slightly different rock types. As a result, he also said that seawater is reacting with a deeper ocean crust material that is slightly higher in base metals. Dr. German was also asked if the higher metal content at this mound is due to more extensive bleaching because of a change in the rock/water ratio relative to the ridge axis itself, and the fracturing of rocks along the fault. Dr German responded that the better guide is the copper to iron ratio and materials to be found in the fluids and the sulphides at the site.

Dr. German was asked if the Argo floats (NEPTUNE) that have been designed to support the measurement requirements of the ARGO PROGRAMME, a major component of the Global Ocean Observing System (GOOS), could be useful in the search for hydrothermal sources. The questioner pointed out that the programme is expected to have 3000 temperature/salinity floats that are to go down to a water depth of 2,000 metres. The questioner wanted to know whether the temperature and salinity data collected in this programme would be useful in searches for hydrothermal sources. Dr. German said that while the temperature and conductivity measurements from these floats are very precise, the depth of the floats placed them out of the threshold for measuring hydrothermal plume signals. He recalled that the depths of mid-ocean ridges are typically 2,500 metres, and that the typical height to find hydrothermal plume signals is between 2000 and 2500 metres. Dr. German however referred participants to the World Ocean Circulation Experiment (WOCE) that he said has been looking at dissolved He_3. He informed participants that under the WOCE Programme a series of vertical CTD stations had been placed throughout all the world's ocean basins over the past five years. He said that the data that the programme has acquired is just being released and that the data contains information on He_3 anomalies in various parts of the oceans.

Finally, Dr. German was asked about the availability of a map that shows the location of mid-ocean ridges outside exclusive economic zones. He was also asked whether under a regime for licensing prospecting/exploration areas a block size of 150 square kilometres is a reasonable size licensing area. Dr. German referred the map question to Dr. Parsons. Regarding block sizes, Dr. German said that based on the endurance of the research vessels that he was accustomed to of 35 days, a reasonable block size would be on the order of 200 square kilometres.

CHAPTER 11

A COMPARISON OF THE POSSIBLE ECONOMIC RETURNS FROM MINING DEEP SEABED POLYMETALLIC NODULES, SEAFLOOR MASSIVE SULPHIDES AND COBALT-RICH CRUSTS

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After a brief description of the characteristics of deep-sea mineral deposits and of the technologies that could be used for their exploitation, the author proposes to compare them on the based on the value of a tonne of "in-situ" ore.

1. Economics of mineral deposits

Since 1994 [1], investment decisions on deep-sea mining have been based on the same economic principles as any other mineral deposit, whether on-shore or offshore. The profitability of a future commercial deep-sea mining operation must be proven in order to encourage investments to develop these deposits [2]. Such profitability is normally established through a feasibility study that will consider *inter alia:*

- The characteristics of the mineral deposit,
- The availability of suitable technology to mine it,
- The availability of technologies for processing the ore and extracting the valuable components from concentrates,
- Commodity prices and market prospects and,
- Last but not least, the protection of the natural environment.

There is a strong relationship between these different topics.

The search for a mineral deposit is driven by considerations on suitable characteristics for mining and processing. Its morphology must comply with known mining technology. The ore mineralogy and metal content must allow sufficient recovery using available treatment processes and must ensure sufficient revenue according to the prospect for metal prices.

Obviously, the selection of a mining method is determined by the geometry of the deposit and the characteristics of its location, and upon environmental protection requirements. The choice of a technology for ore processing and metallurgical treatment is dependent on the kind of minerals, their sizes, and their metal contents. The presence of mineralogical or chemical components that could have a negative effect on the recovery of the valuable metals must also be carefully investigated. Environmental protection requires extensive preliminary impact studies that must be organized during exploration of the deposit and depends on its nature and location.

It is an adage to say that a mineral deposit becomes an ore deposit only when its exploitation can be envisaged with profit, according to the available technology and present economic circumstances. To meet these requirements, exploration must have acquired adequate information and data to estimate the *reserves* of the deposit [3-4] (Table 1).

Table 1: Reserve and resource classification for marine mineral deposits

	Suitable Mine ability	
Study of feasibility	Has been demonstrated	Not yet demonstrated
Economic	Proven reserves	Measured resource
Marginal	Provable reserves	Indicated resource
Sub-economic	Sub-economic resource	Inferred resource

Reprinted from Garnett, 1998

The present level of knowledge of deep-sea mineral deposits is generally considered as insufficient to define reserves. One must use the term *resource* exclusively, referring to a certain volume of material that could be of economic interest.

This paper proposes to compare the economic merit of the three types of deposits that have been proposed as possible deep-sea mineral resources:

- Polymetallic nodules,
- Cobalt-rich crusts,
- Massive sulphides.

There are significant disparities between these deposits with regards to the level of acquired exploration data and the availability of adequate mining and processing technologies.

2. Characteristics of deep-sea mineral deposits

2.1. Parameters to consider

Many parameters have to be taken into account when trying to determine the mineability of a deposit. We will consider only some of them and try to determine the reliability of the available information for each type of deposit:

- Parameters needed to estimate the tonnage and metal content of the deposit,
- State of the art of the mining and processing technologies.

2.2. Evaluation of tonnage and metal content

2.2.1. Polymetallic nodules

These deposits were intensively investigated during the seventies and the eighties. They are still the subject of important programmes of research and development in several countries. A considerable amount of publications is available on the matter. However, few give reliable information on the estimation of economic resource. The competition between the first pioneer investors, when no legal framework was internationally accepted, prevented the diffusion of what was considered as proprietary information.

J. Mero had evaluated the total amount of polymetallic nodules lying on the sea floor to more than 1.5 x 10^{12} tonnes in 1965 [5]. This estimation was reduced to 5 x 10^{11} tonnes by A. Archer in 1981 [6]. However, not all nodule fields are eligible for potential mining. Several attempts were made to calculate the probable resources for (near!) future development. The approach was to determine the number of "mining sites" that the World Ocean could accommodate. A mining site was defined as a portion of the seabed where a commercial operation could be maintained during 20-25 years with a production of 1.5 to 4 x 10^6 tonnes per year of "good nodules". Good nodules were those containing an average of 1.25-1.5% nickel and 1-1.4% copper, in addition to 27-30% manganese and 0.2- 0.25% cobalt. The estimate of the number of sites varied from 8 to 225, which corresponds to a total amount of inferred resources between 480 x 10^6 to 13,500 x 10^6 tonnes [6-10]. Further considerations, on the capacity of the world metal markets to absorb production from this source in the first 20 years of operation along with and more severe mining requirements, reduced this range to 3-10 mining sites with a tonnage of 100-600 10^6 tonnes [11]. These are estimates of "speculative inferred resources".

From 1984 to 1989, the French group Afernod[1]/Gemonod[2] carried out an extensive pre-feasibility study, whose results have been published. It constitutes the basis for the following assumptions on a polymetallic nodule deposit that might be suitable for a possible commercial operation [12-14]:

- The depth of the ocean floor in the area varies from 4,800 m to 5,200 m. The topography is formed of long dissymmetric hills. Their crests are orientated north-south, spaced by 2-5 km, and dominate the lower parts by 100-300 m. Slopes are less than 10% in more than 70% of the area, but vertical cliffs, sometimes 40 m high, have been identified on the flanks of the hills. In some places, potholes 100 to 1,000 m wide and 40 m deep have been observed.

1/ Association Française pour l'Etude et la Recherche des Nodules (AFERNOD).

2/ Groupement d'intérêt Public formed in 1983 by IFREMER, Commissariat à l'Energie Atomique and Technicatome. A parent organisation of AFERNOD.

- The distance between the mining site and a port, where a processing plant could be based, is at least 2 500 km (West Coast of Central America); and

- The mining site is made up of elementary "mine-able fields" averaging 50 km^2 in size (1-5 km E-W on 10-18 km N-S), kilometres apart and flat. Geostatistical simulations demonstrated that such mine-able fields could cover 30% of the most promising parts of the French pioneer area in the north Pacific.

- The average abundance of wet nodules in those fields is 14 kg m^{-2};

- The ratio of dry to wet nodule weight is 0.7;

- The average metal contents are 30% Mn, 1.37% Ni, 1.25% Cu, 0.25% Co.

2.2.2. Cobalt crusts

Encrustations of ferromanganese hydroxides have been found in many areas of the seafloor, but more particularly, where consolidated sediments and hard rocks outcrop. Most of them were discovered on seamounts or plateaux that constitute elevations of the seafloor in abyssal areas. These summits are frequently linked with volcanic structures and sometimes are sunken atolls.

Since the beginning of the nineteen eighties, ferromanganese crusts deposits have attracted the attention of explorers, as potential resources for cobalt. Although several exploration surveys have been carried out in different parts of the world's oceans, mostly by scientific institutions, the state of knowledge is still limited [15-19].

Cobalt-bearing crusts are often associated with low-grade nodules. Both these deposits have a relatively low manganese to iron ratio (1-2.5) in comparison to polymetallic nodules of economic interest (4-6). Their nickel and copper contents are also lower (0.3-1%). While the cobalt content of crusts can reach 3%, on average it is only 0.6-0.8%, or three to four times greater than the average cobalt content of "good" nodules (0.25%). Other metals occur as trace metals. These include vanadium (0.06%), molybdenum (0.05-0.1%), and platinum (0.14 to 5 ppm) [20-21].

The richest cobalt-crusts deposits appear to be concentrated at water depths of 800-2 000 m. Some scientists have considered a link with the oxygen minimum zone as a possible reason for their formation [22]. However, as in fossil stratigraphies, such crustification is an indication of a lacuna of sedimentation, either by a hiatus (no deposition) or by intermediate erosion. Similar encrustations, associated with nodules, were found in cores made on top of seamounts in the Indian Ocean [23] and later in many DSDP cores. They were proved lacunae of sedimentation. Observations of current activities that prevent sediment deposition have been recorded during several surveys [15].

It seems that there are two kinds of cobalt-rich crusts deposits:

- Flat deposits on top of sunken atolls, where the crust covers old coral reef formations;
- Inclined deposit on the flanks of volcanic seamounts, where the crust covers volcanic breccias and associated sediments.

The dimensions of flat deposits can be 50-200 km^2 with 70-90% of the area covered by encrustations. Their topography is relatively even, with slopes less than 5%. Cracks form an irregular pattern that cup up the crust and the underlying material to several decimetres deep. The corresponding slabs are one to several square meters wide.

Slope deposits are inclined up to 25%, as the flanks of old volcanoes. Crusts cover more or less consolidated sediments as well as hard basaltic rock and breccias. Evidence of sliding along the slope has been recorded.

The thickness of the crust can be 2 to 10 cm, sometimes up to 20 cm, but the structure and composition varies from top to bottom. Generally, only the few first millimetres have very high cobalt content (up to 3%). Cobalt grade decreases with depth, as well as manganese and iron, because of mixing with the underlying material. When this material is composed of calcareous phosphorite, there is a corresponding increase of the phosphorus and calcium contents. Therefore, only the first few centimetres (2 to 3) of a deposit have an economic value. Phosphatisation has also been found in slope deposits, probably in relation with up-welling phenomena [21].

The wet specific gravity of crust material is reported to vary from 1.6 to 2.1 g cm^{-3} [24]. The crust material, as is the case with polymetallic nodules, is very porous (43-74%). Accordingly, in the Tuamotu area, the average dry specific gravity was 1.4 g cm^{-3}.

During the surveys made by CNEXO[3] (1970) then IFREMER[4] in this area [25-26], a submerged old atoll was discovered near Niau Island. The depth of the plateau is 1 000-1 200 m limited by steep flanks of 400 m where the slope is more than 25%. Of the total area of 270 km^2, at least 80 km^2 are coated with encrustations, with an apparent coverage ratio of 70%. The surface of the crust is bumpy with smooth decimetric microtopogaphy. Sandy sediments with ripple marks occupy enclosed sectors. One can suspect the existence of buried crust beneath this sediment, as found in other deposits [27]. The large blocks of crust, that have been dredged, showed a phosphatic-calcareous core, light brown and well consolidated. Fossil foraminifers give an age of 45 Ma (middle Eocene). The outer part is altered with micro fissures impregnated by ferromanganese hydroxides. The crust, dark black and 2 to 5 cm thick, is more continuous and compact at the top part of the blocks. From the surface of this crust, the cobalt content decreases from 2% in the first 3 mm to 1.7% in the next 15 mm and 0.6% in the following 15 mm. A bulk sample taken from the crust had average grades of 0.33% Co, 0.2% Ni, 0.06% Cu, 9.7% Mn, 7.9% Fe. In 1986, an attempt was made to sample the deposit with a pyrotechnic multicorer with relative success [28].

The representativeness of such sampling versus future mining is questionable, as is the case for many of the surveys conducted elsewhere. An attempt to be more effective was made using a large gravity corer [29]. However, the penetration through the crust and its substrate is limited and consequently does not show a fair picture of the deposit.

3/ Centre national pour l'exploitation des océans, that formed IFREMER in 1984 by merging with the French Institut des pêches maritimes.

4/ Institut Francaise pour la Recherche et l'Exploitation de la Mer (IFREMER).

At Niau, the tonnage of material with economic merit has been estimated to be 1 million dry tonnes with average cobalt content of 1.2%, based on recovering only the first 2 cm of the crusts. Dilution of this layer by the underlying material will certainly occur, but it seems possible to separate the crust by ore processing techniques. Several similar deposits have been discovered in the vicinity [26] that could increase this speculative inferred resource to five Mt, which could then produce 50 000 t of cobalt.

Total resources of cobalt from Co-rich crusts in the central Pacific have been estimated to 500 million tonnes [30] (100 deposits similar to Niau).

The exploration techniques must be improved considerably in order to provide the necessary parameters for the design of mining and processing methods. A better knowledge of the micro topography can be obtain by using deep-towed multibeam sonar associated with continuous high resolution TV recordings. Sampling methods must be completely retailored. Rotary diamond drilling machines equipped with a multicorer system must be developed to provide a fast and cheap sampling method with better recovery.

2.2.3. Massive sulphides deposits

Unlike polymetallic nodules and crusts, massive sulphides were discovered rather recently. In February 1978, the French manned submersible Cyana went to an area where it found tall conical mounds made of scoriaceous material that was sampled. Several months later, the samples proved to be mostly composed of zinc and copper sulphides [31]. One year later, from the American submersible Alvin, hot springs were observed blowing black smoke at the top of similar "chimneys". Since, many occurrences of black smokers and massive sulphides mounds have been discovered, not only on spreading ridges, but also in back-arc subduction zones and the flanks of intraplate volcanoes, as predicted from fossil massive sulphides deposits [32-34].

In spite of the considerable amount of survey work that has been done, the available information is still inadequate to evaluate the economic potential of these occurrences.

The morphology of the mineral edifices (chimneys, mounds, sedimented layers, blocks, breccias, conglomerates, etc.) makes difficult the estimation of the real volume of material. For the most compact accumulations, such as mounds, which have a less complicated shape, the thickness cannot be determine solely by visual observations or topographic calculations from bathymetric or sonar surveys. The Bent Hill Massive Sulphides (BHMS) of the Juan de Fuca spreading centre give a good example of how misleading such an estimate could be [35]. Obviously, a sufficient number of drill hole samples must be obtained before acquiring an understanding of the third-dimension of the deposit's geometry.

Moreover, the internal structure of the deposit may change with depth, as can be deduced from comparisons with similar land-based deposits [32-36-38]. The following succession can be predicted from surface to depth: (1) oxidized mineral breccias, (2) clastic sulphides, (3) massive sulphides, (4) veins and replacements of a deeply altered host-rock, (5) dense network of small veins in unaltered host-rock (stockwork), and (6) large veins irregularly distributed in the bedrock. The boreholes drilled during leg 169 of the Ocean Drilling Program on the BHMS of the Juan de Fuca Ridge reveal such a structure [35].

The assemblage of minerals is also complex and variable. The main mineral is the ubiquitous pyrite, and its companion pyrrhotite, associated with variable proportions of zinc (sphalerite, wurtzite) or copper (isocubanite, chalcopyrite) minerals. Galena is present in large quantities in Kuroko types of deposits such as found in Myojin-sho or Aeolian island arcs, where sphalerite is predominant and copper minerals are less important [39-41]. It may be a constant feature of back-arc deposits compared to spreading center ones: Mariana and Okinawa deposits are other examples of the same mineral association. Sulphates, as anhydrite and barite, are also present in variable quantities, mainly near surface. Silica occurs in various forms - chert, opal and quartz – associated with chlorite.

To determine the mass of the mineral body from the estimated volume, one must make a tentative assumption of its density. Table 2 gives the specific gravity of the different minerals. The average density, computed after mineral reconstitution from the analyses of Table 3, varies from 2.77

(Okinawa) to 3.05 (Juan de Fuca). However, most samples show a high porosity, which likely reduces the bulk density of the minerals and waste assemblage, and has an effect on the wet density. One must remember that chemical analyses are referred to dry weight, while mining operations are generally related to wet weight. The relation from wet to dry density is not known. It must be established by the recovery of bulk samples that are representative of deposits for future mining operations.

Table 2: Specific Gravity of Minerals and Rocks

mineral	specific gravity (dry) g cm^{-3}
pyrite	5.00
pyrrhotite	4.65
sphalerite	4.00
chalcopyrite	4.20
galena	7.60
anhydrite	3.00
barite	4.50
basalt	2.5 to 3.2
siliceous sediment	1.4 to 1.7

The chemical composition of massive sulphides deposits is highly variable as shown in Table 3. Added to that, these figures are already the arithmetic mean of sets of more variable data. It could be the reason for the absence of a correlation between copper and zinc as shown in Figure 1.

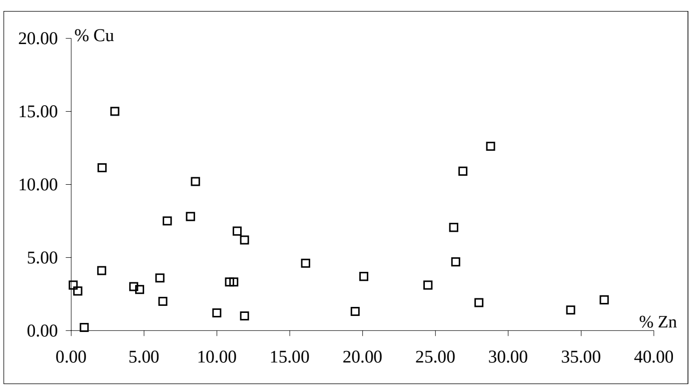

Figure 1. Correlation diagram between zinc and copper contents of massive sulphide deposits

Table 3: Geochemistry of known massive sulphides deposits

Area	Site	Cu %	Zn %	Pb %	Fe %	Si02 %	Au ppm	Ag ppm	As ppm	Nb sp	T Mt
Okinawa	Okinawa all	3.10	24.50	12.10	4.80	10.20	3.3	1160	31000	17	
	Minami	3.70	20.10	9.30			4.8	1900		9	
	Izena	4.70	26.40	15.30			4.9	1645			
Japan	Myojin-sho	2.10	36.60	6.08			1.6	260			5.65
	Suiyo	12.60	28.80	0.80			28.9	203			
Mariana	Mariana	1.20	10.00	7.40	2.40	1.20	0.8	184	126	11	
PNG	Pacmanus	10.90	26.90	1.70	14.90	0.80	15.0	230	11000	26	
	Susu	15.00	3.00				21.0	130			
N Fidji	N Fidji	7.50	6.60	0.06	30.10	16.20	1.0	151		24	
Lau	Valu Fa	4.60	16.10	0.30	17.40	12.50	1.4	256	2213	47	
	White Chch	3.32	11.17	0.23	7.17	22.12	2.0	107		13	
	Vai Lili	7.05	26.27	0.17	10.46	10.48	0.6	143		11	
	Hine Hina	3.32	10.87	0.59	34.57	1.76	1.7	517		5	
N Atlantic	TAG Miller	3.10	0.14	0.00	31.00		0.4	3		23	
	TAGHannington	2.70	0.45	0.01	23.00	55.00	0.5	14	43	66	
	TAG Scott	9.20	7.60	0.05	24.40	6.00	2.1	72		40	14.5
	Snake Pit	2.00	4.80	0.03	34.00	1.80	1.5	50			2.4
NE Pac.	Explorer	3.20	5.30	0.11	25.90	9.10	0.63	97		66	3.0
	Endeavour	3.00	4.30					188		31	
	Juan de Fuca	1.40	34.30				0.1	169		11	8.8
	Juan de Fuca	0.20	36.70	0.26	19.70	5.10	0.1	178			
	Escanaba	1.00	11.90					187		7	
EPR	Rivera	1.30	19.50	0.10			0.1	157			
	EPR 14°N	2.80	4.70				0.5	48			
	EPR 13°N	7.80	8.20	0.05	26.00	9.20	0.4	49			5.8
	EPR 11°N	1.90	28.00	0.07	22.40	1.20	0.2	38			
	EPR 2°N	0.60	19.80	0.21	12.40	19.00	0.2	98			
	EPR 17°S	10.19	8.54		31.28	2.05	0.3	55	141	19	
	EPR 7°S	11.14	2.13		34.63	3.45	0.05	23	122	14	
	EPR 20°S	6.80	11.40				0.5	121			
California	Guaymas	0.20	0.90	0.40				78			23.0
Galapagos		4.10	2.10				0.2	35			10.0
	mean	4.71	14.07	2.41	21.40	10.40	3.19	263	6378		
	mini	0.20	0.14	0.00	2.40	0.80	0.05	3	43		
	maxi	15.00	36.70	15.30	34.63	55.00	28.90	1900	31000		

Compiled from references: [19-34-35-42-47]. T (Mt) rough evaluation of possible tonnage. Ppm = g t^{-1}

Some authors have searched for a correlation between the different metal compositions [42]. However, due to the limited number of samples and their complex mineralogical composition, the results are likely not significant. Surprisingly, gold and silver are correlated to zinc, whereas gold is normally confined in the lattice of pyrrhotite and chalcopyrite, and silver with lead. The presence of arsenic, which is a reagent killer, in some deposits, can create difficulties during ore processing.

The tonnage indications provided in the last column are very speculative. Some come from the literature [19-35], and others have been calculated by the author on very hypothetical and unproven assumptions. They only provide an order of magnitude.

2.3. Mining and processing technologies

2.3.1. Polymetallic nodules

Many systems have been proposed for mining deep seabed polymetallic nodule deposits. From the Afernod prefeasibility study, one can assume that the following assemblage[5/] will be appropriate to mine the French site described above [12];

- A self propelled dredge, crawling on the bottom collects the nodules, crushes them and introduces crushed nodules to a 600 m-long flexible hose connected to a rigid pipe;

- The crushed nodules are lifted to the semi-submersible surface platform in a 4 800 m rigid-steel pipe by airlift or pumps,

- The transfer of the nodules from the platform to the ore carrier is done by pumping them through a flexible hose as a thick pulp;

- The production rate will be 1.5 10[6/] tonnes of dry nodules per year.

During the operations from harvesting on the bottom to delivery at the processing plant on land, it has been assumed by Afernod that 30% of the nodules will be lost. Consequently one can calculate that the total area, that will be mined during the 20 years of operation, is in the range of 4 500 km^2. The corresponding mine-able fields (approximately 100) could be embodied in a total area of 15 000 km^2, but as the most promising parts of the pioneer area are not likely contiguous, a more important surface should be envisaged. It must be pointed out that these results are based on statistical assumptions.

5/ Comparable mining systems have been tested at the end of the seventies at pilot scale level (1/10) by several consortia. In 1997, Japan tested a similar assemblage, with a towed collector, on the top of a seamount at a depth of 2 200 m.

Detailed exploration has not been conducted to precisely delineate mine-able fields.

Table 4: Metal recovery from polymetallic nodules processing

	Smelting	Sulphuric leach
Manganese	87%	85%
Nickel	95%	96%
Copper	86%	95%
Cobalt	83%	94%

One can assume from the information disclosed however, that at least three, and likely six, similar mining sites exist in the north Pacific ocean and probably two in the Indian ocean.

Polymetallic nodules cannot be enriched by ore processing techniques. They must be treated by metallurgical processes. Several methods have been examined. Afernod considered two of them. These were smelting and sulphuric-acid leaching [12-14-48]. During the prefeasibility study, no difference was found between the two processes in relation to their profitability. The results from testing the two processes are the recoveries for the four metals indicated in Table 4.

The French prefeasibility study concluded that the Afernod site could be mined subject to higher metal prices and deep-sea technology reliability improvements. Therefore, the nodules in the site are being considered as sub economic resource.

2.3.2. Cobalt-rich crusts

Several engineering studies have been carried out to define possible methods of mining and processing cobalt-rich crusts [24-49-50]. The studies highlight the current lack of knowledge and the need for better information to be able to design efficient systems.

A revised continuous line bucket (CLB) system was proposed by its inventor for crust recovery [51-52]. Besides the apparent simplicity of the system, strong reservations must be made about its efficiency. It is doubtful that the buckets will be able to extract large slabs of crust that are firmly attached to their substrate. Buckets could be also severely damaged when they impact the bottom of the deposits. The blocks containing crusts will be low grade, retaining a significant amount of waste material. In slope deposits, blocks of lava and volcanic breccias will also be retrieved, as the buckets cannot be manipulated to discriminate between ore and waste.

In 1985, Halkyard [50] proposed a hydraulic lifting system with a self-propelled bottom crawler equipped with cutting devices as suitable technology for mining crusts. The cutting devices would create incisions on the surface layers of the crust, permitting their extraction by suction to the pipe system.

In a study conducted during the same year by Gemonod for the Niau deposit, a similar system was envisaged. The proposed cutting device would be a set of hammer drills or a row of rotary cutting drums. A crusher would also be installed on the self-propelled crawling dredge, in order to produce slurry (60% solid) to be pumped to the surface.

Chung [24] considered the possibility of using water-jet cutting or fracturing to slice or break the crust top-layers. He also considered adopting a hydraulic lifting system, with a towed or self-propelled bottom collector.

Zaiger proposed an innovative system in 1994, known as "solution mining" [53-54]. A large "containment and regulation cover" (CRC: up to 40 000 m^2), consisting of an impermeable membrane, is sealed on the bottom by tubes filled with a heavy medium such as barite mud. A leaching solution is introduced between the CRC and the seafloor. After sufficient time, the enriched solution is pumped to the surface platform for metal extraction. The CRC is then moved to another area. Preliminary tests have raised more problems than providing solutions.

Research on processing has been limited owing to the lack of information on the composition and physical properties of the possible raw ore [55-56]. However, some studies have shown possibilities of using ore processing to concentrate the minerals. Magnetic separation, followed by froth flotation, can separate the ferromanganese hydroxides from the calcareous phosphorite or the siliceous volcanic fragments, and form an enriched concentrate [57-58]. Heavy liquid separation was also proposed to obtain the same result [59].

Minemet Recherche studied this method under a contract from Afernod/Gemonod in 1986. A concentrate grading 1.2% Co, 0.6% Ni, 0.1% Cu and 26% Mn was obtained from the raw ore. The recovery could be better than 70%.

Extraction of the metals from the concentrate can be also effected by hydrometallurgy [55-56]. As for polymetallic nodules, both ammoniacal and sulphuric acid leaching were proposed. Japanese institutions studied the dissolution of the valuable metals (Co, Ni, Cu) in a mixture of ammonium sulphite and ammonium carbonate, or in ammonium thiosulphate. The metals are then extracted from the pregnant solution by selective organic solvents. The refined metals are obtained by final electro winning [60-61].

Minemet Recherché proposed to use sulphuric leaching in a closed cell under one MPa pressure at 180°C temperature. The introduction of Mn^{++} ions favours cobalt recovery. The process derives from the SRM2 tested for polymetallic nodules by the French CEA[6/]. Selective extraction of the different metals (Co, Ni, Cu) is made by organic solvents. Sulphide concentrates are prepared by precipitation for further refining. Cobalt recovery could be 93%. Manganese is confined in a low-grade ferromanganese residue, rich in iron, which could be (doubtfully) used as a manganese ore.

2.3.3. Massive sulphides

Practically no studies have been undertaken on mining and processing of massive sulphides deposits. The lack of knowledge about their exact dimensions and internal structures, the difficulty of evaluating their real metal content and their variability, have prevented any serious engineering studies.

6/ Commissariat à l'Énergie Atomique (CEA).

However, speculations on possible techniques have been attempted [62-63]. For these authors, mining could be done by the following techniques [64]:

- Scraping a surface deposit,
- Excavating the deposit in an open pit,
- Fluidising the ore in a solution or slurry through a borehole.

The fourth proposed solution, tunnelling into the ore, must be rejected as unrealistic for the time being.

Large bucket dredges and grabs were proposed for the two first techniques. These could be deployed from a self-propelled crawler travelling on the bottom and linked to a hydraulic lifting system as designed for polymetallic nodules. Even if the depth of crusts deposits are much smaller, the control of the bottom system needs a more innovative and complex technology than that envisioned for nodules.

Attempts have been made to mine land-based deposits by fluidising methods. Due to the difficulties encountered, particularly control of the permeability of deposits and their natural pipe-systems, it does not seem realistic to envisage an application of this mining method to deep-sea deposits.

Capturing the hydrothermal fluids has also been discussed. The French CEA conducted, on request in 1981, an engineering study to determine if the hot springs could be pumped, using funnels at the end of pipes. Boreholes drilled through the deposit could intersect the natural hydrothermal pipe system. However, it was determined that the corrosive nature of the fluids and the likely precipitation of minerals in the pipe system would rapidly damage the equipment. Moreover, thermal springs are naturally intermittent and will not secure the continuity of the operation.

Processing this mineral assemblage is rather well documented, as they are very similar to ores that are presently mined on land.

The crushed and ground ore can be concentrated by preliminary gravity concentration. Then differential froth flotation can separate the different sulphides - pyrite, pyrrhotite, chalcopyrite, sphalerite, and galena – from the gangue and between themselves. However, difficulties have been encountered when processing finely crystallized material. To guaranty a good differential recovery, grinding must break the different sulphides minerals free of each other. If the crystals are too fine and too interwoven, grinding will either not liberate each mineral species or produce a powder that is so fine that flotation will be impossible. It is suspected that deep-sea sulphides might fall in this category. For such complex ores, flotation may be unable to separate the minerals completely: the copper concentrate can contain 10% of lead and 8% of zinc, while for the same ore, the lead concentrate can retain 12% of zinc.

An alternative to flotation is bio-metallurgy where anaerobic bacteria – possibly the same bacteria living in the hydrothermal environment - can be used to destroy the sulphides and liberate sulphuric acid. The acid will leach the metals, and the pregnant solution will be treated later by hydrometallurgy. The major problem is the abundance of iron that must be inhibited by controlling the redox, a delicate operation.

Concentrates obtained by ore processing are sent to metallurgic treatment plants where two families metallurgical processes can be used to obtain the metals of commercial interest:

- Hydrometallurgy after dissolution of the concentrates by an acid reagent, then eventual separation by organic solvents and final electro winning;
- Hydrometallurgy or smelting of the ore in a reduction furnace and separation using the densities of the different metals and slag.

Direct leaching of the crude ore cannot be envisaged, because the process will be time and space consuming, and the recovery very low, with such a complex mineral assemblage.

Metals recoveries have not been established at the present time. However, some highly speculative hypothesis can be made in comparison with land-based exploitation [65]. Table 5 gives possible recoveries at the different stages.

Table 5: Speculative recovery of metals from massive sulphides deposits

Metal	Ore processing recovery	Metallurgy recovery	Total Recovery
Lead	55-80 %	95%	52-76%
Copper	65-80 %	95%	62-76%
Zinc	80-85 %	95%	76-81%

From Prédali 1983 [66].

3. Comparative Value of Deep-Sea Mineral Deposits

3.1. The concept of the value of a tonne of *"in-situ" ore*

As it is presently impossible, as explained above, to proceed to a complete evaluation of deep-sea mineral deposits, a tentative comparison can be made by considering the revenue that can be expected from selling the metals recovered from a tonne of ore. An important factor for the profitability of a mining operation is the continuity of the revenue stream. By tracing the evolution of the metal prices during the past decades, one can test the effect of price variability on the revenue of each type of deposits.

The revenue is taken as the sum of the sales at market prices. This revenue is referred to a dry tonne of "ore", as no hypothesis can be made on the amount of production. Assumptions on metal content and recovery are made based on the preceding section. It is the theoretical value of a tonne of *"in-situ"* ore, before mining and processing.

The values are based on annual-average metal prices from 1960 to 1999. During this period, important economic changes took place. They likely do not represent the future evolution of metal prices, but are actual situations that can occur again, even if history never repeats itself.

3.2. Assumptions made for each kind of deposit.

Table 6 presents the assumptions made for each category of deep-sea mineral deposits.

For polymetallic nodules, the French case is proposed as a reference. For cobalt-rich crusts, the study undertaken on the deposit of Niau (Tuamotu) provides a set of values that seems reliable.

The case for massive sulphides deposits is more complicated. In the absence of credible information, two sets of values are presented:

- The arithmetic mean of the metal contents contained in Table 3 for the different mineral deposits: "sulphides (mean)”.
- The set of data given for the Pacmanus deposit in Papua New Guinea: "sulphides (rich)".

The "sulphides (mean)" is a virtual deposit that likely does not exist. It gives only a "possible average economic value" of a sulphides deposit, as they are presently described in the literature. As data on the metal contents of these deposits were obtained for scientific purposes rather than for an evaluation for mining purposes, the sampling that was performed is likely to have overestimated the metal contents of these deposits.

The Pacmanus data set does not represent the most valuable of the sulphides deposits contained in Table 3. The records given for the Suiyo deposit, because of their high gold content, produce a higher value. However, the gold values are exceptional and could be suspect in absence of information on the sample representativity. At the time of writing, the data relative to the Juan de Fuca DSDP drilling were not fully published, although they constitute the best evaluation that have been made of a sulphides deposit.

The metal recoveries for massive sulphides deposit are an optimistic guess from the figures given in Table 5.

Table 6: Assumptions made for the different deep seabed mineral deposits

	Nodules		Cobalt crust		Sulphides (mean)		Sulphides (rich)	
	grade	**recovery**	**grade**	**recovery**	**grade**	**recovery**	**grade**	**recovery**
NI	1.37 %	0.96	0.6 %	0.72				
Co	0.25 %	0.94	1.2 %	0.70				
Mn	30.00 %	0.85						
Cu	1.25 %	0.95	0.1 %	0.71	4.71 %	0.7	10.9 %	0.7
Zn					14.07 %	0.8	26.9 %	0.8
Pb					2.41 %	0.7	1.7 %	0.7
Ag					263 g/t	0.8	230 g/t	0.8
Au					3.19 g/t	0.8	15 g/t	0.8

3.3. Metal prices

Figure 2 displays the evolution of metal prices during the period 1960-1999, as annual variations in percent of the 1960-1999 average value.

Most prices indicate a slow decrease from 1980, which marks an important turn in the economy of all "commodities". Since that time, the mining industry has faced a new economic order where world production capacities exceed the market needs. Operators have had to adjust their production to meet this situation by closing their less profitable mines, reducing their staff and modernizing their means of production.

Silver, gold and cobalt show important historical changes (more than 300 % above the mean). For silver and gold, the 1980 highs correspond to the speculations of the Hunt brothers that provoked an important crisis in the precious metals market. The high cobalt prices of the same period were the consequence of the invasion of the Shaba province in Zaire, where the major cobalt and copper mines are situated.

The manganese price increase after 1974 is due to the appearance on the market of ferro-silico-manganese alloys that replaced ferro-manganese alloys or even manganese ore in the making of high-grade steel. The French project was considering the production of this kind of alloy.

Other outbursts of metal prices are linked to increase of industrial activity in the industrialized countries as in 1974 after the first oil crisis, or in 1989 after the opening of Eastern European countries to market economy.

Since 1980 the prices of lead, zinc, copper, manganese, nickel and even gold show a generally decreasing trend. Silver prices have stayed relatively constant, while cobalt prices are improving with successive upswings. During the last four years, the decline was general, but at the beginning of 2000, the prices started to consolidate.

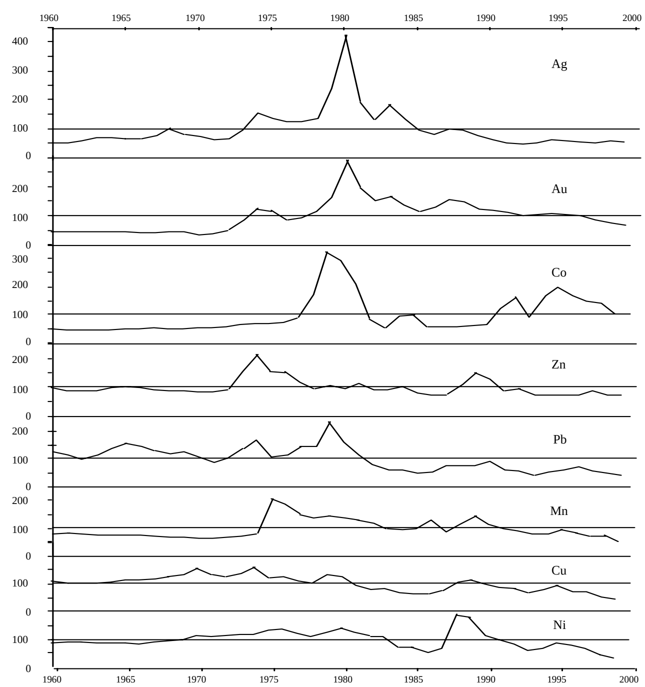

Figure 2: Evolution of the metal prices from 1960 to 1999 as a percentage of their average value.

3.4. Evolution of the value of a tonne of ore

Figure 3 displays the evolution of the value of a tonne of "*in-situ*" ore for each of the four selected deep-sea mineral deposits. Obviously, the variations of the values are driven by the prices of the most important metal contained in each deposit.

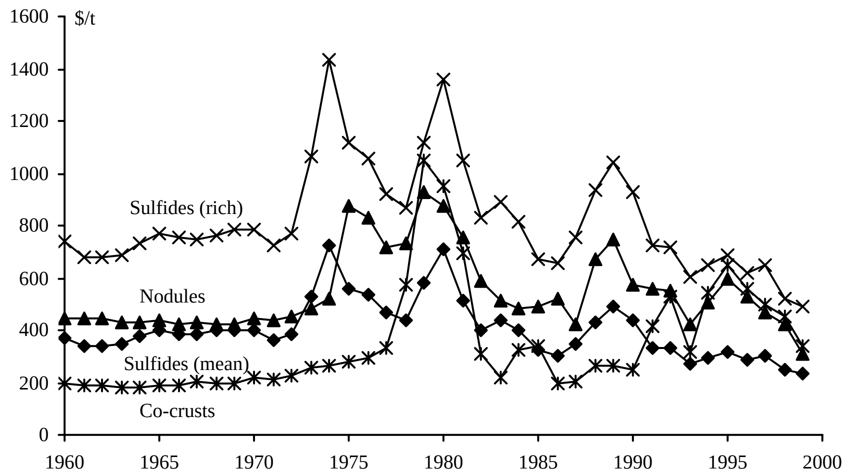

Figure 3. Value of a tonne of "in situ" ore for various deep-sea mineral deposits.

Table 7 displays the weight of each metal in the appraisal of the ore values. They have been determined for their average value along the 39-years period, their maximum (1979 for nodules and Co-crusts, 1980 for sulphides) and their 1999 value.

		Nodules			**Cobalt crusts**			**Sulphides (mean)**			**Sulphides (rich)**		
		1979	**Mean**	**1999**	**1979**	**Mean**	**1999**	**1980**	**Mean**	**1999**	**1980**	**Mean**	**1999**
Ni	%	18.5	24.4	14.8	5.4	12.5	4.4						
Co	%	30.1	15.6	29.3	94.3	86.8	95.3						
Mn	%	45.7	52.5	50.2									
Cu	%	5.7	7.5	5.7	0.3	0.7	0.3	20.0	28.0	20.7	24.1	31.9	23.2
Zn	%							23.4	43.1	51.1	23.3	40.6	47.3
Pb	%							4.2	4.7	3.6	1.5	1.6	1.2
Ag	%							38.9	16.0	15.0	17.7	6.9	6.3
Au	%							13.6	8.2	9.6	33.3	18.9	21.9
Value	$/t	926	544	308	1051	348	337	709	404	237	1360	819	489

The less variable value is for polymetallic nodules. It is regularized by manganese that contributes 50% of the total value, followed by nickel, or cobalt when its price is high. It is also the most valuable, when excluding the rich sulphides. During the 1960-1999 period, the pick values were determined by the cobalt prices, except in 1989 when the boost in industrial activity brought the nickel price to a top. The French study was expecting a long-term value of 450 $/t (in 1999 dollars) for profitability.

Cobalt crusts depend on cobalt prices for more than 83% of their value. Any variation in this metal's price registers on the value of this ore. The cobalt market is driven by the African producers (Zaire, Zambia, and Zimbabwe) that have the lowest production cost. However, cobalt is present in many nickel ores, from which it can be extracted at medium cost. Moreover, the market is rather flexible to price variation. Even if the African producers encounter some difficulties, the market can adjust itself and high prices cannot remain for a long time. During the 1978 crisis, official prices were apparently maintained at top level (or not quoted), but most transactions were made at lower prices because of private contracts between non-African producers and industrial consumers. The development of one cobalt-crust deposit, as well as a nodule deposit, will pour a large quantity of metal on the cobalt market, near 10% of current global consumption. Consequently, the mean (or the 1999) value for cobalt crusts must be considered as a long-term target.

For massive sulphides, as explained above, the available data are not representative of any ore deposit. The number of samples is few and most of these samples were taken because they had an attractive appearance due to their high mineral content. Consequently, the metal grades of a possible "ore" may be much lower than the average of the available analyses. For instance the data given by Scott in 1983 [34] for the TAG deposit showed a metal content of 9.2% copper, 7.6% Zn, 72 ppm silver and 2.1 ppm gold. The average of the 66 analyses published by Hannington in 1998 [45] after the DSDP drilling was only 2.7% Cu, 0.45% Zn, 14 ppm Ag and 0.5 ppm Au.

The value of "sulphides (rich)" ore is probably fanciful. The "sulphides (mean)" is obviously a poor estimation of what could be in this kind of ore deposit. Their highest values were determined by the burst of silver and gold prices in 1980 (Hunt's brothers), and the jump of zinc and copper in 1974 and 1989 (upsurges of industrial activity). The last two metals contribute to more than 70% of the value of sulphides ore, except during the period of high gold and silver prices.

3.5. Comparison of the deep-sea mineral deposits

The mean values of the "*in-situ*" ores are very similar, when discarding the illusive case of "sulphides (rich)".

The costs of mining and processing can make the difference. However, mining at depths of 1, 000 m (Co-crusts) to 2 500 m (massive sulphides) instead of 5, 000 m (nodules) will not necessarily divide the cost of operations by 2 or 5. A scale effect could be in favour of nodule mining, which can envisage a higher annual capacity than the other two can. The energy consumption will be more important for scraping or excavating crusts and massive sulphides than for harvesting the nodules.

The risk of failure of the mining system is the main concern of the aspirant deep-sea miner. The more complex the geometry of the deposit, the more elaborate the bottom collector will have to be. The more sophisticated the bottom equipment, the less reliable it might be. On that subject, the different deposits can be classified from relatively easy (nodules) to moderately difficult (Co-crusts) and more difficult (sulphides) to mine.

The protection of the natural environment is another major concern of the future deep-sea miners. Most of the massive sulphides deposits have been discovered in areas of intense biological activity linked to hydrothermal vents. It seems impossible to admit that mining could be carried out in these areas. It will destroy most of this very active life. Massive sulphides mining would be authorized only in areas where biologic activity is extinct. Those areas are more difficult to find. Currently, exploration is guided by the topography of ridges, and the temperature and geochemical anomalies of seawater. However, some "fossil" deposits have been already discovered. They constitute the actual targets of future mining operations.

For the time being, no commercial operations can be envisaged because either the knowledge of the deposit is too poor, the technology not available, or the metal prices too low. For some deposits, the three preceding conditions are unfortunately combined.

Because the metal market economy is weak and no clear legal status has been defined for cobalt crusts and massive sulphides, either in most Exclusive Economic Zones or in the Area, industrial operators have not yet undertaken exploration. A better international understanding must be developed on the intricate problem of preservation of the environment and on the legal requirements for exploration and mining. For polymetallic nodules, the situation is less ambiguous, but until the International Seabed Authority issues a "mining code", future "contractors" will delay detailed exploration and/or technological tests in order to make more precise feasibility studies.

Meanwhile information will continue to flow from scientific expeditions, even if their data are not fully appropriate for mining evaluation. Data obtained from these expeditions will provide a better understanding of the associated geological features and will be used to outline the technology that is required for future exploration and exploitation.

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Summary of the Presentation and Discussions on a Comparison of Possible Economic Returns from Mining Deep Seabed Polymetallic Nodules, Seafloor Massive Sulphides and Cobalt-Rich Crusts

Presentation

Mr. Jean-Pierre Lenoble, Chairman of the Authority's Legal and Technical Commission started his presentation by observing that it is to be expected that mining polymetallic nodules, polymetallic massive sulphides or ferromanganese cobalt-rich crusts will yield economic returns. He said that his presentation would be based on current knowledge and information on these deposits and he would use this information for the purposes of determining the possible returns from mining each of them. Mr. Lenoble noted that the economics of mineral deposits depend on feasibility studies for which there are a number of requirements. The first requirement according to Mr. Lenoble is the characteristic of the mineral deposit. The second and the third requirements he also said are technologies for mining and processing the ore. He said that the returns, depend on commodity price, and last but not least, the cost of requirements to protect the environment.

With regard to the economic status of the three kinds of deep-sea mineral deposits, Mr. Lenoble referred to a paper that was delivered at the Authority's workshop in 1999 by Dr Robert Garnett, President of Valrik Enterprises inc. based in Ontario, Canada, on the" Estimation of Marine Mineral Reserves" in which a classification of mineral resources was presented. Mr. Lenoble said that this classification system is based on a demonstration of a deposit's mine ability. If a deposit's mine ability is demonstrated and it can yield returns that exceed investors' minimum requirements, reserves of the mineral resource are established. When returns are marginal, the deposit is a provable reserve or an indicated reserve. The second category is when mine ability has not yet been established. In that circumstance, the deposit is described as an inferred resource. Based on this classification system, Mr. Lenoble described the three types of mineral resources of the Area as inferred reserves.

Mr. Lenoble said that to estimate the tonnage and metal content of a deep-sea mineral deposit information is required about the deposit's characteristics. He also said that basic information on technology for mining and processing the ore is necessary. He then turned his attention to the information available for all three mineral deposits, starting with polymetallic nodule deposits.

With regard to polymetallic nodule deposits, Mr. Lenoble stated that he would not introduce any new information. He reminded participants of deposits of polymetallic nodules in the central Pacific Ocean that occur at depths between 4,500 to more than 5,000 metres, on gentle hills that are oriented generally north-south, and widely dispersed.

He told participants that the data for polymetallic nodule deposits in his study is from the IFREMER/AFERNOD work on deposits in the central Pacific in the French registered area. He said that a geostatistical simulation of prime areas in this site was conducted with the objective of finding suitable nodules in flat areas where there are no cliffs. With slides, Mr. Lenoble showed participants the results of this work, including photographs of seafloor areas where the coverage of nodules (abundance) is up to 14 kilograms per square metre. He also showed photographs of areas that he described as targets for future mining pointing out how three or four different areas that were geographically close would be required to fulfil a production target of 1.5 million dry tonnes of nodules per year.

Mr. Lenoble said that a characteristic of these areas is that they are each about 50 square kilometres with an east-west width of 1-5kms. With regard to mining technology, Mr. Lenoble said that a system is required to collect at least 14 kilograms per square metre of nodules from the seafloor with an annual production target of 1.5 million tonnes. He also said that the average grade of the identified deposit is 30 percent manganese, 1.37 per cent nickel, 1.25 per cent copper and 0.25 per cent cobalt.

With regard to cobalt-rich ferromanganese crusts, Mr. Lenoble said that these deposits occur in water depths between 800 metres to 2,000 metres. With slides, he described the morphology typical cobalt-rich crusts deposit that he said are to be found on the flanks of seamounts, and on inclines that are not very steep. Since the mined ores will have to be processed on land, Mr. Lenoble pointed out that the distance to port of known deposits in the Area vary from hundreds of kilometres to 2,500 km. With slides, Mr. Lenoble told participants that the average size of candidate mining areas of encrustations range between 50 and 200 square kilometres. Mr. Lenoble described a known crusts deposit as one where crusts cover 90 percent of the seafloor area, on a seamount slope of less than 5 percent, with crusts' thickness varying from 2 to 20 centimetres, and with average grades of 0.33 percent of cobalt, 0.2 per cent nickel, 0.06 per cent copper, 10 percent manganese and 8 percent iron. He also informed participants that the cobalt rich part of this crusts deposit occurs in the top 0.123 centimetres of the deposit.

With regard to seafloor polymetallic massive sulphides, Mr. Lenoble said that as had been discussed in earlier presentations, these deposits occur at water depths between 1,400 metres and 3,600 metres. Mr. Lenoble said that the morphology of these deposits are different, and comprise chimneys, mounds, sediment layers, blocks, breccias, conglomerates, etc. He noted that the ore might occur as veins in altered or unaltered rocks. Again, based on the need to process these ores on land, Mr. Lenoble pointed out that the distance to ports, as is the case for cobalt crusts deposits of the Area, varies from 700 to more than 2,500 kilometres.

With regard to technology for mining polymetallic massive sulphides, Mr. Lenoble described it as an open question. He pointed out that while a lot of work has been done for nodule deposits, and possible configurations have been decided in the event of an upturn in the relevant metal markets, far less work had been undertaken on cobalt crusts and even less on massive sulphides. The key parameter in mining technology development, according to Mr. Lenoble, is the depth of occurrence of the deposits. Nodules of commercial interest are found at 5,000 metres depth, and cobalt-rich crusts and massive sulphides at 1,000 and 2,500 metres depth respectively. He also said that nodule deposits are two-dimensional, crusts more or less two-dimensional, and massive sulphides, typically three-dimensional.

To recapitulate the sizes and possible mining technologies for the three deposits, Mr. Lenoble said that the total tonnage of nodule ore required for a nodule mining operation would be in the range of 50 million tonnes, for cobalt-rich crusts 10 times less, and massive sulphides in the range of 8.5 to 10 million tonnes. In relation to mining technologies, Mr. Lenoble said that in all cases a motorised dredge would be required, coupled with a hydraulic system to lift the material to the surface platform. For massive sulphides deposits, Mr. Lenoble said that while technology has been proposed to leach the deposit *in situ*, he is of the opinion that it would take some time for such technology to become operational. As a result, he said that at the commencement of massive sulphides mining, scrappers or some kind of dredging system with more power than for the two other kinds of deposits would be used.

For processing the three types of minerals to recover the metals of interest, Mr. Lenoble noted that in the case of nodules, metal recovery would be from smelting or by leaching the ore on land. In the case of cobalt - rich crusts, Mr. Lenoble said that it would require separating the manganese and iron hydroxide contained in the ore before applying metallurgical processes. Finally, in the case of processing massive sulphides ore, Mr. Lenoble observed that although a problem has been identified with the ore's very fine grain crystallization that may pose problems during processing, the ore was similar to land-based ores that are being processed hydrometallurgically as well as pyrometallurgically.

For the purposes of comparing the possible economic returns from mining these three types of marine mineral resources, Mr. Lenoble said that normally the objective of a feasibility study is to estimate the profit that accrues from a given mining operation. He said that profit could be viewed as the revenues from the operation less the operation's cost. For all of the marine minerals in this study, Mr. Lenoble pointed out that the costs to recover the metals of commercial interest are yet to be established. On the other hand, however, Mr. Lenoble said that the revenues from each of the operations can be determined since they consist of sales of the metals of commercial interest which, in turn is related to the sum of the grade of the tonnage produced multiplied by the price of each metal. He noted however, that at present there is no certainty about total production or production per unit of time from any of these deposits. As a result, Mr. Lenoble pointed out that a fair basis of comparison was the value of an "in situ" tonne of ore for each deposit without factoring in the of cost of production.

To determine the value of a tonne of each of the three ores, Mr. Lenoble said that he first ascertained how much of the metals of commercial interest could be obtained from an average grade ore, and together with price information on the metal for the period 1960 to 1999, computed the value of the ore for each year.

For the technical details of the amount of the metals of commercial interest that could be obtained from a tonne of each type of ore, i.e., the likely average grades and processing recovery efficiencies, Mr. Lenoble said that he used data from the French site in the Central Pacific Ocean for nodules. For cobalt-rich crusts, he said that he used data from the work carried out by CNEXO and IFREMER on a crusts deposit found on a submerged atoll near Niau Island. He described current work on seafloor massive sulphides as inadequate for evaluating the economic potential of these deposits. He said that in addition to the inadequate number of samples from these deposits, a high bias is contained in available samples since such samples have been taken for their attractiveness that derives from their high mineral content. He also pointed out the need for drilling, as these are three-dimensional deposits. For his study, he said that he used the arithmetic mean of grades from 32 deposits (described as "mean" in his paper), and data on the Pacmanus deposit in the EEZ of Papua New Guinea (described as "rich" in his paper).

Based on these assumptions, for nodules the metal grades utilized in Mr. Lenoble's study are 1.37 per cent nickel, 0.25 per cent cobalt, 30.00 per cent manganese, and 1.25 per cent copper. In the case of cobalt-rich crusts, the metal grades utilized are 0.6 per cent nickel, 1.2 per cent cobalt and 0.1 per cent copper. Finally, in the case of massive sulphides, Mr. Lenoble presented two sets of data for the mean and rich cases respectively. These are 4.71 and 10.9 per cent for copper, 14.07 and 26.9 per cent for zinc, 2.41 and 1.7 per cent for lead, 263 and 230 g/t for silver, and 3.19 and 15 g/t for gold.

With regard to the associated processing recovery efficiencies, Mr. Lenoble said that he undertook a literature review to obtain information on proposed processing technologies and their recovery efficiencies for massive sulphides and cobalt-rich ferromanganese crusts deposits. For polymetallic nodules, he said that he used well-known results from the French studies on the matter. These results for polymetallic nodules deposits are contained in Table 4 (Metal recovery of polymetallic nodule processing) of his paper. The recovery efficiencies are 96 percent for nickel, 94 per cent for cobalt, 85 per cent for manganese and 95 per cent for copper when the sulphuric leach-processing route is used. As regards cobalt-rich crusts, Mr. Lenoble said that he used 72 per cent recovery efficiency for nickel, 70 per cent for cobalt and 71 per cent for copper. Mr. Lenoble said that the recovery efficiencies for massive sulphides are highly speculative. With virtually no work done in this area, he said that he used analogues from processing similar land-based ores. He therefore utilized the following recovery efficiencies: 70 per cent for copper, 80 per cent for zinc, 70 per cent for lead, and 80 per cent for silver and gold.

Based on these assumptions Mr. Lenoble said that he estimated how much of each metal was contained in a tonne of ore from the three types of mineral deposits.

Mr. Lenoble told participants that the next set of parameters that he obtained values for were the prices of metal. His approach he said was to consider metal price history. He told participants that he obtained the prices of the concerned metals (silver, gold, cobalt, nickel, copper, zinc, lead and manganese) for the period 1960 to 1999 (Figure 2 of his paper). Through slides, he illustrated the price changes for silver, gold, cobalt, zinc, lead, manganese, copper and nickel during this period. He also took the opportunity to explain events that had affected some of the metal prices during this period.

Armed with the amounts of the different metals that can be produced from each ore and their prices, Mr. Lenoble informed participants that he had obtained the values contained in Table 7 of his paper. Mr. Lenoble's study revealed that the mean values of a tonne of ore of polymetallic nodules, cobalt-rich crusts and massive sulphides were US$544.00, US$348.00, and US$404.00 respectively. Based on these values, Mr. Lenoble concluded that the three deposits had similar *in situ* values.

In relation to mining and processing costs, Mr. Lenoble said that even though these costs had not been considered in his paper, he was of the opinion that they would be comparable for the three types of ore because of the nature of equipment to be used. The only area of the operations where he saw the possibility of a significant cost differential he said would be the depth of occurrence of each deposit. In this respect, he said that the cost of energy to lift ore from the seafloor and the cost of the pipe to transport ore from the seafloor to the surface platform that are both directly related to the depths of the deposits could make a difference to production costs. He noted however, that in the case of nodule mining there could be a scale effect since more than 1.5 million tonnes per year would be produced. Mr. Lenoble ended his presentation with the observation that for all three deposits fast, cheap and representative sampling methods are required.

SUMMARY OF THE DISCUSSIONS ON A COMPARISON OF POSSIBLE ECONOMIC RETURNS FROM MINING DEEP-SEA POLYMETALLIC NODULES, POLYMETALLIC MASSIVE SULPHIDES AND COBALT-RICH FERROMANGANESE CRUSTS.

The discussions that followed Mr. Lenoble's presentation focussed on, inter alia, prospects for mining the mineral deposits of the Area, including problems with raising the required finance, comparisons with land-based deposits of similar minerals and issues related to metal prices.

A number of participants asked questions and made comments in relation to Mr. Lenoble's findings about the value of the three types of seafloor mineral deposits. A view was expressed that based on his analysis, Mr. Lenoble was advocating that the International Seabed Authority should place equal emphasis on all three types of mineral resources. It was also said that Mr. Lenoble's presentation tended to invalidate the theory that deep-sea polymetallic nodule mining is dependent on an upturn in the price of nickel, copper, cobalt and manganese. In relation to the weighting to be placed on any one of the three mineral resources, Mr. Lenoble pointed out that now, the international community is only just beginning to discover these mineral deposits. Mr. Lenoble pointed out that he could not describe any of the mineral resources as "ore deposits" because the latter terminology implied knowledge that one could recover the material at a profit. For this to be the case, Mr. Lenoble said, a feasibility study would have had to be successfully undertaken. Mr. Lenoble differentiated between deposits in the Area and in the Exclusive Economic Zones of states. In this regard, in response to a question about the massive sulphides deposits at Conical Seamount in Papua New Guinea, Mr. Lenoble said that with an independent gold mining and mineral processing operation in Lihir, should a rigorous evaluation of these deposits take place, it was possible that such a venture could proceed taking advantage of this relatively close infrastructure.

Mr. Lenoble also pointed out that normally; with land-based deposits, the costs for detailed exploration amounted to 6 per cent of the capital expenditure for starting a deposit. He recalled how during the sixties and seventies, consortia had spent hundreds of millions of dollars on exploration without being able to prove the commercial feasibility of mining polymetallic nodule deposits. In the case of France, he said that it was estimated that the Government had already spent 25 per cent of the projected capital expenditure on its deposits in its pioneer area in the central Pacific Ocean. Mr. Lenoble described this as an important factor if one were planning on obtaining finance from private or public sources.

A number of participants made comments about the data on metal prices presented by Mr. Lenoble. It was noted that metal prices had steadily declined in real terms during this period. It was therefore pointed out that the situation with polymetallic nodules could not simply be resolved by waiting on higher metal prices. It was suggested that the way forward with this resource is either to find richer deposits or to improve mining and processing technology to yield lower production costs. For polymetallic nodules, Mr. Lenoble made the point that until the International Seabed Authority adopts a mining code, exploration contractors with the Authority will delay detailed exploration in order to undertake feasibility studies. Another participant noted that in the case of massive sulphides mining, many of its promoters were of the opinion that declining metal prices would work in the interest of the developing these deposits. This participant was of the view that access to such deposits in EEZs, in particular for detailed exploration, created great advantages for their future development. It was also pointed out that financing these projects is not in itself impossible but that how the project is packaged may contribute in no small measure to raising the funds required.

Mr. Lenoble was asked why he had not included the metalliferous sediments of the Red Sea in his comparison. He responded that he considered these deposits as constituting a special case. He noted that since these deposits had been the subjects of a feasibility study, they could be classified as sub-economic reserves awaiting future development.

Part 2

ISSUES TO BE TAKEN INTO ACCOUNT IN DEVELOPING A FRAMEWORK FOR THE EXPLORING AND EXPLOITATING SEAFLOOR MASSIVE SULPHIDES AND COBALT-RICH FERROMANGANESE CRUSTS AND DEPOSITS IN THE AREA

CHAPTER 12

Open Discussion, Led by the Secretary-General

Introduction

Following the presentations and discussions on the current state of knowledge and technical issues related to the sustainable development of seafloor massive sulphides and ferro-manganese cobalt-rich crusts deposits in the Area, as well as the Government of Papua New Guinea's efforts to devise a marine minerals policy to govern the seafloor massive sulphides in its territorial waters and exclusive economic zone, the Secretary-General of the International Seabed Authority introduced participants to the immediate task of the Authority which is to adopt rules, regulations and procedures for prospecting and exploring for these resources in the Area. The Secretary-General's introduction to the topic is in the form of an informal presentation that, inter alia, addressed how the principle of the Common Heritage of mankind was taken into account for deep seabed polymetallic nodules of the Area, and how the principle could similarly be incorporated into the regulations for these two types of mineral resources. Following the Secretary-General's introduction, workshop participants made their views of how the common heritage principle could be incorporated in rules, regulations and procedures for prospecting and exploring for the two types of mineral resources.

Secretary-General's presentation

The Secretary-General thanked experts who had presented papers on various aspects of seafloor massive sulphides and ferromanganese cobalt-rich crusts deposits of the Area, and expressed his appreciation for the opportunity to have an exchange of views on the formulation of rules, regulations and procedures for prospecting and exploration for these resources taking into account the principle that the resources of the Area are the Common Heritage of Mankind.

The Secretary-General said that the only mineral resource found in the Area for which rules and regulations have been formulated is polymetallic nodules. He noted that the system or regime for this resource is extensively prescribed in the body of the Convention (in particular Part XI) and in its Annex III. Since the adoption of the Convention, the Secretary-General pointed out that modifications have been made to a number of the Convention's provisions. He said that these modifications are contained in what is known as the 1994 Agreement Relating to the Implementation of Part XI of the United Nations Convention on the Law of the Sea. The Secretary-General then described the system for prospecting and exploring for polymetallic nodules. He said that in this system, a prospector submits an application for an exploration contract to the Authority. As part of the application, the applicant is required to submit data and information on a total area containing two areas of equal estimated commercial value. Following a review of the application, one area is given to the applicant, and the other is reserved for the conduct of activities by the Authority through the Enterprise, the operating arm of the International Seabed Authority, or in association with developing States.

Mr. Nandan said that this system was developed as a compromise. He explained that during the Third United Nations Conference on the Law of the Sea, there was a debate as to whether the Authority should be the sole mining operator in the international seabed area through its operating arm, the Enterprise, or whether the Authority should be no more than a licensing body to issue licenses, legitimise claims in the international area and in due course perhaps collect some royalties. Given the conflict between these two approaches, Mr. Nandan said that in 1976, the then Secretary of State of the United States, Mr Henry Kissinger came to New York and met with a number of delegates involved in the negotiations. At the meeting, Mr. Nandan said that Mr. Kissinger proposed a solution that contained a bit of both elements. He said that Mr. Kissinger suggested that a prospective explorer should be required to submit two sites of equal commercial value to the Authority. One site would be given to the operator and the other would be reserved for exploration and possible exploitation by the Authority.

Mr. Nandan pointed out that the circumstances at the time were such that a number of interested entities had gone ahead and located and identified prime areas of nodule resources in the international area for possible exploitation. Mr. Nandan said that the suggestion that applicants should submit two sites was in response to the concern that all the prime sites would have been exhausted by the time the Authority began to operate. A banking system for the Authority was therefore created so that the Enterprise or developing States could also actively participate in seabed mining. Mr. Nandan emphasized that developing States were neither ready to sit back and wait for the proceeds from mining and benefit merely in this way, nor were they willing for the situation to develop where the only operators in the seabed would be those who had the capability to undertake deep seabed mining. Mr. Nandan pointed out that in addition to the financial benefits that would ultimately be derived from deep seabed mining, developing States also sought to become actors or participants in the development of the resources. Mr. Nandan said that at the time of Mr. Kissinger's proposal, these resources had already been declared as the common heritage of mankind. It was therefore in this context that Mr. Kissinger made his proposal.

Mr. Nandan then said that during the negotiations, the next question that had to be addressed if Mr. Kissinger's proposal was acceptable was the question of funding the operations of the Authority. He told participants that it was recognized that the Authority would be starting from scratch, with no funds, no exploration and mining experience, and without the option of approaching a financial institution to raise funds. He compared the situation of the Authority to that of the consortia that were active at the time. He said that these consortia were well-established entities; many of them were mining companies with capital and the ability to raise capital. Therefore, Mr. Nandan said that for many delegations, this difference between the Authority and the potential operators appeared unfair. For that reason, Mr. Nandan informed participants that the American response to the concerns raised was that States Parties would contribute towards the first operation (that is, to explore, exploit a mine site, and transport, process and market the minerals recovered, as well as to meet the initial administrative expenses) of the Enterprise. This was to be done by States Parties contributing one half of the funds required by way of long-term interest-free loans based on the scale of assessments for the United Nations regular budget, and for States Parties to guarantee the other half of the funds that would have to be raised by the Enterprise in accordance with the same scale of assessments.

Mr. Nandan pointed out that the next issue was technology, because it was felt that even with money, without technology, participation in the parallel system would not be feasible. The answer to this issue was an agreement to provide technology on a fair and reasonable commercial basis. Mr Nandan said that these considerations were the basis for the development of the parallel system contained in Part XI that was subsequently modified by the Agreement relating to the implementation of this part of the United Nations Convention on the Law of the Sea.

Mr. Nandan pointed out the modifications introduced by the Agreement included eliminating the contribution by States Parties to the first operation by the Enterprise. This was achieved by a provision requiring that the first operation of the Enterprise would be by way of a joint-venture operation after which the Council would determine how the Enterprise would proceed with subsequent mining operations. Based on the fact that the Authority has a number of reserved sites including some very good sites, Mr. Nandan made the observation that it was felt that the Enterprise could use these sites as its equity participation in future joint-venture operations.

With regard to the transfer of technology, Mr. Nandan said that based on the negotiation of these provisions as they relate to deep seabed mining during the Conference, ideologically some States took the provisions as a requirement for compulsory transfer of technology. Mr Nandan said that the transfer of technology provisions in the Convention required contractors to agree to a number of undertakings to make technology available to the Enterprise under different circumstances if the Enterprise could not otherwise obtain technology on the open market. These included, inter alia, to make available to the Enterprise all of the technology used by the contractor in the Area on fair and reasonable commercial terms and conditions, and to acquire from the owners of any technology used by the contractor by means of an enforceable contract the legal right to transfer such technology to the Enterprise. These and related provisions, Mr. Nandan said have been modified in the Part XI agreement so that the States whose nationals have the technology are called upon to assist the Enterprise to obtain the technology at a fair and reasonable commercial price or through joint-venture arrangements.

In relation to prospecting and exploration for polymetallic nodules, Mr. Nandan said that the Convention provides that a prospector shall notify the Authority of the approximate area or areas in which it intends to prospect. He also said that the Convention confers no rights on the prospector with respect to resources. Such rights, he pointed out, can only be acquired through an exploration contract. He noted that the Convention while using the two terms, neither defines prospecting nor the point when prospecting becomes exploration. Mr. Nandan said that Resolution II that governs preparatory investment in pioneer activities relating to polymetallic nodules defines pioneer activities. He noted that the activities included in this definition go beyond marine-scientific research or prospecting, including activities that he believed are part of exploration.

Mr. Nandan commented on the rigidity of the system that is prescribed in the Convention for developing polymetallic nodules and said that it was neither the fault of the industrialized States nor the developing States but that it came about in response to the proposals made by the United States. From a historical perspective, Mr. Nandan said that negotiators of this part of the Convention were requested to make sure that all decisions that were required to be taken by the Authority were already prescribed and provided for in the Convention. Mr. Nandan emphasized that there was to be no flexibility or discretion given to the Authority. From the viewpoint of the industrialized States, a potential contractor was expected to submit an application that resulted in the award of a contract. Mr. Nandan said that the more this position was advocated, the more the Group of 77 insisted on adequate provision being made for their participation in deep seabed mining, thus compounding the system's inflexibility. He said that in the effort to devise an exploration code for polymetallic nodules, the members of the Authority addressed this rigidity. He said that by and large the Authority had managed to eliminate these problems and to devise a workable exploration code for nodules.

With regard to rules, regulations and procedures for the development of other mineral resources to be found in the international seabed area, Mr. Nandan said that the political and ideological problems with polymetallic nodules had to be borne in mind. He said that he felt certain that these problems would resurface, because in general, people often go back to what they know. Mr. Nandan said that based on the limited knowledge of nodule resources during the negotiations of Part XI of the Convention, as well as the promises of a bonanza from polymetallic nodule mining, the atmosphere in which regulations were formulated led to many problems.

He recalled that during this period, the US vessel, the Glomar Challenger was used by the United States to try to lift a Russian submarine that was disabled on the floor of the Pacific Ocean. He said that many people felt at the time came to the conclusion that all the discussions of deep seabed nodule mining were a cover-up for the lifting of the submarine.

Comparing the scientific knowledge that has been gathered that could assist the Authority in drafting rules, regulations and procedures for prospecting and exploration for polymetallic massive sulphides and ferromanganese cobalt-rich crusts to that which existed when the regime for polymetallic nodules was devised, Mr. Nandan said that the knowledge base for nodules was rather limited. He said it was therefore not surprising that a lot of mistakes were made in the rules that were drafted for nodules. He said that the problem in political negotiations is people seek all kinds of safeguards and overburden the system with these safeguards. Having said that, Mr. Nandan pointed out that we know very little about these other resources even today. For example, he said that as far as cobalt-rich ferromanganese crusts are concerned, he is just beginning to a scratch the surface of scientific knowledge about them. He also said that what he had learnt during the week, in the form of the pictures and the presentations that had been made on both types of resources was much more than he knew about nodules during the negotiations on polymetallic nodules. He said experience suggests that there is some level of objectivity and willingness to allow these resources to be developed because if they are not developed there would be nothing by way of the common heritage principle. He said that the presentations had provided useful information on the nature of these resources even though knowledge of them is still rudimentary.

Mr. Nandan pointed out that the primary task of the Authority is to set up a system of exploitation for these resources that took into account the common heritage principle. In that regard, Mr. Nandan asked participants whether the system devised for polymetallic nodules could be applicable to these two types of resources. In particular, he asked if the parallel system, under which an applicant is required to provide two areas containing deposits of equal estimated commercial value could be applied to seafloor massive sulphides and cobalt-rich ferromanganese crusts deposits. If not, Mr. Nandan asked how the issue of developing country participation in the development of these resources could be taken into account.

He suggested that a possible solution to participants for their consideration. He said that an alternate approach could be through some form of equity participation by the Authority in exploration and mining. If such an approach is taken, he asked participants what equity or interest in the operation should be made available to the Authority.

Mr. Nandan also asked participants for their views on how the proposed code should be developed. He suggested that in view of the limited knowledge that the international community had about these resources, it might be better to progressively develop the code rather than setting up a comprehensive regime on the basis of the limited knowledge. In this regard, he said that for polymetallic nodules one of the great difficulties with the regime is the fact the Convention says that once the Authority enters into a contract with a contractor, that contract can only be modified with the agreement of the contractor. Mr Nandan said that this provision creates a lot of problems because the tendency then becomes to load the contract with everything that the Authority might suspect it needs. He described this provision as one of the defects of the Authority's Exploration Code for polymetallic nodules.

Returning to prospecting and exploration for these resources, Mr. Nandan again reminded participants that in the case of polymetallic nodules, the Convention provides no proprietary right to the prospector, and also says that more than one operator can prospect in the same area. He asked participants for their views on how these issues could be addressed in the case of seafloor massive sulphides and ferromanganese cobalt-rich crusts deposits that were different in nature from polymetallic nodules. He also asked participants whether the rights given prospectors for offshore hydrocarbon prospecting would be more applicable in the case of these two types of mineral deposits.

SUMMARY OF THE EXCHANGE OF VIEWS.

Following the Secretary-General's presentation, participants exchanged views on a number of the matters that he had raised. The exchange of views focussed on the differences between seafloor massive sulphides and crusts deposits, and polymetallic nodules, the costs involved in delineating deposits of the two new types of deposits, the rights of prospectors, whether the Authority should devise a single new mechanism for all other resources of the Area based on the common heritage principle in order to circumvent years of negotiation each time a new mineral is discovered, and alternates to the parallel system as framed for polymetallic nodules such as a carried interest in operations for the Authority.

Discussions on estimates of equal commercial value, differences between evaluating seafloor massive sulphides, cobalt-rich ferromanganese crusts and polymetallic nodule deposits, and prospector's rights.

Discussions on the differences between seafloor massive sulphides, cobalt-rich ferromanganese crusts and polymetallic nodules originated from a consideration of the need to submit two sites of estimated equal commercial value. One participant said that the matter was one of technicalities because it should not be too difficult for a prospective applicant for exploration to submit two sites of equal estimated commercial value to the Authority whether for seafloor massive sulphides or cobalt-rich ferromanganese crusts deposits. In the case of cobalt-rich crusts deposits, this participant said that from a layman's point of view, the primary issue would be to find seamounts containing these deposits. After that he continued, one seamount might contain crusts that are 25 cm thick, and the other seamount crusts that might be 10 cm thick. The size of areas submitted in respect of these two sites might then be 10 sq km and 25 sq km respectively, to satisfy the requirement to submit two sites of equal estimated commercial value. This participant pointed out that the same requirement has been made for polymetallic nodules exploration. He pointed out that in the case of nodules, the interested entities started from scratch, and without any laws to protect their investments. He said that the entities that were interested in developing nodule resources took the financial risk to prospect the Area for polymetallic nodule deposits. Referring to the minimum expenditure requirement for registration as a pioneer investor of US$30 million (1982) as provided for in Resolution II of the Convention, he also said that the concerned entities had already gathered the information required to prove that the two sites were of equal commercial value. The participant however made the observation that at present it appeared unlikely that any potential applicant would risk tens of millions of dollars without the assurance that it would be authorized to continue to develop a mine. As a result, this participant suggested that the Authority should invent a system that protects this initial investment stage of the development of these resources by issuing "an exclusive prospecting right", so that the applicant could start its operation in a broad area. Later, the area could be split in two.

Another participant made the observation that the situation described for the polymetallic nodule regime was different. This participant said that the system for polymetallic nodules worked because prospecting and prospected areas were kept secret. He emphasized this point by referring to the considerable amount of overlaps in prospected areas in the Clarion-Clipperton zone. He further added that it required seven years of negotiations by those concerned to yield a complicated result. This participant expressed support for providing prospectors for seafloor massive sulphides and cobalt-rich ferromanganese crusts with an assurance and guarantee that protect their investments, and a priority right to mineable areas within which prospecting is to occur. In response to a question whether a pioneer status was being requested, this participant responded by saying that what is sought is an opportunity for prospectors to start prospecting and to acquire sufficient data in order to fulfil the parallel system. This participant stated that the period during which the prospected area is protected would be to enable the operator to acquire the data necessary to identify two areas of equal commercial value.

Another participant noted that there is a big difference between two-dimensional deposits like polymetallic nodule deposits and the three-dimensional seafloor massive sulphides and cobalt-rich ferromanganese crusts deposits. This participant pointed out that the biggest difference is in the cost to evaluate the latter two types of deposits that was described as tremendously expensive. Comparing the size of nodule deposits to seafloor massive sulphides and cobalt-rich ferromanganese crusts, this participant said that in addition to the fact that the newer deposits are much smaller than nodule deposits, (almost like the difference between coal which is stratified and a small gold vein deposit), there were many other dissimilarities between them.

With regard to the requirement to submit two sites of equal estimated commercial value, another participant expressed his disbelief that investors would commit large sums of money to explore the worlds oceans with the prospect that when they have done that the best targets might just disappear before they have actually had the opportunity to recover any money on what are traditionally looked at as sunk costs. This participant said that although the concept of equal values is very noble, the value of a deposit is only determined when it has been completely mined. This participant noted that the amount of sampling and evaluation work that can be conducted on a deposit is limited. He also noted that while polymetallic nodule deposits could be considered as monolayered, he was of the opinion that all three types of deposits must contain high variations in grade. In this regard, this participant referred to the information that had been presented at the workshop on sampling these deposits. He pointed out that based on spot sampling, a few hundred samples that have been taken, assertions are being made about the average grades of deposits as if this is going to be what the mining house gets back. He noted that to be able to make an equal value decision, hundreds of millions of dollars would have to be spent because of the vast depths of water, the need to be able to sample the deposits on a consistent grid basis, and to apply geo-statistics to the results. This participant said that the first company that would have to do this kind of work would be the Nautilus Mining Company. The participant reiterated the point of view that industry would not be attracted to a proposition that requires hundreds of millions of dollars to be placed upfront without any protection.

As regards identifying two areas of equal estimated commercial value for cobalt-rich crusts deposits on seamounts, another participant assured the workshop that it would be possible to find areas of seamounts that are sediment free and therefore contain ferromanganese crusts. With respect to estimates of commercial values of seamounts, this participant suggested that because of the variability of grade and tonnages of crusts deposits with water depth and also with longitude and latitude, it would be better if the two areas evaluated for this purpose were found on a single seamount. This participant said that although no seamount has been investigated sufficiently at present to address the question of commercial value, the key word in the provision is "estimated". He said that it is known that on many seamounts, crusts deposits are found for hundreds of square kilometres. When deposits are identified, this participant said that information on the thickness and grade, that show considerable variation, have to be obtained.

Another participant was of the opinion that our understanding of these deposits is better than could be judged from the discussions that were taking place. This participant made the observation that during the workshop all participants were presented with very fine images of data that were collected over relatively short periods of time on seafloor massive sulphides, and that provided volumetric estimates of the resources. This participant was of the opinion that the next step is sampling, for which there are techniques that have been developed in academic institutions to, inter alia, determine the density of sampling required and other relevant factors. This participant raised doubts about the points made on the differences between manganese nodules and manganese crusts and sulphides, as they related to a determination of their commercial values. While accepting the fact that the resources are different, this participant said that there are techniques for evaluating the three types of deposits. The participant said that although the results may not be exact, they should be a reasonable attempt at estimating the commercial values of the deposits.

A participant with a contrary view said that estimates of the commercial values of these deposits should have confidence levels that enable the prospective applicant to go to a bank and to borrow the funds required to float a vessel equipped to mine the deposit, and to do all the other things that come with a mining operation. This participant pointed out that during the workshop, in relation to deposit evaluation the only equipment discussed have been grabs and dredges, and yet to be proven drilling equipment has been discussed. This participant also pointed out that the although the volumetric maps shown during an earlier presentation are a significant step forward, they were not based on a consistent size sample as required for land-based deposits. He said that the current information on seafloor massive sulphides and cobalt-rich ferromanganese crusts is still an order of magnitude away from the kind of knowledge needed to set up a mine plan and to be able to base that plan on a cost analysis that will deliver a certain amount of money in a year.

In relation to the rights of prospectors under the regime for polymetallic nodules, the Secretary-General pointed out that at the time, it was not known what prospectors were doing, and seabed areas in which they were engaged in prospecting activities. He said however that when applications were submitted to the Preparatory Commission for the International Seabed Authority for interested entities to be registered as Pioneer Investors each of them came up with two sites. He noted that under the Exploration Code for Polymetallic Nodules the same provision applies to all applicants for exploration rights. He reiterated that no exclusive rights were given to the pioneer investors for their prospecting work. He said that the proposal made earlier during the discussions that prospectors should be given some understanding that they will have proprietary rights or at least priority for a license in the area that they prospect at the very outset is a new approach.

He said that if this approach were agreeable, it might be preferable to have a grid or block system for these kinds of resources in preference to the system for nodules. He noted that under the system for nodules, other prospectors are allowed to prospect in the same areas because nodule deposits are spread over large areas. He said that the grid or block system would provide for some kind of security and exclusivity but for a limited time period.

Discussions on the principle of the common heritage of mankind, the parallel system and its applicability to seafloor massive sulphides and cobalt-rich ferromanganese crusts deposits, and their distribution in marine areas.

A participant, who made the comment that the Law of the Sea Convention identifies the resources spoken of as the common heritage of mankind, as consisting of the Area, and solid or liquid materials to be found on the seabed, including polymetallic nodules, initiated the discussions on the common heritage principle. This participant said that as a result of this principle, the Authority is fully in charge of all these resources. In this regard he pointed out that as better knowledge makes the discovery of new resources possible, the Authority should be prepared to devise rules, regulations and procedures for their development. In addition to new mineral resources, this participant pointed to other uses including the laying of underwater optic cables as operations that utilize the common heritage. This participant indicated that while it may be necessary to devise new mechanisms for realizing the benefits accruing from the common heritage principle from developing the two new minerals found on the seabed, another approach might be to devise a new mechanism for all resources other than polymetallic nodules. In so doing, this participant noted that there would be problems as well as benefits. He described the benefit by stating that it would eliminate the need to develop a new mechanism each time a resource that differs from nodules is encountered, and eliminate the need for a protracted period of negotiations that may not be able to solve the associated problems. This participant observed that the system in place for nodules took a long time to negotiate, has been tried over the past fifteen years and will be furthered refined during the next fifteen years as part of exploration contracts.

Another participant, recalled that during the Secretary-General 's presentation he had suggested a number of factors to be taken into account in preparing the rules, regulations and procedures for prospecting and exploration of seafloor massive sulphides and cobalt-rich ferromanganese crusts. In this regard, this participant said that other factors needed to be taken into account. These, he said, were the distribution of these new mineral resources in the Area and in Exclusive economic zones, the metals to be recovered from these minerals, and the depths of occurrence of these deposits. This participant observed that cobalt-rich crusts are distributed in the Area as well as in the EEZs of many countries, and that polymetallic massive sulphides are also found in the Area and in the EEZs of many countries. This participant said that the metals to be recovered from these resources introduce an economic perspective, including the markets for the concerned metals and in the determination of the commercial value of deposits. With regard to the depth of occurrence of these deposits, this participant said that such information helps to determine the technology required to recover the minerals as well as how to protect the environment from the impacts of mining.

For those deposits located in the exclusive economic zones of coastal and island States, this participant made the observation that some States may have already prepared or established regimes for prospecting and exploration for these new resources. He said that a new regime for prospecting and exploration for these kinds of resources in the Area should therefore be compatible with those prepared by the coastal States.

Commenting on these statements, the Secretary-General said that in the case of crusts and massive sulphides the difference between those two minerals and nodules also lies in the fact whereas most of the nodules are to be found in the international area these two resources are also found in national areas. As a result, the Secretary-General said that the Authority would be competing with endowed coastal and island States or territories.

In relation to an earlier statement regarding the use of one system for all marine mineral resources, a participant from the United States said that the United State has regulations for offshore petroleum and regulations for marine minerals other than oil and gas. He said that given the differences in the nature of the different types of deposits, separate regimes were established for each one. This participant, who was a member of the drafting Committee established by the Government of the United States, described the work that was done by the United States. He said that initially and where necessary, the Committee tracked all the regulations that were developed elsewhere and extracted the good parts of these regulations. He said regulations had been established for prospecting, exploration and commercial recovery. He said that under these regulations, prospecting is free of cost that is, the company is not required to pay the government for engaging in this activity. He said interested parties are free to prospect and do scientific research. He said that once the work becomes commercial, the interested party has to apply for an exploration license that then gives the party exclusive rights. This participant noted however that the oil and gas regulations contain provisions that would cause difficulties for other marine mineral regimes. As an example, he said that under the oil and gas regulations, after exploring an area, the explored area is put up for bid. He noted that although it appears to have worked for oil and gas, it was a point of dispute with the other minerals and it was not set up in that way for those resources. For other marine minerals in the United States, this participant said that if an explorer finds minerals in a given area, then the explorer would request lease offerings from the relevant department.

This participant recommended that great caution should be exercised at this stage of implementing a new regime so that the Authority does not create a framework that locks out potential developers.

A number of participants were of the view that for all the resources beyond the limits of national jurisdiction, the principle of the common heritage of mankind applies. They were of the view that if the common heritage of mankind principle applies, the parallel system should apply. This group also acknowledged that both seafloor massive sulphides and cobalt-rich ferromanganese crusts deposits are different from the polymetallic nodule deposits.

It was suggested that in view of the practical problem of finding two sites of estimated equal commercial value, the parallel system should be merged into a single operation. The single operation would be a joint venture with a carried interest by the Authority. It was also suggested that the Authority's carried interest would be negotiable, depending on the economic viability of the project. It was pointed out that this method of participation in the development of mineral resources is included in a lot of national legislations. As an example, participants were informed that at the beginning of offshore hydrocarbon development on the Norwegian continental shelf, the Norwegian government obtained a fifty per cent carried interest in operations to develop petroleum deposits. This approach was described as a type of parallel system within one deposit.

Another participant said that the information provided during the workshop suggests that the large majority known of seafloor massive sulphides and cobalt-rich ferromanganese crusts deposits are not found within the Area but within either EEZ's or even territorial waters. This participant suggested that the first deposits that will be worked are either going to be in shallow waters or would be close to land, or again within an EEZ. This participant concluded that the vast majority of these resources would therefore not become the concern of the Seabed Authority for a long time. In that regard, this participant wanted to know if a simple tax system on mining proceeds could not be applied for operations in the Area.

Another participant cautioned against taking the rules, regulations and procedures for the development of the resources of the Area from national legislation. This participant was of the opinion that many national legislations are stricter than the provisions of the Law of the Sea Convention with regard the to the development of marine minerals resources.

Finally, another participant expressed an opinion that based on the presentations on seafloor massive sulphides, cobalt-rich ferromanganese crusts and polymetallic nodule deposits, it has become very clear that for the three types of resources, there is still not enough information for their development. This participant suggested that the core objective of the International Seabed Authority's regulations must be to encourage more prospecting of these resources, and the establishment of their economic viability.

The Secretary-General concluded the exchange of views by pointing out that whether it is a coastal/Island state that owns the resources or the resources are the common heritage of mankind in international waters, the two important things are that no company will invest in developing the resource unless they are going to be guaranteed some form of exclusivity and security of tenure.

Part 3

PROSPECTS FOR OTHER MARINE MINERALS THAT MAY BE FOUND IN THE AREA

CHAPTER 13

PETROLEUM POTENTIAL AND DEVELOPMENT PROSPECTS IN DEEP-SEA AREAS OF THE WORLD

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In the oil industry, the term "deepwater" is applied to the deeper parts of the World's Oceans with water depths of more than 500m. At these depths, the offshore extensions of marginal sedimentary basins and, less frequently, oceanic-type basins are located. About 120 of the known 511 sedimentary basins of the world have volume-balance methods. The total recoverable oil and condensate reserves are 36 Gt; gas, 63 TM^3. The bulk of resources occur in the basins along the Atlantic Ocean margins. Deepwater hydrocarbon exploration began in the 1980s. Exploration work was particularly active in the Campos basin (Brazil), Gulf of Mexico (US sector), and West Africa (Angola, Nigeria). By the end of the century, exploratory wells reached sea depths of 3000 m, and development wells, depths of 2000 m. By the beginning of 2000, a total of 190 oil and gas fields with aggregate reserves of about 3 Gtoe had been discovered in deepwater areas. In the next 5 years, deepwater oil expenditure will exceed $70 billion forecasted spending.

1. Introduction

The term "deepwater" has become quite common at the present stage of offshore petroleum exploration and development, and it carries a geological, and technical and economic sense. Geologically, it refers to the deeper parts of the World's Oceans with water depths greater than 500 m. Passive and active continental margins, trenches, island-arc slopes, the continental rise, and the deep-sea basins of the World's Oceans are located at these depths. In some parts of the World's Oceans, these zones exhibit considerable petroleum potential. From the technical and economic perspective, these areas are the offshore areas where fixed bottom-supported drilling or production platforms cannot be used. Hydrocarbon prospecting and development at these water depths require special technical means and economic estimates.

At present, the technical and economic limit for permanent offshore platforms is a water depth of 300 metres in the North Atlantic (North and Norwegian seas) and 450 metres, in regions with less harsh environments. In future, the depth limit for permanent offshore platforms may be extended by means of new, stronger and more elastic materials.

Exploratory drilling in water depths up to 400 metres dates back to the 1960s. Field development in water depths more than 200 metres began in the 1980s, when deepwater petroleum exploration rapidly expanded. In the 1990s, hydrocarbon exploration and development extended into new areas at even greater water depths.

L. Weeks, an American scientist presented the first estimate of offshore hydrocarbon resources in 1971 at the 8th Petroleum Congress in Moscow. He estimated the offshore recoverable hydrocarbon resources of the World's Oceans as 320 Gtoe (1 toe = 100 m^3 gas), consisting of 230 Gt[1] oil and 90 Tm^3 [2]gas. In the following 20 years, new recoverable hydrocarbon resource estimates were regularly published. They varied from 100–150 Gtoe[3] to 1.5-2 Ttoe, primarily due to poor geologic knowledge of the World's Oceans, the use of different sets of data, and assumptions of different geologic or economic allowances and limits. In all cases, however, the petroleum potential of deepwater areas (deeper than 500 metres of water) was never discussed independently.

The Research institute VNIIZarubezhgeologia (Moscow, Russia) has repeatedly estimated deepwater oil and gas resources of the World's Oceans within the framework of the quantitative estimation of world petroleum potential. The latest estimate that it made was in 1996, and was based on the available geologic and economic data.

2. Sedimentary Basins As The Main Object Of Hydrocarbon Resource Estimation

Sedimentary basins of various sizes, structure and geologic history are considered the main object of hydrocarbon resource exploration. These basins are morphologically expressed in the modern crustal

[1] Gt. Gigatonnes equal to one billion metric tons (tonnes) = 1000 million tonnes.
[2] Tm^3 - Tera cubic metres = 10^{12} cubic metres
[3] Gtoe – Gigatonnes of oil equivalent

structure and filled with sediments capable of hydrocarbon generation, accumulation and retention. Based on this concept, 511 basins have been recognized throughout the world including Antarctica. Two hundred twenty-six (226) contain proven commercial hydrocarbon accumulations and are therefore classified as petroliferous basins (PBs). In other basins, the presence of oil and gas pools is inferred, and these basins are termed as possibly petroliferous (PPBs).

The PBs and PPBs were studied on the basis of a single concept. A lot of data on basin structure and evolution, depositional environment, and formation of hydrocarbon pools in different phase states were analyzed. Particularly detailed analysis was performed on data on sedimentary lithology, structure and origin of the main structural boundaries, lateral and vertical distribution of productive and prospective sequence thicknesses and facies. Particular emphasis was placed on studies of reservoirs, source rocks, seals, and the spatial distribution and structure of oil and gas fields.

Generalization of the data on geologic structure, evolution, and petroleum potential of sedimentary basins of the world enabled us to create an original classification of PBs and PPBs based on the present-day geodynamic setting.

On the basis of this classification, all basins of the world's oceans were systematized and subdivided into categories, groups, subgroups, types, and subtypes (figure 1).

In terms of crustal structure and position within lithospheric plates, all basins were classified into three categories, continental, oceanic, and marginal or transitional. In terms of spatial relationships with the main tectonic elements inside the plates, basin categories were subdivided into groups. For example, the category of continental basins was subdivided into two groups, platform basins and orogenic belt basins; marginal basins were subdivided into four groups, basins of relict margins, continental and oceanic margins, and interplate basins. One group, thalassocratic basins, represents the category of oceanic basins.

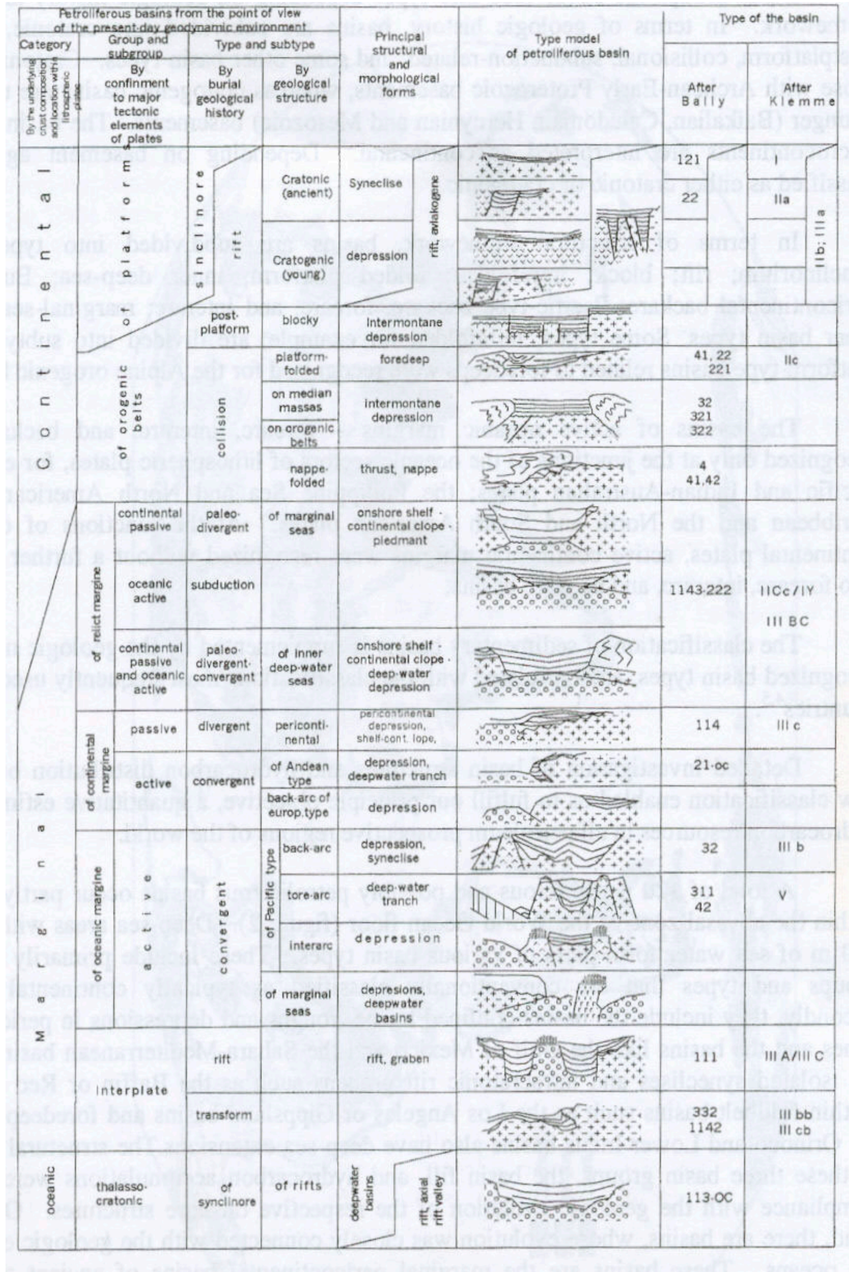


Figure 1. Sedimentary basin classification

Basin groups are subdivided into types depending on their geologic history and structural framework. In terms of geologic history, basins are subdivided into cratonic, cratogenic, and post-platform, collisional, subduction-related, and some other basin types. Cratonic basins are those with Archean-Early Proterozoic basements, whereas cratogenic basins are underlain by younger (Baikalian, Caledonian, Hercynian and Mesozoic) basements. The basins located on micro continents are interpreted as continental. Depending on basement ages, they are classified as either cratonic or cratogenic.

In terms of structural framework, basins are subdivided into types such as synclinorium; rift; block; intrafolded; folded platform; inner deep-sea; European-type pericontinental back arc; Pacific-type back arc, fore arc and inter arc; marginal-sea; and some other basin types. Some types, intrafolded for example, are divided into subtypes. Folded platform-type basins related to foredeeps were recognized for the Alpine orogenic belts only.

The basins of active oceanic margins – fore arc, inter arc, and back arc – were recognized only at the junctions of the oceanic sectors of lithospheric plates, for example, the Pacific and Indian-Australian plates; the Philippine Sea and North American plate; the Caribbean and the North and South American plates. At the junctions of oceanic and continental plates, active continental margins were recognized without further subdivision into fore arc, inter arc, and back arc basins.

The classification of sedimentary basins is supplemented by geologic models of all recognized basin types, and correlated with the classifications most frequently used in western countries[4, 5].

Detailed investigation of basin structures and hydrocarbon distribution based on the new classification enabled us to fulfil our principle objective, a quantitative estimate of total hydrocarbon resources in all prospective petroleum regions of the world.

A total of 120 petroliferous basins occur partly or entirely within the abyssal zone of the World Ocean floor (figure 2). Deep-sea areas with more than 500 m of seawater form parts of various basin types. These include primarily those basin groups and types that are conveniently classified as typically continental structures. Secondly, they include the basins confined to the troughs and depressions in pericratonic sag zones and the basins like the Gulf of Mexico and the Sahara-Mediterranean basin as well as the isolated synclines and intracratonic rift grabens such as the Baffin or Red Sea basins. Within fold belt basins such as the Los Angeles or Gippsland basins and foredeep basins like the Orinoco and Lower Indus basins also have deep-sea extensions. The structural framework of these three basin groups, the basin fill, and hydrocarbon accumulations were formed in compliance with the geologic evolution of the respective onshore structures. On the other hand, there are basins, whose evolution was closely connected with the geologic evolution of the oceans. These basins are the marginal pericontinental basins of ancient and modern passive continental margins at the junctions of platforms and thalassocratons, e.g. the Gulf of Guinea, Campos, or Carnarvon basins, and the marginal perioceanic basins of active continental margins and modern island arcs, often including the sedimentary lenses of trench facies. The deepwater parts of these basins mostly occur in oceans.

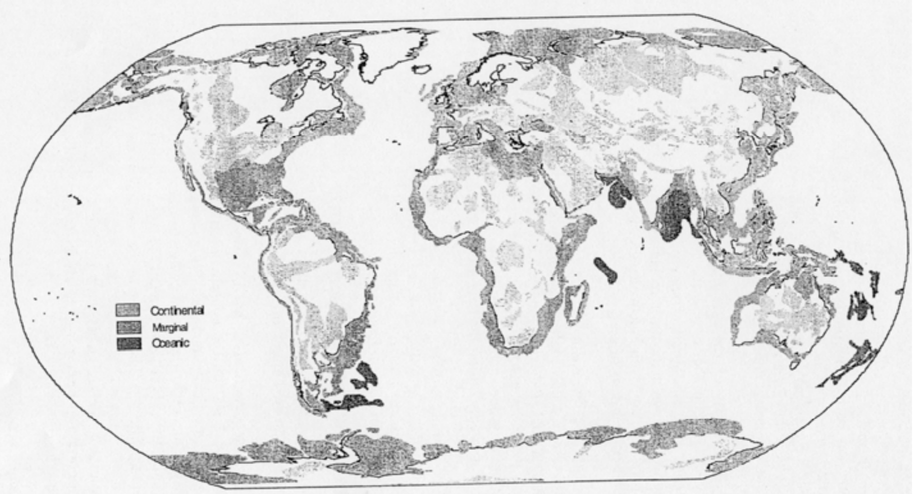


Figure 2. World sedimentary basins

Closed sea basins are vast shallow-water seas with subordinate deepwater basins. The shelves of these basins are characterized by fairly high exploration coverage, and the petroleum potential of adjacent deep-sea basins can be estimated by analogy with a high degree of confidence. The basin onsets in the marginal continent-to-ocean zone are essentially different from the above-mentioned group of basins. Sediment accumulation within them took place in open-marine environment, at least during the late Mesozoic-Cenozoic stage, whereas the closed water basins underwent periods of terrestrial and lagoon sedimentation. In addition, the exploration maturity, not only of deepwater but also of the inner shelf parts of these basins is very low (with the exception of the shelves of the Gulf of Guinea and Kwanza-Cameroon basins and small nearshore areas of North and South America and Australia).

Most basins of the aforementioned three groups, irrespective of the presence of offshore areas within them, show the same characteristic features as their continental tectonic equivalents. The stratigraphic range of commercial hydrocarbon productivity in closed sea basins is well known in the offshore and shelf zones. The sedimentary cover often includes the Lower Mesozoic and even Paleozoic deposits, whose aerial extent is traceable with confidence into the deepwater parts of seas.

In open marine basins, the extent of sedimentary cover deformations on the continental slope and rise is much higher than on abyssal plains, where sedimentary strata are poorly differentiated and flat lying. In pericontinental and perioceanic basins of open marine provinces, the sedimentary cover apparently consists of Late Mesozoic to Cenozoic sediments. This is primarily due to the geologically young age of the present-day oceans, which were initiated presumably during the Late Mesozoic.

The specific structural features of sedimentary cover in the deepwater parts of the World Ocean along with the available data on commercial hydrocarbon reserves on the shelf and adjacent onshore areas of basins were taken into account during the estimation of the world deepwater offshore oil and gas resources.

3. Methods Of Resource Estimation

Hydrocarbon resource estimates for most basins of the world were made using two methods widely applied in the former USSR[6].

The *volume-statistical* method of oil and gas resource evaluation and various versions of this method are based on the concept that the initial total in place hydrocarbon resources ($ITIPR_{HC}$) are genetically and spatially related to sedimentary deposits. Generally, if a sedimentary sequence is the source of hydrocarbons and at the same time host's hydrocarbon accumulations, then the $ITIPR_{HC}$ volume of the studied object is actually a function of the volume of sedimentary fill. Another version of the volume-statistical method suggests and empirically determines a relationship between resource volume density variations (i.e., oil and gas reserves per unit volume of the sedimentary fill, ρV) and certain parameter of the basin's sedimentary fill, particularly the proportion of reservoir intervals in the total volume of the sedimentary fill (efficient holding capacity coefficient, K_{ec}).

The diagrams illustrating the above-mentioned versions of the volume-statistical method, reflecting the empirically determined relationship is shown in figures 3 and 4.

$ITIPR_{HC} = P (V)$ and$\rho V = f (K_{ec}$

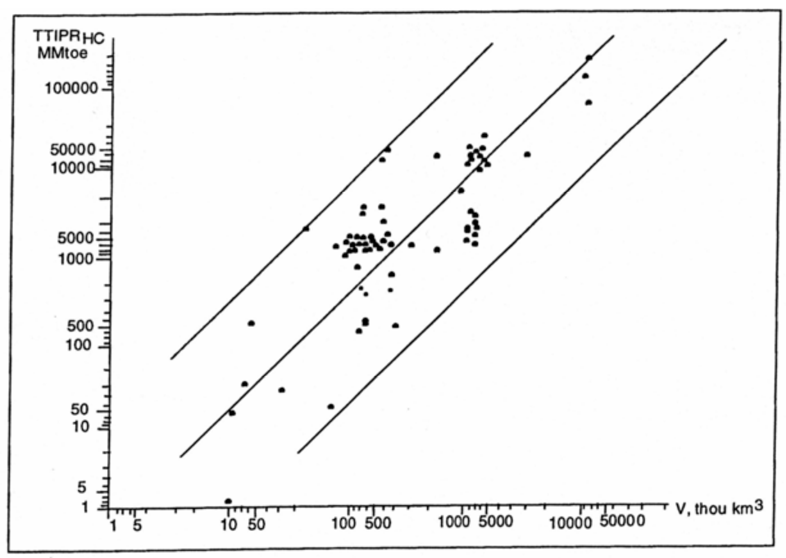


Figure 3: Initial total in place hydrocarbon resources ($ITIPR_{HC}$) vs. basin fill volume

According to the first version, the objects with sedimentary fill volumes between 10,000 and 3,000 km^3 show a practically linear dependence, corresponding to the following equation:

$In\ ITIPR_{HC} = 1.19\ In\ V – 6.\ 47$

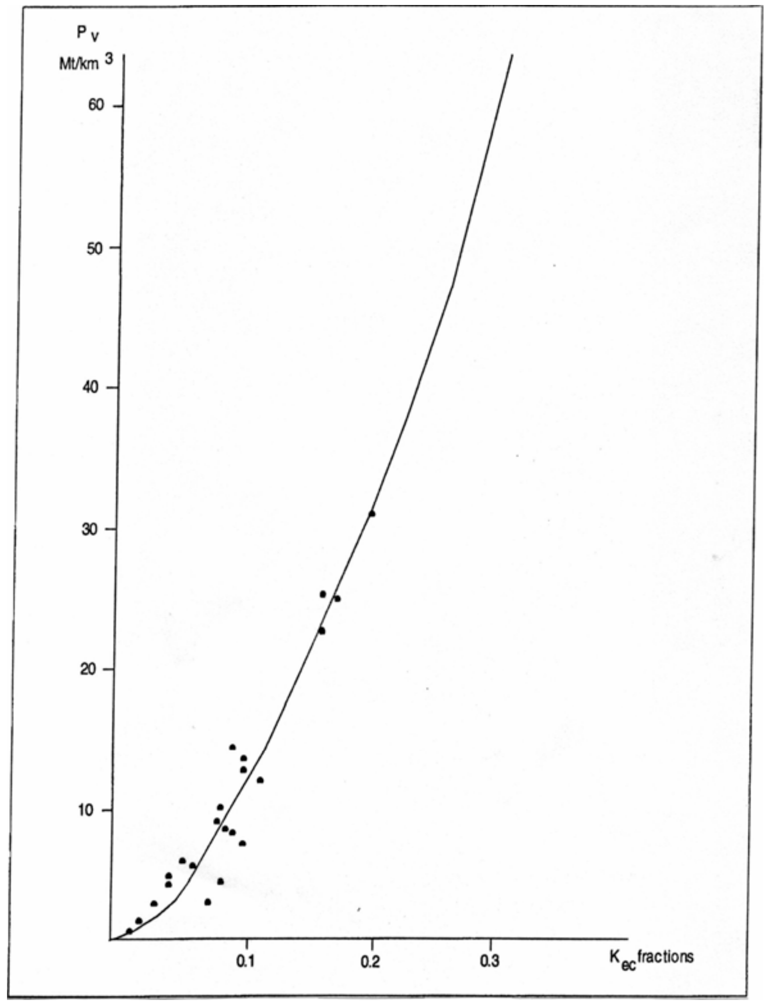


Figure 4: Volume density of initial hydrocarbon resources ρV vs. effective capacity coefficient of the basin fill (K_{ec})

For larger objects, it is described by the following equation:

$ITIPR_{HC} = (e^{1.3.}\ 10^{-4v} - 1)$

In the second version, the following formula was applied:

$\rho V = e^{4.69.}\ e^{2.67Kec} \cdot K_{ec} \cdot 1.12,$

Where the $ITIPRH_{Hc}$ is in Mmtoe (1 t oil = 1,000 m^3 gas); V, in thousands km3; and K_{ec}, is a fraction.

The volume-statistical method enables us to give a first-approximation estimate of hydrocarbon resources in frontier sedimentary basins or their larger parts, for which the theoretical possibility of petroleum generation and accumulation have been established and the sedimentary cover, volume and qualitative characteristics of petroleum potential can be estimated from the available geologic and geophysical data. In this case, the first version of the method is applied (figure 4).

Not all reservoir rocks are interpreted as natural reservoirs. For example, permeable seams without component seals above them or thick reservoir units lacking intraformational seals and that are therefore easily drained by formation water are not considered as "effective porosities". The proportion of natural reservoirs in a sequence or in the basin fill as a whole is characterized by an effective porosity coefficient and depends on the lithology of sedimentary sequences and units. This coefficient ranges in value from 0.001 to 0.3-0.45. The lowest values are usually characteristic of coarse-grained deposits of orogenic complexes; the highest are usually characteristic of biogenic and bioclastic limestones (reefs in particular).

The objects of estimation in the *volume-balance method* of hydrocarbon resource evaluation are large self-regulated equilibrium petroleum–hydrodynamic systems, laterally extending through entire basins or the constituent regions, sags, petroleum accumulation zones, and vertically confined to certain lithostratigraphic units. The petroleum-hydrodynamic system (PHDS) volume encompasses the total volume of natural reservoirs present in the object under consideration, and is filled with three interrelated components, oil, gas, and formation water. The ratio between the volume of oil and gas saturated reservoirs (pools) in place and the total PHDS volume is the concentration coefficient (oil, gas, or total hydrocarbon concentration, respectively).

Based on a simplified version of the volume-balance method, in the absence of data on temperature, pressure, porosity, and other in-place conditions of pay zones, the initial total-in-place hydrocarbon resources are calculated using the following equation:

$$ITIPR_{HC} = V_{nr}\ \phi_{HC}\ \gamma\ 103\ (\text{Mmtoe}),$$

Where V_{nr} is the volume of natural reservoirs, measured in km^3; ϕ_{HC}, the total hydrocarbon concentration coefficient, expressed as a fraction; and γ, the average hydrocarbon density, measured in g/cm^3.

It should be noted that both methods are applied to frontier basins. Where the initial data available were insufficient, more accurate calculation methods were applied.

The latter are the comparative geologic and volume-genetic resource evaluation methods. The comparative geologic method is based on the selection of a mature standard (reference) basin, with which the studied basin is compared in terms of geologic parameters. To make up for the difference in the compared sediment thicknesses, reservoirs, seals, etc., correction coefficients are introduced.

We have applied a modified version of this method (the standard scanning method, worked out in the Petroleum Institute of JSC VNIIZarubezhgeologia) for the evaluation of basins related to continental margins. A number of basins, for which the data on organic matter and maturity were available, were evaluated using the volume-genetic method. This method, essentially, consists of the calculation of a possible volumes of hydrocarbons that could be generated by source rocks, the possible volumes of hydrocarbon migration from source rocks, and the amount of oil and gas which might accumulate in available traps after migration losses. It should be noted that this method is widely applied in many countries. In recent years, it was modified to take into account the concept of petroleum system[7].

4. Oil and Gas Resources of Deep-Sea Areas and their Geographical Distribution

According to our calculations, the initial total recoverable oil resources of the world are 540 Bt, and gas, 546 Tm^3. By comparison, the latest world petroleum potential estimates given by the US Geological Survey are 372 Bt oil and 358 Tm^3 gas[8]. Apart from different calculation methods, the principal cause of the difference is the underestimation of hydrocarbon resources in the CIS countries. Indeed, Masters *et al*.[8] estimate the gas resources in the CIS at 107 Tm^3, whereas the official GAZPROM estimate (prepared jointly by a number of research institutes in the CIS) is 260 Tm^3. Oil resources in the CIS are likewise underestimated. In addition, the American estimates did not take into account the deep-sea (outside the continental shelf) offshore resources.

The aggregate initial total in-place hydrocarbon resources in the deep-sea areas of the World are estimated at about 200 Gt, including more than 110 Gtoe liquids and 85 Tm^3 non-associated and solution gas.

The recoverable portion of these resources was determined with reference to the world's actual average liquids and gas recovery factors of approximately 30% for oil and solution gas; 65%, for condensate; and 80%, for non-associated gas.

Using these recovery factors of various hydrocarbon types, the recoverable oil and gas resources of all petroliferous basins were estimated. The aggregate ultimate recoverable hydrocarbon resources in the deep-sea areas of the world were estimated as 99 Gtoe, including 36 Gt oil and condensate and 63 Tm^3 non-associated and solution gas.

The initial recoverable deepwater offshore oil and gas resource distribution by ocean and by geographic region is given in Tables 1 and 2 and Figure 5.

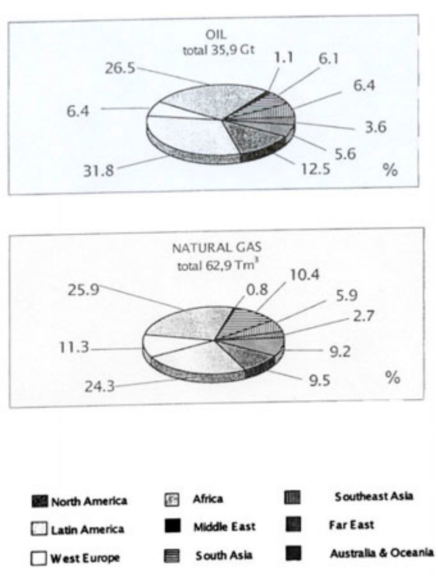


Figure 5: Geographic distribution of the initial total deepwater recoverable oil and gas resources

Table 1: Offshore (deepwater) initial total recoverable hydrocarbon resource distribution by ocean

Oceans, regions	Total, Gtoe	Oil and condensate, Gt	Non-associated and solution gas, Tm^3
Pacific Ocean	16.6	5.8	10.8
North America	1.2	0.5	0.7
Latin America	3.6	1.5	2.1
South Asia	0.2	0.1	0.1
Southeast Asia	3.6	1.3	2.3
Far East	3	1.3	1.7
Australia & Oceania	5	1.1	3.9
Atlantic Ocean	63	25	38
North America	9.3	4	5.3
Latin America	23.1	9.9	13.2
West Europe	9.4	2.3	7.1
Africa	20.6	8.5	12.1
Middle East	0.6	0.3	0.3
Indian Ocean	19.2	5.1	14.1
Africa	5.2	1	4.2
Middle East	0.3	0.1	0.2
South Asia	8.5	2.1	6.4
Southeast Asia	2.4	1	1.4
Australia & Oceania	2.8	0.9	1.9
TOTAL:	98.8	35.9	62.9

Table 2 : Offshore (deepwater) initial recoverable hydrocarbon resource distribution by region

Oceans, regions	Total, Gtoe	Oil and condensate, Gt	Non-associated and solution gas, Tm^3
North America	10.5	4.5	6
Latin America	26.7	11.4	15.3
West Europe	9.4	2.3	7.1
Africa	25.8	9.5	16.3
Middle East	0.9	0.4	0.5
South Asia	8.7	2.2	6.5
Southeast Asia	6	2.3	3.7
Far East	3	1.3	1.7
Australia & Oceania	7.8	2	5.8
TOTAL:	98.8	35.9	62.9

The bulk of oil (70%) and gas (60%) resources are concentrated in the Atlantic Ocean and are mostly confined to three petroleum basin groups, cratonic, pericontinental on passive margins, and pericontinental on active margins.

The Pacific Ocean (mostly basins in foldbelts, foredeeps, and on pericontinental active margins) accounts for 16% oil and 17%, gas resources.

About 14% oil and 22% gas resources of the deep-sea areas of the world are concentrated in the Indian Ocean, predominantly in foredeeps and on pericontinental passive margins.

Speaking about particular geographic regions, the most significant hydrocarbon resources of deep-sea areas are inferred in Latin America (32% oil and 2% gas) and Africa (26.5% oil and 26% gas). The next richest in oil are the deep-sea basins of north America (12.5%); in gas, West Europe (11%), South Asia (10%), North America (9.5%), and Australia and Oceania (9.2%). The deep-sea sector of the Middle East was estimated as the poorest in oil and gas (1.1% oil and 0.8% gas) by contrast to the onshore sector and inner shelf.

West Europe, Southeast Asia, South Asia, Australia, and Oceania account for 5.6-6.4% each, and the Far East, for 3.6% of the world's oil resources in deep-sea areas. The proportion of Southeast Asia in gas resources is 5.9%; Far East, 2.7%

According to VNIIZarubezhgeologia's estimates, the initial total recoverable oil and gas resources in onshore, shelf, and deep offshore basins of the world (without CIS countries) are 404 Gt and 356 TM^3, respectively. Of that, deepwater areas account for 8.9% oil and twice as much (17.7%) gas.

The proportions of hydrocarbon resources in onshore, shelf, and deep offshore areas of foreign countries and their geographic distribution are given in Figures 6 and 7.

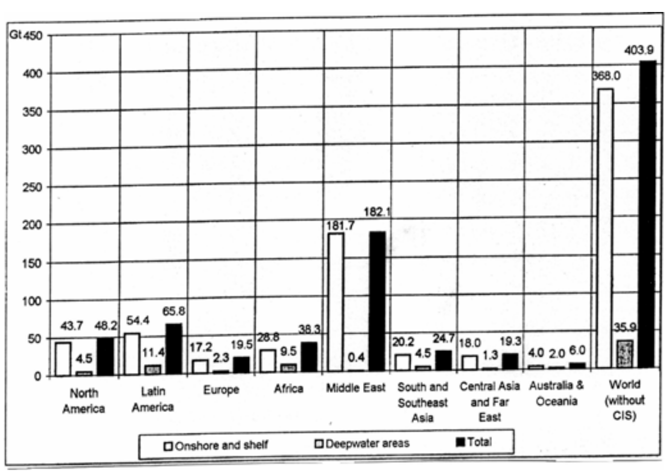


Figure 6: Geographic distribution of the world's initial total recoverable oil resources

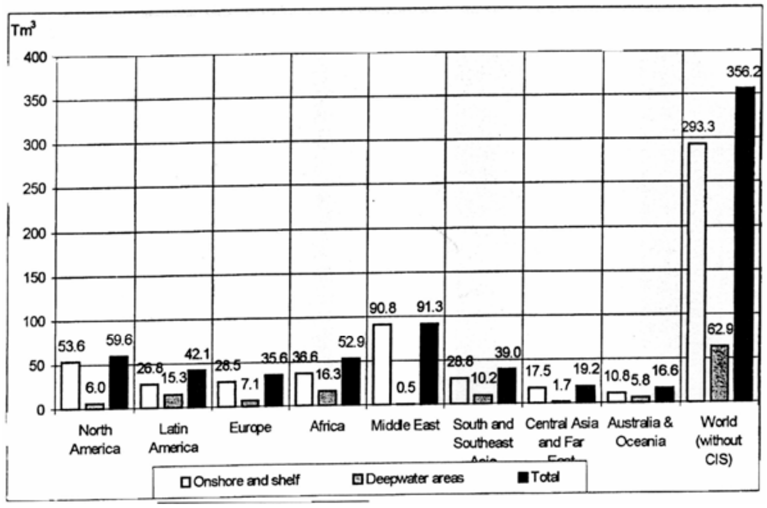


Figure 7. Geographic distribution of the world's initial total recoverable oil resources

5. Development Prospects In Deep-Sea Areas

Commercial development of the hydrocarbon resources of deep-sea areas began in 1980s. The first two countries, in which offshore oil and gas production exceeded the 200-m isobath, were the US (Gulf of Mexico) and Brazil (western margin of the Atlantic Ocean). It is in these two countries that petroleum exploration and development at sea depths more than 500 m were concentrated in 1980s. In the northern Atlantic (North and Norwegian seas) with a harsher physiographic environment, offshore areas were successfully explored at a sea depth of 300 m and sometimes more. During this period, offshore petroleum exploration in deep-sea areas expanded into new geographic regions and deeper parts of seas.

After the geologic setting on the eastern margin of the Atlantic Ocean was found to be similar to geologic conditions in its western margin, conditions responsible for the formation of oil fields on the continental slope off Brazilian coast, the first steps towards extensive petroleum exploration in deepwater areas were made in some West African countries. The interest of oil companies in deepwater areas off the West African coast resulted in its becoming another deep-sea drilling center in the mid-1990s. By the end of the decade of the nineties, deepwater oil and gas exploration extended into the other parts of the

World Ocean, including areas off north-western Australia, the East Mediterranean, and East and Southeast Asia (Table 3.).

Table 3: Number of deepwater offshore oil and gas discoveries as of 01.01.2000

Region	Country	Number of Discoveries	Water depth, m	HC type	HC reserves, MMtoe
North America	US	104	450-2324	Oil, gas	514
Latin America	Brazil	20	450-2400	Oil, gas	884
West Europe	Norway	14	300-350	Oil, gas	546
Africa	*Total*	38			640
	Egypt	1	590-700	Gas	
	Angola	21	450-2500	Oil	
	Congo	4	500-1000	Oil	
	(Brazzaville.)	10	1000-1400	Oil	
	Nigeria	2	700	Oil	
Middle East	Equatorial.	2	670-780	Gas	…
	Guinea	4			184
South and SE	Israel	1	490	Oil, gas	
Asia	*Total*	3	930-1320	Gas, oil	
	India	5	450-1230	Gas, oil	41
Australia	Indonesia				
	Australia				
Total		187			2809

During the two decades of deep offshore operations, Brazil has successively won a number of records in deepwater drilling and development: in 1982, an exploratory well was spudded in 458 m of water; in 1987, 1565m; and late in 1999, at a sea depth of 2445 m. Moreover, the currently applied mobile drilling rig allows for drilling in 2685 m of seawater. Brazil is also currently the leader in deepwater oil production, 1854 m (figure 8).[9]

Prior to 1987, deepwater oil exploration was carried out in the Campos basin; afterwards, it was extended into the Sergipe-Alamosa, and in 1998, into the Santos basin. The first discoveries were made in 1984, at Marimba at a sea depth of 350-700 m, and at Albacora, at a sea depth of between 250-2000 m.

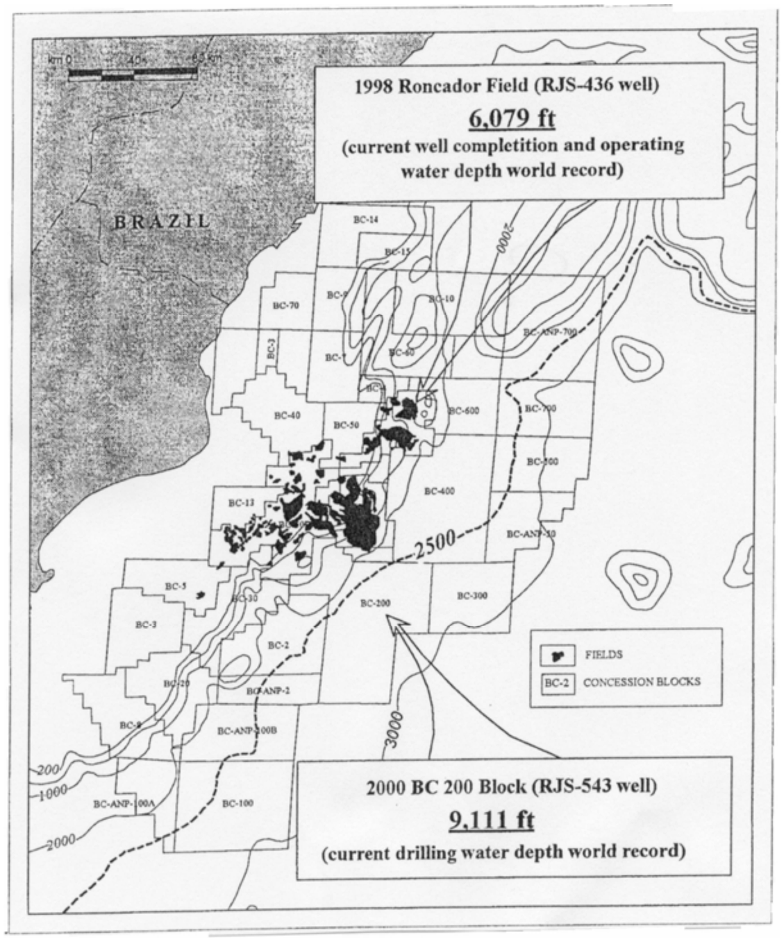


Figure 8. Brazilian margin, Campos basin (modified from OGJ[9])

By the beginning of 2000, a total of 20 deepwater offshore discoveries had been made in Brazil. Five of them hold recoverable hydrocarbon reserves of between 100 to 540 Mmtoe each, to a total of 1100 Mmtoe (Roncador, Albacora, Marlin, Barracuda, and Caratinga). According to the latest estimates, Roncador and Marlin are the world's largest deepwater offshore fields (Table 4, Figure 9) [10].

Table 4: Largest oil and gas discoveries located in more than 500 m of seawater

Field	Country	Discovery year	Water depth, m	Estimated oil and gas reserves, Mmtoe		Remarks
				In place	Recoverable	
Roncador	Brazil	1996	1000-2000	380	…	
Marlin	Brazil	1985	720-2000	1340	330-540	Producing
Dalia	Angola	1997	1340	190	100	
Banzala	Angola	1997	1350	135	…	
Girassol	Angola	1996	1350-1500	135	95	
Bonga	Nigeria	1997	800	135	80	
Agbami	Nigeria	1999	1460	600	240	
Llano	US	1998	825	135	…	
Crazy Horse	US	1999	1830	135	…	

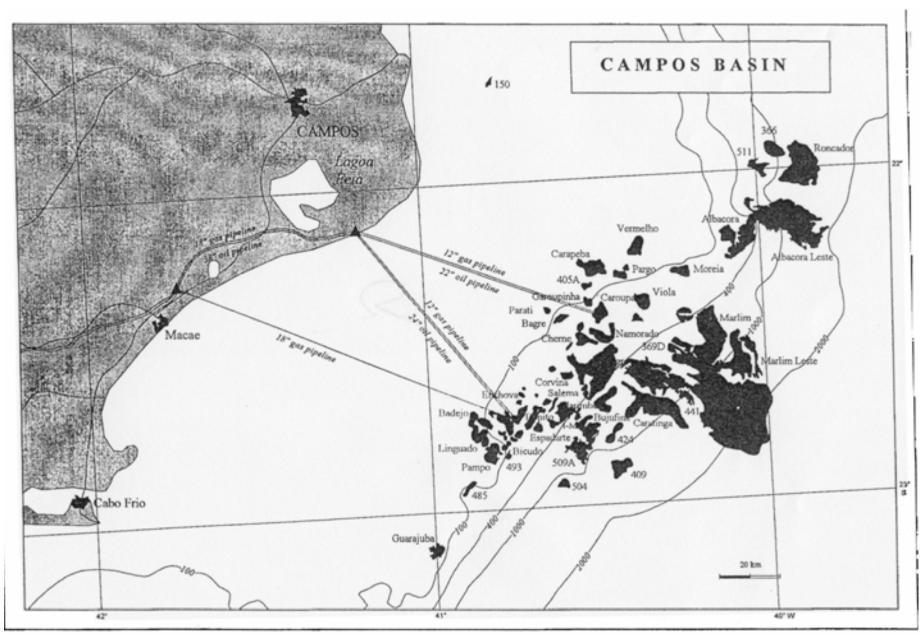


Figure 9. Oil and gas fields in the Campos basin (modified from *Petrobras Magazine*[10])

The next region of the World Ocean, where petroleum exploration has extended beyond the shelf, is the Gulf of Mexico (US sector). This region was the world's leader in deep-sea drilling depth of 2330 m in 1988. At present, the deepest offshore well site depth is 2354 m, and the greatest depth, 2324 m. However, even these achievements are likely to be surpassed in the near future. In July this year, UNOCAL will start to carry out a drilling programme of seven wildcat wells in the Alaminos Canyon at depths between 2930 to 3000 m of sea water[11].

By the beginning of 2000, a total of 148 oil and gas fields had been discovered below 200 to 2324 m of seawater. Of that, 49 are producing, and 112 fields were discovered in more than 500 m of seawater (figure 10). The deepest offshore producing field is the Mensa gas field, 1625 m, and the largest is the Crazy Horse field discovered in the Mississippi canyon in 1999 1830 m of sea water.

Total demonstrated reserves of all 148 fields are estimated as 1300 Mmtoe oil and 1130 Gm^3 gas; of that, 985–1060 Mmtoe occur in more than 500 m of seawater, including 217 Mmtoe proven reserves. Current oil production from the deepwater discoveries in the Gulf of Mexico is about 38 Mmt per annum.

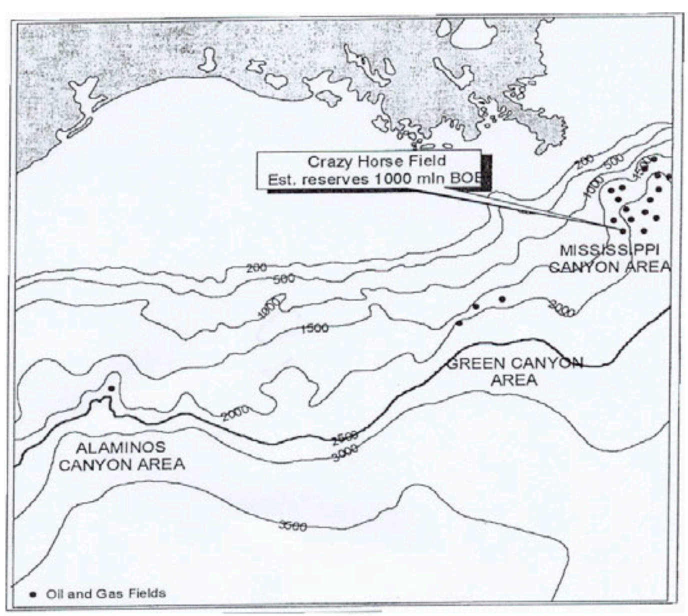


Figure 10: Deepwater discoveries in the Gulf of Mexico (modified from De Luca[11])

The extremely harsh environment brought up the necessity to create extra high tensile steel or concrete floating and fixed producing platforms for the development of deepwater oil and gas fields in the North and Norwegian seas. Therefore the fields discovered as far back as the late 1970s – early 1980s were brought on-stream only in the mid-1990s. Of the 14 known hydrocarbon fields, three are currently producing, Snorre, Troll West, and Heidrun, with total reserves of 285 Mmt oil and 45 Gm^3 gas and a total annual output of 29 Mmt oil.

In West Africa, deepwater offshore exploratory drilling began in the mid-1990s in Angola and then extended into the deepwater areas of some other countries.

Deepwater offshore hydrocarbon exploration was most successful in Angola where 21 fields, including four large ones, had been discovered by 01.01.2000 (figure 11) [12]. The total reserves in place of these discoveries are estimated as almost 600 Mmtoe. The Kuito discovery was brought on-stream first, late in 1999, and the other one, Girassol (in 1350 m of seawater) is due on-stream in 2001.

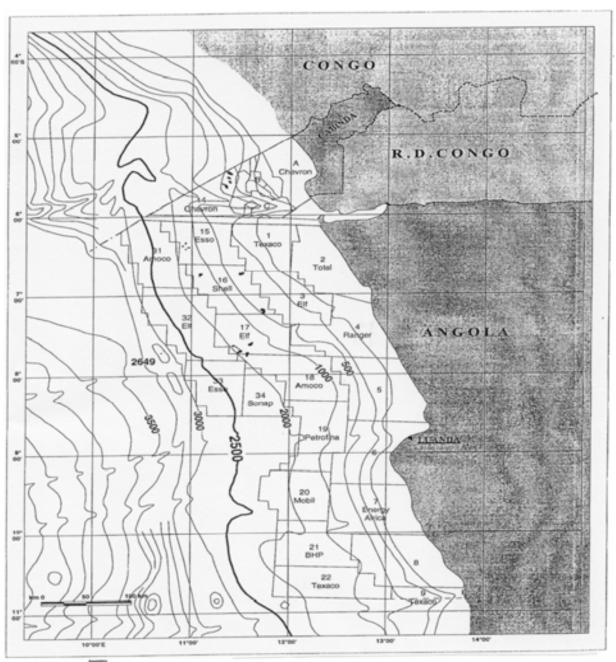
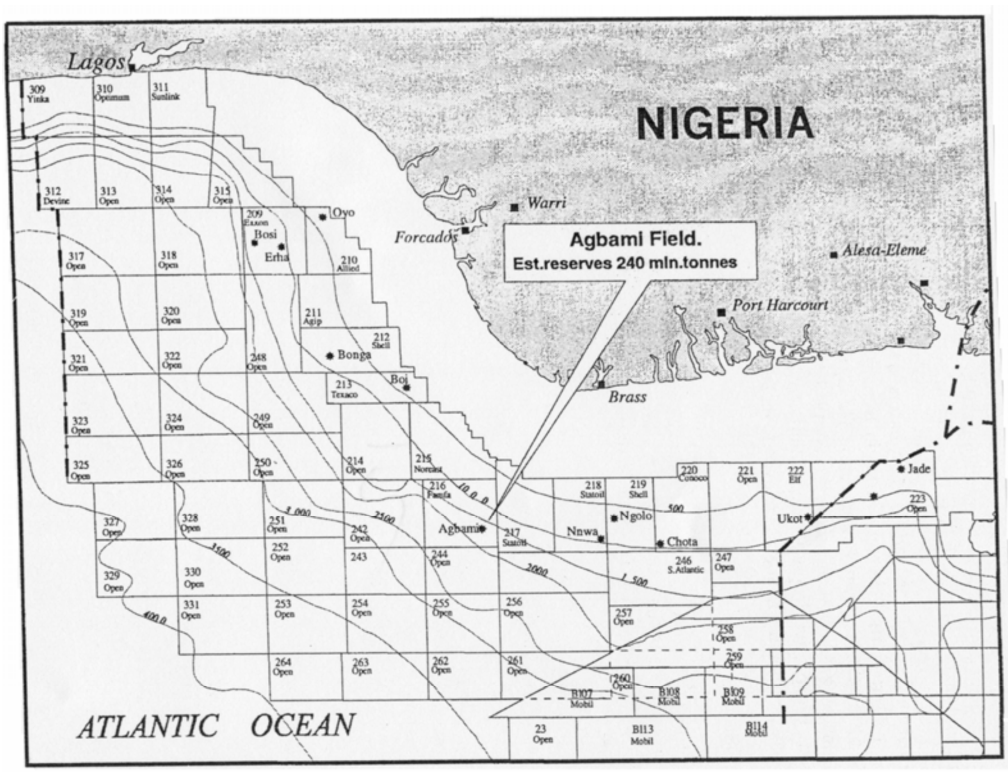


Figure 11: Angola offshore concession blocks and fields (modified from Raposo[12])

Ten deepwater offshore discoveries have been made in Nigeria, including the Agbami field with a recoverable reserve of 240 Mmt under 1460-1516 m of sea water, which is the largest discovery during the whole hydrocarbon exploration history of the country. It should be noted that offshore exploration blocks under up to 4000 m of seawater have been recently offered here (figure 12). Six more discoveries were made in the deep offshore areas of Congo and Equatorial Guinea. The total number of deepwater offshore discoveries made in West Africa by 01.01.2000 is 37. In terms of deepwater offshore exploration intensity and success, this region is second only to the Gulf of Mexico.



Figur 12. Nigerian deepwater concession blocks and fields (after Offshore magazine [13]).

In other regions of the world, encouraging results of deepwater offshore hydrocarbon exploration were obtained in the late 1990s (1998 and 1999). Two gas fields were discovered in Israel; one, in the Nile delta in Egypt; three oil/gas fields, off eastern Kalimantan in Indonesia; and one, in the Bay of Bengal in India.

Five mostly gas discoveries in more than 500 m of seawater were made off northwestern Australia.

In recent years, oil and gas exploration in the deepwater areas of the World Ocean is growing in intensity. During the first half of 1999 alone, about 30 new fields were discovered. By the beginning of the year 2000, almost 190 hydrocarbon fields had been discovered in deepwater areas. Most of these discoveries have been estimated preliminarily, and, with the exception of some fields in the US, Brazil, and Norway, the reserves of these fields are not regarded as proven in respective countries.

The initial total deepwater offshore hydrocarbon reserves estimates for various regions and the world as a whole have been published in some publications. The most conservative estimate (2.8 Gtoe) is given in Table 3. According to some other publications, the reserves of all categories are between 3.1 and 3.4 Gtoe[14, 15, 16, and 17].

These estimates imply that the ratio of deepwater hydrocarbon reserves to resources (99 Gtoe) is 2.9-3.4%, and the undiscovered (forecast) resources are 96 Gtoe.

Production from deepwater oil fields started in 1985 (Brazil). In 1989, a deepwater discovery was brought on-stream in the United States, and in 1992, in Norway. As of 1 January 2000, a total of 31 oil fields were producing in these countries. Cumulative production from these fields was about 420 Mmt. The depletion of the initial potential oil resources is estimated as 1.2%; total hydrocarbon resources, 0.4%.

As regards Russia, its hydrocarbon prospective offshore areas cover 3.7 million sq. kms. However, much of these areas are located on the Arctic shelf, where sea depths are scarcely more than 300 m. The best studied is the West Arctic shelf of the Barents Sea, where 47 wells have been drilled and 13 oil and gas fields have been discovered, including the Shtomanovskoye field with commercial gas reserves of 2.7 Tm^3. This field lies in 320-350 m of seawater and is the deepest in Russia. This field is due on-stream in 2006 at an initial production rate of 20 Gm^3 gas. Production is expected to peak in 2015 at 90 Gm^3.

In the Russian Far East, the margins of six basins in the Sea of Okhotsk occur in more than 500 m of seawater: North Sakhalin (Deryugin trough), Aniva, Tinro, central Okhotsk, and Ishikari-West Sakhalin (southern termination). The thickness of the Cenozoic sedimentary fill of these basins is 3000-4000 m except the North Sakhalin basin with a cover thickness of 5000-7000 m. Prospective deepwater areas jointly cover about 600 thousand sq. km. However, the aggregate petroleum potential is believed to be fairly low, not more than 2 Gtoe.

6. Conclusions

About 120 sedimentary basins are located completely or partially in deepwater areas of the World Ocean. The initial total-in-place resources of the deepwater sectors of these basins are estimated at 200 Gtoe, and recoverable resources, as 99 Gtoe, including 36 Gt oil and condensate and 63 Tm^3 gas.

The bulk of oil (70%) and gas (60%) resources are confined to the basins located along the peripheries of the Atlantic Ocean. In these regions, deepwater hydrocarbon resources are being actively explored and developed.

By the end of the 20th century, exploratory wells actually reached a sea depth of 3000 m; development wells, 2000 m. In the next 5 years, even these achievements will be surpassed. Deepwater oil expenditure for the period 2000-2004 is estimated at $76 billion forecast spending[16], mostly on the Atlantic margins of Africa and Latin and North America.

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SUMMARY OF PRESENTATION AND DISCUSSIONS OF PETROLEUM POTENTIAL AND DEVELOPMENT PROSPECTS IN DEEP SEA AREAS

Presentation

Dr. Vysotsky began his presentation on the petroleum potential of deep-sea areas of the world recalling that during an earlier presentation one of the speakers quoted Jules Verne on the mineral richness of the seas. Dr. Vysotsky said that even the rich fantasy of the writer could not predict that at the end of the 20th century there would be so much by way of hydrocarbon resources in the oceans, called in the jargon of the petroleum industry "elephants", which is understood to mean "rich resources".

Dr. Vyotsky said that the term "deep water" refers to water depths of more than 400m. In Russia, he also said, this depth is taken as more than 500m. He said that ultra deep waters, for instance in Brazil is more than 1,000 m and in some other areas it is more than 2,000m. According to Dr Vysotsky, this division between deep water and shallow water is from an economic point of view. For deep and ultra-deep waters, Dr Vysotsky said that special platforms that are more expensive than simple platforms are required.

Dr. Vysotsky informed participants that the development of petroleum resources at depths below 200 m began in the 50s and by the 1960s exploration of deep-water petroleum resources had started. He said that general exploration and development of petroleum reserves began at the beginning of the 1970s when petroleum rich basins in the Gulf of Mexico, not far from Brazil, were opened. He also said that high productivity was reached in the middle of the 1990s and every year since then more and more reserves have been opened, with more than 300 basins opened in the 90s. He said that the first deep water well was drilled at more than 2700 m in the Gulf of Mexico, and that now, 3,000m was common place in that basin. He said that the basin under development in Brazil is 1700-1800m.

Dr. Vysotsky informed participants that it was an American scientist, L. Weeks, who made the first estimate of the hydrocarbon resources of the world's oceans in 1971. According to Dr. Vysotsky, Weeks estimated the resources of the World's Ocean as 320 million tonnes of petroleum equivalent. After Mr Weeks' estimate, Dr. Vysotsky said that many more estimates were made ranging from 100 million tonnes up to 1 trillion tonnes of the petroleum equivalent in the World's Oceans. Dr. Vysotsky told participants that these estimates depended on different approaches and different methods

He said that for more than 30 years, the Institute of Geophysics and Petroleum in Moscow has provided yearly estimates of the petroleum resources of the world's oceans. He added that every 5 years these estimates are evaluated and that even now, despite Perestroika and changes in Russia these studies continue.

Through the use of a map that depicted the sedimentary basins of the world, Dr. Vysotsky told participants that his presentation would focus on the Russian classification system for petroleum resources, methods of resource evaluation, sedimentary basins as the main objects of resource estimation, the global distribution of hydrocarbon resources, the developments and successes in the development of deep-sea basins, the most interesting areas for development and evaluation, and perspectives on development of deep-sea basins during the next five years.

Dr. Vysotsky informed participants that the primary object for evaluation of petroleum resources are sedimentary basins that have the required characteristics for the migration of hydrocarbons and their retention. Dr. Vysotsky said that globally, there are 511 sedimentary basins of which 120 are located completely or partially in deep water area. Out of the 511 basins, Dr. Vysotsky said that about 60 of them have been developed as petroleum basins. He said that the remainder had varying potential for development as petroleum basins

Dr. Vysotsky noted that sedimentary basins have a variety of designations including categories, types and subtypes. He said that there are continental, marginal and oceanic basins. He also said that there are types according to the history of the basins and the structural model of the basin. Dr. Vysotsky informed participants that Russian scientists are working with their counterparts from western companies in order to better understand themselves and to adopt a common classification system.

Dr. Vysotsky said that estimates of the petroleum potential of marginal and oceanic basins by Russian scientists are based on original methods. In general, Dr Vysotsky said that there are many methods for petroleum resource evaluation. He indicated that some methods can only be used for well-known and well-developed basins and are based on comparative geological methods. He said that there are methods that are based on the geochemistry of the organic substance, an example of which is the volume-balance method of evaluation.

Dr. Vysotsky said that based on the limited information available to Russian scientists about basins, especially oceanic basins, they had to develop their own methods. He described one of these methods that he said was based on 85 well-developed basins in Russia, in the United States, and in the Gulf of Mexico. He said that the method included establishing correlations between different parameters.

Through this process, Dr. Vysotsky said that Russian scientists were able to establish a correlation between the total volume of a sedimentary basin and the resource potential of petroleum and gas condensates in the basin.

Dr. Vysotsky used maps and diagrams to illustrate the results of the study. He said that the study showed that recoverable petroleum and natural gas resources for all deep-water areas are 36 million and 63 million tonnes respectively. He said that the African areas have the most petroleum potential followed by Latin American areas.

With a table, Dr. Vysotsky showed the number of deep-water sedimentary basins that have been opened in different parts of the world. In North America, these numbered 104 basins producing both oil and gas in water depths ranging from 450 to over 2,300 metres, and with reserves of 514 Mmtoe. He said that next was Africa with 38 basins opened, producing oil and gas in water depths ranging between 500 and 2500 metres, and with reserves of 640 Mmtoe. Latin America followed with 20 operating sedimentary basins producing oil and gas with reserves estimated at 884 Mmtoe. Dr. Vysotsky indicated that in Western Europe (Norway) 14 basins had been opened up with production occurring in water depths of 300 to 350 metres, and with reserves estimated at 546 Mmtoe. He rounded up the list with information on operating basins in Australia (5), South and Southeast Asia (4) and the Middle East (2), where he said water depths ranged from 450 to 1230 metres, 490 to 1320 metres and 670 to 780 metres respectively. Dr Vysotsky said that the total proven reserves in deepwater offshore basins is 2.8 billion tonnes.

In relation to perspectives for the next five years, Dr. Vysotsky began this part of his presentation with developments in Brazil where he reiterated that the largest fields, called elephants, had been found. He said that the largest petroleum field is in Brazil (Marlin). He also said that five deep-water fields located in Brazil (Roncador, Albacora, Marlin, Barracuda and Caratinga) hold recoverable hydrocarbon reserves of between 100 to 540 Mmtoe each. He noted that here, license blocks that are given at water depths of 3000 m. He said that these are the records that are now established for recovery in this basin, representing the record for deep-sea recovery of petroleum.

The next region of active exploration according to Dr. Vysotsky is the Gulf of Mexico. He said that in this region, at depths of more than 1200 m, 120 fields are open. He informed participants that the largest field here is Crazy Horse with estimated reserves of 1 billion barrels. He said that UNOCAL, is undertaking a project to bore 7 exploration wells in June 2000 at depths of about 3,000 m.

Dr. Vysotsky said that after the Gulf of Mexico the next area of active interest is West Africa. He described the basin setting for offshore Angola that he said extends out to a depth of 5,000 m. He said that in 1996, the Girassol field opened at a depth of 1450 m. He noted that this field is scheduled for exploitation in 2001, and that its recoverable reserves are estimated at about 100 million tonnes for one of its straits, Strait B. He pointed out that the cost of recovery for oil or petroleum is placed at $5.60 per barrel and compared this with the current price of a barrel of oil that is $30.00.

In Nigeria, Dr. Vysotsky said that blocks are now open to depths of 4,000m. He said that in 1999, the largest petroleum oil field in Nigeria was opened, with recoverable reserves of 240 million tonnes. In Congo and in some other countries in Africa, Dr. Vysotsky said that there are also blocks that are exploited at the same depth. These include Morocco and Mauritania where there are also ultra deep-water blocks.

Dr. Vysotsky said that in the eastern Mediterranean and Israel, two gas fields have been opened at a depth of about 2,000 metres. Similarly, a gas field has been opened in Egypt.

In Southeast Asia, Dr. Vysotsky spoke about the Kalimantan basin on the delta of the river Mahatang. He said that this basin spreads into the Sea of Celebes where the ocean depth is about 5,000m. He said that a company has bought about 12 wells at a depth of 900-1,400 m. In five of them, reserves of oil were opened. He said that exploration is taking place in this area.

Dr. Vysotsky pointed out that in Australia, about 5 big offshore oil fields have been opened. With regard to Russia, Dr Vysotsky said that while it has the longest northern sea area, this area is not a deep-water area. He said that thirteen petroleum fields have been opened in the Barents Sea, not far from Norway.

He said that the largest gas area has been discovered here with reserves of 2.7 trillion m^3, and that it is to be in operation in 2006 producing about 20 billion tonnes per year. He said that this field is situated at a depth of 350 m. Dr. Vysotsky said that another interesting area for Russia is in the Sea of Okhotsk. He noted that while there are some sedimentary basins that are in deep water the resources are not big, not more than 2 billion tonnes of oil.

Finally through a diagram published 2 months earlier, Dr. Vysotsky informed participants that it is estimated that during 1999-2004, US$76 billion will be spent on petroleum and gas exploration of deep-sea areas. He said that a large portion of this amount would be spent in North America, in the Gulf of Mexico, and in Latin America in the Campos Basin. Dr. Vysotsky concluded his presentation by pointing out that all over the world, the exploration of the deep-sea areas is being actively conducted, and that for the last 10 years, large fields have been opened only in deep waters.

SUMMARY OF DISCUSSIONS

The discussions that followed Dr. Vysotsky's presentation focused on the oil and gas potential of the Caspian Sea, the relationship of the price of oil and gas with exploration activity, and the potential for oil and gas production from the Area.

One participant made the observation that during Dr. Vysotsky presentation of the offshore oil and gas resources of Russia, he had not presented any estimates of oil and gas in the Caspian Sea.

This participant wanted to know if Dr. Vysotsky had any information on new discoveries in this geographic area. While acknowledging this oversight on his part, Dr. Vysotsky said that he knew the area very well and had maps concerning the potential of the area. Dr. Vysotsky said that a few months ago in the north part of the Caspian Sea, large oil fields were discovered in the area between Kazakhstan and Russian sectors.

He said that the biggest Russian oil company discovered the fields. The recoverable reserves are 250 million tonnes. In the Kazakhstan section, Dr. Vysotsky noted that a consortium of companies is drilling wells. He described this area of Kazakhstan as containing very good prospects, whilst the Azerbaijan area contains fewer prospects. He said that the Iranian area showed good prospects for gas.

Another participant noting that Dr. Vysotsky had said that the financial parameter is very important for deep-water oil exploration reminded the workshop that in December 1998, when the price of oil was about US$8.50, many small companies disappeared in mergers with bigger companies. This participant asked whether it is to be concluded that only big oil companies can undertake deep-water oil and gas exploration. This participant also wanted to know the basis upon which the big oil and gas companies could sustain this activity. Dr. Vysotsky said that exploration activity is dependent on the price of oil. He said that based on present knowledge it could be said that if the price of oil falls below $20 per barrel, exploration and development work in the deep sea would practically stop. He noted the wide range in operating costs in different producing areas, stating for example, that these varied from $1.50 per barrel in the Middle East, $4.00 per barrel in Libya, between $5.50 and $10.00 in west Siberia, and $12.50 per barrel in Canada. In this regard, he said that operating cost in the deep-sea area is about $5.60 per barrel.

In response to a question by the Secretary-General on the likelihood of discovering oil in the international area, outside the continental shelf, Dr. Vysotsky said that considered thought would be required to respond to this. He suggested possible areas as including offshore Nigeria, in an offshore zone between Vietnam, China and the

Philippines, and possibly Brazil. With regard to offshore Brazil, it was pointed out that sedimentary basins do not extend beyond 200 miles rendering the possibility minute.

Another participant noted that part of the question of whether there will be oil and gas in the international area of the deep sea depends on the hypothesis of how oil and gas form. This participant said that in the past, some Russian geologists thought that oil and gas could form by inorganic processes in the Earth's interior in addition to organic processes relating to the accumulation of organic matter.

This participant also said that since in the deep ocean, at the ocean ridges, much methane is discharged even though there are no sediments, inorganic processes are forming methane. The participant therefore asked Dr. Vysotsky about his opinion of oil and gas forming in the deep seabed as a result of inorganic processes. In response, Dr. Vysotsky said that it was his opinion that inorganic processes account for only a small source of the oil and gas in the deep ocean. Dr. Vysotsky also said that the petroleum resources of the world are from an organic genesis. He said that the hypothesis of an inorganic genesis is an exotic opinion.

Another participant noted that some of the earlier maps by the US Geological Survey that addressed the possibility of petroleum occurrences in the ocean basins used the criterion of sediment thicknesses of 1 km as a minimum. This participant also noted that for the occurrence methane hydrates in the deep ocean, it has to be assumed that sedimentary basins are to be found there.

In response, Dr. Vysotsky explained that for between 5 and 10years Russian experts had worked together with experts of the USGS, and were in agreement with the minimum sedimentary thickness for oil genesis of 1000 m. He noted however that in oil production, a sedimentary cover of 1000-1500 m results in small non-commercial oil fields.

CHAPTER 14

SUBMARINE METHANE HYDRATES - POTENTIAL FUEL RESOURCE OF THE 21ST CENTURY

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Abstract

Natural methane hydrates, which have a potential of being an alternate fuel resource, are known to occur worldwide in the sediments of the continental margins and in the Polar Regions in association with permafrost. Methane hydrates, composed of water and gas molecules are ice-like crystalline solids, which are thermodynamically stable within a limited range of pressure and temperature. The global amount of carbon stored in methane hydrates is estimated to be about 10000 Gigatons, which is nearly double the amount of carbon stored in all known fossil fuel deposits. The presence of methane hydrates within the sediments can largely be detected through geophysical techniques and by non-geophysical proxies. Though harvesting of methane hydrates has not been initiated to date, but some ideas have been conceived for the production of methane from hydrates and its transportation to shore. Apart from being an abundant fuel resource, methane hydrates are also a matter of concern, as destabilization of sub-sea- bed methane hydrates can cause geological hazards and/or release of methane- a powerful green house gas- to the atmosphere. Research on the methane hydrate system may also lead to the development of useful downstream technologies: such as, desalination of seawater, and sequestering of exhaust-generated carbon dioxide in the deep seabed. The paper visits various aspects of methane hydrate and proposes the need for evolving regulations for their safe prospecting and future exploitation.

1. Introduction

Throughout the 20th century, the demand for hydrocarbon-based fuel has been increasing rapidly. To meet this ever-increasing demand, exploration and exploitation of the vast resources of conventional oil and gas has been keeping pace. These resources however are not renewable, and we shall encounter severe depletion in the not too distant future. In this scenario natural gas hydrates appear to be an exciting alternative and if approached holistically may become the main and bountiful source of fuel for an energy hungry world.

1.1. What are gas hydrates?

Gas hydrates are ice-like crystalline accumulations formed from natural gas and water. The building block of this crystalline solid is a cage like structure (Clathrates) in which water molecules form the rigid lattice with the lattice's void occupied by a guest gas molecule. Many gases have molecular sizes suitable to form hydrates, including such naturally occurring gases as carbon dioxide, hydrogen sulphide and several low-carbon- number hydrocarbons but the most common gas hydrates in nature are methane hydrates. Because of the arrangements of the gas molecules within this framework gas hydrates can store large percentage of gas per unit volume[1]. Gas hydrate is thus a gas concentrator; the break down of one unit volume of gas hydrate at standard temperature and pressure produces (Figure 1) about 164-unit volume of gas[2].

In appearance, hydrates are intergrown, transparent-to-translucent, white-to-grey and, yellow crystals, with poorly defined crystal form. Hydrates may "cement" sediments in which they occur, or they may also occur in pore spaces in uncemented sediment grains[3]. Hydrates occupy significant percentage of pore space in high-porosity sediment, and occur in large, contiguous deposits.

Methane hydrates are thermodynamically stable within a limited range of pressure and temperature (P- T) conditions. They exist where such P-T conditions and sufficient quantities of gas and water are available in the pore spaces of sediments. Worldwide these sediments are found in Polar Regions in association with permafrost, and in deep water sedimentary basins[2].

In addition to serving as a kind of reservoir for methane, gas hydrates are also impermeable to free gas so that within the sediments a layer of gas hydrate can trap free gas beneath it. Thus, there are two ways in which hydrates can create deposits of energy gases (i) by binding gas into hydrates within the sediments and (ii) by creating a trap, using hydrate-cemented sediments as a seal [4,5].

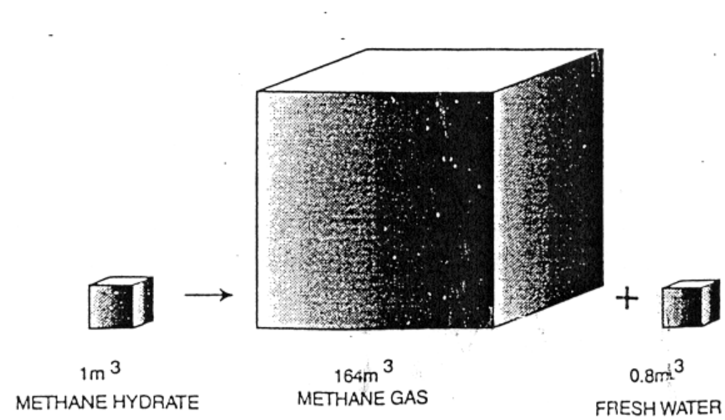


Figure 1. Proportional composition of gas hydrate on dissociation (after Kvenvolden[2])

The significance of gas hydrate is not only in its potential as an alternate fue1 resource, but also in its negative implication on global climatic and geological environments and the role it might have played in the past. Scientists also consider that a proper understanding of the process of formation of gas hydrate may help to develop several other useful technologies.

1.2. Historical background

Sir Humphrey Davy discovered gas hydrate in 1811, when it was observed that under certain conditions, water and chlorine form a crystalline substance - chlorine hydrate[6]. In 1888 scientists succeeded in proving that hydrocarbons (methane, ethane) can form gas hydrates. However, until the beginning of the 1930'5, gas hydrates were looked upon solely as a scientific curiosity, for which there appeared to be no practical use. Gas hydrates caught the attention of industry in 1930's when it was realized that the long distance oil and gas transmission pipelines in the USA were being clogged by formation of gas hydrates within the pipelines. In order to overcome this problem, researchers spent time in studying the compositions and structure of gas hydrates and identifying inhibitors that could prevent formation of gas hydrates[7]. This was the beginning of an experience that changed gas hydrates from a bane to a possible future boon.

In the 1960's scientists discovered that hydrates could also form in natural environments. In 1972, the first pressurized specimen of naturally occurring gas hydrate was recovered from the wildcat well on the north slope of Alaska in the Prudhoe oil field[8]. In the 1970's geophysicists of Lamont-Doherty Earth Observatory of Columbia University found the earliest indication of methane hydrates beneath the seafloor from the seismic data collected over the Blake Ridge, along the southeast US coast[9, 10]. Since then, the presence of gas hydrates has been inferred in many places around the world. In 1997, the first drilling campaign specifically designed for hydrate and related issues such as methane generation and flux was carried out by the international scientific Ocean Drilling Program (ODP) on the Blake Plateau. This effort greatly increased the understanding of the deposits. Recognition of their widespread occurrence on a global scale has recently spurred more focused programmes.

2. Global Occurrences and Resource Estimate

Gas hydrate occurrences are mostly concentrated at the depocenters of the continental margins where both organic detritus (from which bacteria generate methane) and sediments (which protect detritus from oxidation) accumulate rapidly.

2.1. Occurrences

The first worldwide data set summary (published in 1980), on the occurrences of sub- marine gas hydrates listed only nine regions with gas hydrate indications. Subsequently, due to numerous marine geo-scientific investigations and revelations by deep sea drilling (DSDP and ODP), the findings increased continuously and the list now number 48 regions. Out of these, hydrates were directly observed in 16 1ocations[11] and some of the sites are given in Table 1.

Table 1. List of observed gas hydrate occurrences (modified after Ginsberg and Soloviev*; Kvenvolden*)

Ocean	Region	Observations
Pacific	Middle America Trench, off Costa Rica	Hydrates in core from site 565 (DSDP Leg 84)
Pacific	Middle America Trench, off Guatemala	Hydrates in cores from sites 496-498 (DSDP Leg 67), sites 568, 570 (DSDP Leg 84)
Pacific	Middle America Trench, off Mexico	Hydrates in cores from sites 490-492 (DSDP Leg 66)
Pacific	Offshore northern California	Hydrates in shallow cores
Pacific	Cascadia Basin, off Oregon	Hydrates in cores from site 892 (ODP Leg 146)
Pacific	Okhotsk Sea, offshore Paramushir Island	Hydrates in shallow cores
Pacific	Deryugin Basin, Okhotsk Sea, off Sakhalin Island	Hydrates in shallow cores
Pacific	Okushiri Ridge, Japan Sea	Hydrates in cores from site 796 (ODP Leg 127)
Pacific	Nankai Trough, off Japan	Hydrates in cores from site 808 (ODP Leg 131)
Pacific	Peru Trench (south of 9° S)	Hydrates in cores from sites685, 688 (ODP Leg 112)
Atlantic	Gulf of Mexico	Hydrates in core from site 618 (DSDP Leg 96) and hydrates in shallow cores
Atlantic	Blake Outer Ridge, off southeast US coast	Hydrates in core from site 533 (DSDP Leg 76)
----------	Black Sea	Hydrates in shallow cores
----------	Caspian Sea	Hydrates in shallow cores

The worldwide locations of known and inferred gas hydrates that include the areas of outer continental margins, and areas of onshore and offshore permafrost, are shown in Figure 2.

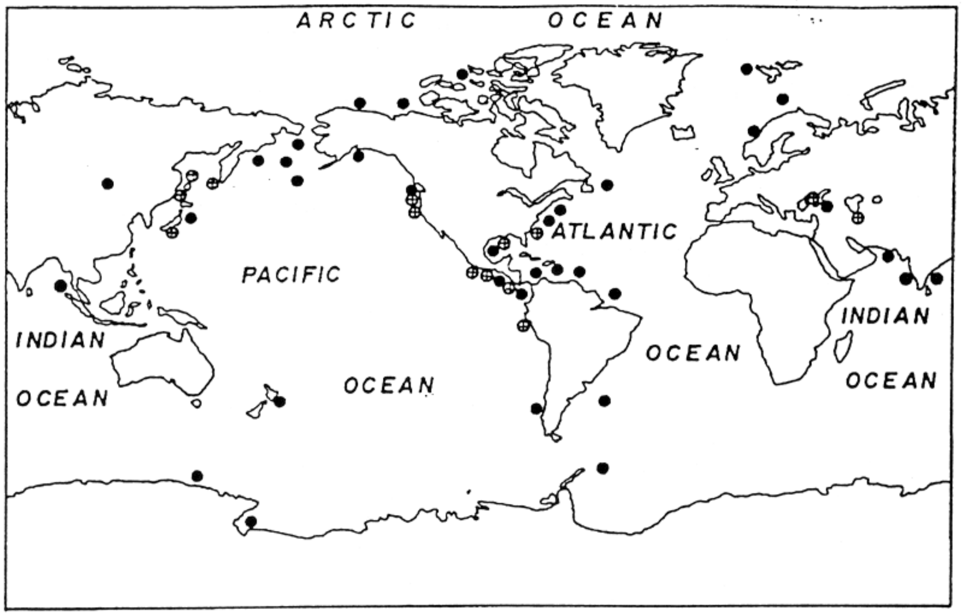


Figure 2. Worldwide locations of known (encircled cross) and inferred (solid circles) methane hydrates in oceanic sediments and in continental permafrost regions (modified after Kvenvolden[12], additional input from Veerayya et al.[13], Directorate General of Hydrocarbons[14], Verma et al.[15], Gas Authority of India Limited[16])

2.2. Preliminary global resource estimate

Gas hydrates in oceanic sediments may in fact comprise the Earth's largest fossil-fuel reservoir (Figure 3).

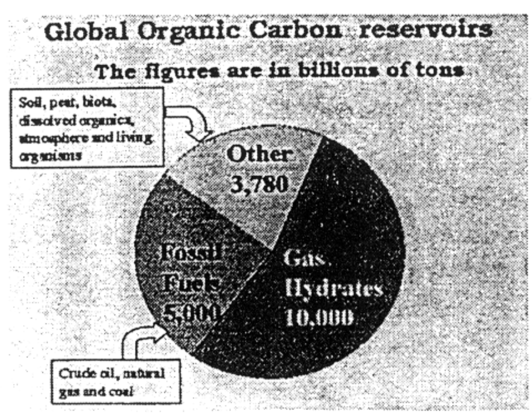


Figure 3. Reservoirs of organic carbon in the Earth (adapted after Kvenvolden[2;] Suess[10])

The present mapping of worldwide distribution of methane hydrate zones is far from adequate and the techniques for proper quantification of the volume of methane in these zones is yet to be developed. In this situation, the amount of methane in hydrates estimated by various workers is highly variable (Table 2).

Table 2. Estimates of the amount of methane in gas hydrates prepared by Potential Gas Committee (Adapted after Kvenvolden*)

Cubic metres	Trillion cubic feet	Gigatons	References
Oceanic:			
3.1×10^{15}	1.1×10^{5}	1.7×10^{3}	McIver[17]
$(5\text{-}25) \times 10^{15}$	$(1.8\text{-}8.8) \times 10^{5}$	$(2.7\text{-}13.7) \times 10^{3}$	Trofimuk et al[18]
7.6×10^{18}	2.7×10^{8}	4.1×10^{6}	Dobrynin et. al.[19]
Continental:			
1.4×10^{13}	5.0×10^{2}	0.75×10^{1}	Meyer[20]
3.1×10^{13}	1.1×10^{3}	1.7×10^{1}	McIver[17]
5.7×10^{13}	2.0×10^{3}	3.1×10^{1}	Trofimuk et. al.[18]
3.4×10^{16}	1.2×10^{6}	1.8×10^{4}	Dobrynin et. al.[19]

However, it is considered that about 10,000 Gigaton is a reasonable estimate of carbon stored in methane hydrates[12]. This quantum of organic carbon in gas hydrates is twice that in all known fossil-fuel deposits. Even if only a small percentage of this is recover- able, it will constitute a major stock of energy.

3. Formation of Methane Hydrate in Sediment

3.1. Generation of Methane in sediments

Sub-seabed methane within the continental margin sediments is produced primarily by microbial and thermogenic processes.

In the **microbial** process the organic debris of the depositing sediments are decomposed by a complex sequence (methanogenesis) into methane by bacteria in an anoxic environment. This decomposition is considered[21] to take place either by acetate fermentation or by carbon dioxide reduction.

i) Acetate fermentation:

$$CH_3COOH \circledcirc CH_4 + CO_2$$

ii) Carbon dioxide reduction:

$$CO_2 + 4H_2 \circledcirc CH_4 + 2H_2O$$

Organic matter is composed of carbon, hydrogen and phosphorus in the ratio of 106:16:1. The summarized' decomposition of organic matter which results in production of methane is also given below:

$$(CH_2O)_{106}\,(NH_3)_{16}(H_3PO_4)_1 \circledcirc\ 53CO_2 + 53CH_4 + 16NH_3 + H_3PO_4$$

The resulting carbon dioxide may further be reduced[22] if there is sufficient supply of hydrogen:

$$CO_2 + 4H_2 \circledcirc 7\ CH_4 + 2H_2O$$

In the **thermogenic** process of methane generation, thermal cracking of organically derived materials takes place to form petroleum hydrocarbons (including methane). This generally occurs at considerable depth (>2km) in sedimentary basins where temperatures exceed 100°C. Thermogenic methane may also be derived by thermal degradation of oil at even greater depths, and by the maturation of coal[1, 22-25].

3.2. Gas Hydrate stability zone

The occurrence of gas hydrates in nature is controlled by an interrelation among the factors of temperature, pressure and composition. The phase diagram (Figure 4) showing the boundary between free methane gas and methane hydrate for a pure water and pure methane system, provides a reasonable estimate of pressure-temperature conditions under which natural gas hydrates, composed mainly of methane, will be stable on the continental margins[5]. The presence of higher molecular weight gases (ethane or propane) will cause the phase boundary to shift right, allowing hydrate to form at lower pressure (i.e. at shallower water) or at higher temperature. The presence of salts in the pore water shifts the phase boundary to the left, causing a decrease in the hydrate stability zone[26-28]. The intersection of the hydrothermal profile with the gas hydrate phase boundary curve corresponds to the minimum water depth beneath which hydrates will be stable. This minimum water depth will be less, if the water is colder, and greater if the water is warmer. Approximately, this minimum depth is about 300 m in the Arctic area, and 600 m in sub-tropical regions[27]. In deep-sea sediments, temperature normally increases with depth and eventually reaches a point at which hydrate is unstable, despite the continued increase of pressure with depth. Thus a zone within the sediments exists in which gas hydrate is potentially stable from the seafloor down to a depth, commonly from a few hundred to a thousand meters below the seafloor. The thickness from the seafloor down to the base of the gas hydrate stability is considered to be the thickness of the gas hydrate stability zone (GHSZ). If gas (methane) saturation exists within this zone, gas hydrate will form.

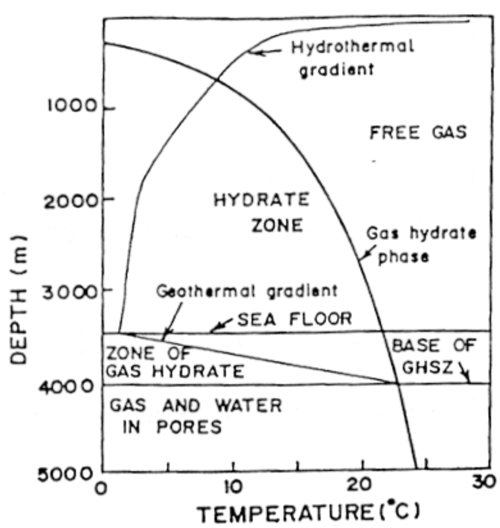


Figure 4. Phase diagram showing boundary between free methane gas and methane hydrate for a pure water and pure methane system (after Kvenvolden[2]; Miles[26])

It has been assumed that the structure of the gas hydrate layer is simple - that its thickness should gradually increase on moving to deeper water because gas hydrate becomes stable at higher pressure-temperature conditions. This assumes that (i) pressure is simply a function of total depth from the sea surface to a position in the sediments, and (ii) the chemistry of the pore waters and the thermal gradient are fairly uniform[29].

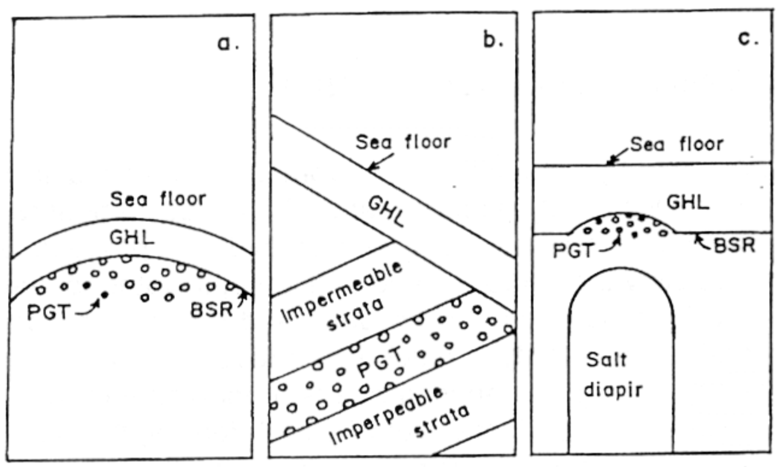
3.3. Formation of Methane Hydrates

After generation of methane, its transportation in sediment can be through various means such as movement of pore-water containing dissolved gas, free gas flow, and molecular diffusion. When the ascending methane molecules reach favourable subsurface-thermobaric conditions (i.e. hydrate stability zone) then, formation of hydrate takes place within the pore spaces of the sediments in the presence of water molecules. It can thus be seen that biogenic methane formation may take place both *in situ* within the hydrate stability zone (HSZ) and beneath it. Thermogenic methane on the other hand has to move upwards from depth into the HSZ. Scientists use various geochemical and isotopic techniques to identify the origin of methane in hydrate samples. After precipitation hydrate progressively fills the sediment pore-spaces and fractures, and eventually cements them to give rise to massive and vein type hydrate deposits[30].

It may be noted that the temperature and pressure conditions for hydrate stability depend on the composition of the gas and on the presence of salts and other components in seawater. It is generally believed that pore water has to be fully saturated with methane before natural hydrate can form. The condition of sufficiently high pore water methane concentration can[31] be met by i) supply of sufficiently large amounts of organic matter in the sediments to generate enhanced methanogenic decomposition; ii) large upward methane fluxes mostly related to fault zones, or other conduits such as diapirs, mud volcanism etc.

3.4. Free gas below hydrates

In the context of methane hydrate deposits, often free gas is mentioned. This free gas refers to methane molecules that exist as gas, which are neither bound to other molecules (for instance, to form a complex hydrocarbon) nor trapped within a hydrate. More commonly, free methane in a geologic formation exists within the pores of low-density rocks. Any hydrate layer may trap free methane as long as the layer forms a seal through which gas cannot migrate. The free methane may be thermogenic gas that has migrated upwards from the earth's crust, or it may be biogenic gas that was previously a hydrate layer but has now melted. Dillon et al.[4] suggested several different types of formations of gas hydrates that can trap free methane (Figure 5).



GHL: Gas hydrate cemented layer; PGT: Possible Gas trap

Figure 5: Schematic diagram of geological situations in which a gas hydrate cemented layer can act as a seal trapping free gas (adapted after Dillon et al.[4]; Kvenvolden[2]).

4. Indicators of Gas Hydrates in Sediments

The presence of gas hydrates within sediments is manifested in various ways. The most common is through acoustically derived geophysical data. This remotely sensed data needs to be verified by ground-truth validation of actual occurrence. Similarly, non-geophysical proxies can also provide some indication of the occurrences of gas hydrate.

4.1. Geophysical indicators

Although gas hydrates have been recognized in drilled cores, their presence over large areas can be detected much more efficiently by acoustical methods, using seismic reflection profiles (Dillon et al.,[4] and references therein). The most commonly used acoustic signature for identification of gas hydrate in marine sediments has been the presence of anomalous signature on marine seismic records known as Bottom Simulating Reflections (BSR). The Carolina Rise along the eastern United States margin, particularly over the Blake Ridge, was the area where marine gas hydrate was first identified[32] on the basis of a BSR. It has been suggested[33] that reflection polarity reversal, a large reflection coefficient and increasing sub-bottom depth with increasing water depth are the different criteria that characterize a BSR. However, at the same time it was felt[33] that none of these criteria are unique to hydrates. Subsequent studies[33-35] have highlighted three manifestations of hydrates in sea-floor sediments, which have been used to recognize gas hydrates in seismic profiles on the U.S. Atlantic continental margin. These are: i) Bottom Simulating Reflections (BSR), ii) amplitude blanking, and iii) velocity inversion.

4.1.1. Bottom Simulating Reflections (BSR)

Sloan[1] observed that hydrate has a very strong effect on acoustic reflections because it has a high acoustic velocity (approximately 3.3 km/sec, about twice that of sea floor sediments), and thus cementation of grains by hydrates produces a high velocity section. Sediments below the hydrate-cemented zone, if water saturated, have lower velocities (water velocity is about 1.5 *km/sec),* and if gas is trapped in the sediments below the hydrate, the velocity is much lower (even with just a few percent of gas). Because reflection strength at an interface is proportional to the change of acoustic impedance, which is the product of velocity and density, the base of the hydrate-cemented zone produces a very strong reflection. As the phase boundary is a distinct limit to hydrate occurrence, this reflection is sharply defined. The base of the gas hydrate stability occurs at approximately uniform sub-bottom depths throughout a small area, therefore, the reflection from its base roughly parallels the sea floor. This reflection has therefore come to known as 'Bottom Simulating Reflection' or BSR.

In literature the term BSR has been used to represent either 'Bottom Simulating Reflector' or 'Bottom Simulating Reflection', causing a degree of ambiguity. According to Huene and Pecher[36] the bottom simulating reflection is the anomalous reflection seen on marine seismic records indicating the position in the sediment column of the base of the zone of gas hydrate stability. On the other hand, the bottom-simulating reflector is the region of impedance contrast in the sediment column at the base of the zone of gas hydrate stability that gives rise to the anomalous reflection on seismic records.

Several different criteria have been used to characterize the anomalous reflections inferred to be a BSR and to help differentiate these reflections from other unusual ones.

These criteria[37] are

i) Reversed polarity of the seismic wavelet relative to the reflection from the sea floor (equivalent to a negative reflection coefficient) at the BSR.
ii) Frequent crosscutting of the seismic reflections from bedding planes by the BSR, indicating that it is not a bedding plane reflection.
iii) Close mimicking of the sea-floor topography by the BSR.

A BSR-like reflection may not necessarily arise from gas hydrate formations. In some areas, these acoustic features may also result from temperature-controlled diagenetic effects. During the Deep Sea Drilling Project (DSDP) Leg 19, seismic reflections akin to BSR in some Bering Sea sediments draped on the Umnak Plateau were observed (Kvenvolden[5] and references therein). The drilling at one of these sites (site 185) however indicated the presence of only methane in the sediment with no evidence of the existence of gas hydrates. In view of this, some researchers (cf. Kvenvolden[5]) attributed those BSR-like seismic reflections to a lithologic transition from hemipelagic diatom ooze to indurated claystone. Thus, there are two types of BSRs, one indicating the base of the gas hydrate zone and the other signalling a diagenetic boundary (cf. Kvenvolden[5]). Since the BSRs represent an acoustic velocity contrast in the sediment, it is not necessary that all BSRs reflect the existence of hydrates; similarly a BSR may not always be discernible when a hydrate is present[38].

Nevertheless the coincidence in depth of the BSR with the theoretical, extrapolated pressure and temperature conditions that define the hydrate phase boundary and sampling of hydrate above BSRs give confidence that this seismic indication of hydrates is dependable[4]. Therefore, gas hydrate areas are generally inferred when the so-called bottom simulating reflections (BSR) are present on seismic profiles, although they need to be ascertained by *in situ* sampling.

4.1.2. Amplitude blanking

The amplitudes of seismic reflections from within the hydrate stability zone are generally much lower in the area where there is an observed BSR. Thus, amplitude blanking is a useful seismic attribute to locate the presence of gas hydrate[39]. Blanking is the reduction of the amplitude of seismic reflections caused by hydrate cementation. The amplitudes of reflections are much smaller above the BSR (where sediments, are cemented by gas hydrates) than they are below the BSR. This phenomenon consistently appears in sediments containing gas hydrates, indicating that the changes in acoustic impedance between the strata are much reduced by hydrate cementation.

4.1.3. Velocity inversion

A third characteristic of gas hydrates is the abrupt decrease in acoustic velocity across the boundary between hydrate-cemented sediments above the BSR and non-cemented sediments below that are water or even gas-filled. This downward velocity decrease, known as an "inversion", is detectable with some seismic techniques (Dillon, et al.[4] and references therein).

The BSR and velocity inversion are only related to the bottom boundary of the hydrate zone, whereas the top of the hydrate zone (within sediments) does not produce a sharp reflection, as it has no such precisely defined boundary[4].

4.2. Non-geophysical proxies

Apart from the BSRs, which are the most important geophysical indicators of offshore hydrate deposits, several geological and biological parameters may be useful tools for reconnaissance.

4.2.1. Chlorinity anomalies in pore water

During gas-hydrate formation, water molecules crystallize into a cubic lattice structure. During this process the hydrate crystals exclude salt ions from the crystal structure. These excluded salt ions increase the pore-water chlorinity in the host sediment[40] initially. With time, this high salinity pore waters diffuse back to ambient levels. When the hydrate is decomposed, the freshwater released from the lattice dilutes the salt content of the pore-water causing the chlorinity to decrease drastically. Though the chlorinity anomalies of the- pore-water can be a useful indicator of hydrate presence, they also can be generated by fluid fiows[30]. Nevertheless, it should be noted that, such fluid flows generally induce hydrate formation.

4.2.2. Sediment grain size parameter

In many of the deep-water ODP and DSDP bore well hydrate records the occurrence of gas-hydrates were generally associated with coarse textured sediment. Thus, grain-size parameters of the sediment may be useful to qualify the likelihood of hydrate deposition in an area.

4.2.3. Carbon isotope signature

The carbon isotopic signatures in marine limestone crusts and nodules can be used as secondary proxies for methane-hydrate presence. This proxy basically depends upon the relative enrichment/depletion of ^{12}C and ^{13}C (Figure 6). The carbonate precipitated due to bacterial oxidation of methane and subsequent reaction with seawater calcium ions, exhibits an order of magnitude enrichment of 12C at the cost of oxidation of isotopically light-methane[41]. In addition the C- and H-isotopes have been effectively used for differentiating biogenic gas-hydrates from thermogenic gas hydrates[42]. Therefore, the isotopic composition of the carbonate slabs, cement and nodules, and organic matter may be useful proxies to detect methane discharge due to decomposition of sub- surface gas-hydrates.

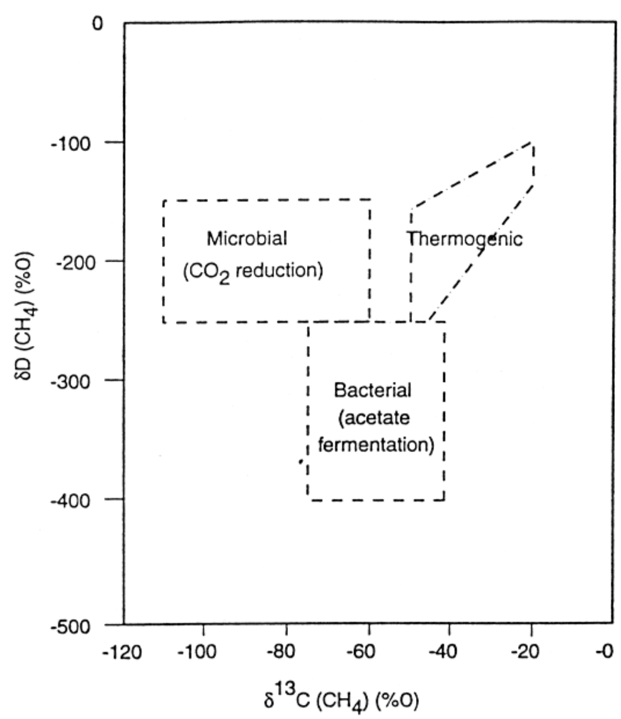


Figure 6: Interpretative plot of hydrogen and carbon isotope composition of methane in gas hydrate (after SchoeI143).

4.2.4. Pore water redox level

In the marine regime several metals are either particle reactive or redox sensitive. Manganese is such an element that has been extensively used in paleo-oceanographic studies for reconstructing paleo-redox levels, productivity etc. (cf. Mangini et al.,[44]). The crystallization and decomposition of hydrates are associated with changes in the pore- water redox levels, which in turn can induce sharp fluctuations in the dissolved and solid-phase manganese concentration of pore water-sediment. Microbial methane is generated in the sediment column in anoxic conditions where sulphate reduction is prominent. In such an environment, the existence of a solid phase of Mn is highly un- likely. Therefore, the dissolved pore water Mn pool can develop a strong positive anomaly at the expense of reduction of solid phase particulate Mn in sediment. Superposing such redox sensitive-element data on other proxies may strengthen the gas-hydrate search approach.

4.2.5. Benthic Biomass

The melting of hydrate at depth generates methane, small amounts of hydrogen sulphide and ammonia, and freshwater. Oxidation of these chemicals into carbon dioxide, sulphates and nitrates provides rich nutrients supply for chemosynthetic bacteria[10]. The Pogonophorans group of organisms in general, and *Scalerolinum* and *Oligobrachia species* in particular have been shown to harbour methanotroph bacteria in areas of increased methane discharge on the seafloor. The three main microbial processes occurring during the diagenesis in sediments (organic matter) can be explained by the following three chemical reactions[41,45].

a) Sulphate reduction:

$SO_4^{2-} + 2H_2O \rightarrow H_2S + 2HCO_3^-$

b) Methane generation:

$CH_3COOH \rightarrow CH_4 + CO_2$ and $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$

c) Methane oxidation:

$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$

The above reactions clearly indicate that in both methane oxidation and methane generation processes, CO_2 is evolved. The evolved CO_2 reacts with calcium in seawater precipitating it as carbonate slabs and nodules in the vicinity of methane emanations. These carbonate precipitates are enriched in the light carbon isotope.

Some recent works have indicated the occurrence of high benthic biomass in methane rich areas, where methanotrophs form the base of the benthic food web. Vestimentifera, tubeworms or clam colonies, on an otherwise sparsely inhabited seafloor, may provide the visible clues for the presence of buried hydrate deposits.

4.3. Gas escape features on the sea floor

In many parts of the world's ocean, high resolution acoustic investigations (side scan imagery, shallow sub bottom profiling) of the sea floor have indicated the presence of exposed and buried pockmarks. Most of these pockmarks are considered to have been caused by escaping gas. Some of these gas-escape features are related to the release of methane from hydrate dissociation during a perturbation in the pressure - temperature regime. These features could be used as additional exploration indicators[46].

Other features such as mud diapirs, bacterial mats and methane-derived carbonates have also been reported on the seabed in hydrocarbon rich sedimentary basins in numerous parts of the world. These features were considered as evidence of gas seepage activity[24], and could also be used as additional exploration indicators in hydrate- rich regions.

5. Some Techniques For Exploration for Methane Hydrates

5.1. Indirect geophysical approach

The objectives of gas hydrate exploration normally are to locate zones of methane hydrates and underlying free gas zones (if any) in the sedimentary layers, and to estimate their quantities in a prospect. The primary source of regional information about the presence of marine methane hydrates is from seismic reflection data, particularly through the identification of BSRs. Initially scientists used the conventionally acquired and processed near normal Incidence seismic reflection data for methane hydrate exploration. Efforts are taking place to improve the data acquisition and enhancement techniques that increase confidence in detection and quantification of methane hydrate and associated free gas.

5.1.1. Tools for data acquisition

Max and Miles[47] have given an excellent appraisal of the various geophysical tools required for detection and quantification of marine methane hydrates. To begin with, one can use the acoustic geophysical methods, such as seismic reflection techniques developed for hydrocarbon exploration, in available configurations.

In seismic reflection, one can collect single or multichannel data. Single channel data is adequate for recognizing the presence of BSR and the amplitude blanking phenomena, but is not informative about the acoustic velocities within the sedimentary layers. Multichannel seismic data on the other hand can provide a first approximation on velocity, which can be used to characterize the BSR and estimate the hydrate concentration.

Conventional seismic techniques use a compressional wave, which is suitable for resolving the structure within the normal sedimentary column. However, the presence of hydrates and associated gas alters the elastic properties of the marine sediments in which they occur. Information about these elastic parameters increases the likelihood of detection and estimating hydrate concentration. Compressional (Vp) and shear wave velocity (Vs) help in inferring these elastic properties. The shear wave velocity can be indirectly estimated from P-wave source experiments of conventional surveys, whilst seismic refraction experiments with Ocean Bottom Seismometers (OBS) in conventional refraction geometry can provide good Vs estimation. A combination of conventional multichannel seismic reflection and high resolution OBS refraction would be a good way to detail the velocity depth discontinuities and elastic properties of hydrated sediments.

Several experimental seismic systems have also been developed specifically for marine hydrate investigation. These equipments have source receiver geometries (that are different from the commonly used geophysical survey equipment) which en- able them to collect seismic data useful for detailed velocity analysis. One of these experimental systems is the Deep Tow Acoustic Geophysical System (DTAGS) developed by the Naval Research Laboratory, USA. The DTAGS uses a Helmholtz resonator (with broad frequency output between 250-650 Hz) as the acoustic source, and a 24 channel towed hydrophone array as the receiver. The source and receiver are towed about 500-700 m above the sea-floor and the system is claimed to provide 2-3 m scale resolution of the geological features and seismic data for fine scale velocity analysis of the near-seafloor sediments.

5.1.2. Data enhancement and analysis techniques

Detection of methane hydrates in marine sediments has been primarily through identification of BSRs based on the characteristics mentioned earlier. BSR reflection is generally a single symmetrical wavelet with a reversed polarity relative to the seafloor, indicating a negative impedance (velocity X density) contrast downward across the BSR. As hydrate density is very close to that of pore water and the amount of free gas below the BSR is usually small, sediment density is changed very little by the presence of either hydrates or gas. It is therefore assumed that this negative impedance contrast at the BSR arises from a velocity change[48], a relatively higher velocity layer overlying a lower velocity layer.

The presence of rigid hydrates causes the seismic velocities in hydrated sediments to increase considerably when compared to the velocities in a sedimentary sequence without hydrates. On the other hand, the presence of free gas, in sediment pore spaces, causes a sharp decrease in the compressional wave velocity (cf. Pecher et af.[49]). The increase or decrease of velocity depends upon the degree of saturation of the sediment pore spaces by hydrate or free gas respectively. Information about the seismic velocity across the BSR can therefore provide an indication about the hydrate and gas concentrations. Estimation of the amount of hydrate can be done in two steps. Firstly, the increase in velocity in the hydrate bearing sediments (relative to the normal water saturated sediments at that depth) is determined with respect to a reference velocity-depth profile, and then the velocity increase is converted to hydrate concentration using a theoretical or laboratory based relation between velocity increase and hydrate concentration (Yuan. T., et. al.[48]). Seismic data enhancement and analysis techniques for hydrate research, is therefore to decipher the high resolution velocity anomalies and other elastic properties above and below BSR, that are associated with gas hydrate and underlying free gas.

a) Conventional seismic modelling

Initially researchers used near-normal incidence reflection data in conventional seismic forward modelling across the BSR and arrived at velocity structure models, with response characteristics that closely fitted the observed seismogram[49,50]. However, the velocity models obtained by these techniques were for an "averaged" structure. Further, in those initial attempts most researchers considered BSRs as originating from the impedance contrast between partially hydrate saturated sediments above and partially gas saturated sediments below. Whereas subsequent studies suggested that the velocity change causing BSR could come from either

i) High velocity hydrates filling sediment pore spaces above the BSR and sediment with normal pore water content containing little or no free gas below, or

ii) Sediment with little hydrate above and considerable free gas concentration below the BSR or some combination of 1 and 2 (cf. Yuan et al.[51]).

Conventional seismic forward modelling cannot distinguish between these two models, and subsequent researchers used the approach of Amplitude Versus Offset (AVO) analysis, of the BSR wavelet, to distinguish between these two models.

b) AVO analysis

The characteristics of the reflection AVO can be an important indicator of sediment physical properties, since AVO depends on the variation of the S-wave as well as the P-wave velocities across the reflection interface. The major controlling elastic parameter for the AVO analysis is the Poisson's ratio of the medium.[52] Theoretical AVO analysis suggests that:

i) Even small amounts of free gas in sediments cause substantial reduction in the p-wave velocity as well as in the Poisson's ratio, such that the BSR reflection amplitudes increase with increasing reflection angle or offset 48.53 and,

ii) The Poisson's ratio of the hydrated sediments decreases as the hydrate concentration increases and porosity decreases. Since the Poisson's ratio is a function of the hydrate concentration, different types of AVO anomalies can exist for a BSR reflection. Thus amplitude decreases with increasing angle of incidence (negative AVO) for high hydrate concentration, and increases with increasing angle of incidence (positive AVO) for low hydrate concentration[52].

According to various studies[48,52,53]AVO analysis of the BSR amplitude can be used for estimating the hydrate concentration in sediment and to provide an indication of the presence of underlying free gas zone.

c) Wave- form inversion

It must be appreciated that AVO analysis alone is not sufficient to distinguish different structural models across the BSR, nor can the AVO technique define the upper and lower boundaries of the free gas zone[49,54]. Identification of the top and bottom of the low velocity zone underlying the BSR can provide information about the thickness and lateral extent of the free gas layer associated with the formation of gas hydrates. Waveform inversion of seismic reflection data can be used to distinguish the models and provide tight constraints on the thickness of a gaseous zone beneath the BSR. With the waveform inversion technique, a velocity model can be created such that the synthetic data over all offsets fits the real data at the BSR.

5.2. Non-Geophysical Proxies

It is not always possible to observe natural gas hydrates directly because they decompose during recovery of samples from the seafloor. There are four groups of proxies providing more or less reliable evidence of hydrate presence in cores. In order to study these proxies, surficial and shallow sub-surficial sediment samples are needed. Since the sediments and water samples are analysed for proxies for gas hydrates, they need to be stored under in situ conditions for later analyses in the laboratory. These sediment samples are normally collected using piston or gravity corers, techniques with limitations in maintaining the in situ characteristics. An advanced technique of sampling is through specially designed pressure core samplers (PCS). The core samples collected through piston/gravity corers are collected in transparent PVC core liners so that the presence of gas pockets in the sediments can be visually inspected. The gas bearing sections of samples should be stored either in liquid nitrogen containers or kept in Nalgene bottles prior to storing them at –80 degrees C for subsequent gas analysis.

In sediments, methane occurs as dissolved gas in the pore fluids and to some extent, adsorbed on the surface of particulate matter. Thus improper thermal or mechanical handling or storage of the sample can alter the gas content of a sediment sample, and methane analyses techniques have to consider these influences. The most common method for the determination of hydrocarbons in sediments is the headspace technique[55], where an aqueous solution of the sediment is equilibrated with an overlying gas phase that is then analysed by gas chromatography. Degassing of sediments has been shown to deliver reliable information on both the gas quantities and the stable isotopic composition of methane in sediments. Methane extraction is done using ultrasonic extraction unit for headspace methane gas collection. This headspace detection helps to identify the higher hydrocarbon (methane) concentrations in the sediments.

Pore water chemistry is studied at various intervals of the core from samples collected using pore water squeezers or centrifuges, and analysed for proxy elements such as sulphate etc., using CNS analysers and other titrimetric methods. The entire core sample can be utilized for understanding both textural (grain size history, porosity and permeability etc.) parameters and microbial signatures. Both water column and near bottom water samples may also be collected using rosette water sampler equipped with CTD, and Niskin sampling bottles, for identifying methane proxies, if any are present.

Recently, carbonate crusts have been found on the continental margin seafloor in association with methane-bearing cold water seepages[56,57], and are suspected to be related to dissociation of gas hydrates[58]. Carbonate lenses encountered within the sedimentary sequences may indicate methane seepages to the seafloor in response to massive decomposition of gas hydrates.

Bacteria too play a dominant role in the degradation of organic matter within the sediments and, as a consequence drive chemical changes and early diagenesis. The estimation of total bacterial numbers and bacterial activity rates may help to investigate methane cycling in deep-sea sediments[59] which probably contain gas hydrates.

6. Harvesting methane hydrates -Some Ideas

The common pool of knowledge acquired to date suggests that methane hydrates, existing in sediments up to a kilometre or so below the sea floor, have the potential of becoming a major resource for alternate energy. Recovering methane from these deposits and transporting it to shore at a reasonable cost, pose a challenge to technologists and scientists. Ideas have been conceptualised and research mounted that address these challenges.

6.1. Production and recovery of methane

The key problem regarding production of methane from the hydrate layer is 'mobilization' of methane from solid hydrates, i.e. dissociation of *in situ* hydrates. Dissociated gas hydrate can serve as one source of methane; the free methane below the gas hydrate zone is another possible source. For dissociation of methane hydrates three processes have been proposed: thermal stimulation, depressurisation, and inhibitor injection[2,3,60].

In the thermal stimulation process, thermal energy can be released into the methane hydrate bearing strata in order to increase the local temperature enough to cause the gas to dissociate. This process has a favourable net energy balance as the heat energy required for dissociation is about 6% of the energy contained in the liberated gas. In simple terms steam or hot water can be pumped down a drill hole to dissociate the hydrate and release methane. The released methane could then be pumped to the surface of the seafloor through another drill hole.

In the depressurisation process, the hydrates are exposed to a low-pressure environment where they are unstable and decompose to methane and water. The heat energy for the process comes from the Earth's interior (geothermal heat flow). The released methane can then be recovered by conventional technology. The depressurisation method as envisaged involves horizontal drilling in the free gas zone, which underlies the hydrate zone. As the free gas is removed, the overlying hydrates become depressurised and decompose into free gas. Continuous removal of produced gas is expected to sustain this pressure-induced dissociation of hydrate zone at its base. This method appears to be most suited to those deposits where widespread gas occurs in a closure below the hydrate cap[60].

In the inhibitors injection process, a chemical inhibitor such as methanol is injected into the gas hydrate zone. Chemical inhibitors shift the pressure-temperature equilibrium so that the hydrates are no longer stable at *in situ* pressure-temperature condition, and hydrate dissociates in the contacted surface.

Of these three production methodologies, the depressurisation combined with the thermal stimulation process appears to be the most practical for zones where free gas is trapped beneath the methane hydrate[2,3].

6.2. Transportation of methane gas to shore

Transporting methane from the production site to shore could be through submarine pipelines as is done for long distance transportation of natural gas. However, submarine pipelines are expensive and the geological hazards of the continental slope (avalanches) make this option difficult. Other alternatives such as liquefying the gas on ship or on a drilling platform can also be considered. The procedure conceived by Timothy Collett of the United States Geological Survey, involves burning part of the methane to obtain hydrogen and carbon monoxide that can then be converted with the help of a catalyst into liquid hydrocarbon, which while easy to transport, results in a loss of 35% of the energy. Another method suggested by Roger Sassen (Texas A&M University) involves the reaction of methane with water on the seafloor to obtain hydrate free from sediment. This pure hydrate then can be stored in zeppelin shaped storage tanks and towed to a shallow water infrastructure where they can be safely decomposed into water and gas in a controlled environment[10].

6.3. Efforts required for commercialising methane hydrate deposits.

Methane hydrate will be commercially exploited when the price of petroleum and conventional gas rises substantially. The apparent abundance of conventional hydrocarbon deposits and their relatively low prices are inhibiting research into various aspects of gas hydrate. Hydrate deposits can be commercial, even in this low cost energy environment[60], provided research and development activities in this field are sustained.

Hydrate recovery will in all probability involve forced dissociation, which will involve significant demand for heat. Supplying and managing this heat and maintaining an artificial thermodynamic balance that allow the controlled dissociation of hydrate and the safe recovery of methane will probably prove the key to commercialisation.

6.4. Gas hydrate research and development -possible by-products

Apart from using methane hydrate as a source of fuel energy, research in the methane hydrate system may also catalyse several other direct and indirect uses of the methane hydrate or the process by which hydrates form.

6.4.1 Desalination of seawater

In this process (Figure 7) it was suggested that if seawater is combined with a hydrate former (for e.g. methane) in a suitable pressure temperature controlled vessel, then hydrate will form. After formation, the brine can be separated from the hydrate and the hydrate can then be allowed to disintegrate. This hydrate disintegration will yield fresh water and the hydrate former. The hydrate former can again be returned to the system for continuing hydrate formation with sea-water[7].

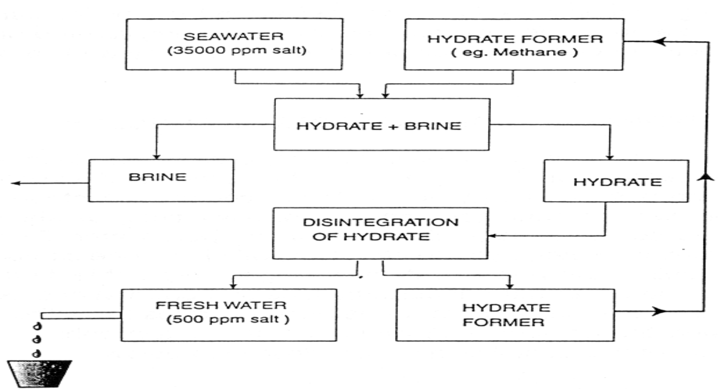


Figure 7. Schematic diagram depicting the principle of seawater desalination through the process of hydrate formation (adopted after Nixdorf and Oellrich[7]).

6.4.2. Storage of CO_2

Carbon dioxide from the environment can be converted into hydrate in deep-sea environmental condition and stored there till dissociation back in terms of CO2 in geological time scale[7]. This subject is the basis of much debate and speculation.

6.4.3. Separation of gaseous mixtures

In another research programme[7] the process of hydrate formation was considered for separating gaseous mixtures. It was demonstrated that using the differing tendencies of gases towards hydrate formation, good separation factors could be obtained by allowing the gaseous mixtures to form hydrates.

6.4.4 Electricity generation from flowing gas

One interesting possibility has also been conceived[60] for energy generation while transporting methane from deep sourced hydrates to shore through pipelines. A pipeline to a land-based terminal will have a large pressure gradient that could conveniently be dealt with by 'stage decompression'. The gas/fluid in the pipeline can be used for driving turbines for electricity generation. This would accomplish the dual objectives of reducing flow velocity through the transfer of kinetic energy and producing electrical current.

7. Methane hydrates -Some Aspects Of Concern

The significance of methane hydrates lies mainly in its tremendous resource potential. Even a small percentage of the estimated global resource, if exploited, can meet world energy demand for centuries. Methane hydrates are located in the shallow submarine geo-sphere, which is a finely balanced system in equilibrium with all its components such as sediment, pore-water, fluid flows, pressure, temperature, overlying water, hydrate etc. Removal of anyone component of this equilibrium may destabilize the whole system leading to irreparable damage. The destabilizing factors may be either natural perturbations or perturbations associated with exploitation. Studies have indicated that methane hydrates have the potential to affect global climate and the geological environment at a catastrophic scale. Some of the perceived impacts of this destabilization are described below.

7.1. Impact on global climate

The earth's atmosphere has a large number of sources and sinks for methane including gas hydrates which exist in metastable equilibrium with the environment. This equilibrium is affected by natural changes in pressure and temperature. The amount of methane that is trapped in gas hydrates onshore and offshore is perhaps 3000 times the amount in the atmosphere and this enormous quantity of methane is available for release with catastrophic consequences for global climate. Some of the postulated ways by which this methane could have been released from these reserves to the atmosphere in the past are as follows:

i) Escape from gas hydrate zones as a result of thermal decomposition caused by climatic warming;

ii) Escape from gas hydrate zones due to the upward shift of the base of the hydrate stability caused by pressure decrease related with lower sea level during glaciation; and,

iii) Large-scale catastrophic release in association with widespread slope instability.

Gas hydrates have been linked with environmental problems mainly because methane is a potent greenhouse gas with a potential about 10 times that of carbon dioxide[3,61]. These figures underline the potential role that hydrates could play in amplifying or damping temperature changes.

It has been postulated that Pleistocene global climate changes may have caused methane release from gas hydrate deposits but the opposite may also have been true, i.e. methane released from gas hydrates might in turn have caused changes in global climate[2]. The study of ice core records of the past 200 Ka suggests that atmospheric carbon dioxide and methane decreased gradually at the initiation of glaciation, but increased rapidly with deglaciation. It is interesting to note that, the rapid climate change in the past from the glacial to interglacial is indeed attributed to the huge release of methane from gas hydrates[62,63]. Some of the models[2,61,64] linked these observations with climatic change caused by hydrate decomposition or vice versa. Accordingly, glaciation and/or sea level fall will reduce hydrostatic pressure on the sediments of shelf and slope at mid latitudes, thereby destabilizing hydrates and consequently releasing methane into the atmosphere. The methane so released will cause rapid warming that will lead to dissociation of hydrates in the permafrost regions and shallow continental margins of the high latitude regions, a positive feedback causing further warming. Consequently ice in the higher latitude will melt thereby increasing sea level. This rise in sea level will in turn increase the hydrostatic pressure on the sediments of shelf and slope at mid latitudes, initiating a negative feed back that inhibit further release of methane from hydrates.

The potential connection, between the gas hydrate reservoir and the Earth's climate is little understood and the quantitative contribution of different elements in this complex loop needs to be established through further research. It may not be amiss to mention here that this lack of understanding of gas hydrates reservoirs and the Earth's climate could be an even bigger inhibitor on hydrate exploration than present low oil prices and lack of funding support for hydrate research. The balance may lie between mounting intensive campaigns on climate research and safety procedures on the ex- traction and use of gas hydrates.

7.2. Impact on geological environment

Submarine sediment slumping or sliding occurs when huge piles of unstable sediments build up. In some cases movement of sediment slumps or slides could possibly be caused by the decomposition of gas hydrates and the resulting expansion or release of gas.

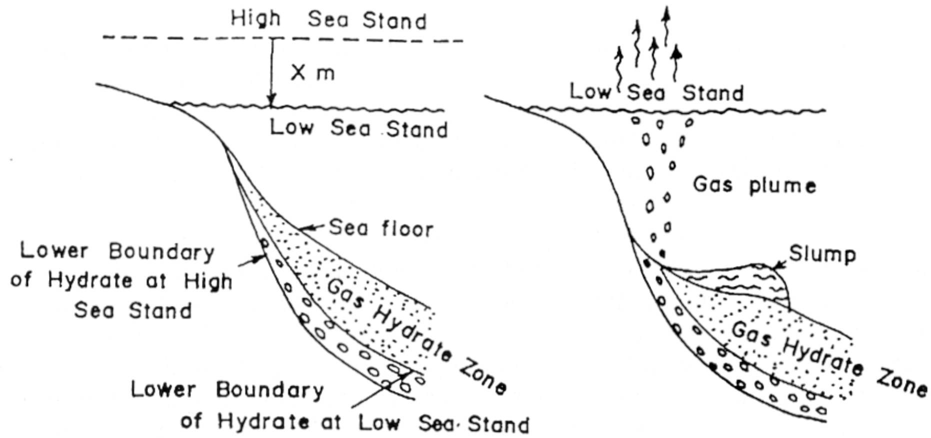


Figure 8. Development of hydrate related unstable layer beneath continental slope after lowering of sea level (modified after Dillon et al.[4];McIver[65]).

In the continental slope area, continued sedimentation may lead to burial of hydrated sediment to such a depth, that the hydrates are no longer stable and dissociate into liquid-gas-water mixtures. The dissociated hydrates create a zone of weakness[2] in the sediment where slope failure could be triggered by further gravitational loading or earthquakes.

Similar slope failures may also occur because of changes of pressure and temperature resulting from fluctuations in sea level (Figure 8) or bottom water temperatures, such as those that took place during the Pleistocene epoch. These changes, though of long duration, may have caused[5] solid sediment to become gas-cut mud and resulted in mud diapirs, mud volcanoes, mud slides or turbidite flows, depending on sediment composition and bottom topography.

7.3. Hazards related to drilling into gas hydrate zones

Drilling for recovery of methane from the hydrate is a challenging task because of the characteristics of the hydrates, especially its unstable nature with change in pressure - temperature conditions. Hydrates may dissociate[2] during the process of drilling and initiate a process of uncontrolled gas release and site subsidence.

7.4. Baseline data and monitoring

The possible short and long term impacts of large-scale hydrate exploitation on the geological environment and global climate need to be studied to develop safe standardized procedures for exploration and production before attempting to exploit this resource. It is also necessary to systematically collect base line information on related environmental indicators and continuously monitor short and long term effects on them. Perturbations associated with exploiting methane hydrates need to be analyzed by careful modelling and techniques have to be developed to avoid or mitigate them.

8. Factors that have facilitated discovery of gas hydrate and fostered continuing research on them.

It has been a little over two decades since hydrates were recognised in the natural environment. Scientific curiosity was the main reason for enhancing our understanding about methane hydrates, though some economic and technological factors may also have contributed to its growth.

8.1 Economic factors

It appears that most of the locales of methane hydrate deposits in the oceanic areas were discovered serendipitously when scientists looked anew (for the characteristic acoustic signature of hydrates), at existing seismic data, which had been collected during marine geophysical expeditions meant for studying structure and tectonics. These initial efforts did not require much expenditure, and scientific curiosity could be sustained without much additional financial support. As the number of 'finds' increased, knowledge about various aspects of oceanic hydrates also increased and scientists began realising its immense potential as a fuel resource. The challenges of its exploration and production and its probable impact on global climate and the geological environment became clearer. While, looking for an abundant, sustainable and low polluting alternate primary energy source for the future, policy makers and planners in some countries, are gradually recognising the long term potential of marine methane hydrates as well. It appears however that the complexities and challenges for exploration and production of methane hydrates from the hostile and difficult marine environment require considerable focused R & D effort in various fields, for which adequate financial support is lacking.

This is perhaps due to the perception that methane hydrate exploitation will be economically viable only when the price of conventional hydrocarbon and other fuels rises substantially. On the positive side, many of the identified hydrate deposits are located on continental slopes not far from major markets in industrialised countries[60]. Furthermore, countries with little or-no hydrocarbon resources have also noticed the presence of methane hydrates in abundance on their continental slopes. It is to be expected that the prospect of energy self reliance will catalyse some of these countries to initiate harvesting methane hydrates as soon as scientists and technologists come forward with dependable, safe and cost effective mechanisms to explore and exploit this resource.

8.2 Technological factors

Most methane hydrate deposits occur in the deeper part of the continental slope and rise. Lack of suitable production technology was a major impediment in considering the feasibility of exploitation of this resource. However the past five years has witnessed a dramatic improvement in drilling technologies for oil and gas in deep water areas and even newer technologies are being developed. The oil exploration industry is now exploring extensively in deepwater regions (where hydrate deposits occur), and drilling capability to about 3500-4000 m (the base of the potential economic hydrate zone) is being built for conventional hydrocarbon drilling[60]. There has also been a distinct reduction in deepwater development costs. All these are positive factors for hydrate exploration and development. Even though located in deep waters, marine hydrate deposits are easily accessible to relatively shallow drill penetration from the seabed. Much of the engineering required to exploit these deposits can perhaps be achieved by suitably adopting proven technology currently in use in connection with exploitation of deep water oil and gas reserves. The present technological base appears to be adequate for exploration, exploitation and sub sea transport capabilities required for marine methane hydrate resources[60]. However as exploitation is not expected in the foreseeable future, the corporate sector is not willing to venture into this field. At present, whatever research is ongoing is mostly supported by governmental sources. The industry view[3] is that when hydrate development is required, challenges will be met, just as industry has mastered other difficult environments in energy resource development.

One interesting outcome of R & D in gas hydrates has been the identification of several possible uses of gas hydrates other than as fuel. Since the benefits from those uses are quite significant, therefore importance of gas hydrate is increasing. If continued research can find an increasing number of such alternate uses of gas hydrates, the economics of exploiting methane hydrates will improve and such activities will gain momentum.

8.3 International scenario of gas hydrate research

Countries that have strong economic bases, or are witnessing high industrial growth rates, but have low energy resource potential, could potentially become energy independent, an event that would affect international affairs, foreign policy and other interrelations. The repercussions would extend to world trade, regional power equations, and foreign currency balance of existing major importers, when gas hydrates begin to be exploited. The realisation that such a situation could come about has lately generated some interest in the field of gas hydrate research in many countries recently.

The first national United States Gas Hydrate Workshop in 1991 brought together government, industry, and academic research interests and proposed that research into hydrates should take place as a broad, integrated research programme. Significant scientific re- search subsequently by various US organisations culminated in the Presidential con- sent of the Methane Hydrate Research and Development Act of 1999. The legislation authorised $5 million in research funding3 for the Year 2000 and about $46 million until Year 2004.

The government of Japan was first to establish a national hydrate research programme. An exploratory five-year plan for hydrate research was established in 1995 and in 1998 the Japan National Oil Corporation (JNOC) sponsored test drilling of known hydrate deposits in the McKenzie Delta of Canada in collaboration with the Geological Survey of Canada, the U. S. Geological Survey (partly funded by U.S. Department of Energy Technology Center, Morgantown, WV) and contracted university and research institutes. The Japan National Oil Corporation (JNOC) is conducting extensive research of a potential hydrate resource off Hokkaido Island and drilled test wells in two locations in 1999. Commercial production is targeted for 2010, barely 10 years away. It is estimated that recovery of only one tenth of Japan's estimated reserve would provide Japan with methane for 100 years. The Japanese government has authorised a second five-year plan, headed by NEDO (New Energy and Industrial Technology Development Organisation), which is intended to develop methane recovery engineering.

India, in 1996, was the second nation to establish a gas hydrate research programme. The Oil Industry Development Board of India, as part of its plan to boost natural gas resources, is funding a program of methane hydrate research. Mainly the early research was carried out under funding of the Gas Authority of India Limited (GAIL) and later, several other public sector hydrocarbon companies such as the Oil and Natural Gas Commission (ONGC), Directorate General of Hydrocarbons (DGH), together with research institutes such as National institute of Oceanography (NIO), and National Geophysical Research Institute (NGRI) have begun a systematic appraisal of the Indian continental margin for methane hydrates. Several promising locales have been identified[14-16] for intensive exploration.

Other nations are also conducting assessment[60] of deepwater hydrocarbons, including hydrates. Canada, which closed its offshore mineral programme some years ago, is revitalising its program. The European Union has allocated funds for development of methane sensors, specialised hydrate coring apparatus, and marine research to identify hydrate and quantify methane prospects in European North Atlantic waters.

9. Conclusion

Natural gas hydrates have come a long way since their discovery in 1960. An enormous amount of methane is believed to be sequestered in the shallow geosphere, even a small percentage of which may meet the energy requirement of the world for centuries. Gas hydrate research has opened a new frontier in ocean and earth sciences that crosses many disciplinary boundaries.

Most gas hydrate deposits have usually been discovered serendipitously during regular marine geophysical surveys that were for studying structure and tectonics. There- fore scientists believe many other hydrate deposits, which cannot be detected with available exploration techniques, are bound to exist. Improved techniques for detection of hydrates and an assessment of its abundance could influence the hydrocarbon industry to take an interest in exploration and exploitation of this resource.

Methane hydrates will most likely constitute an important environmental and geological hazard. It is required to determine their geographical distribution, quantify their abundance in subsurface environments and fully understand their response to environmental perturbations.

It may be right time to consider some global regulatory mechanism for exploration and exploitation of this complex energy resource, by various nations and organizations. Incorporated in the proposed regulations, among other things, should be descriptions of:

i) Possible hazards and their impact on the marine environment
ii) Measures for the prevention, reduction and control of such eventualities
iii) Programme of oceanographic and environmental baseline data collection and monitoring and
iv) Mandate for dissemination of relevant information and sharing of experience with the world scientific community.

Insight about many aspects of methane hydrate system perhaps can be obtained through laboratory experiments or computer simulation modelling. Such studies should also be carried out in parallel with data collected through field investigations. Neural network based modelling of the geological environment and process may have to be developed as a viable exploration aid.

It is hoped that R&D efforts in the field of marine methane hydrate will get enough financial support so that we can develop a new, unconventional, untapped fuel resource which will ensure adequate and affordable energy for the future.

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SUMMARY OF THE PRESENTATION AND DISCUSSIONS ON "SUBMARINE METHANE HYDRATES POTENTIAL FUEL RESOURCE OF THE 21ST CENTURY"

Presentation

Dr. Erhlich Desa, Director of the National Institute of Oceanography of India began his presentation on "Submarine methane hydrates, potential fuel resource of the 21st century" by informing participants that the Government of India's interest in gas hydrates has intensified with the participation of several domestic oil and gas companies as well as the Government itself in studying gas hydrates within India's maritime areas. Dr. Desa said that the Government's participation in this endeavour is through an oil development fund from which, inter alia, studies are paid for. In the case of the National Institute of Oceanography, Dr. Desa said that it is paid to examine seismic data collected by oil companies. He said that some of these data were gathered fifteen years ago, making the Institute the repository of the first bottom simulating reflections that have been recorded and published around the coast of India. He described as a big step in India, the fact that at the present time, oil companies are providing seismic data to a research institute. In relation to work undertaken by the Institute, Dr. Desa said that the Institute had produced a probability map of gas hydrate distribution around the coast of India for the Gas Authority of India Ltd. Dr. Desa informed participants that the Government of India is involved in gas hydrate programmes on a bilateral basis with Russia and some member countries of the European Union.

With regard to the potential offered by gas hydrates as an alternative energy source, Dr. Desa said that while many people in the field were excited by its prospects, many others are very fearful of it. He stated that among those excited by it, one of the reasons is because its exploitation might result in a reconfiguration of the current global energy supply and demand equation, since it might make some countries that have no energy or insufficient energy, suddenly energy sufficient. He noted that the nice thing about hydrates is that they are found in most places and close to coasts. He also noted that the bad thing about hydrates is that their exploitation might result in one of the major climate changes known to man.

Dr. Desa informed participants that his presentation would consist of an introduction to existing knowledge of methane or gas hydrate deposits, information on where they occur, indicative estimates of the amount of methane to be found in such deposits worldwide, how methane or gas hydrates form, including the phase diagram, and free gas below the hydrates, geophysical and non-geophysical exploration techniques for locating these deposits as well as possible proxies for such work. He also said that he would present some of the current ideas being proposed for the production and transportation of the gas to shore, and associated spin-off technologies. He emphasized that spin-off technologies are important because it is these technologies that lend momentum to a system. Dr. Desa stated that his presentation would be completed with a review of the economic and technological factors that facilitate and hinder research on hydrates, as well as international programmes related to gas hydrate research and development.

Regarding methane hydrate composition, Dr. Desa said that they are ice like crystals formed from natural gas and water in which water molecules form a rigid lattice and a guest gas molecule occupies the void. He stated that the gas molecules stabilize the lattice formed by the water molecules. Dr. Desa described hydrates as inter-grown, transparent, translucent, white to grey to yellow compounds with poorly defined crystal formats. He said that they might cement the sediments in which they occur, or they may occur in the pore spaces of un-cemented sediment grains, and exist within a limited stability range of pressure and temperature. Dr. Desa said that hydrates retain the energy they contain either as solid hydrates, or as methane gas below the hydrates. He informed participants that one unit of hydrate, when released from its pressure temperature curve, forms about 164 units of gas and about 0.8 units of fresh water. Dr. Desa informed participants that while several hydrate structures have been identified three common structures are known to form from water in contact with natural gases. These structures are Structure I, Structure II and Structure H. Dr. Desa said that methane hydrate is a structure I type. He described this structure as consisting of two small cages which are 12 phases of a five sided polygon, noting that in addition to methane other gas molecules could be included in the lattice.

Dr. Desa stated that hydrates were first discovered in 1811 by Sir Humphrey Davy, who reported the formation of a yellow precipitate as a result of chlorine gas bubbling through water. In 1888, Dr. Desa said that a scientist by the name Vilard pointed out that hydrates could be formed out of hydrocarbons. While other academic work/laboratory work was pursued on hydrates, Dr. Desa said that it was not until the 1930s, when it was discovered by US engineers that natural gas pipelines were being clogged up by an ice-like substance, that research focussed on hydrate formation. Dr. Desa said that in the 1960's scientists discovered that hydrates could also form in natural environments. In 1972, Dr. Desa said that the first pressurized specimen of naturally occurring gas hydrate was recovered from the wildcat well on the north slope of Alaska in the Prudhoe oil field. In addition he pointed out that in the 1970's, geophysicists of Lamont-Doherty Earth Observatory of Columbia University found the earliest indication of methane hydrates beneath the seafloor from the seismic data collected over the Blake Ridge, along the south east US coast. Since then he also said, the presence of gas hydrates has been inferred in many places around the world. In 1997, Dr. Desa said that the first drilling campaign, specifically designed for hydrate and related issues such as methane generation and flux, was carried out by the international scientific Ocean Drilling Program (ODP) on the Blake Plateau. He noted that this effort greatly increased the understanding of these deposits. He further noted that recognition of the widespread occurrence of gas hydrates on a global scale has recently spurred more focused programmes.

With regard to the worldwide occurrences of gas hydrates, using a map, Dr. Desa said that whereas in 1980 there were 9 regions where hydrate occurrences had been indicated, by 1998 there were 48 such regions. Of these, Dr. Desa further stated that it is only in 16 regions where hydrates had actually been observed. He went on to say that that these regions are mostly in the Pacific Ocean with a couple of regions to be found in the Atlantic Ocean. Dr. Desa also said that hydrates mostly occur at the deposition centres of continental margins primarily by microbial and thermogenic processes.

As concerns estimates of the amount methane in hydrates, Dr. Desa said that 10,000-gigaton is a reasonable estimate of the amount of carbon stored in methane hydrates. He pointed out that this quantum of organic carbon in gas hydrates is twice that in all known fossil-fuel deposits. He further pointed out that even if only a small percentage of this were recoverable, it would constitute a major stock of energy.

Dr. Desa then turned his attention to how methane hydrates deposits and the free gases found beneath them are formed. He pointed out that with the correct pressure and temperature, and with enough gas there is a good basis for the formation of hydrates. Dr. Desa said that sub-seabed methane is produced primarily by microbial and thermogenic processes. He said that in the microbial process, the organic debris of the depositing sediments is decomposed by a complex sequence (methanogenesis) into methane by bacteria in an anoxic environment. He added that decomposition is thought to take place either by acetate fermentation or by carbon dioxide reduction.

He stated that in the thermogenic process, thermal cracking of organically derived materials takes place to form petroleum hydrocarbons (including methane). He said that thermal cracking generally occurs at considerable depth (>2km) in sedimentary basins where temperatures exceed 100°C. He also said that thermogenic methane might also be produced by thermal degradation of oil at even greater depths and by maturation of coal.

Through the use of an illustration, Dr. Desa pointed out the gas hydrate stability zone, which he said was of the phase boundary type. He pointed out the locations of both free gas and hydrates in the diagram. Dr. Desa briefly described how a geothermal gradient is formed, its relationship with the phase boundary, and the possible thickness of the gas hydrate zone. He said that the top of the zone is not accurately defined because it is not known whether methane is to be found there, and whether or not there is enough of it to produce hydrates. Dr. Desa informed participants that the National Institute of Oceanography of India has produced a stability zone thickness map for India for an oil company. He showed participants a map of the maritime areas of India containing this information, and said that scientists produced this map by synthesizing data such as the bathymetry of the seabed, seabed temperature, the geothermal gradient, organic carbon and sediment thickness. He said that a big oil and natural gas cruise in India's maritime areas is planned to investigate some of the findings.

Turning his attention to a phase diagram of a hydrate deposit, Dr. Desa stated the need to examine this diagram in relation to the stability zone with a view to ascertaining whether the methane migrates to the deposit. He noted that although it is known that methane comes from biogenic production and there is a common belief that the pore waters of associated sediments should be saturated, but there is an ongoing debate about how saturated they should be. He pointed out that methane could migrate in different forms, as bubbles, as rich fluids, and by molecular diffusion. He also pointed out that hydrates occur in many different ways, including disseminated bits of hydrates within pore spaces, as fine layers, as nodules, and as massive hydrates.

With regard to free gas, Dr. Desa said that it is formed from those gas molecules that are neither bound to other hydrocarbon molecules nor bound as hydrates. He also said that the presence of free gas could be determined through acoustic techniques.

At this point in his presentation, Dr. Desa turned his attention to the geophysical indicators and non-geophysical proxies that could facilitate prospecting/exploration for hydrate deposits, as well as to gas escape features on the seafloor.

In relation to geophysical indicators, Dr. Desa said that three phenomena are associated with gas hydrates in seismic reflection profiles. He described these as:

1. A reflection known as the "bottom simulating reflection," or "BSR", a very strong reflection that occurs at the base of the zone of gas-hydrate- cemented sediment;

2. A reduction in acoustic velocity at the base of the gas hydrate zone, such that high-velocity deposits occur over low-velocity deposits (known as "polarity reversal" or "inversion"), and

3. A reduction in amplitude of reflections within the gas hydrate zone, known as blanking.

Dr. Desa said that the first gas hydrates were identified on the Blake Ridge on the basis of bottom simulating reflections. Their manifestation from seismic profiles was that the BSR had a high reflection for polarity reversal. Dr. Desa described a high reflection for polarity reversal, a large reflection coefficient and increasing sub bottom depth with increasing water depth as different criteria that characterizes a BSR.

Dr. Desa also informed participants of the following non-geophysical proxies for locating hydrates deposits; the chlorinity anomaly, sediment grain size and benthic biomass. On the chlorinity anomaly, Dr. Desa said that when hydrate is forming the salts around them have high salinity, resulting in very sharp salinity anomalies. He said that salinity measurements could provide an indication of the presence of methane hydrates. As concerns sediment grain size, Dr. Desa said that drill cores from ocean drilling for petroleum and the deep-sea drilling project are h often associated with coarse textured sediments that allow fluid to migrate and carry methane. He suggested that a study of these cores could help to identify the optimum grain sizes for fluids to run through and for the formation of hydrate deposits. Dr. Desa also identified carbon isotope is another non-geophysical proxy because as methane is produced by bacterial action there is an enrichment of the carbon isotope C-12. Dr Desa said that both carbon (C) and hydrogen (H) isotopes are seen in signatures for hydrate deposits.

Finally, in relation to benthic biomass, Dr. Desa said that it is known that as hydrates start melting they produce methane, hydrogen sulphide, ammonia and fresh water. When this mixture gets oxidized, Dr. Desa said that it gets oxidized into carbon dioxide, sulphates and nitrates, and that these are rich food for chemosynthetic bacteria. He said that it has been discovered that the Pogonophorans group of organisms in general and *Scalerolinum* and *Oligobrachia* species in particular harbour methanotroph bacteria in areas of increased methane discharge on the seafloor. He noted that sulphate reduction, methane generation, and oxidation could explain the three main microbial processes occurring during diagenesis in sediments. He further noted that the reduction of carbon dioxide results in the precipitation of calcium from seawater as calcium carbonates. He observed that these carbonate precipitates are enriched in the light carbon isotope. He also remarked that tubeworms or clam colonies are clues to gas emanations that are associated with hydrate deposits.

Continuing his presentation, Dr. Desa said that in many parts of the world's ocean, high resolution acoustic investigations (side scan imagery, shallow sub bottom profiling) of the sea floor have indicated the presence of exposed and buried pock marks. He said that most of these pockmarks are considered to have been caused by escaping gas. He also said that some of these gas-escape features are related to the release of methane from hydrate dissociation during a perturbation in the pressure/temperature regime. He concluded that these features could be used as additional exploration indicators.

He noted that features such as mud diapirs, bacterial mats and methane-derived carbonates have also been reported on the seabed in hydrocarbon rich sedimentary basins in numerous parts of the world. He said that these features are considered as evidence of gas seepage activity, and could also be used as additional exploration indicators in hydrate-rich regions.

With regard to techniques for exploring for methane hydrates, Dr. Desa identified two approaches, the indirect geophysical approach, and non-geophysical approach. As concerns the tools available for data acquisition he suggested the use of single and multichannel seismic reflection, stating that single channel seismic reflection is available with many people. Dr. Desa said that single channel seismic reflection is adequate for recognizing the presence of BSR and the amplitude-blanking phenomenon. He said that multi channel seismic data in addition provides an approximation of velocity that is useful for BSR characterization and in estimating hydrates concentration. He further noted that since hydrates and associated gas alter the elastic properties of sediments, two properties of sediments should be examined. These are the compressional (V_P), and the shear wave velocities (V_S).

Dr. Desa said that the shear wave velocity could be indirectly estimated from P-wave source experiments of conventional surveys, and from seismic refraction experiments with Ocean Bottom Seismometers (OBS) in conventional refraction geometry. He also said that a combination of conventional multichannel seismic reflection and high resolution OBS refraction data would be a good way to detail the velocity depth discontinuities and elastic properties of hydrated sediments.

Dr. Desa emphasized that because the density of sediments remains about the same, whether it is sediments and hydrates or sediments with gas, velocity becomes the primary tool for distinguishing between the two. He said that the tools he had spoken about are those that are required to make measurements on velocity. He stated that with accurate measurements of velocity, models could be created to assist in the evaluation of the deposits. He said that these include models of the thickness of the sediments, the thickness of the hydrate and the thickness of the free gas.

Dr. Desa described waveform inversion as a technique that allows the searcher to place tighter constraints on differences between the free gas and the hydrate zone. With the waveform inversion technique, Dr. Desa stated that a velocity model could be created such that the synthetic data over all offsets fits the real data at the BSR.

He informed participants that in addition to the proxies that he had described, there where are other methods and proxies available. In this regard he mentioned hydro proxies that he said were of four types consisting of the headspace, the pore water, the carbonate crusts and bacterial indicators.

In order to study proxies Dr. Desa said that a surficial and shallow sub-surficial sediment sampler is required. He emphasized the need for such proxy data to be stored under special conditions. Dr. Desa informed participants of an advanced technique of sampling using specially designed pressure core samplers, (PCS). He said that using this sampler, one is able to store gas samples up to minus 80 degrees for later analysis. Some of the advantages of this sampler include the ability to examine sediments and the free gas absorbed on sediment surfaces through ultra sonic extraction. He also said that pore water chemistry could be conducted with special squeezers

In relation to harvesting hydrates, Dr. Desa said that his Institute undertook searches of the US, Japanese and the European Patent Offices and found that in the last two years approximately 400 patents have been registered. He therefore said that even though a lot of funding for hydrate research is not taking place, it would appear that a lot of thinking is going on resulting in patents being filed for the day that hydrate production and recovery become a reality.

For the production and recovery of gas hydrates, Dr. Desa stated that while several methods have been proposed, the main concept is to mobilize the hydrates, melting them for easier access and recovery. In this regard, Dr. Desa mentioned thermal stimulation as a means of melting the hydrates, noting that only a small amount of energy is required. He also said that depressurisation is also another method where the free gas beneath the hydrate seal is accessed, releasing the gas and reducing the pressure. He said that with the same geothermal gradient, the hydrate layer disassociates from the bottom and provides gas into the system. Dr. Desa described a third potential method called an inhibitor injection, which takes advantage of shifting the phase boundary.

After the production and recovery of the hydrates, Dr. Desa said that several ideas have been offered for their transportation to shore. These included the use of pipelines to transport the recovered hydrates to shore or converting the recovered methane hydrate to liquid hydrocarbon and transporting this product to shore, or converting the recovered methane to pure hydrate (methane free of sediment), storing it in zeppelin shaped storage tanks for subsequent towing to a shallow water infrastructure where the hydrates can be safely decomposed into water and gas in a controlled environment. Dr. Desa said that many scientists do not think that the pipeline idea is a good one because it would involve transportation across the continental slope that is sometimes unstable because of avalanches. On the conversion of methane to liquid hydrocarbon, Dr. Desa said that in this method the methane would be broken down to form carbon monoxide and hydrogen. Through the use of a catalyst, Dr. Desa said that these two chemicals could be converted to liquid hydrocarbon that is easy to transport. He noted that it is estimated that 35% of the energy contained in the methane would be utilized in the process.

On the matter of by products from the production of methane hydrates, Dr. Desa mentioned desalination, the sequestration of carbon dioxide, the separation of gasses and energy generation as possibilities. He said that by products are important because of the possible ancillary funding that they could provide, and also because of the perception of progress in the project being undertaken

Dr. Desa said that concerns that have been expressed about developing gas hydrates arise because these deposits represent a delicate balance between many facets of the environment. Among these, he mentioned pore water, sediments, fluids, the overlying water pressure and temperature. He identified the global climate and the geological environment as situations that could be adversely impacted by hydrate production. With regard to the global climate, Dr. Desa said that methane in hydrate form is about 3,000 times that found in the atmosphere, with a green house potential output of about 10. He said that during the last glaciation there was a fall of sea level. He also said that a reduction in the pressure at sea level leads to hydrates melting. According to Dr. Desa, as hydrates melt, faults are created in the deposits that lead to the release of methane into the atmosphere. When methane is released into the atmosphere, Dr. Desa said that it results not only in warming at high latitudes, but of the permafrost defrosting, the seas and shallow continental shelves of high latitude margins warming up and releasing hydrates. On the other hand, Dr. Desa said that the methane that is released into the atmosphere warms it up and causes the ice cap to melt. This generates more water and returns sea level to previous levels, thereby reinstituting the pressures on the hydrate deposits. He described the chain of events as a double take, stating that nature is so wonderful that starting off with methane that is released, the system warms up and causes the ice cap to melt, shutting down o the system. Dr. Desa pointed out the term used to describe the impact of the release of gas at low sea level is slumping. Dr. Desa described this impact on the geological environment as comprising the build-up of unstable sediments that then slump. He also said that the over-burial of hydrates causes other problems because the hydrates decompose to form water and gas, therefore creating a weak zone. Dr. Desa characterized weak zones as triggers for gravitational loading or earthquakes that could then cause further slumping, fluctuations in pressure and bottom water temperatures, and resulting in situ hydrates turning into methane gas.

With regard to the factors that have hindered and fostered research in India, Dr. Desa said that for the oil and gas companies, the amount of certainty required for them to invest funds in this endeavour has not been attained. Under the circumstances therefore, it is the Government of India that has to provide the funds for research and development. In this regard, an Oil Development Board Fund has been set up to fund research in this field. He said that the initial discovery in India came from looking at old records. He pointed out the assistance of the oil companies that is given by making their old records available to the Institute for analysis. He also pointed out that the deposits that have been identified are located on slopes, and are therefore not far away from major markets, suggesting that transportation costs should be reasonable. He noted the major improvements in drilling technologies, in particular the large cost reductions in drilling technologies in deep water, and that technology being used for normal hydrocarbon work can still be used for hydrate work as positive signs.

On the international scene, Dr. Desa said that the United States of America has an interest in developing methane hydrate deposits; that Japan is very active in this field and is presently drilling a deposit, and that the European Union has funded work on methane sensors and hydrate coring apparatuses. He said that the Russian Federation is engaged in a bilateral collaboration with India in hydrates development.

Dr. Desa concluded his presentation by pointing out that gas hydrate research is not just for geophysicists and geologists but also for the entire community of ocean, earth and atmospheric scientists. He said that a need exists to sharpen techniques for detection and assessment. He felt that after this, the oil industry could become actively engaged in methane hydrate development. He noted the need to negotiate the major environmental and geological hazards that have been identified, stating the importance of understanding the link between the hydrates, and the earth's climate. He recommended that a lot of strong climate research programmes should be funded so that some of the related questions could be answered. Finally, he said that a mechanism is needed to oversee preventive measures and possible hazards, to encourage proactive research and to assist in establishing predictive models business and a database through which information could be shared and disseminated.

SUMMARY OF THE DISCUSSIONS:

The discussions following Dr. Desa's presentation focussed on the potential environmental impacts arising from hydrates development, examples of BSRs that do not reveal the presence of hydrates, the glaciation cycle and the release of methane, and the intent of Dr. Desa's proposal in regard to an international mechanism to regulate research and exploration for methane hydrates.

With regard to the potential environmental impact of methane hydrate development, Dr. Desa was asked whether earthquakes could affect such development, in particular in the case of Japan that was described by a participant as being earthquake sensitive. Dr. Desa responded that if the hydrate deposits were to be found in an earthquake zone and an earthquake occurred, it would destabilize the deposits. He described the bigger problem as the possible release of methane into the atmosphere resulting from an earthquake. He also noted that he was not aware of any studies of natural earthquake zones and the location of hydrate deposits.

Another participant made the observation that the term slumping as used by Dr. Desa was a little euphemistic because there have been massive failures in some continental margins because of methane hydrates. This participant said that these failures led to the creation of tsunamis.

Yet another participant said that it has been estimated that a single methane eruption has the potential to change the composition of the earth's atmosphere in methane by four (4) per cent. This participant while noting the large amounts of carbon in hydrates spoke about the concerns of the Australian mining industry as they relate to carbon emissions. With regard to hydrate development this participant made the point that since it is the general public that would bear the associated social and economic costs, the information on the potential benefits and risks from developing these resources should be fully brought out.

While congratulating Dr. Desa on his statements on bottom simulating reflectors, it was stated by another participant that there are bottom simulating reflectors that are not associated with hydrates. This participant said that the very first BSR that was described by the US Geological Survey in the Bering Sea was not methane related. To this comment, Dr. Desa made the observation that in contrast hydrates could be found with no manifestation of BSR.

Another participant noting that Dr. Desa had mentioned glaciation as one of the effects of methane's release in the atmosphere said that since the glaciation cycle is roughly between 100 to 1000 years. This participant wanted to know why this cycle is not considerably reduced if this effect governed or controlled climate. Dr. Desa responded by stating that the methane released caused an abrupt change in the cycle.

With regard to stimulating research funds, one participant recalled that recent drilling by industry in offshore northwest Europe that was directed to looking at BSRs found silicate. This participant said that drilling was to ascertain potential risks in the area and not for the discovery of gas hydrates. This participant stated that this project illustrated how funds could be stimulated from industry for research.

It was recalled that in Dr. Desa's closing remarks, he had made a call for some kind of international mechanism to regulate research and exploration for methane hydrates. In this regard, he was asked how much work on hydrates had been conducted in international waters, and whether it would justify the international community to actually consider at this stage making plans to regulate research and exploration activities or whether that could fall within the realm of scientific research.

In his response, Dr. Desa said that he had no idea of any work that is being undertaken on hydrates in international waters. It was his belief that almost all work is being conducted in EEZs. He said that his proposal for a global regulatory mechanism is because of the potential dangers from mining this resource. He said that a set of mechanisms or safety procedures for drilling and associated activities would benefit all potential developers because once methane gas is released into the atmosphere control over it is lost.

CHAPTER 15

A CASE STUDY IN THE DEVELOPMENT OF THE NAMIBIAN OFFSHORE DIAMOND MINING INDUSTRY

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Diamonds were initially discovered in the main deflation basin of the Namib Desert in 1908. Subsequent discoveries located diamonds in the preserved paleovalleys of the Orange River and raised marine beaches. Complex interaction of high-energy fluvial, marine and aeolian sedimentary environments over at least the last 80 My[4] is responsible for the formation of the southern Namibian diamond deposits, representing part of the greatest placer concentration of high quality gem diamonds known on Earth.

The initial discovery of offshore diamonds in shallow (<30 m water) water on the Namibian continental shelf occurred during 1959 following the pioneering exploration work initiated by Sammy Collins, an entrepreneurial Texan marine contractor. The Marine Diamond Corporation (MDC) commenced shallow water production during 1962, and applied for the mineral rights to exploit deposits to the edge of the continental shelf (set at 200m isobath). Deeper-water diamond exploration commenced in 1972, after the cessation of shallow water mining operations by MDC in 1971. Following successful discovery of diamonds in water depths exceeding 70 m in the mid-1970's, Mineral Resource development continued until 1982 when the decision was taken to commence mining operations. A substantial period of test mining and development then ensued until 1990 when production officially produced 29 000cts. Today De Beers Marine produces in excess of 500 000cts for the Namibian Diamond Corporation (Pty) Ltd (NAMDEB). NAMDEB is an equal partnership between the Government of the Republic of Namibia and De Beers Centenary AG. The company is an important contributor to the Namibian Gross Domestic Product, and accounts for a significant amount of tax revenue in Namibia.

[4] Millions of years. The proper SI symbol is Ma.

Forty years of experience shows that effective exploration and mineral resource management will be fundamental in sustaining long-term development of the offshore mining industry, with success being critically linked to the communication of accurate mineral resource knowledge to engineers and metallurgists responsible for the design of new and improved systems. Given the highly variable rugged, challenging physical nature of both the deep- and shallow-water environments, mining system innovation will play a fundamental role into the future by maintaining profitability of offshore operations whilst ensuring that responsible mining practices are followed to the benefit of all stakeholders.

In addition to job and wealth creation, offshore diamond mining operations present valuable opportunities to develop new insights into the life and dynamics of the world's oceans to the benefit of the broader community with interests in marine resources, making this a most stimulating and rewarding mining environment to work in.

1 Regional Setting and Synopsis of Discovery

The onshore diamond deposits were discovered in the harsh, hyper-arid deflation basin of the Namib Desert in southern Namibia during 1908 by Zacharias Lewala, a railway labourer working near Luderitz for August Stauch. The marine beach deposits along the high-energy Namibian coastline were discovered by Werner Beetz in 1928, following discoveries in Namaqualand by Jack Carstens and Hans Merensky, to the south of the Orange River (Figure 1).

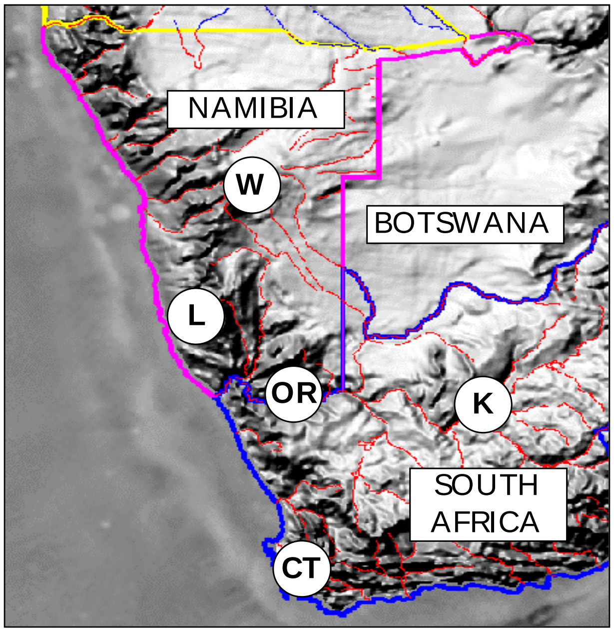

Figure 1. Locality map based on gravity data with extent of continental shelf visible. W=Windhoek, L = Luderitz, OR = Orange River, K = Kimberley and CT = Cape Town

The onshore marine beach deposits have been the main stay of Namibian diamond production since mining operations began in Oranjemund in 1929, although large-scale operations only commenced in 1943 after World War II. Continuous innovation in exploration to generate new mineral resources and mining to introduce new generation large-scale mining technology capable of extracting low-grade ore bodies has played a crucial role in optimising the life of the onshore operations through the application of responsible mining practices.

Samuel V Collins, an entrepreneurial Texan marine contractor involved in the installation of an offshore fuel line for CDM (Pty) Ltd., the precursor of NAMDEB [1], first ascertained the presence of offshore diamond deposits. Pioneering exploration by Collins successfully discovered diamonds with the "Emerson K" during 1959 in Wolf Bay near Luderitz.

Following indications that the shallow-water mineral resource was effectively depleted in the late 1960's (at least for the generation of mining technology available at that time) MDC ceased mining operations during 1971. The exploration focus then shifted to deeper-water on the Namibian continental shelf, with diamonds being discovered in water-depths exceeding 70 m during the mid-1970's. The present distribution of onshore and offshore mining and exploration licenses in southern Namibia is summarised in figure 2. Some exclusive prospecting licenses extend to 2000 mbsl.

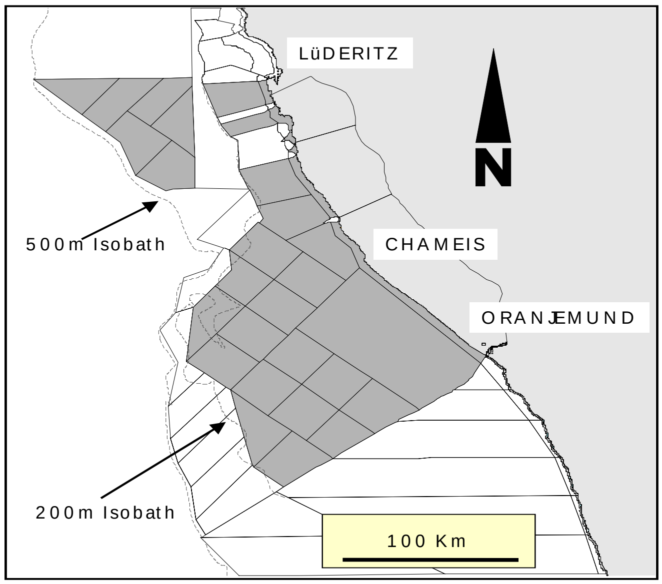

Figure 2. The extent of NAMDEB offshore mining and exploration licenses shown in grey.

2 Geology of the "West Coast" diamond deposits

2.1 Overview of regional-scale model

Namibia's diamonds are famous throughout the world for their high quality. This is the result of transport in some of the world's highest-energy sedimentary systems, which ruthlessly destroy fractured, lower-quality stones and concentrate a very high quality product in placers that occupy a number of different settings. To date, in excess of 100 million carats of diamonds have been recovered by mining operations, with the largest weighing 246 carats having been recovered during early onshore prospecting operations.

The Orange River, one of Africa's great rivers, has largely been responsible for the introduction of diamonds to the southwestern continental margin of Namibia. The erosion of kimberlite pipes within the interior of southern Africa has released large quantities of diamonds for transport to the continental margin, with the most recent pipes being intruded into the Kimberley region of the KaapVaal craton from 120 to 90 Ma[5]. Diamonds have also been derived through the erosion of older sedimentary sequences ranging in age from 2700 My (Archaean) to 70 My (Cretaceous) within southern Africa [2,3]. Since establishment in its current position some 80 Ma, the Orange River has supplied clastic sediment to the post-Gondwana continental margin, making a major contribution to the development of the continental shelf [4,5,6]. Changes in the base level of the system driven by eustatic and tectonic changes from the Orange River mouth upstream have promoted placer formation within onshore reaches of the palaeo-Orange system. At the same time this has presented opportunities for the river to supply coarse clastic gravel to the sub-aerially exposed continental shelf, with the result that the deposition of extensive fan-delta complexes have provided enormous quantities of material for subsequent shore faces to rework. Fluvial ore bodies are preserved within palaeo-valleys [7,8,9] that were operative from 19 to 17 Ma and 5 to 3 Ma [10,11,12,13]. Strong evidence also exists for diamond introduction during the Eocene (50 to 35 Ma) based upon the presence of diamondiferous palaeoshorelines up to 160 masl [14,15].

Repeated marine regression(s) and transgression(s) spanning some 60 My, which became more frequent during the Pleistocene (approximately the last 2.5 My), have been instrumental in the formation of both the onshore and offshore marine diamond deposits. In both instances, the destruction of the clastic beaches by arid zone processes has released diamonds for further transport – principally by the aggressive sand-laden southerly winds. Subsequently, river systems within the deflation basin have periodically reworked the aeolian placers [14,17,18]. Exoreic systems reintroduce the diamondiferous sediments onto the continental shelf, where reworking by long shore wave transport reconcentrated the diamonds in well-developed trap sites sculpted by nearshore and shore face processes into the Precambrian rocks flooring the inner continental shelf [18].

[5] Millions of years.

The combined interaction of the fluvial, marine and aeolian sedimentary environments together with arid zone weathering processes along the Namibian coastline essentially acts as an enormous "sediment transport conveyor" breaking down, recycling and transporting large volumes of sediment to the north (Figure 3) [19]. Ultimately, much of this material is incorporated into the coastal tract of the Namib Sand Sea where the initial diamond discovery was made, and diamonds were literally picked up from the desert floor in such quantities that Stauch is reputed to have carried on prospecting in the desert moonlight.

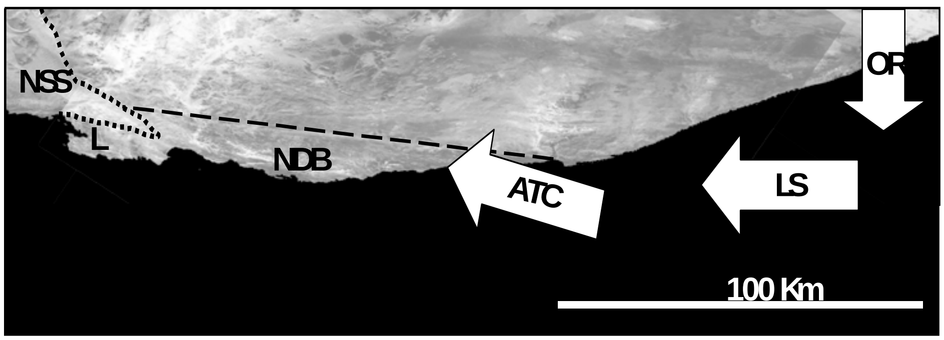

Figure 3. Principal elements of the "Sediment Transport Conveyor" produced by interaction of sedimentary environments. OR = Orange River, LS = long shore littoral transport, ATC = aeolian transport corridor(s) feeding the Namib Sand Sea (NSS) via the Namib Deflation Basin (NDB) which starts at Chameis, approximately 100 km north of Oranjemund. L= Luderitz

2.2 Physical character of the marine onshore and offshore diamond deposits

2.2.1 Onshore littoral systems and shallow-water ore bodies

The coastal marine deposits to the north of the Orange River form a wedge of predominantly coarse clastic gravels tapering to the north over 110 km in the prevailing direction of the long shore littoral current. Recently, sedimentological studies at NAMDEB have provided new insights into the spatial changes in the architecture of the littoral ore body (Figure 4). In the south, in the immediate vicinity of the Orange River, high-energy wave-dominated littoral processes have resulted in the formation of a large accretion coarse gravel barrier system some 4 km long and 0.5 km wide [20]. In contrast to the linear beaches further north, the barrier sequence directly overlies fluvial sediments of the palaeo-Orange River. The erosive contact is commonly identified by a low-angle, seaward-dipping surface on which cobbles and boulders (termed locally "water-melon gravel") form a transgressive gravel sheet. The internal geometry of the accreted barrier complex above this contact is complex, with gravel spit, sub-tidal, inter-tidal and back-barrier facies preserved. In the absence of Precambrian footwall, the processes of transport and deposition characterising the different facies have controlled diamond distribution and concentration.

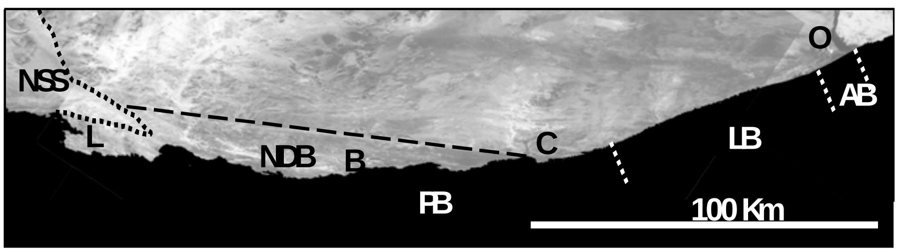

Figure 4. Spatial variability in littoral ore body architecture based on applied research by NAMDEB. AB = accretionary coarse gravel barrier complex, LB = linear beach complex, PB = pocket beach. O = Oranjemund, C = Chameis, B = Bogenfels, L = Luderitz.

The reduced supply of coarse gravel to the north of the accretionary barrier complex appears to have lead to the development of narrower linear beaches that are underlain by late Proterozoic bedrock. This predominantly schistose bedrock has been sculpted by the high-energy nearshore and shore face processes to form extensive wave-cut platforms with magnificent examples of large-scale gullies and potholes, some of which can be several metres deep (Figure 5). These features form stable (fixed) trap sites in which diamond concentration has taken place over substantial periods of time, significantly increasing the diamond grade with respect to those found in the accreted gravel barrier complex to the south. For this reason, the linear beaches have played an extremely important role as the main source of diamonds from mining operations at NAMDEB throughout the past sixty years.

Figure 5. Spectacular examples of gullies eroded into the late Proterozoic bedrock. The features present a considerable challenge for underwater mining systems

Detailed mapping by diver-geologists of Anglo American's Oceanographic Research Unit (ORU) in the late 1960's confirmed that the physical character of the marine diamond deposits on the inner continental shelf closely resemble the higher-grade linear and pocket beaches that are characteristic of the onshore marine beaches [21]. It was in this environment that Collins' initial discovery of offshore diamonds was made in 1959. Subsequently, both the early mining barges and the later shallow-water vessel-based remote and diver-assisted mining operations have concentrated on deposits of this type. Although extensive areas of overburden are known to occur offshore, particularly in the south due to the deposition of fine-grained sediments introduced by the Orange River, extensive areas are characterised by the absence of overburden [22] – much like polymetallic nodules [23].

2.2.2 Physical character of diamond deposits on the middle and outer Shelf

In contrast to the inner shelf, the footwall of the diamond deposits on the middle and outer continental shelf consists of both unconsolidated and cemented Cretaceous and tertiary sediments [24]. This fundamentally influences the physical character of the ore body and presents many new challenges to mining engineers and metallurgists as well as people involved in mineral resource management.

The deep-water ore body more closely resembles the accreted gravel barrier complex in broad terms due to the highly variable physical character, rather than the narrow linear beaches that are characterised by rugged fixed bedrock trap site morphology. Repeated regression(s) and transgression(s) across the middle to outer continental shelf has presented the high-energy shore face with numerous opportunities to erode, truncate and plane the Cretaceous and tertiary sequences preserved there within an "active erosive zone" spanning about 20 m depth at any one time (pers. comm. H Swart, 1986). Gravel deposits presented to the high-energy shore face conditions are comprehensively reworked under these conditions to produce a complex, super-condensed, coarse gravel lag containing large intraclasts (metres in diameter) of shelf sedimentary rocks plus quartzite-dominated terrigeneous cobble gravels supplied principally by the Orange River.

Although fixed footwall trap sites do occur, they are probably more rapidly destroyed by shore face reworking during regression(s) than the more competent features eroded in the late Proterozoic bedrock of the inner shelf. Diamond distribution and concentration is therefore likely to be more controlled by sedimentary processes than fixed trap sites in this environment. Hence the deeper-water deposits are generally less patchy and exhibit greater continuity compared to the onshore linear and pocket beach environments, but they are characterised by lower grades. These observations have proved to have important implications for exploration and mineral resource management.

3. Deep-water mineral resource management

Given that the deep-water offshore mining industry is comparatively new, and the ore body is both remote, complex and highly variable in character, the development of the approach to mineral resource management forms part of a continuous learning process that guides many aspects of De Beers Marine's (DBM's) applied research and development aimed at delivering an appropriate level of mineral resource knowledge to support all of the associated activities required to: -

- Sustain immediate production requirements;
- Develop DBM's long-term future;
- Effectively mitigate both technical and financial risk.

With continued experience, it is clear that the geological model of an ore body provides the fundamental platform for all subsequent development; hence the quality of the model is critical. If the resolution of the model is too low, the information incomplete, or the interpretation on which it is based is flawed, it could have disastrous consequences for subsequent production planning and/or engineering design projects, with serious financial implications.

The development of mineral resources and their transformation to reserves is a complex process involving many variables (Figure 6). This process therefore requires widespread collaboration across many different functions to deliver optimised mine plans to achieve required and acceptable levels of profitability and to ensure that the mineral resource is depleted in a responsible manner in accordance with legislative requirements.

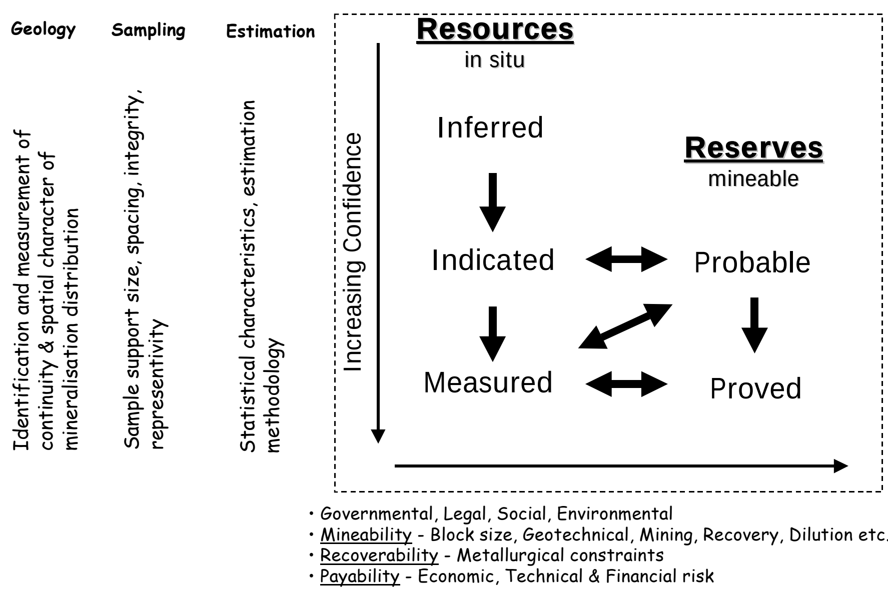

Figure 6. The critical path used for mineral resource to mineral reserve transformation by De Beers based on SAMREC.

4. The mineral resource management cycle

Based on experience gained during 10 years of large-scale deep-water mining operations, De Beers Marine continuously reviews and develops its approach to holistic mineral resource management, which spans the spectrum of requirements from conceptual exploration to post-mining depletion and reconciliation (Figure 7).

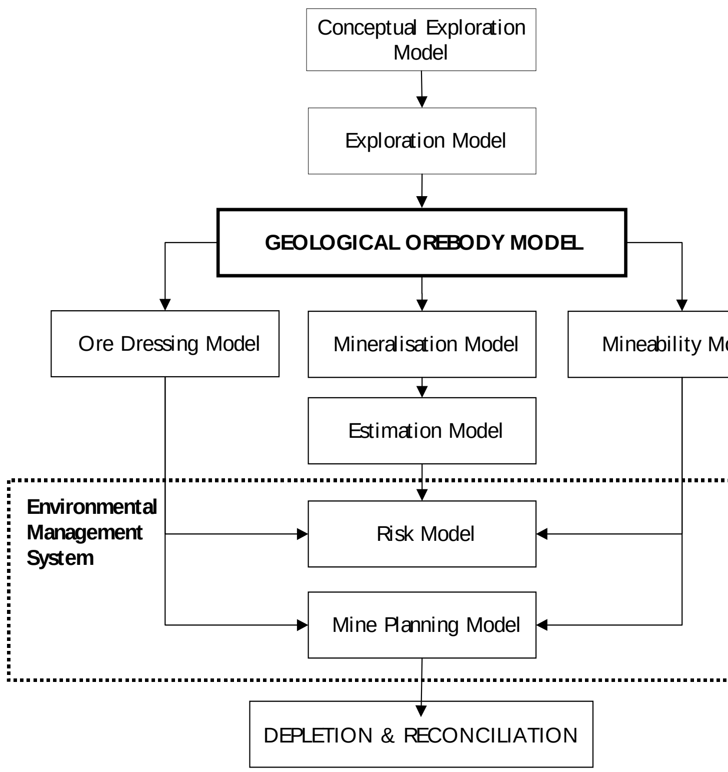

Figure 7. The Mineral Resource Management Cycle.

In terms of the mineral resource management cycle, estimation of west coast placer deposits has proved to be complex due to the size and continuity displayed by the discrete trap sites. The importance placed upon accurate mineral resource evaluation has driven geostatistical research since the early 1970's, and it continues to receive significant attention. In-house specialists in collaboration with Fonteinbleu School of Mines have developed many new techniques. The application of linear programming to mine planning, which also becomes complex due to the multiplicity of variables is also an area of active research. Both optimisation of depletion strategy and mine planning are fundamental to ensuring profitability, and their effectiveness depend heavily upon the accuracy of estimation.

5. The significance of the geological model and research and development aimed at improving model resolution

The power of the geological model in mitigating technical and financial risk was identified early in the development of the offshore diamond mining industry. Consequently, seafloor mapping has been a focus of activity from the outset both in terms of developing technology and interpretative expertise of people to specifically support the development of the offshore diamond minerals industry.

In 1964, De Beers contracted Ocean Science and Engineering to undertake a comprehensive evaluation of the shallow-water prospective ness between the Olifants River and Meob Bay. This was the first seismic and sampling programme of its kind to be undertaken and based on the results; De Beers exercised its option to become a majority shareholder in Marine Diamond Corporation (MDC) in 1965. Anglo American's Oceanographic Research Unit (ORU) founded in 1965 immediately began a programme of applied diver-based research to map the nearshore marine deposits in detail. This programme did much to develop the expertise of the team involved through direct observation. Subsequently however, the need to map areas more rapidly to support mining operations lead to visual observation being superseded by the application of sidescan sonar (the first applied marine geophysics to support offshore diamond exploration and mining) and later seismic.

There has been a continuous improvement in technologies employed in seafloor mapping since the mid-1960s when the third sidescan sonar unit produced by Klein was introduced to map shallow-water deposits. De Beers Marine and the Institute of Maritime Technology in Simonstown developed the first Chirp seismic acquisition system in 1990 for use in high-resolution seafloor mapping to support offshore diamond mining to replace the previous use of Sparker technology. This system consistently delivers 10 to 15 cm vertical resolution and is deployed on a MacArtney FOCUS 400™ ROTV platform that is operated from DBM's specialist survey vessel "Zealous". This system has been used to acquire datasets at 12.5 m line spacing and a technical team is currently evaluating a 3-D airgun dataset that is reputed to be one of the highest resolution datasets ever acquired. Research projects are also investigating alternative acquisition technologies for use in areas where gas-charged sediment cover prevents the use of conventional survey techniques.

Following the completion of full open ocean sea trials using Zealous during 1999 DBM plans to implement survey acquisition using a fully Autonomous Underwater Vehicle (AUV) based acquisition system in late 2000 in collaboration with MARIDAN, a Danish company. This initiative will be the first off its kind in underwater mining. Although this has obvious implications for reducing geophysical acquisition costs, the primary motivation is to significantly improve the quality of data acquisition and survey resolution. This will further increase the definition of ore body models for mineral resource evaluation, production planning and mining system design.

Despite the extensive use of Remotely Operated Vehicles (ROV) fitted with still and video camera technology, the ability to develop a true understanding of the seafloor characteristics was proving to be elusive in the deep-water, beyond the reach of conventional diving. In part, this resulted from the relatively narrow field of view presented by ROV mounted systems flying close to the seafloor, which makes it difficult to contextualise the image with the surrounding geology and topography. This can introduce and/or accentuate technical risk if inaccurate knowledge transfer results about the nature of the seafloor environment and ore body character between geologists, mining engineers, metallurgists and the ship-based operators of the seafloor-based mining systems. It can also negatively impact the safety of an operation in areas with rugged and highly variable seafloor topography and result in expensive operational downtime through damage to equipment. For these reasons, the implementation of advanced survey acquisition technologies by De Beers Marine has been complemented by a commitment to improve the interpretative capability of the team responsible for the creation of geological ore body models and the specialists with whom they interact on an operational and/or project basis.

One of the primary applications of the geological model is to aid in the process to cost-effectively produce estimates of the spatial variability of diamond grade at an appropriate level of confidence to both secure funding for projects and manage the technical risk associated with meeting future production demand. The following statement by King (1982) containing great vision, " If one could achieve a complete three dimensional interpretation of the internal features of an ore deposit, ore reserve estimation in situ would be a straightforward calculation" prompted DBM to investigate the possibility of utilising manned submersibles for direct seafloor observation. This dream became a reality during 1996, when De Beers Marine formed an alliance with Professor Hans Fricke and the team responsible for the operation of the Jago submersible. Subsequently, Jago has been operated extensively from Zealous. With some 163 dives to date, this makes the southern continental shelf of Namibia one of the most intensively studied submersible dive sites in the world. The highly accurate underwater positioning systems aboard Zealous permit dives to be pre-planned in considerable detail (Figure 8) to optimise time utilisation. It also allows Karen Hissmann to note when geologists become so engrossed in their studies that time "stands still" together with the Jago – a frequent situation given the fascinating nature of the work.

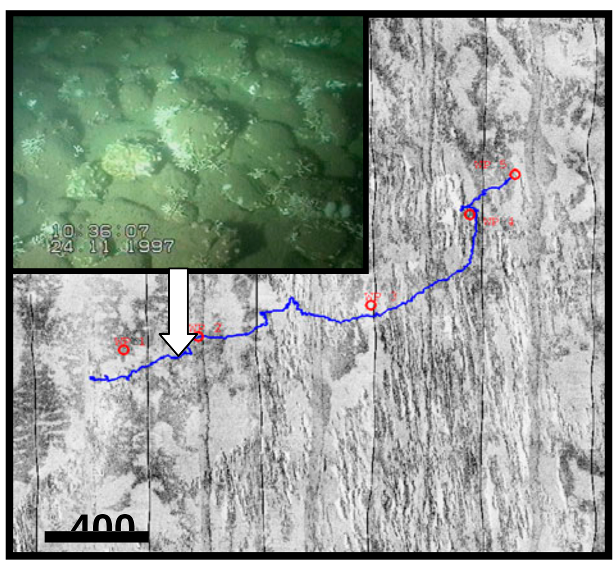

Figure 8. Jago flight plan showing the waypoints plus the actual dive track. The picture shows quartzite cobble gravel that forms part of an ore body associated with the early Pleistocene palaeo-Orange River fan delta.

Utilising Jago has made very detailed, focused observation possible, and allows specific aspects regarding the nature of sidescan sonar and Chirp response to differing sediment textures to be examined. This allows project geologists to produce extremely detailed acoustic facies maps with very high-resolution interpretation of the variable ore body character verified through observations. This has proved to be of considerable value to design teams responsible for the development of new mining systems and it is also important for people involved in mine planning to optimise depletion of ore bodies through appropriate selection of mining tools and recovery systems to meet specific physical conditions. This is a particular challenge that will face any deep ocean mining venture of the future.

The observations also make it possible to improve the understanding of factors controlling the deposition and concentration of diamonds to improve models explaining the distribution of mineralisation on the seafloor. This contributes to determining how advanced geostatistical techniques to estimate grade variation and/or computationally simulate deposits need to be developed and improved. Both of these aspects can make a considerable contribution to lowering the cost of mineral resource delivery by reducing the need for sampling in deep-water offshore environments, which is an expensive but essential element in maintaining offshore diamond production.

Exploration and evaluation sampling and grade estimation

As already commented, offshore sampling operations are expensive, and it is therefore important to optimise the design of programmes. The high spatial variability of offshore diamond ore bodies, coupled with the robust nature of the coarse gravels, presents a considerable challenge for sampling systems. Considerable up front geological knowledge is required to ensure that sampling system designs are appropriate for the conditions in which they will operate. The accuracy and resolution of a geological model developed for a specific ore body plays a critical role in determining the spacing and orientation of a sampling grid required to produce results at the desired confidence level with a specific sample size. Given that the behaviour of sampling tools in different ore body conditions will vary, influencing the overall efficiency of the tool and thus the integrity of the results, this is an important aspect that also has to be well understood.

The requirements for sampling to locate mineralisation differ considerably from the rigorous requirements associated with sampling to produce mineral resources in the inferred and indicated levels of confidence, with the latter being a prerequisite for transformation to mineral reserve (see Figure 6 above). The demands placed upon the sampling systems also changes considerably depending upon the nature of the footwall being sampled. For example, hard bedrock and clay footwalls present radically different problems for sampling tools and recovery plants to deal with.

Due to the scale of the operations DBM manages for its clients, the company operates two vessels with sampling capabilities. The Douglas Bay equipped with a "mega drill" has, and continues to play an important role in developing offshore mineral resources. However, in order to overcome some of the challenges presented by the rugged ore body and footwall conditions that have to be sampled on the Namibian shelf to confidently deliver indicated resources, the Coral Sea has been equipped with a large-bore "decadrill" system. Based on direct observation of Coral Sea sampling holes utilising the Jago submersible, this system has proved to be capable of sampling very rugged terrain indeed.

Considerable ongoing applied research and development is focused upon both improving existing sampling tools and designing completely new sampling systems to further improve the confidence of results, increase productivity and allow new types of ore body to be sampled. In addition, a philosophy of continuous improvement is also followed in terms of the recovery plants aboard the company's fleet. Very high levels of security also protect the diamond product, which is not touched by hand from the moment it is sampled/mined to the time it is delivered to the client.

Given the long history of involvement De Beers has with the "West Coast" environment, considerable geostatistical research has been undertaken. Much of this work is ongoing as geological models; sampling and mining technologies continue to evolve. In addition, with the expansion of the mining fleet a lot of research is focused on optimising mine planning – a very complex area due to the multivariate nature of the data input required. This is very computationally intensive and demanding, even for linear programming to resolve.

Although at first glance the nature of diamond deposits appears quite different to polymetallic nodules and crusts, they are likely to bear many similarities in terms of mineral resource management. This indicates that the development of mineral resources for transformation to reserves could be an important aspect for companies to address if funding is to be secured. Currently, data available about deep-sea mineral deposits might only permit estimation of resources at an inferred level of confidence in general. Substantial research may be required to determine how variable the grade and metal content of these deposits might be in a spatial context at a level of resolution suitable for indicated mineral resource category. This could imply that considerable expenditure will be required for mineral resource development to properly establish a producing mining industry with manageable financial risk.

Experience in the deep-water diamond industry has shown that effective and efficient sampling to establish mineral resources for transformation into reserves is a critical success factor. The ability to cost-effectively sample deep-ocean polymetallic nodule and Ferro-manganese crusts in a manner suitable for mineral resource estimation will impact on the financial viability of future mining operations in terms of cost. Depending upon the variability of parameters, the confidence level of the results will determine the ability to manage technical and financial risk effectively whilst delivering an acceptable return on investment through optimisation of depletion strategy.

Mining system development

Ten years on from the initiation of large-scale offshore deep-water diamond production, DBM is intensively focused on the development of new and improved mining systems. This trend is not unusual in the mining industry - it has been a characteristic throughout the entire history of NAMDEB, which now spans almost 100 years. This type of continuous innovation has been an essential factor in enabling the company to responsibly mine the mineral resources on the West Coast of Namibia by maximising the profitable extraction of both high and low grade deposits. A similar trend is likely to characterise future development of the offshore mining industry.

Early shallow-water mining systems

The early shallow-water mining barges utilised “digging head” technology that was suspended from a gantry (Figure 9). Later systems had the capacity to systematically move the “Traversing Digging Head” across the deposit by utilising anchor wires, thereby increasing productivity by increasing the mining rate. The systems currently in use in the shallower water operations on behalf of NAMDEB essentially represent more efficient forms of this early technology. However, despite the relative ease of access in overburden-free areas, the efficiency and rate of coverage that the mining systems are able to achieve makes profitable exploitation of lower-grade deposits a difficult challenge to meet due to the extremely rugged bedrock morphology, which is difficult to clean effectively. Working so close to shore with large vessels can also be hazardous, as early MDC barge operations demonstrate. NAMDEB is currently developing a major project aimed at increasing production from this rugged, high-energy ultra-shallow water zone that perhaps represents the last diamond frontier on Namibia’s Atlantic coast.

Figure 9. An example of one of the earliest shallow-water barge mining systems.

Applied research and development by NAMDEB has enabled the introduction of new, onshore large-scale mining technologies to support innovative mining methodologies that allow safe access to the lower-grade deposits within the nearshore zone using conventional mining systems to optimise extraction. This approach permits NAMDEB to responsibly mine extensive areas of the nearshore to water depths of between 15 to 20 mbsl by building seawalls made from stripped overburden sands. Initially, the use of bucket-wheel excavators made it possible to increase stripping rates to levels capable of sustaining seawalls from the relentless Atlantic coast. More recently, the introduction of dredging technology for overburden stripping has proved very effective in sustaining seawall development whilst adding a new dimension to these operations through the treatment of very low-grade suspended gravel lenses within the overburden that could not be mined profitably using conventional methods.

Such cycles of process and technology innovation characterise many different aspects of the mining industry throughout the world. There is no doubt that the future of the offshore diamond mining industry will also be dependent upon similar progress being sustained. This will require the commitment of significant financial resources as well as the development of specialised intellectual capital. A similar scenario can also be envisaged for deep ocean mining operations, with important implications for teams involved in mineral resource development and the process of resource/reserve transformation.

Deep-water diamond mining systems

Already in the ten years of large-scale mining there has been considerable development in mining technology, and there has been a clear progression from the early pioneering attempts to make the transformation from exploration to full production. The De Beers board recognised that this change would require a major commitment of financial and technical resources in the early 1980's. As a result, DBM purchased and converted a vessel to specifically act as a platform for mining system development, the "Louis Murray" named in honour of one of Anglo American's consulting geologists who was tragically killed in an aircraft accident. This vessel was used to test many systems before it was brought into full-scale production using a track-mounted seafloor "crawler" at considerable cost to De Beers.

Improved knowledge about the physical nature of the deep-water diamond deposits and insight into the variable way in which any one mining system interacts with different types of ore body and seafloor terrain make it clear that no one mining system will be effective and efficient across the spectrum of conditions that exist. Realisation of this led DBM to examine non-crawler-based mining systems in the late 1980's leading to the purchase of the first drill ship for conversion to a mining system in 1989. Following a number of modifications throughout 1990, the success of the Coral Sea as a production facility from April 1991 resulted in the rapid expansion of the drill ship component of the mining fleet, which now consists of four vessels. Today, the mining fleet is comprised of two elements (Figure 10), with crawler-based mining ("horizontal attack") systems and drill ship-based systems ("vertical attack").

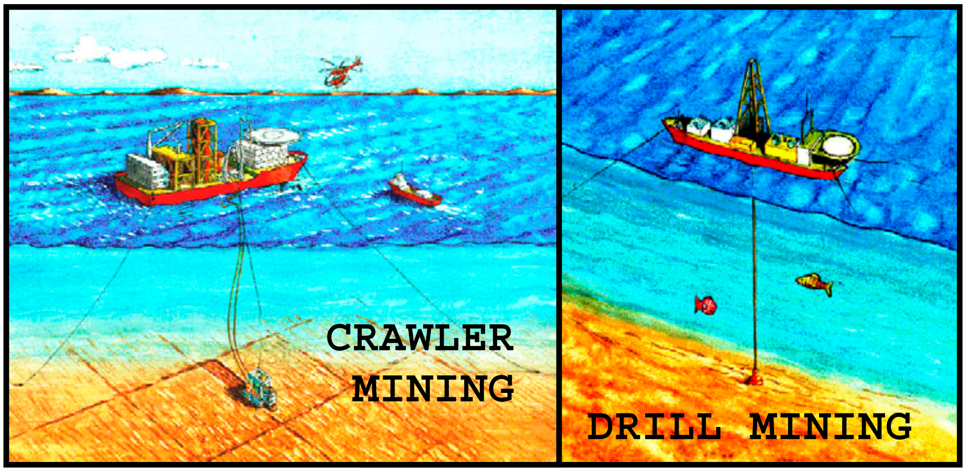

Figure 10. Schematic illustration of the two approaches used for deep-water diamond mining by De Beers Marine depending upon the nature of ground conditions.

Experience has shown that the vertical attack systems, which consist of large-bore drill bits several metres in diameter are ideally suited to mining in more rugged terrain, where the ore body is commonly very coarse due to the incorporation of large slabs of Cretaceous and Tertiary shelf sandstones and claystone. Crawler-based systems have been found to be better suited to areas in which the ore body predominantly consists of quartzite cobbles and the presence of large slabby clasts is less common. Such conditions lend themselves to "continuous mining", which enables systems to operate profitably in lower-grade deposits. However, this results in the need to transport and treat higher-volumes of material, which introduces challenges of a different nature for system designers because vessels have finite power and space available on which to fit the footprint of treatment plants. DBM therefore undertakes a considerable amount of research to identify innovative metallurgical solutions to allow plant capacity to be increased and recovery costs to be lowered without loss of recovery efficiency. In the marine environment this specifically means overcoming the difficulties created by large volumes of clay and shell, issues that DBM has made considerable progress in overcoming.

In accordance with De Beers' overall asset management philosophy, continuous productivity improvement is an important focus of teams involved in offshore operations. In addition to research and development to enhance the actual performance of mining tools, a stringent approach to asset management has been specifically developed for the marine operations. The aim of this programme is to maximise time utilised in physically mining. The objective is to safely operate the mining systems in the operational areas for periods of two years (or more) between downtime for scheduled in-port maintenance, with refuelling performed at sea to further reduce time off station. Currently, the Debmar Pacific with 1027 days holds the record for a vessel remaining at sea. Engineering availability for the drill ship fleet was 93% for 1999, having been maintained at 88% in the two preceding years. Approximately 78 to 79% of time at sea is spent with the mining tool engaged in full operational mining mode. This high performance level has been achieved through the focused application of engineering expertise to devise effective planned maintenance. Innovation during introduction of successive drill ships has also enhanced performance by enabling safe mining operation in swells of around 6 m (a reasonably common occurrence on this high-energy coast) in order to minimise downtime due to adverse weather. The NOSA Sea Safe audit team rates the entire DBM fleet of vessels annually, and all vessels have been awarded the top 5 star rating.

Approximately 120 Namibians are currently employed by DBM. Most of these work at sea on the production vessels. Given the size and power consumption of the vessels used for deep-water mining, the training period for deck and engineering officers is extensive. DBM vessels are flagged in South Africa and they are operated according to the legal requirements of the Department of Transport. In addition to the course work involved, it takes approximately 11 years for a person leaving school to qualify for a Master's certificate. DBM has numerous capacity building initiatives underway in Namibia. These include programmes to improve maths and science education at school level to produce a larger talent pool for development. This is one of a number of strategies aligned to the company's long-term outlook for the offshore mining industry in Namibia.

DBM is also actively involved in promoting technical development in the natural sciences to produce students with appropriate qualifications to become involved in Engineering, Mineral resource management and

Environmental management. Some examples of these initiatives are discussed in part II of this case study.

New challenges for mineral resource management

Mineral resource management is striving to innovatively meet the many challenges presented by offshore diamond exploration and mining. With continued experience and more in-depth knowledge about the behaviour of mining systems in different types of ore bodies, mining engineers, design engineers and metallurgists are able to request more specific, quantitative data to aid them in their quest to support the future development of the industry.

The accuracy of the geological model is proving to be an important aspect in the testing of new mining systems, which places significant emphasis on the geotechnical characterisation of the ore body to allow mineability to be accurately predicted ahead of mining. Detailed information of this type is also fundamentally important for ore dressing studies to allow treatment and recovery plant design to be optimised to meet the demanding conditions presented by the offshore mining environment. Consequently, geologists are becoming increasingly involved in the reconstruction of seafloor conditions for full-scale and model testing of mining system prototypes and concepts. This is proving to be both challenging and stimulating, as it adds another dimension to the work being addressed by mineral resource management teams. It also emphasises the criticality of mineral resource management to the future development of the offshore mining industry. With these stringent requirements for accurate information, the development of geological and associated models required by colleagues in many different functions is being transformed into a process of continuous learning, with new insights being provided almost on a daily basis. There is little doubt that the move to increasingly quantitative ore body models will bring with it new challenges, both in terms of the technology available to acquire the correct data and in terms of the ability to interpret this data correctly for the design and testing of advanced mining and recovery systems.

These demands are unlikely to be met without open collaboration across entire multi-disciplinary teams involved in projects aided by high-quality feedback from operationally based staff directly involved in the mining process. Such feedback loops are essential for continuous learning and the long-term development of the offshore diamond mining industry, which is still in its infancy.

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SUMMARY OF PRESENTATION AND DISCUSSIONS ON A CASE STUDY IN THE DEVELOPMENT OF THE NAMIBIAN OFFSHORE DIAMOND MINING INDUSTRY

Presentation

Dr. Ian Corbett, Group Mineral Resources Manager of De Beers Placer Resources thanked Ms. Inge Zaamwani, Managing Director of NAMDEB Diamond Corporation of Namibia and a member of the Authority's Legal and Technical Commission for initiating his presence at the workshop, and the International Seabed Authority for inviting him. He informed participants that in addition to this presentation, that is to provide an insight into the development of a now real and established offshore mining industry focused on diamonds, his second presentation would be on the steps that have been taken to minimize the impact of offshore diamond mining on the marine environment and the rich and viable fishery industry that it exists alongside this industry off the Southern coast of Africa.

Dr. Corbett started his presentation that focused on the forty years of diamond mining off the Southern African coast of Namibia and possible applications from this experience to deep seabed massive sulphides and crusts deposit mining by pointing out that an earlier statement made by Mr. Julian Malnic about the way in which the mining industry has evolved and its outlook over the last few years in terms of the environment is also true for De Beers and the offshore diamond mining industry. He emphasized the statement's significance in the case of De Beers, stating that for De Beers mitigating the environmental impacts from mining is placed first, and profitability is placed second. From a corporate point of view, Dr. Corbett said that it meant that the environmental impact of mining is minimized to acceptable levels that are established in consultation with stakeholders. Dr. Corbett said that his presentation would begin with a bit of background about the Namibian diamond industry, the origins of the diamond deposits, how they were formed and how the industry has developed during the past forty years. He informed participants that there are some fundamental differences in the operating environments of diamond deposits, and of seafloor sulphides and ferromanganese crusts deposits. He pointed out that the primary purpose of De Beers and its associated companies is very clear and that is to recover diamonds. He also said that while his presentation would be based primarily on the approach of De Beers, it would focus on two companies; NAMDEB, a joint company between the Government of Namibia and De Beers, and De Beers Marine.

Dr. Corbett said that diamonds were discovered in Namibia in 1908, in the deflation basin of the Namib Desert by a railway worker who was living near Luderitz. Dr. Corbett described the location as a very hostile, an aggressive windswept environment. He said that when the deposits were discovered, people were able to crawl across the desert floor and pick up diamonds, and that he had the opportunity to do that in the early morning sunlight. With the use of slides, Dr. Corbett showed the area and its proximity to the Orange River, Cape Town and Windhoek (Figure 1). He said that after the initial discovery, diamonds were then discovered in Clancy on the Buffels River, then in 1926 in Alexander Bay by Hans Merensky, and subsequently in 1928 to the north of the Orange River by Werner Beetz.

Dr Corbett provided participants with information on how the offshore diamond deposits were formed. He said that kimberlites are present in the interior of southern Africa, in both South Africa and Botswana, but that the principle source for many of the diamonds that were delivered to the west coast are the kimberlites that were intruded between 120 and 80 million years ago. Following erosion in the interior of these kimberlite pipes, Dr. Corbett said that the diamonds were transported westward by the palaeo Orange River. He pointed out that this very large river system has been in existence for at least 65 to 80 million years. Subsequently, Dr. Corbett said that once the diamonds were introduced to the continental margin, on one of the highest energy coastlines in the world, Dr. Corbett said that they were reworked by long shore processes, predominantly north bound long shore transport and in the process, the diamonds were deposited in onshore beach complexes which extend over hundreds of kilometres. Dr. Corbett said that during regressions, of which there have been many since the Gondwana break-up and the formation of the Atlantic Ocean, the Orange River had been able to transport diamonds further west beyond the present day coastline right down on to the middle continental shelf of Namibia. He also said that in the process, the Orange River deposited a fan delta or a very large fan shaped body of extremely coarse clastic material containing diamonds. Dr. Corbett said that this fan shaped body of material was extensively eroded during regression and transgression. Dr. Corbett informed participants that as a result of erosion, this high-energy shore face has moved in a northerly direction on the continental shelf reworking and retransporting the diamonds. He said that in many cases, during the regressions and transgressions, arid-zone processes have operated because the coastline is an extremely high-energy wind environment that supports the Namib Desert. According to Dr. Corbett, diamonds were transported by these winds back up the palaeo slope, across the continental shelf, and on shore into the deflation basin of the Namib Desert. Dr. Corbett said that some of the deposits to be found here are actively being mined at Elizabeth Bay by NAMDEB.

With slides, Dr. Corbett showed participants the deposit at Elizabeth Bay. He described the environment as exceptional, from both a scientific and a diamond quality point of view. He said that the deposit is to be found under 126 metres of seawater in a high energy environment has essentially destroyed any diamonds that were flawed in any way. He described the quality of the Namibian diamonds as absolutely extraordinary, higher than 95 percent of high quality gems. He said that from this deposit, the science behind how placers are formed not only in fluvial environments but also in aeolian and marine environments could be determined. He said that through the work of De Beers Marine (DBM) and NAMDEB in shallow waters, the science behind these offshore deposits have been studied in some detail.

In this regard, Dr. Corbett identified some of the many opportunities for scientific interaction between industry and academia. He said that these included work on the paleontological side. As an example, Dr. Corbett revealed that the Orange River is the southern-most example of Miocene bearing, vertebrate faunas in southern Africa containing fantastic deposits for research on vertebrate palaeontology. He informed participants that a French team from the Musee de Paris is currently undertaking vertebrate paleontological work. Dr. Corbett said that De Beers and NAMDEB have built up an extremely detailed knowledge of diamond introduction, transport and concentration in a wide variety of different placer environments that have operated over 50 million years on this remarkable stretch of coastline. On the onshore side, Dr. Corbett pointed out that the deposits have now been mined for almost a century because there has been continuous innovation and improvement of diamond extraction technology, with new types of systems being introduced periodically. Through slides, Dr. Corbett showed examples of dredge technology that has been introduced, and sea walls that have been built so that normal mining practices are able to systematically mine 20 metres below sea level along large stretches of the Namibian coastline. Dr. Corbett stated that innovation has been the key, pointing to innovation as the common thread between onshore and offshore mining operations.

With regard to the terminology that De Beers and NAMDEB utilized to describe operations on the coast, Dr. Corbett said that ultra shallow water means operations conducted between the high water mark on the present day beach out to 15 metres of water depth; shallow water means operations conducted from a water depth of 15 to 30 metres; mid-water means operations conducted between 30 metres to about 70 metres water depth, at about which the shelf break from the inner shelf to the middle shelf of Namibia occurs, and deep water means operations conducted between 200 metres and 500 metres depth. Dr. Corbett described the mid-water depth as an extremely rugged area, containing gullies that could be several metres deep (Figure 5).

Once more through slides, Dr. Corbett showed participants the geographic locations of some of NAMDEB's prospecting licenses. These included the Atlantic 1 mining licence, and other areas for which it had obtained exclusive offshore prospecting licences (Figure 2). He informed participants that some of the prospecting licenses extend approximately to 200 metres water depth at the edge of the continental shelf and that their deepwater exclusive prospecting licences extend from 200 metres to 500 metres water depth. Dr. Corbett said that other companies hold deepwater licences in the south in particular, that extend to 2,000 metres of water depth.

Dr. Corbett emphasized that the key to offshore diamond discovery in Namibia came with entrepreneurial spirit, through Sammy Collins, a Texan entrepreneur who was involved in Namibian contract to lay a fuel pipeline to allow diesel to be brought in by offshore tankers to CDM. Making the point that the tankers are still the largest privately owned earthmoving fleet in the world, Dr. Corbett said that according to folklore, it is reported that as Sammy Collins stood on the beach one day he said, "Well, if there are diamonds here, why aren't they there?" Dr. Corbett said that " why aren't they there" was a question that not many people had asked and at the time conventional wisdom said diamonds would not be found there. In 1961, Dr. Corbett said that Sammy Collins formed the Marine Diamond Corporation, and initiated the offshore diamond mining business. Dr. Corbett told participants that Sammy Collins placed a converted tug in the shallow water that he described as a very primitive system, with a steel digging head, an airlift, and a trommel to recover the diamonds. Dr. Corbett stated that he was of the opinion that this was reconnaissance level work, where an interested party questions whether any minerals could be found at a location. Following this event, Dr. Corbett said that very quickly, divers were sent in the water to study the situation in more detail. He described this stage as similar to what is currently going on in the deep seabed.

Continuing his narrative on the evolution of the industry, in particular practices related to the identification of the resource, Dr. Corbett said that it was quickly recognized that a lot of innovation would be required in mining these deposits because of the rugged and high-energy environment in which they occurred. He said that while digging remained as the option for mining, the systems got larger and the processing plants became more sophisticated. He said that from those early beginnings came the expansion of the fleet, and barges were used as totally contained systems that enabled an operator to have the full extraction and treatment plant on board (Figure 9). He described as a significant move the use of media separation plants, non-chemical plants involving the introduction of ferrosilicon into a cyclone which allows a dense media to be created with light material floating and heavy material sinking.

He also said that at the same time, it became very apparent that mineral resource knowledge was going to be key to the sustainability of an offshore operation. He pointed out that without detailed knowledge of where the resource is to be found, planning could not take place and a mining operation could not be sustained. Dr. Corbett showed participants a slide containing a photograph of the first geophysical vessel to operate in the waters of the west coast. He said that after the introduction of this vessel all offshore diamond operations have been utilizing cutting edge high-resolution geophysics.

Dr. Corbett pointed out that the mining methods changed as well, and although the digging heads were still used, they became far more sophisticated in their deployment and it was possible to traverse across the seafloor over significant areas with them, thereby increasing the rate of coverage and the profitability of mining operations. Dr. Corbett summarized his account of what happened by informing participants that by the late 1960s it became apparent that the industry was going to be a very technologically dependent industry, driven by a capacity to locate and deliver new reserves. He stressed that reserves are that portion of the mineral resource that you can extract profitably with a known mining system. He pointed out that as long as the deposit is a resource, it is just money in the ground and not money in a bank account. He said that not having made a profit out of any deposit was a key learning experience from the early days going through into the late 1960s. Dr. Corbett said that by the end of the 1960s, the initial production fleet was phased out largely because the technology was unable to deliver at lower grades and had limited capacity to deliver new reserves. He noted however, that over a million carats of diamonds were produced between 1963 and 1971 from an embayment called Chameis. He said that at this location, one barge was able to produce 250,000 carats in a year, a performance that he characterized as a stunning, given the kind of technologies that were being used at the time.

Dr. Corbett illustrated some diving operations through slides that NAMDEB had contracted out to divers in the difficult environment of the shallow water deposits. He explained that the deposits occur in very well defined trap sites carved into the pre-Cambrian rocks that form the coastline and extend off into the shallow water He said that typically these deposits are extremely well packed so that it might take a day to take out a relatively small area working with a crowbar as part of the diving operation. Dr. Corbett said that the divers operate with pipes attached to pumps that are vessel based or shore based. He said that one could operate either off the shore going directly out from beaches into the gully system, or using small boats that have a very rudimentary trommel system to screen off the oversize rocks, bag the gravel and take that onshore for treatment

With regard to the transition that has been made from the time of Sammy Collins to where the industry is today, Dr. Corbett described the era of pioneering deepwater diamonds exploration as beginning at the end of the 1970s when geologists were born optimists, with those that worked for De Beers and NAMDEB believing that diamonds would be found in deeper waters. He said that starting with trying to determine whether diamonds could occur in deep water resulted in an offshore concession of about 30,000 square kilometres on the Namibian continental shelf, and deepwater licences that extend down to the upper part of the slope. He informed participants that this was a shift from working in effectively 35 metres to 200 metres of water depth. Stating that this was no small technological step, Dr. Corbett suggested that the shift from 200 metres to 2,000 metres of water, a big jump for a production unit, would similarly be a significant technological step.

In relation to the initial stages of exploration, Dr. Corbett said that it was based on surveying and coring in order to find out what the shelf looked like, pointing out that there was very little geological knowledge available at this stage. Dr. Corbett said that De Beers then started a very comprehensive programme of sonar and seismic surveying together with a very comprehensive coring programme. He said that this work was initially to water depths of 70-90 metres, and that samples were taken to try to determine whether they contained diamonds. Based on the knowledge acquired, Dr. Corbett said that it was deemed that whatever was there was going to be too small to support the capital-intensive requirements for mining system development. Upon the discovery that there were indeed diamonds in those deposits, Dr. Corbett reported that exploration started to move further offshore going out to about 180 metres water depth, from the late 1970s through the early 1980s. He said that at that time, things started to look interesting in terms of the developing the mineral resource and further vessels were then brought in so that the rate of resource generation could be increased. Dr. Corbett said that by 1982 it was quite clear that there was indeed an exploitable diamond resource that had been defined and delineated in sufficient detail to give the organization the confidence to actually form De Beers Marine. He also said that at that point, a critical decision was made by the consultants of the group where they said, "Enough is enough, and we now make the transition". Dr. Corbett pointed out that while it is easy to carry on exploration, at a point there is a need to decide that "This is it, we are going to make it now, and this is when we make that move." He noted that for some of the contractors for deep seabed polymetallic nodules exploration and for Mr Malnic, this is the point where their deepwater operations are now poised.

Having completed his overview of the steps leading to the formation of De Beers Marine, Dr. Corbett's presentation focused on resource development, in particular mineral resource management. Dr. Corbett described mineral resource management as managing the technical and financial risks that organizations are exposed to in opening up a new mining operation. He stated that without the right information, errors happen, accidents occur and the desired results are not attained. He said that with the right information these kinds of problems could be avoided. He also said that the geologists, engineers and people involved in the offshore surveys, in geostatistics, and in linear programming are all focused on providing the right mineral resource information for the decision makers who ultimately have to take the financial decisions within the organization.

Dr. Corbett described the work of this group as an effort to ease investment decisions by strengthening the organisation's technical knowledge. He explained that the group takes a very holistic view of the mineral resource cycle, applying a lot of statistics to being able to model the geological environments and the mineralization characteristics of the offshore diamond deposits. He said that the group increasingly uses computer-based simulations of these types of deposits to be able to model and predict likely outcomes from sampling programmes and to make people aware of the dependencies and inter-dependencies between technical factors. He stated that this is the key to successful development of the offshore mining industry. As part of the process, Dr. Corbett informed participants that it is important for the group to operate within internationally acceptable mineral resource classification categories. He observed that over the last few years with the introduction of a lot more venture capital, people are using stock markets to raise funds for exploration. He pointed out that stock markets have found that they needed to have extremely rigorous criteria that could protect the investor from unscrupulous activities. These criteria, he also said include the ability of the developer to mine and deliver the mineral concerned.

Dr. Corbett pointed out that in order to exploit mineral resources, information on the geology of the deposit, sampling data and geostatistical information have to be combined in order to be able to proceed from a situation of fairly scanty information to a point where there is increased knowledge of the deposit and increased confidence in resource delivery. He said that in South Africa, this is based on the SAMREC Code developed by the minerals industry.[6] He said that the SAMREC Code is modelled on the Australasian Code for Reporting of Mineral Resources

[6] SAMREC is the South African Mineral Resource Committee. It was established in 1998. The Committee consists of various stakeholders in the minerals industry in South Africa such as the Johannesburg Stock Exchange, the South African Council for Natural Scientific Professions (SACNASP), representatives of SAIMM, and the Geological Society of South Africa. In 2000, under the Auspices of the South African Institute of Mining and Metallurgy (SAIMM), SAMREC prepared the South African Code for Reporting of Mineral Resources and Mineral Reserves.

and Ore Reserves (JORC). He also said that the definitions in the SAMREC Code are consistent with those agreed to at the Denver Accord by the Council of Mining and Metallurgical Institutions (including The United States, Australia, Canada).

In this regard, Dr. Corbett said that typically the categorization of mineral resources starts at the inferred level when a reasonably good idea of what is in the ground is available. He said to be able to generate funding or capital through banks, a critical threshold has to be crossed. He described this threshold as the point at which the "inferred resource" is designated as an "indicated resource". He stated that the designation confers a confidence level on the resource and that it is from the " indicated resource" that one is then able to extract what is going to be possible to profitably mine, called reserves. Dr. Corbett described this eventuality as the key transformation. He suggested that the challenge for people in the offshore deep ocean mining fraternity is going to be, not only to move from 'inferred' to 'indicated' resource but also as was the experience in the offshore diamond mining industry, to move from an indicated resource base and to be able to predict what material could profitably be mined, and to be able to deliver that ore. He noted that the type of factors that come into play in this transformation are not only the governmental, legal, social and environmental factors but the actual mining and metallurgical factors. In this connexion, he identified some critical factors as including the mine ability of the deposits, as well as the recoverability of the target commodities in the ore.

Dr. Corbett said that in the offshore diamond mining industry, designating ore as a probable reserve means that production must be no less than 15 percent of the estimated dollars per tonne per unit mined on an annual basis. He described this condition as stringent and pointed to the need for effective planning in order to meet this target, and to manage financial risks. He made the observation that very few companies in the world operate at this level, making mining in the offshore extremely difficult.

With regard to some of the difficulties associated with offshore diamond mining, Dr. Corbett identified the estimation or evaluation of deposits as a principal source of difficulty. He said that the difficulty arises because of the variability of the grade of the deposit and its geological continuity (Figure 4). He clarified the meaning of geological continuity of the deposit describing it as the fragmentation of the economically viable portions of the deposit. He pointed out that although one might have a very large deposit, it is possible that the portions that are mineable are found in very small areas.

In terms of the mineral resource management cycle that is typically followed by the De Beers Group, Dr. Corbett said that a conceptual exploration model is the starting point (Figure 7). He said that from the conceptual model, an exploration model is developed to deal with real data that are acquired in the offshore environment. He said that these data include survey and coring data. He said that using these types of data iteratively in the model results in obtaining in a model of the ore body with higher levels of confidence. With additional data, Dr. Corbett said that the exploration model becomes an ore body model with three critical components. Dr. Corbett identified one component as the distribution of mineralization, another as the mineability of the deposit and third component as ore dressing, or the metallurgical aspects of how to treat the ore to obtain the commodities of value. Dr. Corbett said that through this process a number of different databases are established to characterize the ore body in physical terms, including, the footwall conditions, and the terrain over which vehicles are going to have to transit in order to be able to mine the deposits. He said that the different data are then fused to create the ore body model. Dr Corbett stated that success in the mining operation depends on the initial ore body model, and geologic understanding of the ore type. He said that if the initial ore body model is incorrect, it creates a fundamental problem through the rest of the resource management cycle.

Dr. Corbett described some of the tools that are used by De Beers to develop the right model in the offshore environment. With slides, he showed participants photographs of "the Zealous" a De Beers Marine survey vessel. He said that the vessel is well equipped and focused on very high-resolution survey work for the minerals industry. Dr. Corbett said that the vessel also had drilling capabilities. Dr. Corbett informed participants that De Beers has also operated the Jago very successfully since 1996. Dr. Corbett said that in order to predict mine ability effectively, the JAGO is utilized to obtain first hand knowledge of operating conditions. Dr. Corbett said that while the process generates massive volumes of information and data, it is the fundamental starting point for developing three-dimensional models of ore bodies.

With another slide, Dr. Corbett showed participants a photograph of a fully Autonomous Underwater Vehicle (AUV) that he said traverses the seafloor at a 25 metre line spacing. He described the spacing as typical of the line spacing used by De Beers in its high-resolution work. Dr. Corbett described the transition from conventional seismic acquisition platforms to autonomous underwater vehicle technology by De Beers as one of the more exciting developments. He informed participants that De Beers would take delivery of the first AUV that will be focused exclusively on the development of offshore diamond resources later in the year. He said that this particular AUV was developed in an alliance with a company called MARIDAN in Denmark who arguably are the world leaders in terms of AUV survey mapping technology. Showing participants a test dataset with sonar that was obtained in 1999, Dr. Corbett remarked on the astonishing accuracy and precision in terms of positioning systems of the AUV. He said that De Beers believed that this technology could be a fundamental breakthrough in remote sensing technologies for diamond deposit evaluation. Dr. Corbett said that a part of the high-resolution work was the acquisition of geophysical data in preparation for areas of the deposit to be converted from inferred resource to indicated resource

Again through the use of slides, Dr. Corbett showed participants images of the ore bodies on the shelf (Figure 6). He pointed out two environments: the pro-delta slope of the Orange River with fine grain sands, silts and mud, and the deep-water. He said that one of the irritating problems in the pro-delta slope is that a lot of sediments are gas charged which effectively creates an acoustic blanketing layer for conventional seismic technologies. He said that as a result it is difficult to image down underneath and find out whether the ore bodies that are suspected to found are indeed there.

Dr. Corbett spoke about the importance of being able to interpret the vast quantities of extremely high-resolution data acquired by De Beers. He described the acquisition of acoustic data from Sonar and Chirps and ground checking maps of the terrain produced from these technologies using the JAGO (Figure 8).

Utilizing a slide, he showed participants a cross section of an ore body produced from acoustic images with Chirps technology. He also showed a slide containing the interpretive work done by being able to cross check between Jago footage containing real observations and with remote seismic data. He pointed out that with these methods, De Beers is able to build extremely detailed high-resolution acoustic maps of the seafloor. He described these maps as containing the kind of information that is required by mining system designers and people that are involved with mine planning. Used in modelling, Dr. Corbett said that this type of information is equally invaluable to decision-makers. Finally, he said that this type of data gives De Beers a much higher capability in terms of predicting the distribution of mineralization, a factor that has significant benefits in terms of resource delivery. Dr. Corbett provided an illustration of a computer simulation of mineralization distribution in a deposit. The simulation contained examples of sample holes, the overburden, and the ore body with coarse clastics and a clay footwall.

With yet another slide, Dr. Corbett showed participants a picture of the Coral Sea, the first drill ship that De Beers Marine brought into production in 1991. Dr. Corbett said that the Coral Sea is now equipped for a 24 hour switchover between evaluation sampling or mining. He also showed participants the drill system on board the vessel that is used down on the seafloor for evaluation sampling. He said that the drill system was specifically designed for De Beers's purposes and is capable of sampling very effectively, extremely coarse clastic material down on the seabed. He described the ore body that was being sampled as very coarse-grained complex lag gravel that was produced by repeated shore face reworking during regression and transgression over at least 50 million years.

With regard to processing, Dr. Corbett said that once the ore containing the diamonds is taken up by the drill system, it is not touched by human hands during the entire processing operation. He said that the ore is taken up, passed through a dense media separation plant where the diamonds are concentrated together with other heavy minerals. He said that the diamonds are then passed through an X-ray sorting system that identifies the diamonds specifically. The sorted diamonds are then canned on a sample-by-sample basis in a specially designed canning machine. Dr. Corbett said that he final recovery is done under very strict security because sample integrity is absolutely essential and diamonds are very small, very valuable. He noted that data analysis and the evaluation of sampling results is tricky business and has required a lot of very specific focused research since the mid 70's.

Dr. Corbett provided participants with an overview of mining development in terms of deepwater operations. He said that after the start of De Beers' deepwater operation in 1983, developments in this part of De Beers' activities took a significant step forward when the organization took the unprecedented decision to move forward with a test-mining vessel. He said that it was the work done using this vessel, the Louis Murray, which helped transform the organization's work from exploration and resource development to actual production. He recalled that initially, some of the types of systems that were used required the equipment to be suspended over the side of the vessel. He also said that various types of digging heads were used. These he said, in trying to create coverage bounced on the seafloor. He said that creating coverage is very difficult to achieve, and it was very rapidly realized that this was not going to be the type of system that was going to allow systematic, precise mining of a deposit. Following on from there, Dr. Corbett said that seafloor crawlers, track mounted vehicles that could traverse directly on the seafloor were introduced. According to Dr. Corbett, this configuration required a lot of work in terms of launching and recovering these systems. He said these systems were in the region of 40-50 tonnes. He said that the systems that are currently deployed are closer to 150 tonnes. He emphasized that hanging this type of technology over the side of a vessel in an offshore environment with large swells is not a trivial issue. He said that various types of cutter tests were undertaken, and suction methods tried. He also said that it was a time of great experimentation and stated that parallels would unfold as things happen in the deep ocean. He told participants that one of the early realizations in mining system selection was that they had to differ according to the geological environment in which these systems are going to operate.

With another slide depicting a deposit in a very rugged terrain, Dr. Corbett said that it was this type of deposit that lead to the idea of the "vertical attack system". To develop this system, Dr. Corbett said that in 1989, De Beers purchased an oil exploration vessel and converted it to operate as an offshore diamond-mining vessel (the Coral Sea) for operations in water depths of up to 200 metres. Dr. Corbett described the vertical attack system as large-bore drill bits, up to 7 metres in diameter based on the vessel that is used to drill the diamond deposit. He said that experience has shown that these systems are very effective for mining in more rugged terrain, where the ore body is commonly very coarse due to the incorporation of large slabs of cretaceous and tertiary shelf sandstones and clay stones. Dr. Corbett said that by April 1991, the vessel had been transformed quite substantially again in order to be able to contain the ore that was brought to surface using airlift. He pointed out that the ore comes up the drill string as slurry, containing cobbles up to 40 centimetres in diameter and travelling at speeds between 11 and 15 metres per second. Dr. Corbett said that the drills are deployed on to the seafloor; they are then lifted from one position to another in an overlapping sequence of holes that allows the complete extraction of any one area at a time. Noting the need for precise positional accuracy in this operation, Dr. Corbett said that this need was addressed by equipping drill ship vessels with real time sonar systems, sonar heads that provide images of the seafloor. Dr. Corbett informed participants that many different innovations and revisions have been incorporated in the three other drill ship vessels subsequently developed by De Beers.

Dr. Corbett said that presently, De Beers Marine has two arms to its production capability, crawler-based mining systems, and drill ship-based systems (Figure 10). As to the fleet configuration, Dr. Corbett said it consists of the Zealous that is used as a survey vessel, the Douglas Bay that is used as the exploration-sampling vessel, and the Coral Sea that is used as the evaluation-sampling vessel. He said that the production fleet consists of the Louis Murray that is currently laid up, the Grand Banks, the Debmar Atlantic, the Debmar Pacific and the Karib.

Dr. Corbett spoke about the feedback loop between the ore body model and production. He pointed out that in addition to having actually gone to the deposit and mined it, it is critical to be able to analyze the mining performance against the model created from exploration and used to develop a mining plan. He also said that a binding requirement of the Government of Namibian is for the operator to demonstrate responsible mining practice. Such practice requires that the operator not high grade the diamond deposit, but that the full spectrum of the economically mineable areas of the deposit is recovered. He said that the feedback loop, also serves to respond to this requirement. He emphasized the importance of well-constructed databases for modelling the ore body. He indicated that in addition to some of the parameters that he had mentioned earlier, other types of information that De Beers captures in the databases include production costs etc. He also spoke about the value of these databases in the audit of the performance of the team, and by the clients of De Beers.

Dr. Corbett said that security is very important to De Beers. He said that for De Beers, it is critical that proprietary information is held in a secure environment. He described this environment as a centralized system that allows other functions access and use of the data sets for costing and mine planning. He said that the reconciliation aspect is continuous, and that data management is extremely important because it allows the integration of geology with production, with survey data and above all with mine planning. He also said that in order to facilitate access on a more rapid basis, De Beers's management has direct satellite data transfer links with vessels.

In terms of the future plans of De Beers Marine, Dr. Corbett said that the vision is that the organization is going to lead the field of offshore diamond exploration and mining forever. He said that De Beers strives to improve in all aspects of its business. As an example, Dr. Corbett said that De Beers considers it important to examine its waste products with a view to eliminating as many of them as possible.

Dr Corbett said that De Beers Marine is a service industry. With regard to diamond mining in Namibia, he described De Beers' role as a contractor/operator to NAMDEB that holds the offshore licences. He said that initially when mining started, vessels came back and forth to port on a monthly basis. He informed participants that the Debmar Pacific has operated out at sea for 1,027 days on a continuous basis. He said that a policy of De Beers Marine is that production vessels are on a two-year cycle for maintenance. He described maintenance as an extremely important aspect within the organization and said that rigorous processes and procedures have been developed to avoid unnecessary down time.

In relation to the overall performance of De Beers, Dr. Corbett said that from its initial tentative steps in 1990 when 29,000 carats of diamonds were produced with great excitement, currently annual production is in the region of half a million carats of diamonds per annum. He said that he future would require further innovation particularly in mining systems and mining system design. In this regard, he said that De Beers has constructed different types of test facilities, which enable it to test full-scale prototype systems onshore, and conduct scale model tests of the different types of production systems.

Finally, Dr. Corbett touched on the prospects for employment in countries where these developments might take place offshore. Noting that many offshore mining developments might happen in the exclusive economic zones (EEZ) of countries, Dr. Corbett said that he thought it important to relate the impact of De Beers's operations in Namibia on national employment. He said that De Beers Marine has been able to significantly increase its employment of Namibians in this foreign operating environment. He said that over the last five years (1994 to 1999), the overall employment of Namibians rose very sharply from 21 people to 120 people, many of whom are directly involved in the vessel-based operations. He said that the full complement of staff working offshore is about 550. Dr. Corbett said that De Beers Marine has been able to produce 10 Namibian cadet graduates who have now become officers. He said that nine more cadets are expected to become officers in 2000. Dr. Corbett mentioned other successes, including the first apprentice electrician that has come through De Beers' Debnap training programme, and specialized training for marine geologists required to deal with the type of data generated and used by De Beers Marine. He also mentioned issues and problems that need to be addressed. These included the fact that not all persons are comfortable working at sea, and the high level of technical courses required that are not readily available in countries like Namibia.

Dr. Corbett concluded his presentation by informing participants of a major initiative that he said had been launched to by De Beers to be able to increase the training of teachers and thereby increase the calibre of people coming out from schools. In addition to funding teacher development in mathematics and science, Dr. Corbett said that De Beers also donates technical equipment to training establishments. He reported that this has led to an increased number of Namibians who are being trained in different aspects of the diamond mining operation that might become a pool of trained personnel for different Departments within De Beers' operations.

SUMMARY OF THE DISCUSSIONS

Due to the limited time available for discussions following Dr. Corbett's presentation, it was decided that discussions on his presentation should take place after Dr. Corbett's second presentation on "A case study in the development of an environmental baseline in large open ocean systems off Southern Namibia by De Beers Marine."

CHAPTER 16

A CASE STUDY IN THE DEVELOPMENT OF AN ENVIRONMENTAL BASELINE IN A LARGE OPEN-OCEAN SYSTEM OFF SOUTHERN NAMIBIA BY DE BEERS MARINE

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The continental shelf of Namibia is strongly influenced by the Benguela Current, and is recognised as one of the main upwelling sites in the world's oceans. Hence the region in which deep-water offshore diamond mining occurs is characterised by high biological productivity. Although not directly within the area being mined, the continental shelf of South Africa and southern Namibia is known for its stocks of pelagic and demersal nekton, with important fisheries contributing both to the local economy and to employment along the coast.

The development of deep-water diamond mining has progressed significantly since 1991, when De Beers Marine (DBM) delivered the first official production. To date, some 13 km² of the continental shelf has been mined within the 6098 km² Atlantic 1 Mining License held by NAMDEB (an equal partnership between De Beers and the Government of the Republic of Namibia). Annual production from DBM is extracted from between 2 to 2.5 km² of seabed spread over a wide area. The mining process is precise, with extraction of diamond from plant feed gravel being a non-chemical process aided by dense media separation. Undersize and oversize materials, together with tailings are discharged overboard and settle back to the seafloor.

Given the unique nature of the operation, no previous experience was available to guide De Beers Marine in its assessment of environmental impacts for deep-water offshore diamond mining operations. De Beers Marine has opted for a transparent, proactive approach to the development of an environmental management programme. Progress through continuous improvement of environmental management culminated in the company becoming the first ISO 14001 certified marine diamond mining company in the world. The application of the ISO approach customised specifically to offshore mining ensures that environmental management is holistic, encompassing the direct impacts of mining together with the management of waste.

DBM has progressed in understanding the nature and extent of impacts since the initial studies to establish an environmental baseline. This was an essential aspect in developing an understanding of the company's environmental impacts due to the paucity of detailed information about the dynamics of the Benguela system. A key element was to understand the system's natural variability driven by large-scale natural events that see low oxygen water introduced across the shelf on a regular basis, with the introduction of large volumes of suspended sediment from Orange River flood events providing an additional factor. Without this, discrimination of local-scale mining impacts from the influence of natural events would not be possible. Experience has proved that conventional sampling techniques to determine impacts have inherent difficulties. Many new insights have been derived from direct visual observation using the Jago submersible, coupled with detailed analysis of video material collected during submersible transects – a first for the Benguela system.

This paper draws upon many contributions from studies commissioned and aided by De Beers Marine to develop an environmental baseline for the determination of impacts related to offshore diamond mining on the southern continental shelf of Namibia and for the continuous improvement of environmental management. As such, it presents an overview based on the contribution of many different scientists and staff of De Beers Marine. It is hoped that the paper will contribute to the development of environmental management philosophies for the deep-sea mining industry of the future.

1 Macro-Scale Ocean System Setting of Offshore Diamond Mining in Southern Namibia

Offshore diamond mining operations occur on the inner and middle continental shelf along the southwestern continental margin of Africa [1], with Exclusive Prospecting Licenses awarded by the Namibian Government extending to 2000 mbsl on the continental slope. The Benguela Current strongly influences the continental shelf, which has long been recognised as one of the world's major upwelling regions and the site of prolonged scientific study [2] since the Challenger and Discovery Expeditions over a century ago. More recently, the ocean's role in climate change through heat transport and control of carbon dioxide has resulted in a programme of integrated studies to examine the physical and chemical oceanography in greater detail. In a system characterised by high variability, these studies contribute to an improved understanding of the macro-scale system.

Two principal components of the Benguela system are recognised [3], building on earlier work [4] (Figure 1).

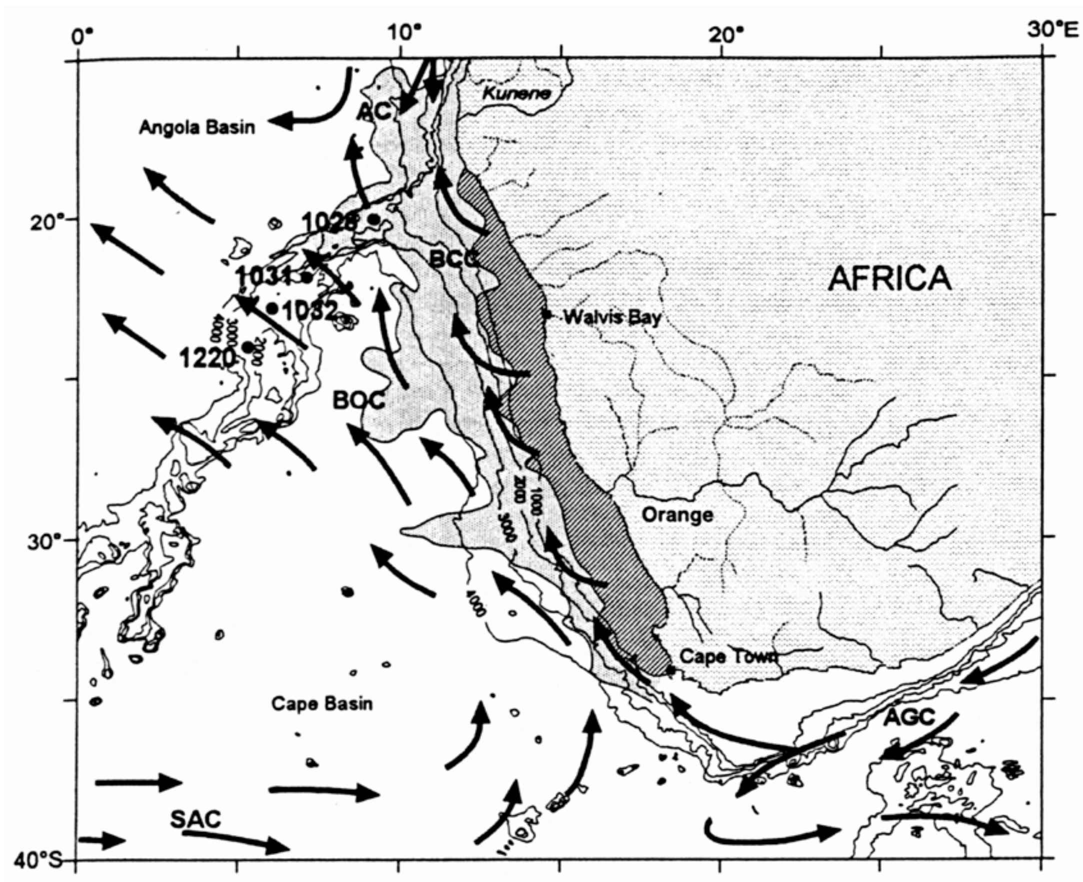

Figure 1. Main components of the Benguela System. BCC defines the dark grey zone representing the Benguela Coastal Current (characterised by coastal Upwelling) and the Benguela Oceanic Current (BOC) during Southern Hemisphere winter (August). [3], modified after [4].

The Benguela Coastal Current influences the entire continental shelf and large areas of the upper slope, with the Benguela Oceanic Current further down slope to the west separated by a zone of mixing. Large upwelling filaments extend west off the Orange River and to the north of Luderitz northwards. The offshore surface flow driven by strong, persistent southerly winds is usually accompanied by an onshore flow at depth.

The southern Namibian coast is influenced by particularly high wave-energy driven from the Southern Ocean. As a consequence of the strong wind and wave regimes, the upper water layers are subjected to high levels of turbulence. Although strong northward currents predominate, the inshore Benguela Counter-Current identified [5] can be observed to transport suspended sediments introduced by Orange River floods to the south. The predominant flow of bottom water is also to the south.

Upwelling, driven by strong long shore wind stress [2], introduces dissolved nitrates and other nutrients into the region, making the waters of the Benguela Ecosystem amongst the most productive in the world [6]. Productivity values exceed 180 $gC/m^2/yr$ [7] and the region supports several commercially valuable pelagic and demersal fisheries. The pelagic fisheries (principally anchovy and sardine) represent the larger catches, but demersal species (principally hakes) are more valuable [8]. The fisheries account for the presence of approximately 225 bottom-trawling vessels operating on the western margin of South Africa and Namibia [9]. In addition, rock lobster represents an important shallower-water industry in southern Namibia, especially with respect to the local economy in Luderitz, where diamonds were first found.

Two further factors are significant in terms of the macro-scale system dynamics across the continental shelf. Firstly, the formation of low-oxygen water along the southwestern continental margin of Africa adds to the complexity of the natural large-scale variability of the Benguela Ecosystem (Figure 2), with important implications for natural catastrophism of the benthos. Secondly, periodic flooding of the Orange River catchment in Namibia and South Africa results in the introduction of large volumes of suspended sediment to the inner and middle continental shelf environments, where it contributes to natural fine-grained sedimentation, which can result in burial of sedentary benthos.

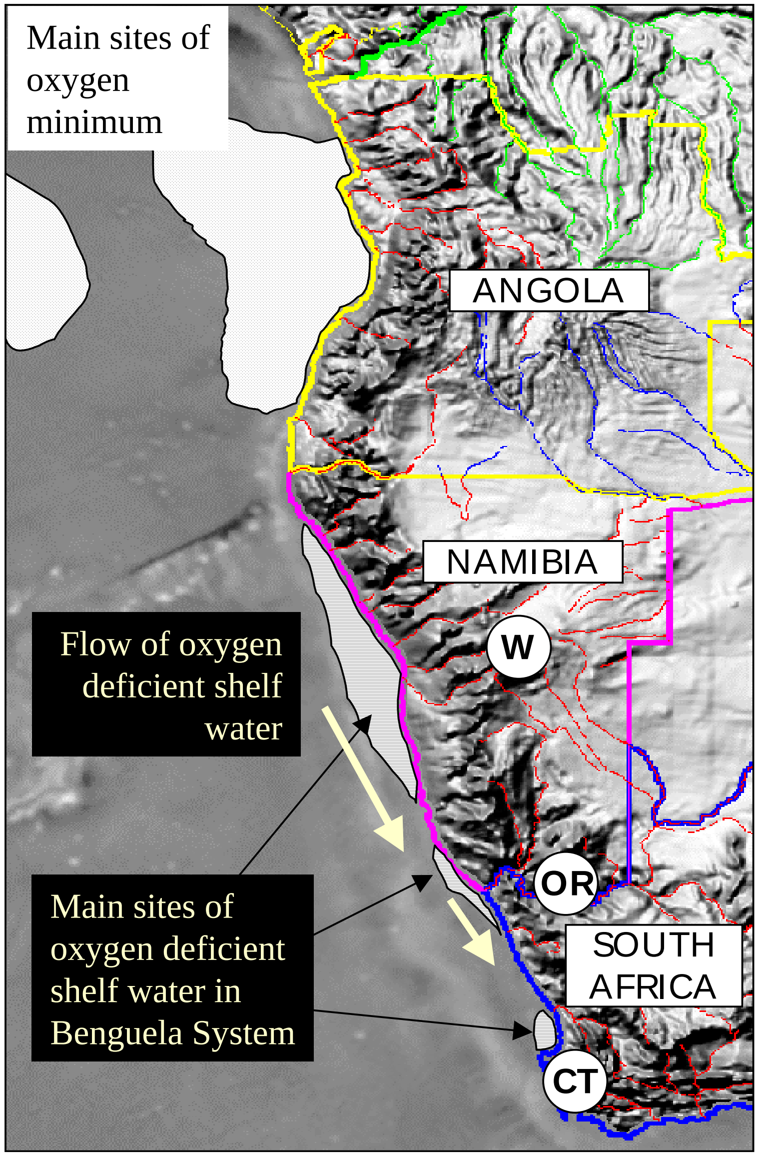

Figure 2. Model showing areas of low-oxygen water formation and the inferred movement. (Modified from Chapman and Shannon, 1987).

These natural physical characteristics have important implications for environmental studies to determine the impact of offshore mining and environmental management of offshore mining operations. On the establishment of the first large-scale mining system by De Beers Marine (Pty) Ltd (DBM) in 1990, it was immediately evident that given the natural variability of the system, the establishment of an environmental baseline would be a priority. Without this, accurate discrimination between the effects of natural system variability and the localised impact of mining systems would not be possible and the long-term future of the offshore diamond mining industry could not be secured. Although not required at the time, DBM (with the support of the Namibian Diamond Corporation (Pty) Ltd., an equal partnership between De Beers and the Government of the Republic of Namibia (NAMDEB)) then proactively established an environmental impact assessment including collection of critical baseline data during 1991 to protect its own interests and those of other stakeholders with commercial interest in the marine resources.

2. Environmental Management At De Beers Marine

2.1 Overview Of Namibian Legislative Requirements

The following section briefly summarises the legal obligations license holders and/or operators are required to fulfil in the context of Namibian offshore mining operations.

General Obligations to be included in a Pro-forma Environmental Contract

- Company recognises that its operations may have significant impacts on the environment and accordingly undertakes every practicable step necessary to ensure mitigation of such impacts in liaison with MET, MFMR & MME.
- Undertake necessary and adequate steps to ensure environmental damage is reduced to a minimum and prevented insofar as is possible

- Should the Company not carry out its environmental obligations it shall be liable for the environmental damage which may result

- The Government reserves the right to

    - Demand at any time financial or other guarantees to restore the environment or mitigate environmental damage

  - Undertake necessary mitigatory or restorative measures and recover the costs from the Company

  - Claim compensation for environmental damage

- On competition or suspension of activities the Company shall ensure environmental impacts are minimised

- The Company will be required to carry out an Environmental Assessment in compliance with Namibia's Environmental Assessment Policy

- Prepare and submit an Environmental Management Programme Report providing information in accordance with s68 (f) of the Minerals (Prospecting & Mining) Act 33 of 1992 with information on:

  - The condition of the environment prior to undertaking operations,

  - Estimated effects of the proposed operations and proposed steps to minimize or prevent such effects

- The manner in which it is intended to prevent pollution, to deal with any waste, to safeguard the mineral resources, to reclaim and rehabilitate land disturbed by way of the prospecting operations and mining operations and to minimize the effect of such operations on land adjoining the mining area.

- Environmental Assessment is required in compliance with Namibia's Environmental Assessment Policy

- The Company shall undertake necessary and adequate steps to ensure environmental damage is reduced to a minimum and prevented insofar as is possible

- The Government reserves the right to demand at any time financial or other guarantees to restore the environment or mitigate environmental damage

- Furnish Ministry of Minerals and Energy with bi-annual Environmental Reports required to assess performance

Minerals (Prospecting & Mining) Act 33 of 1992

Applications for licenses shall contain the following particulars (s 68(f)):

- The condition of, and any existing damage to, the environment in the area to which the application relates;

- An estimate of the effect which the proposed prospecting operations and mining operations may have on the environment and the proposed steps to be taken in order to minimize or prevent any such effect; and

- The manner in which it is intended to prevent pollution, to deal with any waste, to safeguard the mineral resources, to reclaim and rehabilitate land disturbed by way of the prospecting operations and mining operations and to minimize the effect of such operations on land adjoining the mining area;

For areas with non-exclusive prospecting licenses, mining claims or mineral licenses holder will be required to:

- Remove property on abandonment, cancellation or expiration, and

- Remedy damage caused to surface of, and environment on, land situated in such areas.

- Take such other steps as may be specified by the Minister

Liability of holders of licenses or mining claims for pollution of environment or other damages or losses caused:

When in the course of any reconnaissance operations, prospecting operations or mining operations carried on under any non-exclusive prospecting license, a mining claim or a mineral license, water is polluted or any plant or animal life (including on land an in the sea) is endangered or destroyed or any damage or loss is caused to any person, including the

State, by such spilling or pollution, the holder of such license or mining claim shall forthwith

- Report such spilling, pollution, loss or damage to the Minister;

- Take at his or her own costs all such steps as may be necessary in accordance with good reconnaissance practices, good prospecting practices or good mining practices or otherwise as may be necessary to remedy such spilling, pollution, loss or damage.

2.2 De Beers Marine Approach to Environmental Management

During 1999, NAMDEB delivered 1.3 million carats (79% of the country's total diamond production of 1.6 million carats), and contributed Namibian $ 533 million (± US$76 million) in taxes and royalties from sales valued at N$ 2.4 billion. The contribution of deepwater offshore marine diamond production by DBM to NAMDEB's total production was 514 000 carats. DBM's contribution to NAMDEB is likely to increase in future as the output from land-based operations declines through responsible depletion of the remaining onshore Mineral Resources. Consequently, the continued long-term operation of the offshore marine diamond mining industry will be crucial to the future of a diverse group of stakeholders and it will play an increasingly significant role in the Namibian economy.

From the outset of large-scale mining operations in 1990, DBM has proactively led the way in developing a rigorous approach to the environmental management of offshore diamond exploration and mining operations. Today, DBM mines between 2 to 2.5 km^2/year with a total of about 10 km^2 mined to date, representing about 0.00002% of the 6098 km^2 Atlantic 1 Mining License. The vast majority of DBM mining activities occur outside the territorial waters of Namibia, beyond the 12 nautical mile limit at water depths exceeding 115 m. NAMDEB also holds a further 20 000 km^2 of Exclusive Prospecting Licenses which are operated exclusively by DBM on behalf of NAMDEB.

The mining process is precisely controlled, whether material is extracted using large-bore drill or seafloor crawler devices. Generally speaking, the depth of sediment extracted does not exceed one metre. The pattern of disturbance on the seafloor differs according to the technique used to extract gravel from individual mine blocks, which are either 50 by

50 m or 100 by 100 m (Figure 3). The mining system is selected on the basis of the specific physical characteristics of the ore body to be mined. Drill system position is determined using ship-based sonar, whilst crawler positioning is determined through the use of an acoustic underwater positioning system and/or ship-based sonar. Approximately 1 to 1.5 million m^3 of unconsolidated gravel is extracted per annum.

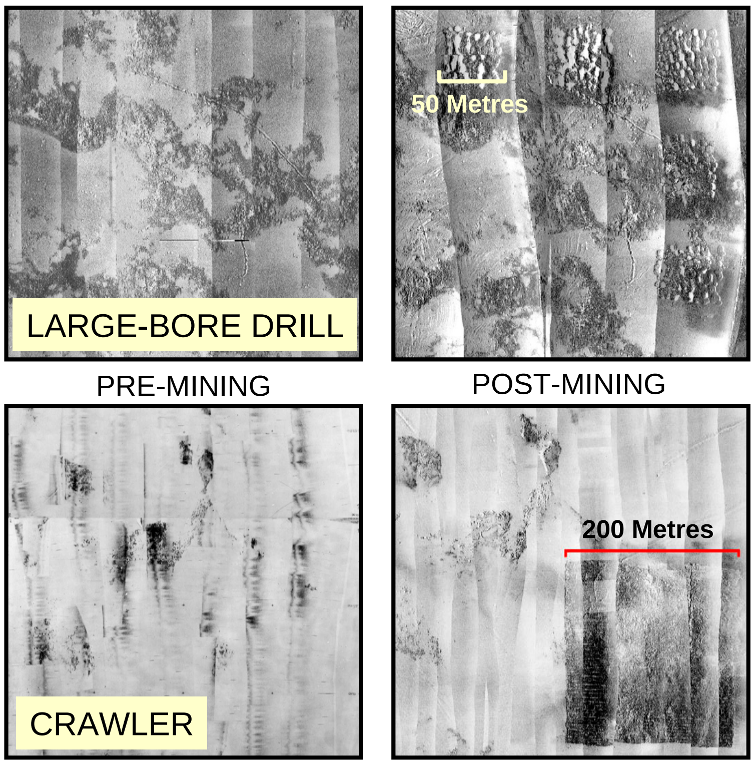

Figure 3. Sidescan sonar images illustrating the different seabed disturbance pattern produced by mining tools. Note the precise distribution of mining.

The extracted sediments are airlifted onboard the vessel where they are screened, sized, and processed. Diamond recovery is a non-chemical process. Extraction is achieved utilising a dense media separator in which plant feed gravel is mixed with ferrosilicon (the only substance added to sediment onboard) and pumped under pressure into a "cyclone" which separated high-density material from the low-density "floats". Treatment plants are designed to recover as much ferrosilicon as possible from the process. The low-density material is discharged overboard and returned to the seabed whilst the high-density material is dried prior to being passed through an X-ray unit that separates fluorescent particles, including diamonds, from non-fluorescent material. The fluorescent material is automatically sealed in cans for transport to the client where final hand sorting recovers the diamonds in a high-security environment. Some 99.99% of the gravel and sediment extracted are returned to the seabed.

The initial environmental focus in DBM was on marine issues related to the direct impacts of mining and the submission of the legally required Environmental Management Programme Report. This was completed in 1997 for the Atlantic 1 Mining License Area on behalf of NAMDEB, which documented:

- Existing knowledge of the bio-physical environment;
- Information on the socio-economic environment;
- The range of De Beers Marine's activities in the area;
- Described the potential impacts;
- An environmental management programme to address these impacts.

The scope of the Environmental Management System (EMS) has since broadened to embrace all aspects of the company's business including shore-based issues, making it holistic.

The philosophy underlying DBM's approach to environmental management is that all diamond mining activities have an impact on the environment. These require management and monitoring to mitigate the negative aspects and optimise the positive effects to the benefit of all affected parties.

A key difference between onshore and offshore mining operations is that the former approach requires funds for post-mining rehabilitation, whilst the latter must intensively focus upon understanding and monitoring the consequences of offshore mining operations in order to effectively minimise impacts during the extraction process. From a marine perspective, for example, this means that waste management is framed within a policy of "nil overboard" other than macerated foodstuffs and treated sewage in accordance with, and developing on, the international MARPOL convention.

The DBM Environmental Management Team has two focus areas:

- Maintenance of the ISO 14001 certification plus continuous improvement of the environmental standards for all aspects of the operation;

- Provision of environmental services for clients.

2.3 ISO 14001 Certification and the Environmental Management System

ISO 14001 certification is formally incorporated into De Beers' corporate policy for environmental management, and the target date for operations to be compliant is end 2000. DBM was the first diamond mining operation to achieve this in 1998, and it was the first marine diamond mining company in the world to do so [10].

The international ISO 14001 standard provides a rigorous framework for the management of environmental issues that has been customised specifically to address the requirements of DBM. The key elements of the ISO 14001 standard include:

- **Company policy** – the environmental policy is integrated into the company's functioning and demonstrates serious commitment to continuously improve environmental management practices and prevents pollution.

- **Responsibilities/accountability** – DBM currently employs two full-time environmental staff and one full-time researcher. Partnerships with a variety of academic and research institutions planning, evaluating and reviewing research results ensures independent assessment. A multi-disciplinary Environmental Management Team has been assigned specific responsibilities, and vessel and shore-based environmental monitors are in place;

- **Legal requirements** – International conventions such as MARPOL are applied to prevent pollution at sea by marine operations. Countries in which DBM operates have numerous requirements. For example, prospecting and mining license agreements require that government must approve EMPRs prior to the commencement of operations.

- **Communication/training** – a strong emphasis is placed on open communication and consultation with interested and affected parties. These include internal stakeholders and external ones such as fishermen, government officials, and representatives from local development organisations, scientists and conservationists. Employees receive specific training and general environmental awareness material including magazines, notice boards and an intranet site that is available to the vessels via satellite link. This site includes all documentation necessary for the EMS. External feedback and comment is obtained through a variety of formal and informal fora;

- **Impacts, management plans, procedures and environmental objectives** – following approval of an EMPR, an impact register is drawn up for each concession area, with a management plan for addressing specific bio-physical and socio-economic environmental issues. Operational, monitoring and emergency procedures are in place to ensure impacts are minimised. Objectives and targets are set annually to drive continual improvement in environmental management;

- **Corrective action** – standards are maintained through recording of deviations and corrective actions. Safety and environmental incidents are recorded via an integrated system. Root causes of incidents are identified and remedial action taken;

- **Environmental auditing and review** – DBM has implemented a three tier audit process:

  - Monthly internal audits – self-checking at each site/ship;
  - Quarterly Environmental Management Team audits to verify monthly reports with twice-yearly checks at each site/ship;
  - The South African Bureau of Standards, the certificating body, conducts six-monthly external surveillance audits to review different elements of the EMS.

The Environmental Management Team provides an annual review to the executive committee of DBM. Issues arising are discussed, together with the audit results, and objectives and targets are reviewed. The concerns of interested parties are also discussed. The management team is required to comment formally on the suitability, adequacy and effectiveness of the EMS. These discussions are valuable as the ISO 14001-based EMS requires commitment throughout the company and it ties in strongly with the corporate commitment to the highest safety standards. In the future, annual reporting is a likely development, with publication of key findings related to the business with environmental implications.

DBM's EMS covers all of the company's operations, which involve approximately 900 employees. The operation includes:

- Eight ships operating off Namibia and South Africa;
- Shore-based offices in Cape Town, Port-Nolloth, Walvis Bay and Windhoek;
- Four storage facilities and engineering workshops in the Western and Northern Cape;
- A purchasing depot;
- In-port operations such as vessel conversions, maintenance and upgrades at various harbour facilities.

3. Initial Baseline Development For Environmental Impact Assessment

All of the world's oceans contain a rich diversity of marine life ranging from microorganisms to large marine mammals such as dolphins and whales, and birds. Complex interactions exist between each component of the marine ecosystem. In the region under discussion, further complex interactions also occur between the biological components of the ecosystem and the system's physical oceanography, which is dominated by the influence of the Benguela Current. In an inherently variable system that is prone to natural catastrophism of benthos in response to widespread low oxygen "events", knowledge of the specific conditions in the vicinity of the mining operations proved inadequate for the reliable assessment of impacts of offshore diamond mining.

Although as a system, the Benguela Current had ostensibly been studied over a long time period, scientific study has for the most part been limited to the macro-scale research. Consequently little published detail was available about natural variability of the biophysical environment, including current velocities, oxygen levels, and sediment structure and benthic communities within the Atlantic 1 Mining License Area. Effective environmental management required that this had to be developed.

DBM commissioned the Environmental Evaluation Unit of the University of Cape Town to conduct an independent initial baseline study in 1991 although this was not required under Namibian law at the time. This study was completed during 1996, and the results incorporated into an Environmental Impact Assessment that contained the results in a legally required Environmental Management Programme Report, submitted to the government of the Republic of Namibia in 1997. The team that conducted the project was comprised of thirteen specialists. A further 16 researchers from the departments of Geology, Zoology, Oceanography, Environmental and Geographical Science and the Centre for Marine Studies at the University of Cape Town, the JLB Smith Institute of Ichthyology at Rhodes University, and Resource and Environmental Services cc, the Two Oceans Aquarium and the Institute for Maritime Technology in Simon's Town assisted.

The key specialist studies investigated the effects of mining on all potentially affected areas:

- **The surrounding sea –** the influence on seawater of discharging sediment produced from the mining process overboard, and on the bottom waters resulting from the activity of mining tools;

- **The seabed and resident biological communities –** the effect of removing and returning seabed sediments, and the consequences for the communities of organisms living in these sediments;

- **Fish and marine mammals –** the presence of mining operations on their distribution and behaviour;

- **Birds in the Orange River estuary –** the consequences of frequent flights over the area.

3.1 Brief Summary of Results from the Environmental Impact Assessment

The following provides an overview of the principle findings from the initial baseline work [11,12] and also incorporates some subsequent findings.

3.1.1 Effects on the surrounding sea water

A plume of fine-grained suspended sediment is generated through the discharge of sediment overboard from mining vessels. This plume is visible from vessels and it is present for the duration of active mining. Due to its buoyancy, most of the plume descends to mid-water below the biologically productive zone. All of the major concerns raised by scientists [13] were investigated. It was found that outside the immediate vicinity of a mining vessel (<1 km^2) there was no significant change in water quality.

The concerns investigated included:

- **Reduction in light for photosynthesis in surface waters –** The plume created by the discharged sediment increases the turbidity of the water and reduces the light available for photosynthesis causing a reduction in productivity at the base of the food web. The spatial extent of this impact was determined to be limited based on computer simulation of the plume.

- **Increase in the nutrient density for filter feeders in the water column –** The dominant silt size-range of particles in suspension includes the particle size filtered by zooplankton. Any potential effect of this was deemed to be limited to the vicinity of the vessel.

- **Effect of sediment-derived nutrients on microbial activities in surface waters –** Large concentrations of ammonium (and other nutrients) originating from mined sediments and released in dissolved form in tailings could stimulate phytoplankton and bacterial activity, which could alter phytoplankton communities and affect the food web. Computer simulation demonstrated that the ammonium is rapidly diluted to background levels and confined to a very restricted zone around mining vessels.

- **Effects of trace elements and pesticides on organisms in the water – Seabed sediments introduced to the continental shelf by the Orange River contain** metals and pesticides that are remobilised through mining activity. The metals and pesticides are then liable to bio-accumulate if taken up by organisms. Small quantities of ferrosilicon are introduced to the gravel during the treatment process, and are lost overboard with the tailings, but this is considered to have no effect on water quality. The presence of trace elements and pesticides is considered to be limited both to a short time and over a small spatial extent.

- **The effect of low oxygen levels in the water as a result of tailings and mining on the seabed –** Bacterial decomposition of organic matter in the sediments can deplete oxygen concentrations. Reduction in oxygen concentration of bottom waters was considered to be most significant as oxygen depleted bottom water is characteristic of the Benguela Ecosystem.

  Mobile animals such as fish migrate out of areas influenced by low oxygen concentrations whilst less mobile organisms perish since few can tolerate zero-oxygen water. Field measurements indicated that tailings would produce no measurable decrease in bottom water oxygen, but resedimentation could result in burial of organisms unable to escape [14,15,].

This aspect of the study considerably increased the understanding of the Benguela Ecosystem by providing new, higher-resolution datasets about currents and oxygen levels within the system. As a result of the baseline study, three years of current data and two years of oxygen measurements are now available. These provide the first time series analysis proving that low or zero oxygen events periodically occur naturally across large areas of the continental shelf. These data were recorded over an extended period by the Institute for Maritime Technology and further supplemented with data from RACAL.

3.1.2 Changes to the seabed and resident communities

The mining process, treatment and the overboard discharge of tailings comprehensively mixes the sediment horizons overlying the footwall directly beneath the ore body. This alters the natural habitat of the infaunal communities. The process also destroys the organisms in the mined sediments, and others are smothered by resedimentation of the coarser-grained material discharged overboard as it settles on the seabed. Recolonisation of the mined areas (termed "chronically artificially disturbed") [15] by benthic organisms requires time, and the structure of the communities is altered – benthic community structure is commonly considered to be an important indicator of environmental conditions.

Researchers identified some 233 infaunal species, including at least one species that is new to science. The organisms range in size between worms of 20 cm in length to minute snails millimetres in diameter [16,17,18,19].

The spatial extent of this impact is restricted to the area in which mining occurs and most likely to a couple of hundred metres beyond due to the resedimentation of sediment put into suspension during the mining process. The analysis of the communities based on grab sampling from mined and unmined areas shows that recovery to a stable biological community may take from 4 to 8 years [19,20,21].

3.1.3 Effects on fish and dolphins

The initial study showed that within the mining area there are relatively few species, no fish spawning grounds and currently no commercial fishing activity. Rock lobster is the basis for an important fishery in Namibia, but DBM's operations do not overlap with the optimal habitat or any rock lobster fishing activities. Consequently, potential for conflict between the deep-water diamond mining operations and the fishing industry is avoided.

The potential for noise from vessels and/or from the mining process to impact on fish and marine mammals was considered. Measurements of noise levels established that the frequencies generated are lower than those used by marine mammals for communication [22,23,24].

Sonar equipment used on some DBM vessels does overlap with the communication frequencies of marine mammals, but little is known about the hearing in these animals. Hence the EIA recommended that further studies should focus on detecting behaviour of the dolphins in relation to the use of sonar equipment.

Heaviside's dolphins are frequently sighted "frolicking" and giving birth in close proximity to the DBM vessels operating closest to the Orange River mouth [25]. Since it is endemic to the region, and of special conservation significance, Heaviside's have been adopted by DBM and are used as the logo for the DBM Environmental Management Team. The company sponsors research on them through the Worldwide Fund for Nature in South Africa (WWF-SA). With increased environmental awareness of vessel-based staff, the company has been able to provide dependable and consistent records of marine mammal sightings on the west coast – a valuable dataset for researchers in an area in which little data would otherwise be collected.

3.1.4 Effects on birds in the Orange River Estuary

The Orange River estuary is a RAMSAR site, and it is thereby designated to be a wetland of international importance. Large numbers of water birds, including pelicans, flamingos and spoonbills characterise the wetland, and are particularly sensitive to aircraft flying overhead.

Flight paths for helicopters used for crew changes and supplies to DBM vessels avoid flying over the river mouth to minimise disturbance.

3.2 Ongoing monitoring requirements arising from the EIA

At the conclusion of the EIA none of the impacts studied were considered to be highly significant for the current scale of the DBM mining operation, and no impacts identified were considered to be sufficiently significant to prevent mining in the area.

The development of the EIA pointed to the fact that DBM is but one of a number of operators and license holders actively mining on the continental shelf of southern Namibia. This raises the need for a strategic assessment of the cumulative impact of all mining operations as the basis for better management of the marine resources [26]. Such an initiative, ideally driven by Namibian governmental bodies, would also critically monitor trends in relative impacts of mining operations in different parts of the Benguela Ecosystem as these are likely to vary from one area to another given changes in the physical character of the sediments forming the deposits.

Three aspects were identified for continued monitoring to better understand:

- The dispersion of the tailings and the extent to which its resedimentation could influence areas in close proximity to the mining operation were identified as an issue requiring further monitoring. The aim of this study is to develop a better understanding of tailings plume dynamics based on more detailed vertical profiler measurement over a longer time frame at stations in and around plumes to determine changes in the currents, salinity, oxygen and turbidity with depth.

- The way in which benthic communities are influenced by, and recover from, mining activities. At the time, the ongoing monitoring programme was designed around annual, ongoing benthic sampling. The aim of the study was to develop better insight into the effect of natural changes in the Benguela Ecosystem and develop the capacity to differentiate them from local impacts directly attributable to mining.

- The influence of mining activities on marine mammals, with special reference to Heaviside's dolphin through twice daily sightings from each DBM vessel to allow trends to be identified and tracked.

3.3 Uniquely Powerful Insights from Direct Observation – Jago and the Future of Impact Studies

The decision to deploy the research submersible *Jago* from the DBM vessel Zealous in 1996 to place specialists down on the seafloor to directly observe the natural environment in which the company operates was a defining moment in the history of DBM. This approach has provided a key platform for innovation through technical and operational observation coupled with the development of new insights into the nature of the marine biophysical environment off southern Namibia and through this, the growth of new expertise. Hence it is interesting to note that [16] advocated this approach for environmental impact assessment of deep-water mining of polymetallic nodules and crusts, which can now be reaffirmed through this actual case study. To date a total of 163 dives have been conducted with Jago from the DBM vessel Zealous, with some 470 hours of video material collected between 1996 and 1999.

Conventional sampling of the marine environment is reliant upon the collection of physical samples. Pelagic and demersal fish abundance and distribution is normally determined using trawl surveys [27]. In Namibia these surveys have resulted in subdivision of the fish fauna into assemblages associated with the neritic zone, the continental shelf and continental slope. Although benthic invertebrates are sometimes caught in bottom-trawls, little information is added about the associated biological environment. Such data are more conventionally obtained using dredges, sleds, grabs or corers. Due to the paucity of data in the region discussed here with the exception of the Challenger and Discovery Expedition reports, these systems were deployed by specialists involved in the DBM funded specialist studies to develop the basis for the EIA [17,18].

It is now recognised that conventional sampling methodologies are influenced by a number of inherent problems [27,28]. In the first instance, dredges, grabs, sleds and corers are only efficient when used to sample soft substrates. In the Namibian environment, where extensive seafloor outcrop of Tertiary and Cretaceous strata occur, this has severe limitations. Secondly, the sample size is generally quite small. As in Mineral Resource Management to develop Mineral Resources and Reserves, problems are encountered with sample support size that impacts on the confidence levels of results and in the worst case this renders data semi-quantitative.

Direct visual observation from a submersible presents an alternative approach to "sampling" the marine biological environment, and allows simultaneous collection of information about the macroscopic benthic organisms and fishes in the context of their physical environment. Deployment of Jago from the specialised offshore survey vessel Zealous, coupled with the extensive high-resolution sonar coverage available to DBM has a further advantage. Extremely accurate underwater positioning to within 5m permits "flight-paths" to be pre-planned, enabling researchers to precisely contextualise their observations within the highly diverse physical seafloor environment allowing observation across the full spectrum of conditions that exist. Hence the physical environment can be characterised in considerable detail and quantitative assessment can be achieved using correct recording equipment and technique (e.g. [29,28]. A further advantage is that behavioural studies in the natural habitat become possible [30,31,32,33].

These studies initiated by DBM represent the first account of the benthic environment and communities in the mid-shelf region of the Benguela Ecosystem based on direct visual observation using a submersible. In addition, although the observational technique precludes an appreciation of the infauna, specially designed sampling equipment operated from a manipulator arm does allow precision sampling of unmined and mined areas for laboratory analysis. This is a significant improvement on conventional techniques, as it reduces the problems that arise through ineffective sampling technique.

3.3.1 Initial Submersible Sampling and Observation

The first Jago dive series supplied video material from 14 dives conducted between 100 to 140 m water-depth over the middle shelf of southern Namibia. The analysis of the biological content was identified as an excellent opportunity to work in collaboration with researchers from the University of the Western Cape in South Africa, led by Dr Mark Gibbons.

Given that this was the first submersible observation to be undertaken on the west coast, and the dives were not designed specifically for biological research purposes, the approach used for acquisition of video coverage proved to be insufficiently rigorous for quantitative analysis. The video camera was not operated continuously throughout each dive, and the levels of illumination used were too low for good videography. In addition, although red lasers were used to provide perspective on size at a constant separation of 50 cm, the laser intensity was too low for easy identification on video.

The video reviewer recorded the major physical and sedentary biological features, counted all nekton within each videotaped segment within a specific habitat. In many instances, more than one physical characteristic applied to the habitats, leading to descriptors such as “soft sediment with scattered cobbles”. New records were started on entry to a different habitat. Synchronisation of the video recorder clock with the Zealous clock allowed cross-referencing based on the on-screen clock so that accurate positional information allowed analysis with respect to the local geology, sedimentology and mining activity. To maintain objective assessment, the reviewer was not informed whether the submersible was positioned in mined or unmined terrain, and sections of video where data was considered to be ambiguous were removed as part of the quality assurance procedures.

At the end of each dive analysis, the quantity of time spent in each habitat was totalled to provide frequency of occurrence data. Whilst relatively crude, this provided insight into how the environment can be partitioned within a dive or summed across dives for comparative purposes. Examining the relationship between nekton abundance and feature frequency assessed associations between nekton and environmental features. Multiple regression was used to analyse the data.

Example of physical and biological descriptions from dive analysis: Dive 14 [27]

Unmined: Sediment thick and textured, with numerous biogenic holes of diverse shape and size. Without sessile fauna projecting through surface. Hard substrata patchy. Boulders large and slab-like, on surface: with thick sediment layer and sparse epifauna on upper face, epifauna more diverse and thick on vertical faces. Small cobbles projected through sediment, scattered (never aggregated in piles) with sparse epifauna. Massive boulders infrequent and with sparse epifauna.

Mined: Sediment thick and for the most part as above. Else thin, flat and with few biogenic holes. Some areas thickly covered with shell debris (common), without any biogenic holes or projecting epifauna.

Cobbles and boulders aggregated densely, often without superficial layer of sediment, completely without epifauna.

3.3.2 Post 1996 Video Transect Analysis

A further dive programme was conducted with Jago during 1997. The primary objectives were to investigate the influence of different geology on mining system efficiency and effectiveness and to characterise different ore body types in detail to aid the interpretation of high-resolution geophysical data. Hence the biological content of videotapes was largely incidental. Some dives were, however, focused on environmental data acquisition.

The video equipment used was upgraded to a digital system and the intensity of the red laser dots for measurement was increased so that they could be readily detected on video footage. As with the previous analysis, video collected when the submersible was stationary, or when it moved off the bottom, or in poor visibility was ignored. Video acquisition was not continuous throughout dives, but at the discretion of the observer. Out of a total of 51 dives, 36 dives were conducted off Namibia.

The initial analysis of video data demonstrated that application of the technique is non-trivial! The analytical method was improved significantly by [28]. The entire videotape for each dive was inspected, but only samples were examined in detail and analysed. Each sample had to meet the following criteria:

- Recorded along linear sections of the cruise track;
- The submersible was moving at a slow but constant speed;
- The visibility was good.

The samples were of multiples of 31 seconds duration and the environment in each sample was categorised by major (>50%) and minor (>20%) substratum type, and all sedentary biological features were recorded as present or absent. All nekton were identified and counted, and these were subsequently converted into densities (m^2) with knowledge of horizontal distance traversed and the width of the video frame. Following quality control, a total of 476 samples were obtained from the complete collection of videotapes. These samples covered an area of 12 087 m^2, and a total of 1 455 transects (between the red lasers) were obtained from the video coverage to analyse the epifauna and infauna communities of the benthos.

More advanced methodologies were used to determine the associations between nekton and features of the physical and biological environment [34,32]. This allowed the species mean to be determined, which reflects preferences for individual species for different variables. From a correlation matrix for all species' means for the measured environmental variables, patterns of habitat usage can be examined. Factor analysis on the matrix can then be used to resolve patterns of interrelationships amongst the variables with the result that trends in habitat use can be determined statistically. It is also possible to compare habitat use between different species. It was found that the application of

Levene's test could also be used to examine whether a particular habitat is being actively selected by a species, which allows impact to be investigated.

Factor analysis was used to reveal the way in which species are distributed along composite environmental axes, and were supplemented by using a variety of other statistical techniques. Comparison of the density of demersal nekton between different sites is complicated by the dissimilar distribution of samples from video transects and the fact that distinct associations with substrata do occur. It was possible to partially resolve these problems by examining substrata by comparison on the following basis:

- Disturbed vs. Undisturbed, soft vs. Mixed vs. Hard;
- Disturbed vs. Undisturbed, Assorted Major Substrata

In order to try to understand behaviour of the demersal fishes in their natural environment, the activity of each demersal fish was assigned to one of the following behaviours [28]:

- Hovering off substratum
- Positioned on the substratum
- Swimming in the water column
- Positioned in a crevice or under an overhang
- Occupying a shelter hole
- Buried (fully or partially) in the substratum.

Observations on the substratum on which fish were seen were also recorded to try to correlate behaviours to the physical environment. Hence the activity of each of the dominant species of demersal fish was analysed. Perhaps surprisingly for people who have not experienced diving in submersibles, no fish species has been found to flee the craft until it is next to them [27,28]. However, seals have been known to quickly realise the opportunity of enhanced hunting during dives off Namaqualand on the west coast of South Africa. Not only is this a hassle for the fish, but also for the Jago observers who disappear in clouds of suspended silt due to the frenzy of external activity. A notable, if unusual observation is then that seals are pretty tricky to shake off in a slow moving submersible!

Gibbons et al [28] recorded counts of all sessile macro fauna for a minimum of 10 "video samples" for each dive from a habitat of uniform substratum over a 50 cm transect delineated by the red lasers. Whilst species identification was not always possible, they were assigned to a specimen type. Descriptive, multivariate statistics were used to examine relationships among samples to see whether any horizontal pattern in the assemblages could be observed. Summary statistics describing the community were computed for each "sample" to estimate species richness, diversity, and evenness of distribution. The impact of direct disturbance from mining on communities was examined together with the areas surrounding mining activity through the influence of the plume generated by mining operations. However, since the level of knowledge about plume movement is too low to fully account for it, approximation was required using minimum and average distance from mining activity. Attempts were also made to differentiate the effect of indirect impact on soft and hard substrata.

3.3.3 Impact of Disturbance At Seafloor Mining Sites on Biodiversity and Seafloor Community Structure

Results from the classification analysis indicate that epifauna from disturbed hard substrata more closely resemble the fauna of sandy substrates than they do fauna from undisturbed hard substrata sites. The overall diversity, richness and abundance of epifauna are reduced on disturbed substrata. This is a direct result of the mining and treatment process, which strips the epifauna from the gravel clasts before they are returned to the seafloor [28].

Evidence was found to show that the disturbance causes a reduction in the diversity of nekton. A total of 25 species of nekton was observed during video analysis. Only 9 were sufficiently common to permit further analysis, which showed that these species are associated with either rocky and/or soft substrata and that they show a strong or weak selection for the associated biota [28]. The nekton study demonstrated that submersible video transect analysis is a valid technique for fish stock assessment. However, the cost is a prohibiting factor. The introduction of Autonomous Underwater Vehicle technology (see section 3.4) may overcome this barrier in the near future and allow larger areas to be surveyed remotely.

If all offshore seabed-mining impacts were destructive, resulting in long-term sterilisation of seabed, the concept of "chronic artificial disturbance" previously discussed with the ISA [16] would unquestionably be alarming, and the future of the industry could be in doubt. However, in the continental shelf environment studied by DBM, it can be demonstrated that sterilisation does not occur, based on both conventional sampling, which indicates that recovery can occur in 4 to 8 years and from submersible-based visual observation.

More recently direct seafloor observations have indicated that in some instances mining disturbance can promote environmental enhancement, for example by resulting in increased habitats through surface rock exposure for rockfish such as false jacopever [9]. Non-west coast examples of environmental enhancement have also been reported, principally by environmental studies linked to the aggregate dredging industry on the Scotia Shelf of Canada, where environmental enhancement has resulted in improvement of lobster habitat [35]. In other instances, dredging practices are being reviewed to examine the possibility of deliberately creating new fishery habitats where future aggregate extraction is being planned [36]. It is too early to determine whether similar effects are resulting from deepwater diamond mining on the west coast of southern Africa.

3.3.4 Impact of Resedimentation and Artificial Plumes

Offshore diamond mining generates a plume of suspended sediment at the surface. The direction the plume travels as the material settles changes with depth. Transport is to the northwest at surface and to the south at depth [37].

The analysis of Jago video transects has provided clear evidence of impact on the epifaunal species diversity, richness and total abundance at sites surrounding those areas impacted directly by mining tool disturbance [28]. The research indicates that there is a minimum distance (100 to 200 m generally) from mining sites beyond which the epifauna is not negatively impacted by mining activity (Figure 4). Similar relationships have been noted in numerous studies of pollution in the marine, freshwater and terrestrial environments.

The research findings based on visual observation are less conclusive in terms of the infaunal communities, as it is currently difficult to determine which organisms are responsible for the different types of holes and mounds observed. It is however clear that the density of burrows is significantly less in mined sites than it is in those furthest from mining activities [28]. At this point, it can only be concluded that more research is required to determine the disturbance of infaunal abundance.

3.3.5 Resedimentation and Artificial Plumes vs. Large-Scale System Variability

Although Jago observation has demonstrated that bottom currents are unlikely to entrain fine-grained seafloor sediment [38], dives with Jago have provided new insights into large-scale natural processes. In particular, a dive in November 1996 by Rob Smart of DBM was badly affected by a 2 m ground swell running on the seafloor in 126 m of water. This event severely buffeted Jago and caused the submersible to be trapped on the seafloor for a period of 20 minutes after an appendage was rammed under a large rock slab. Visibility rapidly declined due to the suspension of fine-grained sediment in the nepheloid layer directly above the seafloor. Although not previously recorded, such events must be responsible for widespread sediment entrainment, suspension and resedimentation, and the Jago team has noted that visibility has been very poor due to similar conditions in areas far removed from the direct influence of DBM mining activities (Hissmann, pers. Comm., 2000). This demonstrates the difficulty of differentiating natural events from the more localised suspension and resedimentation of fine-grained sediment through mining activity in continental shelf environments. In addition, should natural events of this sort result in oxygen depletion of the bottom water on the shelf, natural catastrophism of the benthos could result. Depending upon the frequency of such events, this could mean that elements of the benthic community that are unable to escape the effects of oxygen depletion might frequently be in a state of recovery. This may add to the prevailing harshness of the environment related to frequent intrusions of low oxygen bottom water [39].

Observations such as these demonstrate that we are only now beginning to understand the dynamics of the large-scale Benguela Ecosystem in sufficient detail to meaningfully interpret impact from mining. This demonstrates not only how complex it is to discriminate between natural and artificial impacts, but also the quality and quantity of data that are required to make this possible.

3.4 Future Innovation in Video Transect Application to Environmental Monitoring

DBM is currently awaiting the delivery of an Autonomous Underwater Vehicle (AUV). Implementation of this vehicle will revolutionise the acquisition of geophysical data. It also presents many exciting possibilities to enhance the application of low-cost video transect acquisition as it will be possible to operate the AUV at significantly reduced cost compared to a conventional research submersible such as Jago. There is, however, no doubt that there is a definite place for both approaches. The use of Jago has proved invaluable in the development of interpretative expertise, for example in this previously inaccessible environment for people.

The introduction of AUV technology should make it possible to establish fixed sites for continuous monitoring using video transect technology. This paves the way for more frequent video data acquisition over control sites and mined areas as the basis for more detailed assessment of recovery rates which, due to Jago, are now known to vary significantly for different biophysical environments within the Benguela Ecosystem. More frequent data acquisition also promises to shed further light on the dynamics of the Benguela Ecosystem, as the AUV will continuously gather CTD data as part of its normal survey acquisition programmes. Mapping to determine the influence of resedimentation patterns on the health of the benthic community may also become a practical reality with the development of increasingly advanced remote survey capabilities.

Working with researchers from Herriot-Watt University, De Beers Marine has developed new techniques for mosaicing video data to produce a seamless image that is more readily viewed by the human eye. Due to the precision with which AUV technology can "fly", it will be practical to use this approach for the analysis of video data for the first time. It is believed that this will enhance results, as it will improve the interpreter's appreciation of spatial context, which has always proved to be a difficult aspect of underwater video work.

4. DBM-Driven Scientific Interaction and Development

From the outset, DBM recognised the need for and/or benefit of:

- Specialist scientific input in developing its approach to offshore environmental management;

- Involvement of the *local* scientific community in specialist research on the physical and biological characteristics of the Benguela Ecosystem;

- Collaboration with local academic institutions to use opportunities presented by the offshore diamond industry to develop expertise in South Africa, Namibia and other countries in which the company may operate in future;

- External independent assessment to ensure transparency and independent quality assurance throughout the process [40,41,42].

Pursuit of these objectives continues to be a rewarding aspect of involvement with DBM, as the nature of the operation presents a rich and diverse array of opportunities for research and education interaction together with interaction with internationally recognised specialists in the greater scientific community.

The Environmental Management Team has forged numerous mutually beneficial partnerships with academic and research institutions in southern Africa. Such interaction is recognised as being an important part in assuring rigorous high-quality research and is a source of inspiration and innovation. Partners gain through the many opportunities presented for novel research on material provided through the activities of DBM and their ability to contribute to the development of knowledge about the Benguela Ecosystem. Interaction also serves to heighten the environmental awareness of DBM employees who for example, continue to greatly enjoy interaction with world-class scientists with a passion for the natural environment.

The collaborative partnership with the University of the Western Cape to analyse Jago video footage is a good example [43]. In addition postgraduate research projects have ranged from studies of jellyfish, sponges and bryozoans to more general ecological projects. Undergraduate students are also regularly involved in sample sorting during DBM's environmental research, which contributes to their biological training.

Given the significant role that the marine resources play in Namibia's economy, similar involvement has been initiated by DBM with the University of Namibia (UNam) where a B.Sc. course has recently been established in Natural Resources. In this way the company aims to encourage the study of marine biology by Namibian students to create opportunities for capacity building amongst the local scientific community. Such expertise will be essential for the government to produce a strategic management plan based on the study of the cumulative effects of impacts by the diverse users of marine resources.

UNam students are provided with material for project work, and visit the Environmental Management Team to learn about seabed sample analysis. The scope of involvement from DBM has increased this year, with students spending a six-week experiential training period with DBM as the basis for four student projects. These varied from Jago video analysis to seabed species identification to analysis of DBM meteorological data to investigate correlation between environmental factors such as wind and swell conditions with rock lobster catches on the Namibian coast.

Interaction with the University of Cape Town and the University of the Orange Free State has produced a further four MSc theses based on environmental research undertaken for DBM on the impacts of deep-sea diamond mining.

All of DBM's vessels collect twice-daily sightings of Heaviside's dolphins and other marine life in their vicinity. A final year Cape Technikon student spent a three-month experiential training period with the Environmental Management Team sorting seabed samples, and analysing the sightings. The results were presented at a national marine science conference.

As will be seen from the above examples, the application of direct visual observation using the Jago submersible has created numerous opportunities. DBM also donated five dives off the Cape south coast to the South African marine scientific community in 1996 to mark the centenary of marine science in South Africa. The dive programme between 40 and 386 mbsl produced the first direct observation from a submersible off the Cape Point nature reserve and at least one new species to science was recorded together with many new and novel observations [44,45]. The dive programme was used to increase marine environmental awareness throughout the nation through the broadcast of a documentary on 50/50, an environmental programme produced by the SABC. Many aspects observed using Jago have also been broadcast throughout Europe, and especially in Germany, through the documentary films produced by Professor Hans Fricke. In particular, DBM contributed footage to his latest film, which explores the fauna and flora of the west coast influenced by the Benguela Fog – a phenomenon on which many endemic organisms depend. The opportunity to dive in the Jago has also been made possible for staff from the Namibian Ministry of Fisheries and Marine Resources and the Ministry of Minerals and Energy and academic institutions.

The collaborative partnership that has developed between DBM and the Jago team consisting of Professor Hans Fricke, and Drs Jurgen Schauer and Karen Hissmann continues to be a particularly important one. This interaction with world-class scientists is stimulating for all involved and serves to increase environmental awareness throughout De Beers.

It is DBM's hope that the Benguela Current Large Marine Ecosystem Project funded by the United Nations will provide the financial and scientific basis for an integrated assessment of mining (and other) impacts to examine the cumulative impact of the offshore mining industry. The industry has demonstrated environmental commitment and interaction with other marine resource-based industries in order to qualify for support. The project will cover the continental shelf of South Africa, Namibia and Angola, and has potential to do much to build the scientific capacity within those countries and contribute significantly to science generally.

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SUMMARY OF PRESENTATION AND DISCUSSIONS ON A CASE STUDY IN THE DEVELOPMENT OF AN ENVIRONMENTAL BASELINE IN LARGE OPEN-OCEAN SYSTEMS OFF SOUTHERN NAMIBIA BY DE BEERS MARINE AND ON A CASE STUDY IN THE DEVELOPMENT OF THE NAMIBIAN OFFSHORE DIAMING MINING INDUSTRY

Presentation

Dr. Ian Corbett, Group Mineral Resources Manager, De Beers Placer Resources made a second presentation to the workshop on "A case study in the development of an environmental baseline in large open systems off Southern Namibia by De Beers Marine." At the outset, he said that presentation would attempt to provide participants with the practical approach adopted by De Beers Marine in terms of developing an environmental baseline and also in actually evolving that process into an environmental management system within the organization.

Dr. Corbett said that although the focus of his second presentation would be Namibia, De Beers Marine also operates over a very extensive area of some 26,000 sq. kilometres of the South African continental shelf as well. With regard to the macro scale oceanographic conditions in which diamond deposits occur, Dr. Corbett said that Cape Town is essentially the area in which De Beers Marine operates and the principle oceanographic current that influences the region is the Benguela Current (Figure 1). Recently, he said that research following upon work that was accomplished in the 1970s and the 1980s has provided a better understanding of the macro scale Benguela system. He said that the system consists of two components. He said that one component is the deep ocean, and the other, the coastal current of the Benguela system. Dr. Corbett said that upwelling occurs extensively within the coastal current of the Benguela system, making this area one of the highest biological productivity areas that are known on the continental shelf. Dr. Corbett also said that the upwelling system is driven by the southerly and southwesterly winds, which are extremely high energy. He recalled that he had mentioned in his first presentation that the wind system in this part of Namibia is one of the highest wind energy systems on the planet and probably the highest outside of the Antarctic region. He said that given the biological productivity in this area, there are large fisheries present off the west coast, starting from the Orange River, going up into Northern Namibia, and extending into Angola. He also said that this is an area that is in demand by a large number of different users of marine resources.

He stated that these other uses of marine resources in the area has a key bearing on the way De Beers Marine has been looked at, and the evolution of its approach to environmental management. With slides, Dr. Corbett showed the relative proximity of areas of rock lobster and other fisheries to the Atlantic 1 Mining Licence that is one of De Beers' diamond producing areas on the continental shelf.

With another slide, Dr. Corbett said that a further feature of the macro scale Benguela system is that there is natural low oxygen depletion in the system. He indicated an area up in the north in which he said oxygen is depleted from deep water. He also pointed out an area on the continental shelf characterized by natural low oxygen conditions, that he said actually lies right over an area in which De Beers' mining operations occur. He emphasized the fundamental importance of an overall understanding of the marine life in that region.

Dr. Corbett informed participants that one of the other principal natural phenomena on this coast is the discharge from the Orange River into the Atlantic, periodically flooding the Benguela system. Dr. Corbett said that this discharge contains large volumes of suspended materials that are flushed out onto the continental shelf, creating extremely large sediment plumes out. He said that unlike the deep ocean where sedimentation from land sources is very low, this area is subjected to very large inputs. Another contributory phenomenon according to Dr. Corbett is the easterly winds that blow vast volumes of dust from the Kalahari Basin to the coast.

Dr. Corbett said that in 1990 when the whole issue of environmental impact assessment was first being looked at in considerable detail, De Beers tried to grapple with the state of knowledge of the natural variability within the ecosystem as distinguished from impacts from mining. De Beers had to ask itself if the level of knowledge about this ecosystem was sufficient to allow the differentiation of the local scale environmental impact driven directly by mining as opposed to the very large macro scale natural events in the system. He stated that during his presentation he would show that knowledge of these macro scale events, many of which were never known before, is still being developed.

Dr Corbett said that his presentation would provide an overview of the environmental milestones achieved by De Beers, and what is required to drive a major environmental programme such as the programme operated by De Beers. He also said that De Beers Marine was the first diamond-mining company in the world to be certified with ISO 14001.

Dr. Corbett informed participants that the first environmental impact statement completed by De Beers was in 1996. He said that De Beers Marine initiated the assessment as a self-regulatory matter. He said that at the time, there was no legislative requirement for environmental impact assessments. He said that the decision to undertake this work was made in 1990, when the management of De Beers realized that protection of the environment was going to be fundamental to the long-term sustainability of mining operations. He said that the work that was initiated in 1991 involved a very considerable volume of research, and a very large number of local specialists. He said that the view was taken that for the studies to be really meaningful, the best way forward was through the use of the available local experts whom would also benefit from the inter-action with industry. In 1997, Dr. Corbett said that De Beers decided to implement ISO 14001. He informed the workshop that the work required to achieve the ISO 14001 status was concluded during 1998, with certification granted in that same year. He also said that NAMDEB is currently in the process of certification and that so far, the audit has gone particularly well for a large operation onshore.

In relation to how the environmental management team of De Beers Marine evolved, Dr. Corbett said that De Beers has pro-actively taken a very open policy with its environmental work and, recognizing that as an industry, it has a contribution to make to the scientific community, creates many opportunities by its presence in the offshore environment. He said that over the years De Beers Marine has been a large contributor to the creation of national databases for oceanographic research. He said that this has been achieved through external partnerships with independent scientists whose work is judged credible by the scientific community, both nationally and internationally. He said that the work De Beers asks of the scientists provides them with an opportunity to be able to enter into contracts with the organization, to design and review work, and in that way contribute to their own scientific research. He said that this approach allows De Beers to combine research expertise. As an example, Dr. Corbett said that De Beers has developed some very innovative approaches to the analysis of video transects using Jago footage with the University of the Western Cape.

Dr. Corbett said that De Beers is linked to the Namibian Ministry of Fisheries and Marine Resources and the South African Marine and Coastal Management Department. He also said that De Beers works with the University of the Western Cape, the University of Namibia, the University of Cape Town, and the Cape Technocon. He described as most important De Beers' alliance with the Max Plank Institute in Germany, in particular with the team led by Hans Fricher who operates the Jago submersible.

With regard to the organizational base of De Beers Marine, Dr. Corbett said that it covers a very large area of the country – some six to seven hundred kilometres between Cape Town and Oranjemunt. He said that it includes offices in Namibia, Walvis Bay and Windhoek, store facilities in Port Nolloth in a small town called Darling to the North of Cape Town and in Cape Town itself, Suldana Bay where there is a port that we operate from occasionally, and the port of Cape Town where De Beers' principal office is located. Dr. Corbett said that the adoption of ISO 14001 by De Beers has created responsibility and accountability throughout the organization, and that a core team for environmental management has been established. He said that the team consists of a number of technical experts led by Dr. Patty Wichens who is a marine biologist. He said that De Beers also has a team that spans the entire breadth of its operations, engineering, commerce, stores and logistics, and that this group is supported by a team of environmental researchers. He pointed out that this team is net worked throughout the organization by a group of environmental monitors. He said that the environmental monitors are placed on vessels and onshore, and play a key communicational role throughout the entire organization. He also said that this arrangement has proved to be extremely important in terms of making this process work.

Implementation and Operation

Dr. Corbett said that training and awareness building have been the keys to the success of the environmental management system developed by De Beers. He said that as part of the system, there is a process of self-regulatory checking and corrective actions, such as auditing and incident reporting. He pointed out that in addition to helping to protect the environment, the system is also improving the productivity and efficiency of the company as a whole. He said that all the reports have to be reviewed by senior management, specifically the Executive Committee of De Beers Marine on an annual basis. In addition he said that there is an independent audit that is conducted on a regular basis.

With regard to waste management, Dr. Corbett said that for the offshore fleet, waste is collected by a launch or tug and taken to Port Nolloth, south of the Orange River. From here, Dr. Corbett said the waste material is transported to Cape Town by lorry. Dr. Corbett said that the waste material is re-cycled or disposed of in Cape Town. He said that one of the most important aspects of the whole process is the compilation of reports. He said that the reports have to look at a variety of parameters. These include legal, economic, natural and social parameters that contribute to a thorough baseline information data set.

He pointed out that it is important to identify all activities that are to be carried out, in particular their duration, what techniques and technologies will be involved, and where they aware to take place. He said that through the analysis and the assessment of these kinds of information it is then possible to create a baseline for environmental impact assessment. With the baseline and an understanding of what is to happen, Dr. Corbett said that one is in a position to develop the environmental management programme. He said that it is important that that process takes in as broad a spectrum of science as possible, given that the ecosystem under study is a complex natural environment. He said that reports are given to the relevant government department that analyzes them and requests revisions as appropriate. When the reports are approved, Dr. Corbett said they constitute the environmental management report. He said that the report becomes a legally binding contract between the organization and the government department involved.

Dr. Corbett said that internal auditing is on a monthly and per voyage basis by vessel. He said that the environmental management team itself does quarterly audits and that the South African Bureau of Standards, the accredited body for ISO 14001 certification, visits the organization's operations on a six monthly basis to survey what is going on and ensure that the company is doing what it said it would.

In terms of communication, Dr. Corbett informed participants that De Beers has developed an extremely detailed Internet site, which is available over satellite link to their vessels at sea and to all the staff involved in environmental issues. He said that the site gives everyone live access to any updates that become available.

Dr. Corbett explained that as a result of the environmental impact assessment, De Beers Marine undertook a review of its approach to waste management. He said that the organisation examined the provisions of the MARPOL Convention and decided to meet these requirements and, wherever possible, to go beyond them.

Based on this decision, Dr. Corbett said that De Beers Marine then adopted a cradle to grave approach for the full spectrum of waste types it generated so that again, wherever possible, waste is separated and treated on site. He gave an example of the tracking system under the ISO 14001 framework. He said when De Beers Marine brings its waste onshore; the load is monitored through the full spectrum of the logistical operation. He said that when the waste brought to shore, there is a transfer log that keeps track of any waste that is moved from the launch to the jetty. He also said another set of receipts are provided at the jetty for the dispatch of waste to disposal sites

He said that there are differences between the approach to environmental management offshore and onshore. Onshore, Dr. Corbett said that there would be a rehabilitation programme, but that offshore this is not a practical consideration. He said often, in trying to rehabilitate the environment, further problems and complexities in terms of the environmental response are created. He said that at De Beers, rather than rehabilitation the focus is on understanding the impacts in some detail, monitoring those impacts, and minimizing the overall long-term effects. He said that monitoring the habitat is a good approach because it provides a very clear indication of environmental health. At the same time, he cautioned that it is very important to be able to monitor and assess the natural variability of communities within the habitat and to be able to look at the impact of mining on these communities.

In this regard he said that a key issue is to determine how quickly impacted areas recover. From the work of De Beers, Dr. Corbett said that a principal finding is that impacted areas never become sterile. He said that it has been found that there may be a very brief period of sterility after initial mining, but that within a very short period of time, pioneering communities come to re-colonize these areas of the seafloor.

Dr. Corbett said that based on the history of mining by De Beers in the region, it has been able to implement a continuous monitoring programme to gain more insight into the community structures on the sea floor, and the severity of mining impacts on these communities.

He defined two types of mining impacts; direct disturbance of the sea floor caused by mining tools that are actively extracting the gravel from a given area, and the other as the disturbance caused by the settlement of tailings plumes.

With regard to the condition of the seafloor after mining, Dr. Corbett said that it appears as a series of overlapping circles of disturbed ground caused by the large bore drills. He said however that based on the science for studying these impacts; the approach to monitoring them is with two basic techniques that follow conventional grab sampling.

He described as a major transformation of this approach the use of the Jago submersible. He explained that during dives, the Jago provides video transects that can be analysed in some detail. He said following bottom grab sampling, control sites comprising undisturbed areas on the soft seabed that are uninfluenced by mining and an area that has been mined can be set up. Thereafter these sites can be used to deduce whether there are differences due to mining or natural disturbances. At the same time, he said that mined out areas have to be sampled over different time intervals to look at the recovery of the community.

Dr. Corbett informed participants that Dr. Mark Gibbons, a researcher at the University of Western Cape is in the process of publishing a number of papers on this type of approach. He said that the approach enables researchers to obtain a good analysis of the changes in the seabed communities between the disturbed and undisturbed areas at a much higher confidence level. He pointed out that with a grab, even if equipped with a camera, one does not obtain a real context of the sampling area whereas by flying over the area in a submersible, the human brain is able to absorb the perspective. He also said that this approach enables a researcher to create very specific sampling programmes and to obtain results at a very high confidence level. He stated that the approach has opened a new window on the marine diversity within the Benguela Ecosystem and resulted in the creation of a very important data set for De Beers for environmental management of mining operations, and for other users of marine resources such as the fisheries community.

Dr. Corbett said that the work conducted by De Beers with the Jago submersible has allowed it to interact extensively with the scientific community. He said De Beers donates a number of dives to various members of that community for their own research dives whenever it uses the Jago.

In summary, Dr. Corbett said that De Beers is producing unique data sets based on the Jago submersible and grab sampling. He said that this approach allows De Beers to look at local scale, short-term changes. He also said that De Beers has learnt that mining alters the habitat on the sea floor, but that the response is different for different animals. With regard to the long-term perspective, Dr. Corbett said that it is only through long-term baseline datasets that one can really start to understand the impact of mining and the disposal of sterile material originally recovered from the seabed back to the seabed, He said that one of the things that has been found is that when the material is dumped over board, it can create what is termed by some Canadian scientists as environmental enhancement. He noted that in parts of Canada on the Scotia shelf, this process has been able to regenerate the lobster stocks through aggregate extraction, which creates breeding ground scenarios where formerly the lobsters were at risk. In this regard, he asked whether in fact De Beers is enhancing the environment in a way that could, for example, enhance the fisheries stocks in Namibia?

He emphasized that it is to be appreciated that the Benguela ecosystem is a dynamic environment with natural variability both in time and space. Dr. Corbett said that in 1997 employees at De Beers were able to witness a 2 to 3 metres swell operating directly on the sea floor in 126 to 128 metres of water. He said that employees were able to watch a natural event where vast volumes of the very fine silts on the sea floor were picked up and suspended in a column, that was about 50 or 60 metres thick. He noted that this event had never been witnessed by anybody previously. He said that this event showed that there are very large-scale perturbations in the natural system that may be caused by internal waves impinging on the continental shelf. He also said that these natural events have the capacity to create low oxygen conditions over vast areas of the continental shelf. He suggested that the overall cumulative effect of mining i.e. the settlement of the plume generated from the surface, the discard that goes back to the sea floor, and the action of the mining tool need to be looked at in terms of seas adjacent to mining areas.

In terms of the future, Dr. Corbett made the observation that significant changes would occur as a result of the new autonomous underwater vehicle that is under construction by De Beers for deployment later in 2000. He said that this is because with one an autonomous underwater vehicle the seafloor can be traversed in transects. He said that equipped with high quality video acquisition systems, these autonomous vehicles could help to produce video maps of the sea floor. He was of the opinion that this is going to be a fundamental leap forward for studies of benthic communities and other communities in the Benguela system.

To conclude his presentation, Dr. Corbett said that the approach to environmental management by De Beers is long-term and has to be looked at over a period of time. He said that the first step is setting up the control sites and a transect area. He said that the second step is continuous monitoring of the sites. He pointed out that although the Jago is presently being used for this purpose, the introduction of the autonomous underwater vehicle promises a great deal of excitement. He said that the AUV could be deployed at anytime and at a fraction of the cost of submersible deployment. He stated that opportunities are forthcoming with this type of work by De Beers Marine, and that it would promote valuable research by scientists. He spoke of the benefits to be reaped through this work by other members of the Namibian and South African research communities, in particular students, and mentioned the use of data obtained from this work by students working on their MScs and honours projects at the University of Namibia. Dr. Corbett said that De Beers Marine is linked to the Benguela ecology programme and is a major sponsor of the Two Oceans Aquarium project which is one is the foremost aquariums in the world and linked to the World Wildlife Fund. (WWF).

Finally, Dr. Corbett said that De Beers Marine believed that the scientific studies that the organization has been involved in have increased its knowledge of the impact of deep-sea diamond mining on the environment. He said that the studies provide new insights into aspects of the Benguela ecosystem that are beneficial to many people. He ended his presentation saying that underlying philosophy of De Beers Marine is the belief that if you take a responsible approach to offshore mining it not only creates wealth but it can also create a very diverse and wonderful spectrum of scientific opportunities.

SUMMARY OF THE DISCUSSIONS

During the discussions on the case studies in the development of the Namibian offshore diamond mining industry, and in the development of an environmental baseline in a large open-ocean system off southern Namibia by De Beers Marine, the focus of participants questions were in five areas. These were with regard to the productivity of the drills used in offshore mining, the grades of deposits in production, the long-term impacts from mining, the impact of plumes and tailings disposal on the seabed on seafloor communities, the applicability of ISO 14001 to deep-sea mining of nodules, sulphides and crusts, the comparative costs of using manned versus unmanned vehicles for observations and measurements in the deep ocean, and the cost of the environmental work undertaken so far.

Dr Corbett was asked about the productivity of the drilling machines that he had described, in particular the quantity of ore recovered per hour. He was also asked about the grades of the deposits that De Beers is currently mining. In response, Dr. Corbett said that there has been a lot of proprietary knowledge that has gone into developing this offshore industry, new technologies, neo-science and also the security of the product. He pointed out that the acquisition of data in the offshore environment is a very expensive. As a result, he said that from a De Beers Marine perspective it has to guarantee the security and confidentiality of the commercial data that it holds and uses on behalf of its clients. He therefore informed the workshop that he could not provide answers to these questions since they the responses had to do with commercial data. He did however say that the productivity of the drilling machines vary quite significantly around the different types of terrain. He also said that while he could not provide the workshop with the actual grades of ore that is being mined, the grades are low and in some areas, comparable to the type of grades that one would see in terms of the raised beaches in Namibia that have been published.

A participant asked Dr. Corbett the area of the seabed mined each year and the total area that had been mined so far in De Beers' operations. It was noted that since the mining process is locally destructive, mining would result in the extermination of all the benthic communities in the mined area. Another participant wanted to know whether De Beers Marine had determined the likelihood of species extinctions and identified the species that might be affected. Dr. Corbett was also asked if De Beers Marine had undertaken an environmental impact survey prior to mining the area.

Dr. Corbett said that generally speaking De Beers Marine mines between 2 – 3 square kilometres per annum, and that since the start of operations about 10 sq kilometres of continental shelf had been mined. He pointed out that mining the seabed does not result in the creation of a desert, but that life returns to mined- out areas and re-colonizes them at a very early point. Dr. Corbett said that the recovery of the seabed communities is in the order of between 4 – 8 years, but like all things it is not the same everywhere, depending on the type of substrata and the communities involved. Dr. Corbett emphasized that the deployment of the new AUV should result in a major benefit because De Beers would be able to conduct better monitoring operations and to examine recovery rates in these areas in more detail. In relation to possible species extinctions and identification of the species that might be affected, Dr. Corbett described them as fundamental aspects of the work in environmental protection. He said that at the moment, De Beers Marine is in the process of establishing the database that would allow the organisation to investigate these of issues.

As to whether De Beers Marine had conducted an environmental impact survey before initiating mining operations, Dr. Corbett said that the organisation started a survey once it proved that it could mine the area. He described the process as evolving in so far as De Beers Marine was not in a position to set up a lot of data ahead of that realization and the decision to go ahead with mining.

A participant wanted to know whether De Beers Marine had links with oceanographers and meteorologists who could assist in predicting windows of operation, and points where tailings could be disposed of, given the high-energy environment within which operations take place. Another participant wanted to know how far down the water column tailings disposal takes place. This question was in relation to the residence time of tailings in the water column and its impact on marine life. Another participant wanted to know whether or not De Beers had examined the impact of plumes on marine life in the water column in view of the

Upwelling that occurs on the shelf, and highly rich marine life. Yet another participant wanted to find out whether De Beers Marine had conducted fish counts before mining started and then monitored the fish to study migration patterns at the mines and in proximity to them.

In response to the question about the links with oceanographers and meteorologists to assist in predicting windows of operation, Dr. Corbett said that De Beers has a very wide network of links with the scientific community. He said that De Beers Marine works extensively with oceanographic units and that it considered this a fundamental requirement in the establishment of a baseline for environmental work. He pointed out that outside the military, De Beers Marine is probably the highest resolution survey and mapping organization in the world. He said that there is therefore a lot of interest in De Beers Marine to collaborate with university research departments and to engage in activities such as sonar development high-resolution Chirp development. He also said the MARIDAN project was borne of that kind of sort of alliance and collaborative interaction.

With regard to the question on how far down the water column to dispose of tailings, Dr. Corbett said it is quite a complicated thing to dispose of the tailings far down the water column. Additionally, he said that it is uncertain whether there would be significant benefits from disposing of the tailings close to the seabed. He said that this was an issue to be investigated along with a few others on the effects of the plumes generated during mining. He pointed out however that the material that formed the tailings was rather coarse, resulting in a rapid settling time.

As concerns the impact of plumes on marine life, Dr. Corbett explained that there are two very active aspects to the dynamic Benguela system. One is the upwelling and the other, the swells that are generated in the southern ocean. He said that these cause turbulence and mixing in the water column. He said that both factors were examined in detail. He said that there is evidence to show that the turbidity increases in the water column for a period but that one of the things that came through as well was that the overall size range of the material in the plume is quite coarse, so settling is quite quick. He said that the measurements show that the overall effect on the water column is limited to less than a kilometre away from any one vessel at any one time. He described this as a very small-scale effect, and not a dramatic effect on the water column.

The participant from Saudi Arabia recalled their experience twenty years ago in the Red Sea. He said that during their experimentation with tailings from mining the Red Sea muds, the tailings were disposed of at different levels. He said that the tailings were marked with a tracer to monitor the dispersion of sediments. He pointed out that the scientists that were involved in the study were not concerned with large sediments but rather with the ultra fine particles. He said tracing continued for over one year after the mining experiment, until a good idea of where the particles settled had been obtained. He suggested that the report of this experiment might be useful to De Beers Marine. He also informed the workshop that the report on the study is available at the University of Hamburg as well as Cambridge University since their collaborators were associated with these institutions.

In relation to the question on fish counts, Dr. Corbett said that a very wide body of evidence worldwide suggests that conventional sampling technology does not work very well for conducting fish counts. He said this technology has limitations because it introduces biases in the estimates. He said that with the use of a submersible, a completely new understanding of the fish in a given area could be established. He said that the University of the Western Cape completed this study the previous month for De Beers Marine. He pointed out that De Beers Marine is still studying the problem, and that their operations might change the mix of fish in any mining area.

Stating lack of familiarity with the ISO 14001, one participant asked Dr. Corbett about the implications of this standard, the difficulty De Beers Marine had with its implementation, and whether these standards could be incorporated into environmental protection regulations for mining in the international area. Dr. Corbett was also asked if he felt that the adoption of these standards for deep seabed mining would ease the concerns of environmentalists as regards the impact of mining.

In his response, Dr. Corbett said that the ISO provides a kit for developing a framework for managing environmental impact in any aspect of an operation. He also said that it is a standard that could be used for mining in the international area. He said that subsequent to De Beers Marine going in that direction, a number of other operators off Namibia have also adopted this standard. In relation to the concerns of environmentalists as regards the impact of deep-sea mining, Dr. Corbett said that the IS0 140001 standards provide the outside world an auditable window on the conduct of an organization. He said that they provide a framework that is internationally recognized with a science back up and that is of a good standard. He said that these two points ought to commend the standards to environmentalists.

It was pointed out by a participant that there has been recent work in the United Kingdom on plumes with an AUV fitted with Light Scattering sensors (LSS). He said that although these sensors will eventually be used for hydrothermal monitoring or sniffing, this technology seemed to be ideal for looking at a plume disposal. Dr. Corbett acknowledged the potential of this technology, stating that part of the problem with actually monitoring a plume particularly in a system that is a very dynamic is that mixing is very fast. He said that with an AUV equipped with such sensors, the results would be very useful.

On the comparative costs of manned versus unmanned vehicles for measurements and observations in the ocean, one participant stated that operators of the manned submersible Alvin had informed him that the cost of using this submersible is the same as using an AUV because the costs are in the personnel. He told the workshop that outside of the personnel that are part of the dive, the same team is required to operate and maintain either vehicle. He asked Dr Corbett for the reasons why De Beers Marine believes that costs would be lower for an AUV. Dr. Corbett pointed out that in De Beers Marine's operations, there are five vessels permanently stationed in the mining area. He said that this means that no other vessel is needed for deployment, and eliminates the over-riding overhead costs.

Finally, Dr. Corbett was asked what percentage of the cost of the project he recommended should be invested in environmental studies. He responded by stating that because very large sums of money are involved in the project, he could not provide a figure for environmental studies. He said that De Beers Marine sees a cost- benefit in its environmental work, noting that a number of communities have benefited from it. He pointed out that the cumulative effect of environmental impact need to be looked at not just from an offshore mining point of view but also from the viewpoint of the spectrum of marine uses of the resource. He was of the opinion that the mining industry had invested significantly in doing environmental work, not just De Beers Marine and NAMDEB, who have done extensive work in the coastal zone, but also other companies that are operating in the marine environment. He suggested that one of the roles of the Namibian government would be to bring together the data sets on this environment because it is an extremely valuable data set. He informed participants that there is currently a programme between the South African, the Namibian and the Angolan marine scientific communities, funded by the World Bank or the UN, on the marine ecosystem.

CHAPTER 17

EVALUATION OF THE NON-LIVING RESOURCES OF THE CONTINENTAL SHELF BEYOND THE 200-MILE LIMIT OF THE WORLD'S MARGINS*

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Summary

This report examines the non-living resource potential within the extended "legal " continental shelf (ELCS). These areas lie beyond the 200 nautical mile jurisdiction of nation states' exclusive economic zones, and their outer limits are defined by the criteria established by the United Nations Convention on the Law of the Sea, Article 76, 1982.

The offshore non-living resource potentials described in this report are based on a statistical evaluation of known occurrences and reserves, the geologic environments favourable for their formation, models for sediment type and thickness, and basement composition. The result is an assessment of the potential for non-living resources to occur. These estimates are based on the current state of, largely, publicly available information. In many instances these data are incomplete. Hence these resource estimates are to be considered as a guide to the relative potential for occurrence only, and not a definitive statement of the resources or reserves present.

Placer deposits comprising heavy minerals, gold and diamonds are limited to near-shore areas and have negligible resource potential in the ELCS regions. Similarly, phosphorites occur in the equatorial oceans, mainly between 400 m and 1,500 m depth, but have limited resource potential in ELCS areas. Evaporite deposits occur on many continental margins. However, they only overlap with ELCS regions off eastern North America and western central Africa, where their resource potential is low. Polymetalic sulphides (PMS) are formed at active plate boundaries.

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With the exception of the West Pacific, Mid-Atlantic (adjacent to the Azores islands) and off the western coast of North America, PMS resources are low in all remaining ELCS regions.

The major resource potential within the ELCS regions is held in iron-manganese nodules and crusts, conventional oil and gas and gas hydrates. In manganese nodules and crusts, four elemental metals comprise the main components of commercial value: manganese, copper, nickel and cobalt. World-wide, the total value of these metals within the ELCS regions is: US$ 4,05,377 millions of manganese; US$ 179,779 millions of copper; US$ 1,316,566 millions of nickel, and US$ 1,603 millions of cobalt. Conventional oil and gas comprise an estimated US$ 2,402,680 millions with a similar estimated value of US$ 2,373,000 millions for gas hydrates. In total, the resource potential (excluding recovery and production costs) contained within the ELCS regions of the world amounts to an estimated US$ 10, 328 trillions.

The real value of the non-living resources in the ELCS regions depends on their cost of recovery and production. With the probable exception of conventional gas and oil, most of these resources will remain unrecoverable until technological advances allow recovery from deep water. In addition, economic conditions must be favourable for the relatively expensive recovery and production of these marine resources compared with their onshore equivalents. Such conditions may be met through a reduction in onshore availability, an increase in demand, or technological innovation leading to lower recovery costs. The medium term future (i.e. the next 5 to 10 years) is likely to see exploration for, and exploitation of, marine gas hydrates. These have substantial economic potential. As conventional hydrocarbon reserves dwindle, the prospect of gas hydrate exploitation becomes increasingly probable.

1 Introduction

1.1 Background

The non-living resources of the sea bed and the oceans are increasingly being turned to as an alternative to land-based resources. For example, offshore oil and gas reserves now constitute a major portion of overall energy sources (IEA, 1996). As other non-living resources become scarce on land, or offshore exploitation becomes more feasible through technological advances, more minerals can be expected to be mined from the offshore areas. Many of these resources are usually found on the continental shelf and its extensions and therefore give to the adjacent coastal state a potential for control over their exploitation. In some circumstances, these offshore resources may come to acquire a strategic significance to the coastal state by providing a reliable, if presently expensive, source for certain minerals (anon, 1984).

In response to the growing potential of sub-sea resources, basic questions have arisen about who has a right of access to sub-sea resources in the deep-oceans, and how may this right be enjoyed. As a result, in 1967, Malta called upon the UN General Assembly to declare the deep sea bed and the ocean floor beyond the limits of national jurisdiction as areas for the benefit of common humanity. It was requested that an international agency be established to define, control and regulate all activities in these areas. This proposal eventually resulted in the adoption of the Untied Nations Convention on the Law of the Sea ("the 1982 Convention") and the establishment of the International Seabed Authority.

The main types of mineral deposits of potential economic value that occur on and beneath the seafloor in the extended continental shelf areas are: conventional hydrocarbons (crude oil and natural gas), gas hydrates, placer deposit, phosphorite deposits, evaporite deposit, polymetallic sulphides (PMS), and manganese and cobalt-rich nodules and crusts (Kesler, 1994; Cronan, 1980). Aggregates are not considered relevant here since we regard their economic value beyond any 200 nautical mile limit is unlikely to be significant.

1.2 Aims

This report aims to examine the non-living resource potential offered by offshore minerals in areas that lie beyond the 200 nautical mile jurisdiction of nation states' exclusive economic zones, but have the potential to lie within the extended "legal " continental shelf. The outer limits to these areas are defined by the criteria established by the 1982 United Nations Convention on the Law of the Sea, Article 76. These criteria are based on bathymetry, sediment thickness and an assessment of geological continuity from the adjacent land masses.

1.3 Resources

The oceanic regions of the world's continental margins are those areas primarily located in deep water beyond a depth of 2500m. They have evolved either as rifted continental masses have been moved apart or modified by converging seafloor and landmasses. Many "continental shelf" areas adjacent to oceanic islands or ridges have seafloor characteristics different to those close to large land masses in that they generally occur in deep-water and on oceanic basement. Consequently they contain different non-living resource potentials. Although many of these natural, non-living resources will be common throughout the world's oceans, there are significant differences dependent on plate-tectonic location, geological history, basement structure and sediment supply (Kesler, 1994).

Technology developed in recent years has enabled direct observation and research on the deep parts of the seafloor. There is already a capability for drilling for oil and gas in water depths beyond 1,500 m, and this is expected to increase as future deep-water prospects are realised (International Energy Authority, 1996). Similarly, exploration of the deep seafloor using manned submersibles and remotely operated vehicles has been highly rewarding scientifically. Since the 1960s, reconnaissance surveys have had a profound impact on our understanding of seafloor mineralisation. As a result of academic-led research, substantial mineral deposits are now known or predicted to occur on the seafloor in many parts of the world (Gross and McLeod, 1987; Herzig, 1999, Herzig and Hannington, 2000).

Offshore non-living resource potentials described in this report are based on a statistical evaluation of known occurrences and reserves, the geologic environments favourable for their formation, models for sediment type and thickness, and basement composition. The result is an assessment of non-living resources. These estimates are based on the current state of, largely, publicly available information. In many instances these data are incomplete. Hence these resource estimates are to be considered as a guide to the relative potential for occurrence only, and not a definitive statement of the resources or reserves present.

The term "resource" is used here to describe the potential for materials to occur. It is not, and should not be taken as, an assessment of non-living reserves. "Reserves" are, by definition, proven deposits of known abundance and volume. Feasibility projections for resource exploitation are based on surveys of current activities and those projected over several decades. These projections will almost certainly change with technological advances, variations in supply and demand, and evolving local and global economic conditions.

The offshore non-living resource potentials described in this report are based on a statistical evaluation of known occurrences and reserves, the geologic environments favourable for their formation, models for sediment type and thickness, and basement composition. The result is an assessment of the potential for non-living resources to occur. These estimates are based on the current state of, largely, publicly available information. In many instances these data are incomplete. Hence these resource estimates are to be considered as a guide to the relative potential for occurrence only, and not a definitive statement of the resources or reserves present.

1.4 Data sources

Data for this report have been compiled from the resources of the United Kingdom's National Oceanographic Library (NOL) including published literature and manuscripts at the facility, atlases, charts, CD-ROMs and core texts on marine resources, as well as the data bases of the British Oceanographic Data Centre (BODC) and Marine Information and Advisory Service (MIAS). Electronic sources such as the broad science and technology databases (e.g. the ISI Web of Science, PASCAL, GeoRef, Geobase, EEVL (Engineering Virtual Library), MOFR (Marine Oceanographic and Freshwater Resources), OCEANIS (Ocean Information System), Ocean Treaties data-set, and online data inventories) are used to further support the data bases. These sources are utilised alongside the in-house and international databases of world bathymetry (GEBCO), sedimentology and geophysics (such as the National Geophysical Data Centre, NGDC) to enable a comprehensive and quantitative synthesis of the offshore, non-living resource potential. An Appendix containing web-site addresses of all sources researched for this assessment is included at the rear of this report.

2 Physiography of the Ocean Floor and its Bearing on Non-Living Resources

In order to apply the criteria defined by the 1982 United Nations Convention on the Law of the Sea, Article 76, to identify those areas of the global oceans that lie beyond 200 nautical miles of coastal baselines, it is necessary to consider the regional geology and physiography of the seafloor. This is essential before considering the potential for, and occurrence of, non-living resources forming in or on the deep seafloor.

Figures 1 to 5 respectively are preliminary maps showing the age, physiography, tectonic boundaries, sub-division of basement types, and sediment thickness underlying the global oceans and their continental margins.

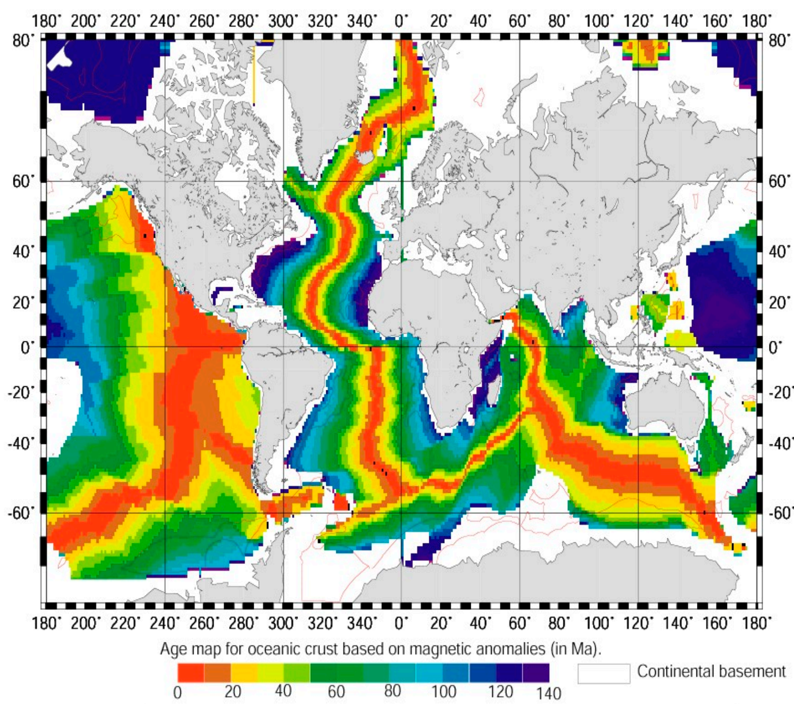

Figure 1. Age map of the ocean floor constructed from a digital data base based on magnetic isochron data (Mller, et al., 1997). Shown in red are the areas of the extended legal continental shelf identified in the text, and the subject of this report.

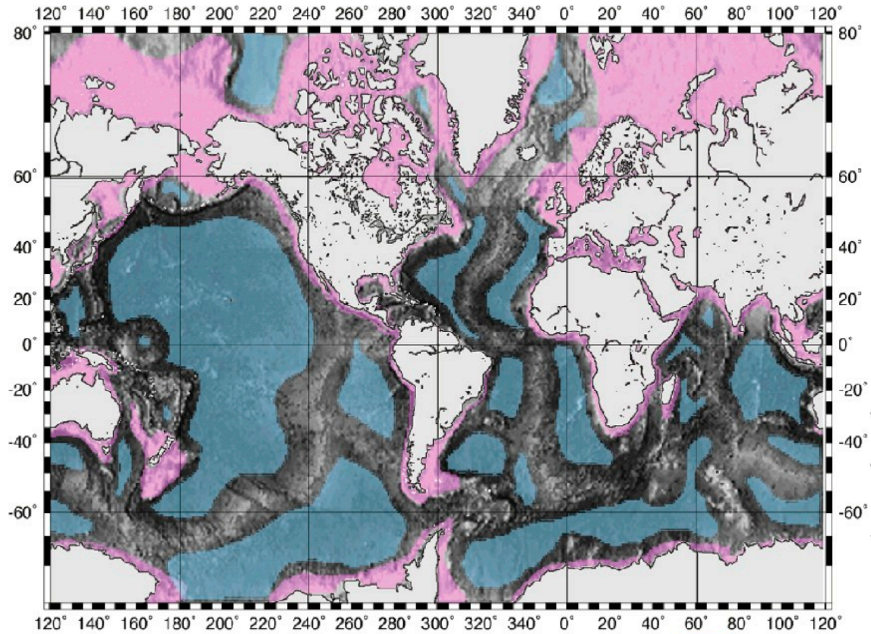

Figure 2. Physiography of the ocean floor based on bathymetry (after ETOPO5, N.G.D.C.); basement type and age. The continental margins extend to the base of continental rise. Abyssal plains are generally deeper than 4,000 m.

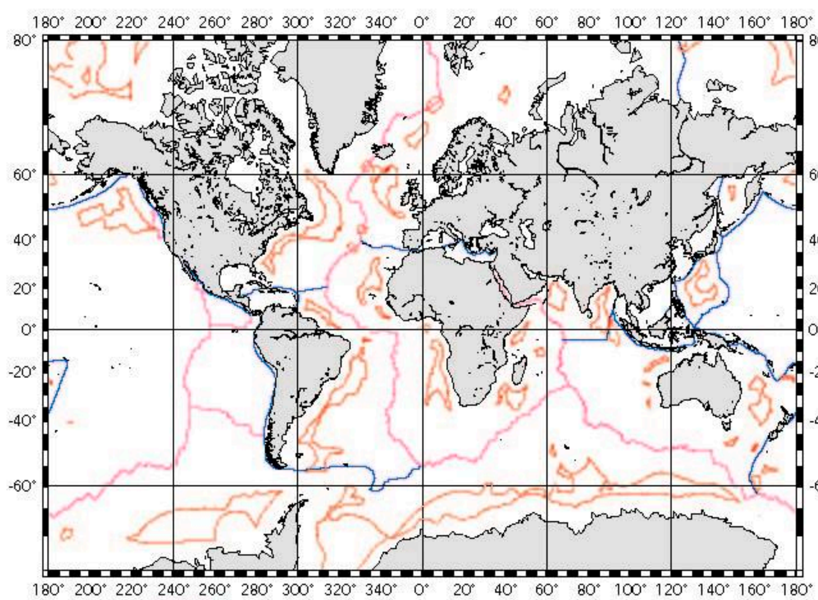

Figure 3. Map showing the major plate tectonic boundaries on the ocean floor. Shown in red are the areas of the extended legal continental shelf identified in the text.

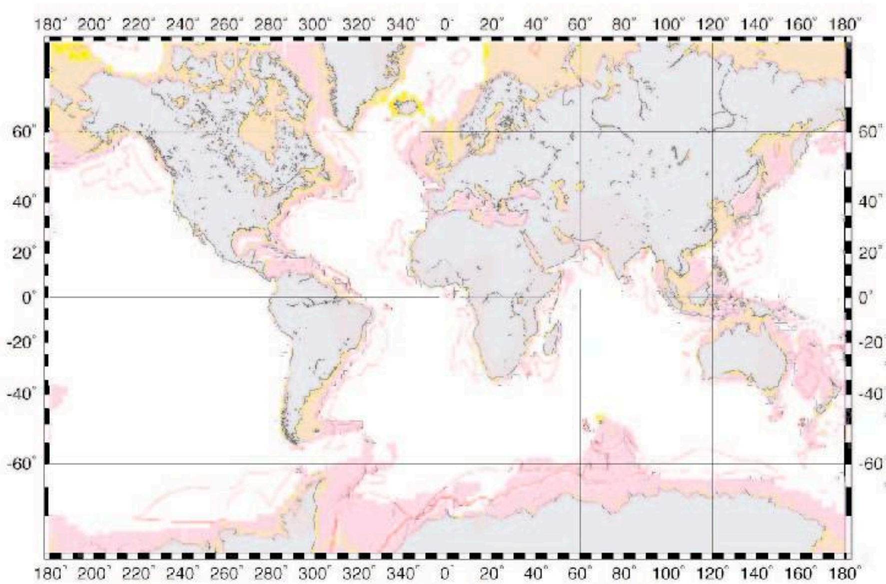

Figure 4. Map showing seafloor regions underlain by oceanic and continental crust.

Composite age and depth map showing areas of seafloor that are:
(1) less than 300m deep (yellow)
(2) composed of non-oceanic crust (purple)
(3) both non-oceanic and less than 300m deep (orange)

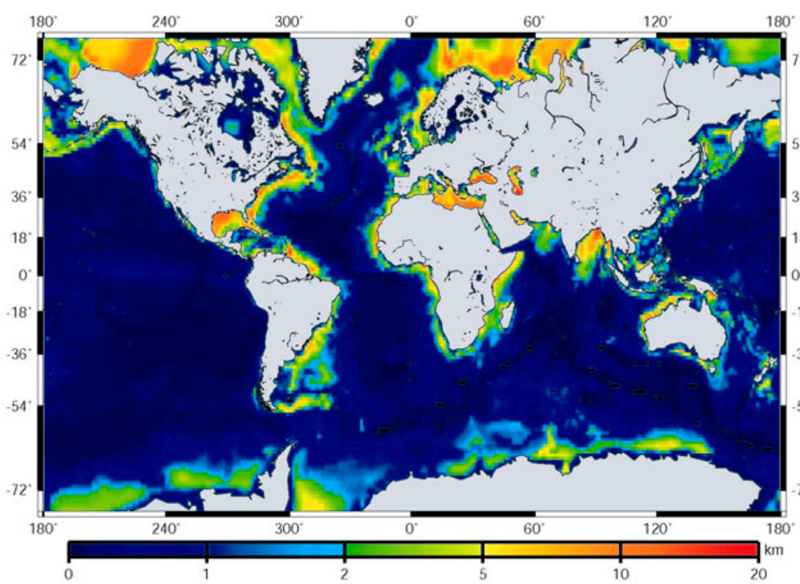

Figure 5. Sediment thickness model in kilometres and gridded on a 1 latitude and longitude basis (compiled by NGDC, based on work by: Mathhias et al., 1988; Ludwig and Houtz, 1979; Hayes and LaBrecque, 1991; Divins and Rabinowitz, 1991; Divins, D.L., and Eakins, in prep).

The solid earth's surface consists of two physiographic provinces (Figure 2): the ocean basins with a mean depth of 5,000 meters, and the continents that rise to a mean height of about 5800 meters above the ocean floor. The oceans extend over the margins of the continental masses for distances ranging from a few tens of kilometres to more than 1,300 km. The boundary between the continents and ocean basins is everywhere submarine, generally ranging in depth from 2,000 to 4,000 m. The physiographic contrast between the continents and the ocean basins reflects fundamental geologic differences between them. Continental crust (being richer in silica and the alkalis and poorer in iron and magnesia) is less dense, and averages about 35 km in thickness, compared with the approximately 5 km-thick oceanic crust. Many physiographic features of the ocean basins are related to volcanism, crustal stretching and subsidence, and seafloor spreading that brings basaltic igneous rock to the surface along mid-ocean ridges and carries new crust away from the mid oceanic ridge at the rate of up to 25 cm per year.

2.1 Physiographic features of the seafloor.

The deep seafloor is dominated by the following features:

(1) Continental margins that contain the continental shelf (down to a depth of about 300 m), the continental slope (with typical gradients of 1:20) and the continental rise (typically down to 4000 metres below sea-level). These features were formed during rifting of larger continental blocks and the subsequent development of oceanic crust by seafloor spreading (Figure 4). The continental margins have a history of subsidence and are, therefore, mainly covered in thick sedimentary sequences. These sequences may approach 20 km in thickness and are typically composed of clastic material (sand and mud), evaporites (salt deposits), carbonates, and pelagic clays. In areas where volcanic activity accompanied initial continental rifting, many continental margins also comprise voluminous extrusive layers (flood basalt) that occur over wide regions of many thousand square kilometres. In places, the initial continental rifting may have involved several failed episodes. During these, continental fragments may have been partially separated from the main land-mass by the formation of deep sedimentary basins underlain by stretched and thinned continental crust and volcanic material. These

partially separated continental fragments often form shoals or plateaux located seaward from the continental margins.

(2) Oceanic ridges, often called mid-ocean ridges or spreading ridges, are developed where parts of the earth's crust or plates are separating along linear belts at rates of up to 25 cm/yr. or more. As a result, compared with continental crust, oceanic crust is relatively young. It ranges from zero age (at the spreading ridges) to a maximum near the continental margins of about 140 Ma (Figure 1). The spreading ridges form global systems, with a total length of about 100,000 km, along which major volcanism, PMS formation, and deep-seated fractures develop (Figure 2 & 3). Immense amounts of mineralised fluid and thermal energy are discharged from the seabed through open vents and fissures, from seepage springs and by exhalation through the bedrock (hydrothermal activity).

(3) Transform fault zones are deep-seated fault and fracture systems that separate segments of the spreading ridges and form an integral part of the major tectonic ridge system. They are also important focal areas for seismic activity, limited volcanism and effusive hydrothermal activity. In continental settings, large-scale fault structures are recognised as common foci for mineral deposit formation.

(4) Abyssal plains and hills occur on both sides of the mid-ocean ridges. They are overlain by a thin veneer of pelagic sediments and lie between 3000 and 6000 m below sea-level. Individual volcanoes and composite volcanic ridges formed by overlapping volcanoes, are scattered throughout the ocean basins. These structures are often locally clustered to form groups of islands, seamounts, plateaux and linear chains along, or adjacent to, continental margins.

(5) Deep-ocean trenches reach depths of 11,000 meters below sea-level and are commonly present adjacent to volcanic island chains (island arcs) at the periphery of the large ocean basins. They can extend to thousands of kilometres in length and are focal areas for intense volcanic and hydrothermal activity. Subduction zones, major components of deep-ocean trenches,

are formed where one plate or a part of the earth's crust is under-thrust or overridden by another plate. These zones are usually marked by thrust faulting, folding, uplift, seismic and volcanic activity. In some places small ocean basins and spreading ridges lie adjacent to deep-ocean trenches and can have an abyssal plain below a depth of 2,000 meters. Those that border landmasses often contain thick accumulations of sediment.

(6) Seamounts are formed on the oceanic crust in conjunction with the spreading ridges, subduction zones, and mantle plumes (hot spots). They form circular, conical or irregular structures that may rise more than 1000 m above the seafloor. Many Island States have developed on seamounts that have subaerial summits, some with coraline overgrowths (i.e. atols). These seamounts are developed by a combination of geological processes involving mainly volcanism, but also including tectonic uplift of the earth's crust.

2.2 Composition of oceanic and continental crust

In contrast with continental crust, oceanic crust is thin (5-10 km), of relatively uniform composition and exposed at or near the surface over much of the mid-ocean ridges. Sediments increase in thickness, on the older parts of the ocean floor (reflecting greater accumulation time), toward the ocean/continent boundary, continental rises and continental margins. Throughout the majority of the ocean basins, away from continental rises, sediments do not attain a thickness of more than a few hundred meters (Figure 5).

The oceanic crust originates by partial melting of rocks in the underlying mantle during seafloor spreading. Other rocks and minerals produced by this process include polymetallic sulphides (PMS). In addition, the ocean basins contain large concentrations of manganese oxide nodules and crusts on the surface of the seafloor that are rich in manganese, nickel, copper and cobalt (and other trace metals). The areas of the sub-sea physiographic provinces are summarised in Figure 2. Compared to the ocean floor, submerged continental margins and small ocean basins contain the majority of potential sub-sea non-living resources. This is both in terms of their variety and potential value. Most important among these are the hydrocarbons, most of which probably occur beneath the continental shelf and slopes, and possibly in small ocean basins. Although only a relatively small number of other minerals are presently recovered from the continental shelf, it potentially contains a similar array of minerals currently returned from the land-based mining. The total amount of these metals in the ocean basins and crust is very likely far larger than in the continents, but significant technological advances will be required to make them economically viable.

3 Methodology

3.1 Determination of the area of interest

For the purposes of this report, we have used the criteria provided in the 1982 Convention to identify legal continental shelf areas beyond 200 nautical miles from baselines. We have not identified all of the potential outer limits of individual states, as our aim was to make a general assessment of resources and resource potential. Instead we have relied on published sources for this information, and integrated these data with our own results of investigation of marine mineral and other deposits.

Article 76 of the 1982 Convention is the principal set of guidelines by which a coastal nation state may define an outer limit to its legal continental shelf beyond 200 nautical miles. The Article includes the definition of, and the criteria for, the location of the outer limit of the legal continental shelf. It also provides details of a combination of geodetic, geophysical, geological and hydrographic techniques for determining this outer limit. The Commission for the outer limits of the continental shelf has published technical guidelines that further discuss these criteria and their application. These details may be found at the UN LOS website at http://www.un.org/Depts/los/tempclcs/docs/clcs/CLCS_11.htm

We hereby summarise the main parameters of the guidelines:

Article 76, paragraph 1, states:

"The continental shelf of a coastal State comprises the sea-bed and subsoil of the submarine areas that extend beyond its territorial sea throughout the natural prolongation of its land territory to the outer edge of the continental margin, or to a distance of 200 nautical miles from the baselines from which the breadth of the territorial sea is measured where the outer edge of the continental margin does not extend up to that distance".

It continues: "For the purposes of this Convention, the coastal State shall establish the outer edge of the continental margin wherever the margin extends beyond 200 nautical miles from the baselines from which the breadth of the territorial sea is measured".

"The continental margin comprises the submerged prolongation of the land mass of the coastal State, and consists of the sea-bed and subsoil of the shelf, the slope and the rise. It does not include the deep ocean floor with its oceanic ridges or the subsoil thereof".

The second provision, contained in paragraph 4 (a) (i) and (ii) of the Article, determines the position of the outer limit of the continental margin by means of complex formulae:

> "(i) a line delineated in accordance with paragraph 7 by reference to the outermost fixed points at each of which the thickness of sedimentary rocks is at least 1 per cent of the shortest distance from such point to the foot of the continental slope; or
>
> "(ii) a line delineated in accordance with paragraph 7 by reference to fixed points not more than 60 nautical miles from the foot of the slope."

In practice, this means that if a coastal state can prove that its submarine extension is a natural prolongation of its continental mass, then the continental shelf can be continued by reason of a extensive sediment deposit lying beyond its morphological shelf edge, or if the morphological shelf edge lies a considerable distance from the coastal baseline. In some cases this can be an enormous additional area of maritime territorial jurisdiction. But it is not without limit. The Article also carries a set of restrictive or constraining paragraphs, viz:

"The fixed points comprising the line of the outer limits of the continental shelf on the sea-bed, drawn in accordance with paragraph 4 (a) (i) and (ii), either shall not exceed 350 nautical miles from the baselines from which the breadth of the territorial sea is measured or shall not exceed 100 nautical miles from the 2,500 metre isobath, which is a line connecting the depth of 2,500 metres."

Using these criteria, a number of authors have made attempts to identify the areas of the worlds oceans which, as legal continental shelf, fall beyond 200 nautical miles from the baselines from which territorial limits have been determined. One of the most widely cited is Prescott's work of 1985, which although undoubtedly requiring some revision, is a useful starting point for an analysis and is used here as a guide to locating and assessing the non-living resource potential of the extended continental shelf regions (Figure 6).

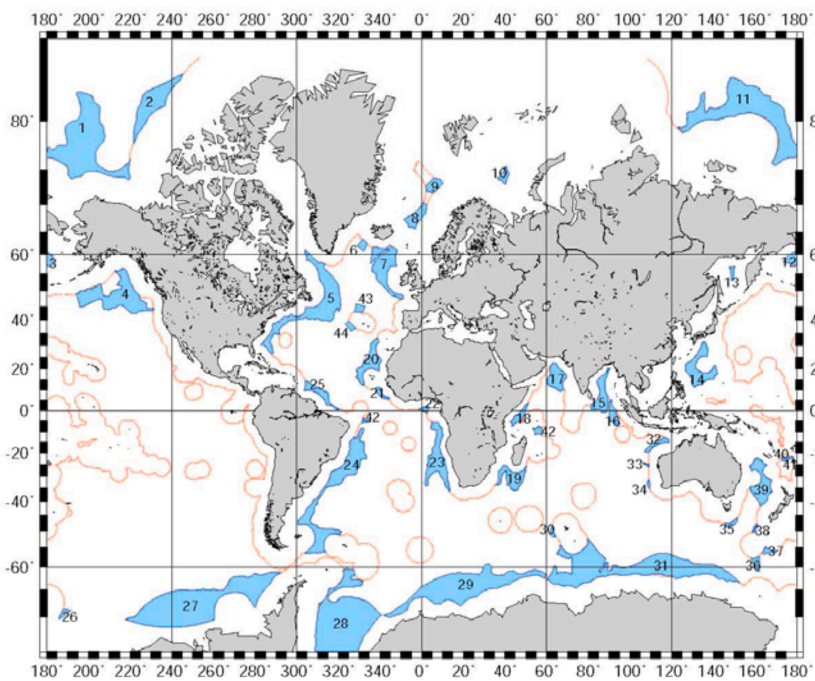

Figure 6. Areas filled in blue are the extended legal continental shelf (ELCS) regions identified in the text (after Prescott, 1985). Areas outlined in red are the 200nmile limits of EEZ claims. The criteria for the identification of these boundaries is described in the text (section 3.3.1). Each region is identified by a number that is referred to in the text.

Other workers, notably Carrera (pers. comm. 2000), have attempted to summarise the general pattern of legal continental shelf areas for the world's coastal nation states. It is a certainty that the final determination of the outer limits of every coastal state's legal continental shelf will take a great deal of time, perhaps another decade – and will then have to passed through the endorsement process set up by the Commission. Even without the inevitable delays resulting from disputed boundaries which will beset the operation, it would seem unlikely that this process would near completion within the next twenty five years. This factor may be significant in the view that the ISA may take on assessing the resource potential of the legal continental shelf, and indeed, the Area.

3.2 Classification of mineral resources

Although sub-sea resources of petroleum and other minerals are potentially large and widely distributed, only a small part are likely to be economically recoverable within the next few decades and some may never be recoverable (Pearson, 1975; Kesler, 1994). To give economic and geologic perspectives to estimates of resource potentials, they must be examined a framework that accounts for the degree of uncertainty of knowledge about their existence, formation and character. The feasibility of their recovery and sale also needs to be considered.

In the original classification of McKelvey (1968) and McKlevey and Wang (1969), individual mineral deposits evolve from being an estimated resource to a known reserve with progress in exploration, advance in technology, and changes in economic conditions. Recoverable reserves comprise known abundance and volume of materials that are both marketable and economically feasible to produce under local economic and technologic conditions. In contrast, resources comprise estimates of the potential occurrence and abundance of materials, regardless of their feasible exploitation. MacKlevey and Wang (1969) further subdivide resources into: "para-marginal resources that are prospectively marketable materials recoverable at prices as much as 1.5 times those prevailing now or possible with likely advances in technology", and "sub-marginal resources that are materials recoverable at prices higher than 1.5 times those prevailing now but that have some forseeable use and prospective value".

Seen in this framework, the presently recoverable, proven reserves of most minerals are relatively small when compared with the estimated resources that may be found by future exploration or become recoverable as a result of technologic advances or changes in economic conditions. This is particularly true for sub-sea resources, because only a small part of the seabed has been explored and most of the resources it contains are not yet economically recoverable (Li, 1995).

3.3 Methods used to assess resource potentials

We use essentially four stages to assess potential non-living resources in the extended legal continental shelf (ELCS) regions. For some resources, not all stages are possible. In these cases we progress the stages as far as reasonable, or possible, to reach a qualitative ranking of resources by region.

(1) The first involves the identification of all known and documents occurrences of the potential resource materials in the global oceans. These occurrences include coastal, continental shelf, continental slope, continental rise and abyssal locations, regardless of their relationship to the ELCS (legal extended continental shelf) regions.

(2) The second stage is to determine, where possible, all known and estimated determinations of the resource density in mass per unit area of various minerals and elements. For manganese nodules and crusts, for example, these are based on reports in the literature of seabed surface coverage determined from sampling and photographic observations. For conventional hydrocarbons (gas and oil), existing regions of production are identified, as well as reserve and resource estimates based on regional compilations.

(3) Where appropriate, a third stage assesses chemical compositional data for elements of significant economic value. These are largely restricted to manganese nodules and crusts, for which there is global data coverage. Other minerals, for which global coverage is absent, require further exploration prior to being treated this way.

(4) The fourth stage multiplies the occurrence, frequency or density of resource minerals (in mass per unit area) with elemental compositional data for those minerals (in wt. %) to arrive at abundance values in units of mass per unit area for individual elements. These values are further multiplied by the area occupied by each of the identified ELCS regions (including their sub-divisions) to arrive at estimates of the total mass of material in those ELCS regions.

The global data of both abundance and composition are compiled on a 1° latitude and longitude grid. Interpolation of data between sampled localities is based on a minimum surface tension routine (Smith and Wessel, 1990). This method has the advantage of adjusting value gradients locally according to the actual sample values, their location and frequency of occurrence. Interpolation is not believed to give meaningful results beyond 10° ranges from known localities and, therefore, the data grids do not extend beyond that limit.

Where abundance, density and compositional data are absent, the likelihood of occurrence of specific resource types have had to be estimated from predictive models. These models use knowledge of the presence or absence of conditions favourable for resource formation to establish often non-unique predictions of likely occurrence. This method is especially applicable for gas hydrates and conventional hydrocarbon resources, although the latter are also described with reference to adjacent known reserves and estimated resources.

Finally, a value is placed on the resources at current (June 2000) commodity prices. These estimates are valid only as far as they describe the total abundance and hence value of the resource in question. They do not include any recovery, treatment or other production costs that would be incurred but which, at present, are unknown. A state-by-state summary of the non-living resources within ELCS areas is given in appendix 1.

4 Non-Living Resources on the Seafloor: Their Formation, Occurrence and Magnitude

4.1 Marine Placer deposits

4.1.1 What marine placer deposits comprise

Marine placers are detrital heavy metallic minerals which have become separated from their normally associated light minerals, and can form in economic concentrations. The most economically important of these minerals are: cassiterite (tin), ilmenite (titanium), rutile (titanium), zircon (zirconium), chromite (chromium), monazite (thorium), magnetite (iron), gold and diamonds (Harben and Bates, 1990).

4.1.2 How marine placer deposits are formed

Marine placer deposits are formed in high-energy environments such as the surf-zone along beaches. As a result of their specific high density, placer minerals are generally confined to locations within a few tens of kilometres from their source rocks. The relationship between sea-level changes and the formation and preservation of placer deposits puts limits on their occurrence offshore. During the last glacial maximum 18,000 years ago sea level was lowered by ~120 m. At these times, fluviatile placer deposits may have extended to the edge of the present-day continental shelf. However, subsequent rises of sea level have produced a cover of transgressive sand and shelf mud, burying the placer. In general, two different types of marine placer deposits are recognised (Emery and Noakes, 1968; Kudrass, 1987, 2000; Jury and Hancock, 1989).

1. Fluviatile placer deposits of gold and cassiterite (tin oxide) on the inner shelf originated during glacial periods of falling sea level, when rejuvenated fluviatile erosion concentrated these heavy minerals in lag sediments. These were further transported and concentrated on the shallow continental shelf during periods of falling sea level occurring during interglacial-to-glacial transitions.

2. Beach placers originated during periods of stable or slightly fluctuating sea level, typical during extended intermediate glacial periods. Most of these beach placer deposits were subject to dispersion or shoreward removal during periods of rising sea level during interglacial periods. The wealth of placer deposits along present shorelines is largely a result of transgressive beach-barrier migration, by which much of the shelf sand with its pre-concentrated heavy-mineral assemblages was moved to its present coastal position. This lateral and vertical migration was especially effective during the last two transitions from glacial to interglacial periods.

4.1.3 Where marine placer deposits are found

Figure 7 shows the presently known placer deposits of economic significance (Emery and Noakes, 1968; Cronan, 1980; Earney, 1990). However, none are located within the areas of the ELCS regions (legal extension of the continental shelf) beyond 200 nautical miles.

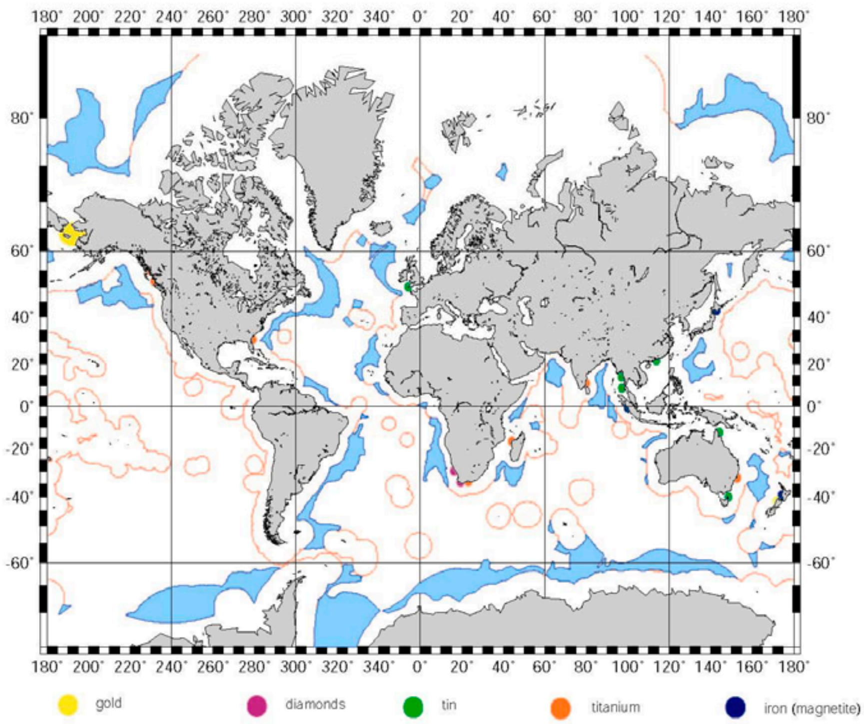

Figure 7. Map showing known locations of offshore placer deposits with reference to the ELCS regions (after Emery and Noakes, 1968; Cronan, 1980; Earney, 1990, and other sources cited in the text).

In most placer deposits, economically valuable minerals have been mechanically concentrated in rivers along beaches, fan-aprons and river deltas as a result of their higher density (>3.2 gcm^{-3}) compared to the bulk of detrital minerals, which consist mostly of quartz and feldspar (with a density of 2.7 gcm^{-3}). These placer minerals, sometimes called heavy minerals, are derived by weathering from continental rocks of mostly volcanic, plutonic, or metamorphic origin and have a broad compositional range. Therefore, the majority of heavy mineral marine placer deposits are intrinsically linked close to their geological sources and to near-shore or shallow continental shelf environments.

The majority of placer deposits are found along many present shorelines and are predominantly a result of beach migration during periods of marine transgression. Although few shelf deposits large enough to survive the transgression are preserved, they form disseminated shelf deposits of low grade and hence little economic value (Komer and Wang, 1984).

Kudrass (2000) reports the main areas where placer deposits are currently known, are being mined, and their common usage. These are summarised below and their major locations shown on on Figure 7 (Yim, 1991, 2000; Jones and Davies, 1979; Shilo, 1970).

The minerals rutile and ilmenite are the main sources of titanium and are or have been mined from placer-derived deposits from beach sand in south-east and south-west Australia, in east South Africa, south India, Mozambique, Senegal, Brazil, and Florida. Titanium is used as an alloy or, more commonly in its oxide form, as a pigment for paint.

The minerals zircon, garnet, sillimanite, and monazite are frequently recovered as by-products of mining ilmenite-bearing sands. They are used as refractory or foundry sand (zircon, sillimanite), as abrasives (garnet, zircon), or as raw material (monazite) for rare earth elements (cerium, lanthanum, neodymium and thorium), which are recovered for various purposes including: catalysts in refining crude oil, VDU screens, fluorescent lamps and some radioactive uses.

The iron-titanium-rich placer mineral magnetite has been mined in large quantities from the northwestern coast of New Zealand (North Island), Indonesia (Java), the Philippines (Luzon), and Japan (Hokkaido). In Japan this type of magnetite is added to other iron ores to prolong the durability of expensive furnace linings.

The fluviatile placer mineral cassiterite, a tin oxide, is recovered from near-shore and offshore sediments in the "tin-valleys" of the Indonesian Sunda shelf (extending from the islands of Bangka, Belitung, and Kundur), Malaysia, and Thailand, where about one third of the world's production derives. Tin is used as corrosion-resistant plating for steel and in alloys.

The majority of presently recovered gold is derived from fluviatile placer deposits. Although it sometimes occurs in beach placer deposits (New Zealand, Alaska), it is limited like other placer deposits to coastal areas and the shallow continental shelf. Thus it is not considered a resource in the ELCS regions. Besides being used for ornaments and bullion, its consumption for industrial purposes is increasing

Diamonds are mined in beach and shelf sediments along the West coast of South Africa and Namibia and are used as jewellery and for industrial cutting and grinding processes.

4.1.4 Resource potential of marine placer deposits

Because marine placer deposits are generally confined to locations within a few tens of kilometres from their source rocks, and are related to Pleistocene sea-level changes, they are limited to continental shelf regions less than 120 m deep. Therefore, it is almost certain that no placer deposits will occur as resources in the regions identified as potential ELSCs, since these regions generally lie deeper than 120 m. However, there remains a remote possibility that submarine mass-erosion and deposition may have reworked and transported shelf placer deposits to deeper water. It is not possible to predict the location, grade or abundance of such deposits under these circumstances which must, therefore, remain a sub-marginal resource.

4.2 Marine phosphorite deposits

4.2.1 What marine phosphorite deposits comprise and how they are formed

Phosphorite deposits are naturally occuring compunds containig phosphate in the form of a cement binding sediments in tropical to sub-tropical regions. They tend to occur in waters of medium depth and are widely distributed on the continental shelves and upper slopes in areas of upwelling currents. They also occur on oceanic islands, seamounts or the flanks of atolls (Burnett and Riggs, 1990).

Phosphates in the form of phosphorites are composed of calcium phosphate which is an important fertiliser, and thus are of principal use in agriculture. Phosphorite, consisting of varieties of the heavy mineral apatite, is not a detrital mineral like other heavy minerals, but is authigenically formed in sediments (Manheim, F. T., 1979; Cruikshank, 1992; Bentor, 1980).

4.2.2 Where marine phosphorite deposits are found

Present-day locations of phosphorite deposits are shown on Figure 8.

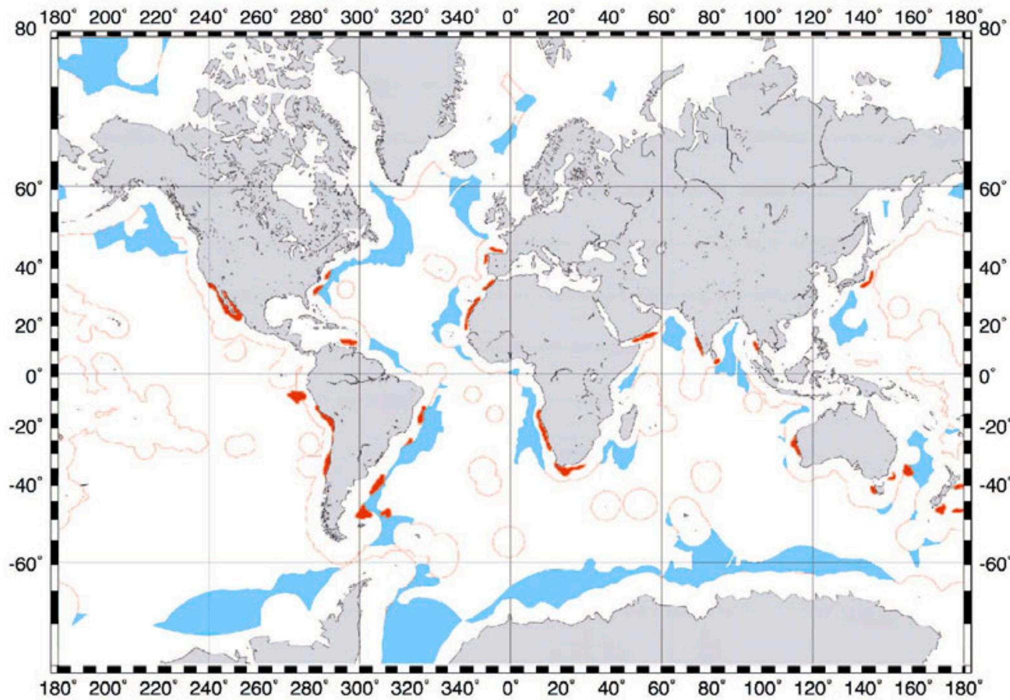

Figure 8. Location of known marine phosphorite deposits (in red) with reference to the ELCS regions in blue (after Baturin and Savenko, 1985; Baturin 1998; Rao and Nair, 1991; Earney, 1990).

Relatively rich deposits are known to occur in areas such as off the coast of Baja California, southern California, and east of New Zealand. However, in many places they consist of cemented nodules scattered within sediments, and are too sparsely distributed to be recoverable. Their phosphate content of known deposits varies considerably and is seldom more than 29 wt. % (Baturin and Savenko, 1985; Baturin 1998; Rao and Nair, 1991).

The large, commercially valuable deposits of Nauru, Ocean and Christmas Islands are well known, and there is the potential for similar deposits to occur on shallow (less than 120 m deep) submerged seamounts, within the Pacific region, which were above sea level prior to the last sea level rise (Bentor, 1980). There are also potential and low grade phosphorite deposits on the Chatham Rise off New Zealand, (~5 wt. % phosphate) and offshore from Cochin and Bombay, India. Other major localities include: south and south-western Africa, north-western Africa, the western and eastern margins of South America and western Australia (Cruikshank, 1992; Manheim, 1979).

None of these locations overlap with the extended continental shelf regions, except for a small portion on the south-eastern margin of Argentina.

4.2.3 Resource potential of marine phosphorite deposits

World sub-sea resources of phosphorite are probably at least of the order of hundreds of billions of tonnes (Kent, 1980; Pearson, 1975; Manheim, 1979). As a consequence of the prevailing economic conditions and the alternative availability of phosphates from non-marine sources no offshore deposits are being mined at present. Although land deposits are large enough to meet world demands, sub-sea production may become economically viable in local areas far removed from on-shore deposits. Although possibly a few billion tons of offshore deposits may be classed as para-marginal now (in those areas with already identified major deposits), the bulk of sub-sea phosphorite resources in ELCS regions must be classed as sub-marginal and hence of little economic value.

4.3 Marine evaporite deposits

4.3.1 What marine evaporite deposits comprise and how they are formed

Anhydrite and gypsum (calcium sulphates), common salt (sodium chloride), and potash-bearing minerals are termed evaporite deposits (Holser, 1979; Peryt, 1987; Holser et al., 1988). They are formed by evaporation of sea water and other natural brines in geologic basins of restricted circulation. Important deposits of magnesium bearing salts are also deposited in such basins. Elemental sulphur forms in some of them by biogenic processes involving the alteration of anhydrite. Because rock salt tends to flow at relatively low temperature and pressure, salt in thick beds squeezed by the weight of a few thousand metres of overlying sediment often protrudes upwards forming salt domes, plugs, and other structures. Such masses, which can be a few kilometres in diameter, may bring salt to or near the surface. They can also form structures in the intruded sedimentary layers that are favourable for the accumulation of hydrocarbons.

Evaporite deposits, including some potash and magnesium minerals and elemental sulphur can be recovered by the Frasch process, which involves solution mining methods of injecting hot water into reservoirs through bore holes Thus the presence of geothermal water sources locate near evaporite deposits greatly enhances their potential value (Kildow J. T., 1979).

4.3.2 Where marine evaporite deposits are found

Figure 9 shows the present day occurrence of sub-sea anhydrite, potash and magnesium evaporite deposits.

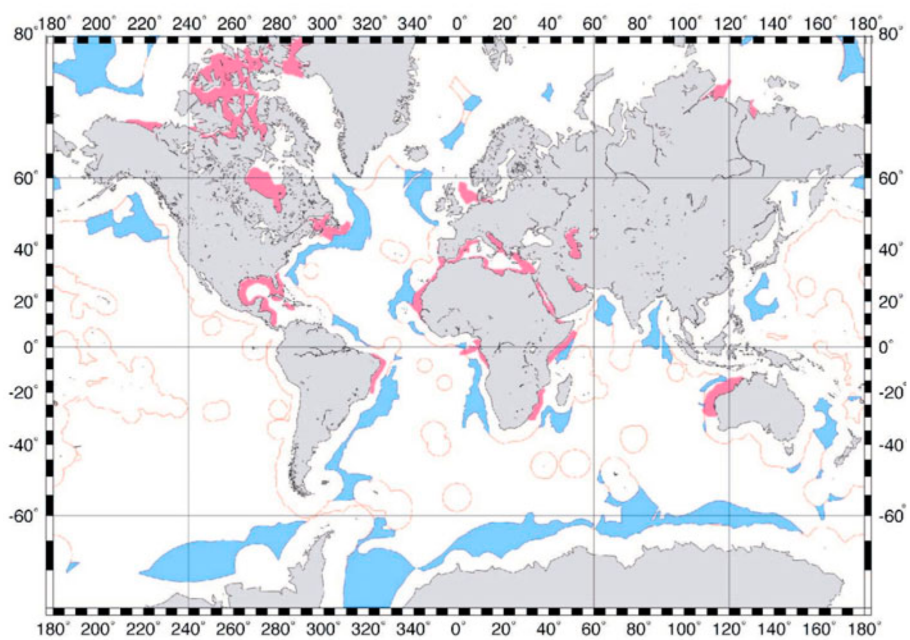

Figure 9. Location of known marine evaporite deposits (in purple) with reference to the ELCS regions in blue (after Cronan, 1980; Earney, 1990; Warren, 1999; Teleki et al., 1987 and others cited in the text).

Although evaporite deposits formed in ancient marine basins are extensive on land, many of these also extend beneath the sea, not only under the continental shelves but also under some marginal ocean basins (for example, the Sigsbee Deep salt domes in the Gulf of Mexico). Other areas area: the Canadian Arctic (including Hudson Bay), the north-west African shelf, the Mediterranean Sea, north-eastern margin of Brazil, the

Grand Banks and Newfoundland, parts of eastern African margin and western Australia (Warren, 1999; Teleki et al., 1987). However, very few of these known areas of anhydrite, potash and magnesium evaporite deposits occur within the ELCS regions. Possible exceptions to this are: the Grand Banks and Newfoundland deposits, west Africa and north-western Australian deposits. However, very little data exist on the abundance or concentration of these deposits.

4.3.3 Resource potential of marine evaporite deposits

Because of the widespread occurrence of anhydrite, gypsum, and common salt on land, and the ease of obtaining salt by evaporation from seawater in many coastal regions, these minerals are widely available at low cost. Consequently, there is little value in sub-sea sources, except perhaps in areas far removed from other sources.

To our knowledge, no attempt has been reported to quantitatively estimate potential sub-sea resources of salt and anhydrite, but they probably amount to at least tens of trillions of tonnes. Potash deposits in evaporite basins are not as widespread as salt and gypsum, but individual deposits are large generally in the range of hundreds of millions or billions of tonnes (Warren, 1999). World supplies from land sources are presently abundant, but because potash is a relatively valuable mineral, there are opportunities for the development of strategically located sub-sea deposits, particularly those amenable to dissolution extraction processes.

Potential world resources in sub-sea deposits are probably in the range of tens of billions of tonnes of potash, some of which maybe economically recoverable. Thick beds of a magnesium salt and tachydrite (calcium-magnesium hydrate) previously known only in trace amounts, occur in areas associated with potash in the Sergipe salt basin along the eastern coast of Brazil and in the Congo basin along the mid-south-western coast of Africa. Tachydrite is highly soluble, forms concentrated brines, and probably can be mined by dissolution methods. Magnesium is currently recovered economically from seawater and other natural brines (Pearson, 1975). However, if it can be produced more cheaply from marine tachydrite deposits, then these and other favourably situated deposits may have some economic value. Until then, however, all marine evaporite deposits must be regarded as sub-marginal resources.

4.4 Marine Polymetalic sulphides

4.4.1 What marine polymetalic sulphides comprise

The majority of sub-sea polymetallic sulphides (PMS) are massive ore bodies containing varying proportions of pyrrhotite, pyrite/marcasite, sphalerite/wurtzite, chalcopyrite, bornite, and isocubanite. Some massive polymetallic sulphides located on spreading centres behind deep-ocean trenches also contain galena (lead sulphide) and native gold. Other minor sulphides of tin, cadmium, antimony, aresenic and mercury also occur in varying amounts at different localities (Rona and Koski, 1985; Herzig and Hannington, 1995).

4.4.2 How marine polymetalic sulphides deposits are formed

Polymetallic mineral deposits on the seafloor are intimately related to the formation of new oceanic crust by seafloor spreading. At mid-ocean ridges, convection-driven circulation of seawater through the oceanic crust is the principal ore-forming process (Scott, 1985; Herzig and Hannington, 1995). Hydrothermal fluid leaches and transport metals and other elements from their host rock to the surface of the seafloor. As they discharge, at temperatures up to 350°C from the "black smoker" chimneys (at depths in excess of 2,500 m), metal sulphides deposits form at the seafloor (as mounds) or as sub-surface stock-works. Lower temperature systems are also present and generate mineralisation of considerable economic potential. In the southern Lau Basin, for example, the first examples of actively forming, visible primary gold in seafloor sulphides were documented at "white smoker" chimneys (Hannington, M.D. and Scott, 1988; Herzig et al., 1993).

4.4.3 Where marine polymetalic sulphides deposits are found

Sub-sea massive polymetallic sulphide bodies are found along the earth's major tectonic belts (and identified in Figure 10).

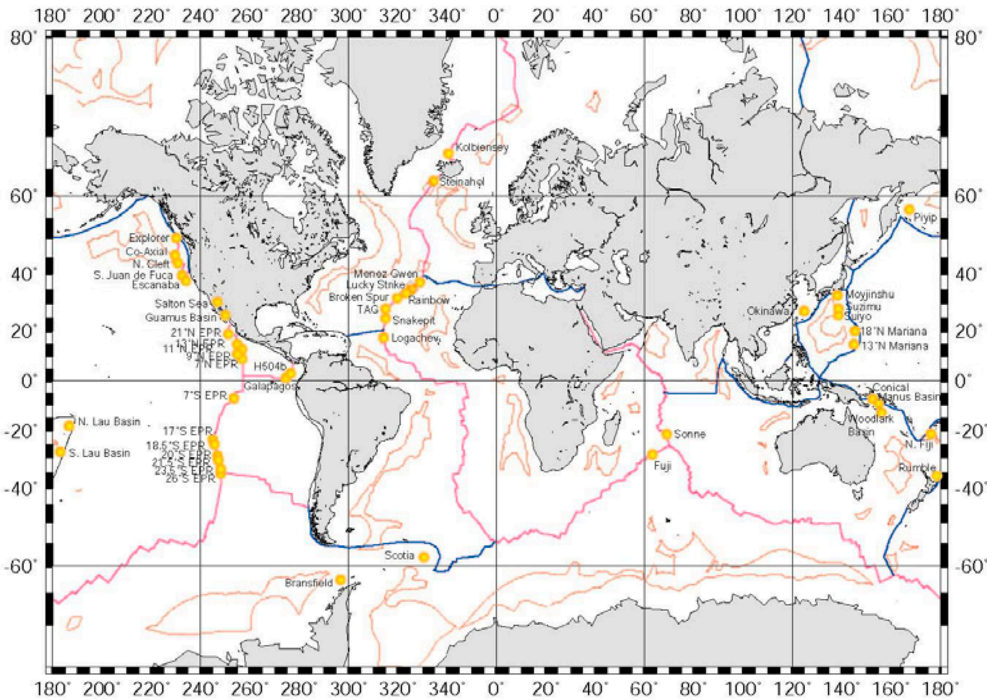

Figure 10. Location of known marine polymetallic sulphide (PMS) deposits (orange-filled circles) with reference to the ELCS regions outlined in red (after: Rona, 1988; Rona and Koski, 1985; Herzig, 1999; Herzig and Hannington, 2000 and others cited in the text).

The main areas of occurrence are fast-, intermediate-, and slow-spreading mid-ocean ridges, on- and off-ridge volcanoes and seamounts, in sedimented rifts adjacent to continental margins and in volcanoes and spreading ridges related related to deep-ocean trenches (Rona, 1988; Rona and Koski, 1985; Herzig, 1999; Herzig and Hannington, 2000). High-temperature hydrothermal activity and large accumulations of polymetallic sulphides are known at some 25 different sites world-wide (Figure 10).

Small oceanic basins related to deep-ocean trenches are important sites for PMS mineralisation. For example, the "PACMANUS" hydrothermal deposits are scattered along a 10 km-long crest of an active volcanic ridge in the Eastern Manus Basin, Papua New Guinea. Here, chimneys dominated by chalcopyrite and sphalerite, with barite and some bornite, have average compositions of 11 wt% Cu, 27% Zn, 230 ppm Ag and 18 ppm Au (Moss et al., 1997; Scott and Binns, 1995; Binns et al., 1993). The shallow depths (less than 1,500 m) and high gold content make such sites potentially viable for mining.

4.4.4 Resource potential of marine polymetalic sulphides deposits

Very little is known about the total metal content of sub-sea PMS deposits and their sub-surface extent. However, it is unlikely that sub-sea PMS deposits, such as those located in international waters on the mid-ocean ridges (e.g. the Mid-Atlantic Ridge, East, Northeast and Southeast Pacific Rises, and the Indian Ocean ridges), will become mining targets in the forseeable future (Agterberg, F.P. and Franklin, 1987). This is largely because of their depth (greater than 2500 m) and remote locations from shore. However, marine mining may become economically viable under some conditions where there are high gold and base-metal grades, sites are located close to land, and in water depths less than 2000 m. Under those circumstances, massive sulphide mining may become economically viable (Broadus, 1985).

With reference to Figure 10, showing the locations of known hydrothermal activity and PMS deposits and their geologic setting, it is possible to identify those areas where conditions for recovery may become viable. These are: the south-west Pacific, the Scotia Sea, the Guyamus Basin (Gulf of California), northern East Pacific Rise, the Mid-Atlantic Ridge south of the Azores islands, and possibly parts of the Juan de Fuca Ridge of western North America.

Only the PMS deposit known as lucky Strike on the Mid-Atlantic Ridge, located to the south of the Azores islands lies within potential areas of extended legal continental shelf (ELCS). Even for those PMS deposits that are already known, and lie within 200 nautical miles of coastal states, the logistical difficulty for mineral recovery make them all currently para-marginal resources. The only exception to this is the PACMANUS deposit in the Eastern Manus Basin (Bismarck Sea, north of Papua New Guinea), for which the Papua New Guinea authorities granted in 1999 two exploration and development licences to Nautilus Mineral Corporation PLC.

4.5 Marine manganese nodules and crusts

4.5.1 What manganese nodules and crusts comprise

Manganese nodules are concentrations of iron and manganese oxides, ranging from millimetres to tens of centimetres in diameter. They can contain economically valuable concentrations of nickel, copper and cobalt (together, making up to three weight percent). They occur mainly on the deep-seafloor. Apart from manganese and iron oxide, nickel, copper and cobalt, the nodules and crusts include trace amounts of molybdenum, platinum and other base metals (Cronan, 1980; Manheim, 1986).

Manganese nodules were first dredged by the HMS Challenger Expedition in the Pacific Ocean in 1872-76 (Murray, 1878; Murray and Irvine, 1895; Murray and Renard, 1891). The currently known distribution of manganese nodules and crusts on the ocean floor (shown on Figure 11) is based on information acquired by sidescan sonars, drill cores, dredged samples, seafloor photos, video camera records and direct observation from submersibles.

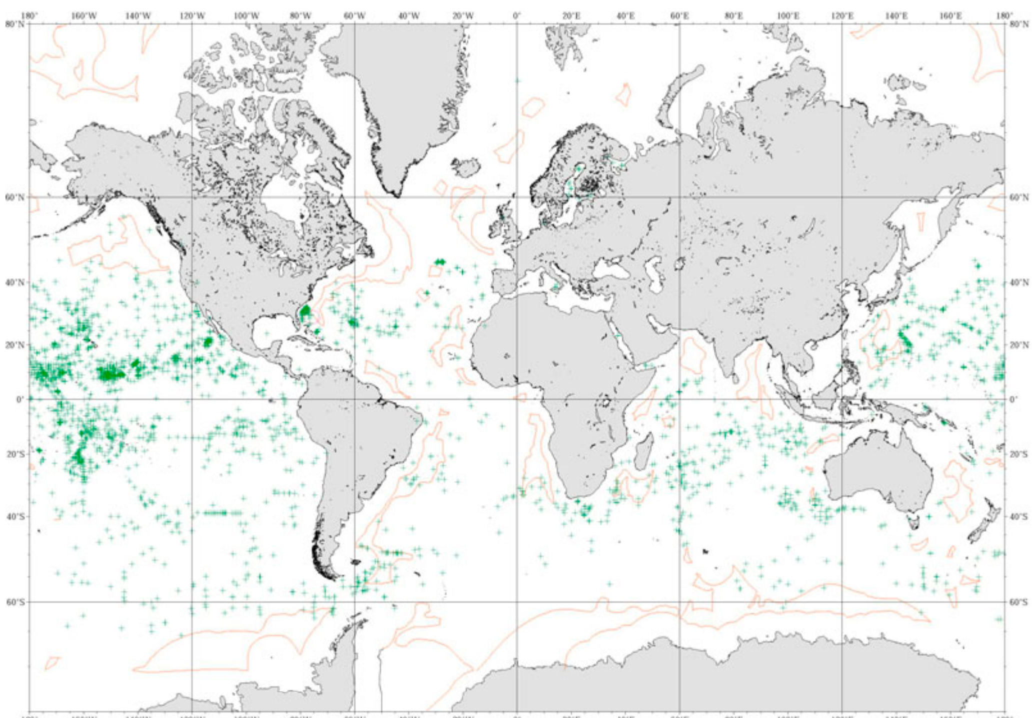

Figure 11. Location of all reported marine manganese nodule and crust deposits (green crosses) with reference to the ELCS regions outlined in red (after: Anon., NOAA & MMS Marine Minerals CD-ROM Data Set, World Data Center for Marine Geology & Geophysics, Boulder, 1991; Gross and McLeod, 1987; Kessler, 1994, and other sources cited in the text).

The most up to date information of nodule and crust locations, their compositions and abundance, has been compilation by the USGS, NOAA and US Mineral Management Service (Anon., NOAA & MMS Marine Minerals CD-ROM Data Set, World Data Center for Marine Geology & Geophysics, Boulder, 1991) These data form the basis of the analysis of this resource assessed here in this report.

Manganese rich crusts, similar in composition to the nodules, are found in some areas and range from coatings and veneers a few millimetres thick to layered crusts that are several centimetres thick. They are deposited on sand grains, pebbles, rock fragments and bedrock, or blanket unconsolidated sediments. They occur as coatings or encrustations on hard rock substances, on seamounts and the submerged portions of islands, and can be enriched by up to two per cent in cobalt. (Mero, 1965; Glasby, 1977).

4.5.2 Mineralogy of nodules and crusts

Nodules and crusts consist predominantly of amorphous and very fine grained hydrated manganese and iron oxide minerals with variable amounts of silica, carbonate, and detrital and biological materials (Gross and McLeod, 1987). The major mineral phases of iron and manganese oxides control the uptake and retention in the nodules of minor elements such as nickel, copper, cobalt, molybdenum and rare earth elements (Cronan, 1977). Identification of specific mineral phases is difficult because of the intimate intergrowth of the different mineral phases and associated detrital material. Of the large number of complex hydrous manganese oxide mineral phases identified in the nodules and crusts, todorokite and birnessite, are the most common. The ratio of different mineral phases and their relationship to different environments has been documented by Burns and Burns (1977).

In addition to the iron and manganese minerals, nodules and crusts contain a variety of non-metallic minerals, amorphous material and biological debris that may comprise up to 25 wt. % of their (dry) mass. These include clay minerals, quartz, feldspar and chlorite, mostly of detrital origin along with silica gels, chalcedony, calcareous and phosphatic components in varied proportions.

4.5.3 Chemical composition of nodules

Gross and McLeod (1987) report that the major elements in dry nodules are oxygen, manganese, iron, silica, lesser amounts of aluminium, calcium, sodium, and magnesium and trace elements of which nickel, copper, and cobalt are of greatest economic interest. The amounts and proportions of constituents vary considerably within single nodules, in nodules of different sizes, and in nodules from different regions and ocean basins. (Calvert, 1978; Haynes et al.,l985).

The average composition of nodules from the Atlantic, Pacific and Indian Oceans are given below in dry wt. %, (Cronan, 1977, 1980, 2000; Gross and McLeod, 1987):

Table 1. Average elemental concentrations for manganese nodules (from Gross and McLeod, 1987).

Average content (in dry wt. %)	**Atlantic**	**Pacific**	**Indian**
Manganese	15.46	19.27	19.27
Iron	23.01	11 79	13.35
Nickel	0.308	0.846	0.534
Copper	0.141	0.706	0.295
Cobalt	0.23410	0 290	0.247
Manganese/Iron	0.67	1.6	1.14

4.5.4 Chemical composition of manganese crusts

The composition of manganese crusts varies from 15 to 31 wt. % manganese, 7 to 18 wt % iron, and has Mn/Fe ratios from 1.0 to 3.4. In general, cobalt content is higher for crust than for nodules with up to 2 wt % cobalt being found in samples from seamount summit areas less than 1500 m in depth. The average cobalt content in crusts is 0.8 wt %, which also contain significant amounts of nickel, lead, cerium, molybdenum, vanadium and other minor metals including platinum group elements (Manheim, 1986).

Manganese crusts that are rich in cobalt are widely distributed on the slopes of seamounts and islands in the equatorial Pacific, on the Blake Plateau in the north-west Atlantic, and with denser concentrations of nodules in many parts of the ocean basins. The main factors controlling distribution of cobalt rich manganese crusts in the Central Pacific are described by Cronan (1983, 1985), Morgan (2000), Halbach (1983); Halbach and Manheim (1984); and Manheim (1986) as:

(1) elevated biological activity and extraction of cobalt from seawater by organisms;
(2) water depths less than 2000 metres in the vicinity of seamounts;
(3) manganese enrichment at certain ocean depths related to zones of minimum oxygen;
(4) low rates or absence of turbidite sedimentation.

Clark and others (1984; 1985) state that "the most favourable areas for cobalt bearing crusts lie on seamounts older than 25 Ma, within water depths of 800 to 2400 m, from 5° to 15° from the equatorial zone and in areas where two generations of crusts with ages from 16 to 9 Ma and 8 Ma or younger occur".

For example, cobalt concentrations in manganese-iron crusts and nodules in the Mid-Pacific Mountain and Line Islands area increase from less than 0.4 % at water depths of 4000 m to 1.2 % on seamount slopes and summits less than 2500 m in depth (Gross and McLeaod, 1987). The thickness of these crusts ranges from 2 cm in the upper slope areas to 9 cm in the lower areas and may contain more than 16 kg/m (dry weight) of encrusted surfaces (Halbach and Manheim, 1984).

4.5.5 How manganese nodules and crusts are formed

Manganese nodules and crusts are formed through sedimentary, concretionary and biogenic processes. The metals contained in them are derived from hydrothermal, diagenetic, halmyrolytic, and sedimentary sources (Cronan, 1980; Eldesfield, 1977). The development and distribution of nodules are influenced by a variety of regional and local factors (Burns and Burns, 1977 – also see Cronan 2000 for references therein). These include:

(1) their size, morphology, mineralogy, age and rate of growth;
(2) the availability, size and composition of nuclei;

(3) bathymetry, paleo-bathymetry and seabed topography
(4) the carbonate compensation depth;
(5) seawater composition;
(6) bottom currents and paleo-currents;
(7) redox potential at the sediment-water interface;
(8) composition, thickness and age of underlying sediments;
(9) thermal gradients in the sediment column;
(10) rates of detrital or chemical sedimentation, and biological productivity in the water column;
(11) activity of bottom organisms; and
(12) the proximity to volcanic, hydrothermal-effusive and tectonic activity.

However, both Eldersfield (1977) and Cronan (1980) state that the lack of detailed systematic sampling of nodules has limited research and understanding of the respective role and interrelationship of these factors.

The source of metals in the nodules is attributed to the following factors (Greenslate, et al. 1973: Glasby,1977; Calvert,1978):

(1) discharge of hydrothermal solutions along active tectonic belts;
(2) leaching of metals from the bottom sediments and volcanic rocks during diagenesis and consolidation and subsequent transport and deposition by interstitial water;
(3) solution and transport of metals by seawater with precipitation at favourable sites; and
(4) the deposition of metal-bearing elastic or colloidal sediment derived from a landmass.

Gross and McLeod (1987) identify a number of interrelated environmental factors which control the deposition and concentration of nickel and copper bearing nodules that are of significance as resources. These are found:

(1) below the carbonate compensation depth in abyssal areas isolated from the deposition of continental clastic detrital material, where sedimentation rates are low and bottom sediments commonly consist of siliceous ooze or red clay;
(2) in proximity to active spreading ridges, major fracture systems, and active volcanism that provide sources of metals and nuclei for nodule growth;

(3) where bottom currents are effective in transporting metals in solution and supplying oxygenated water conducive to the precipitation of metals and in promoting the growth of nodules by inhibiting sedimentation;

(4) in areas of high biological productivity, where metals are collected from the seawater by organisms and contributed to the pelagic sediments.

The size, shape, mineralogy, physical and chemical properties, and distribution of nodules are highly variable, on both broad and local scales reflecting the complex interplay of environmental factors and the dominant role of one or two genetic processes (Hein and Morgan, 1999; Hein et al., 1997; Frazer and Fisk, 1980; Halbach et al., 1989).

4.5.6 Distribution and composition of manganese nodules and crusts

Manganese nodules and crusts occur in many different environments including freshwater lakes, fiords, continental shelves, seamounts or abyssal plains and basins. The most extensive nodule fields are on oceanic crust that is Mesozoic or younger in age. At the present time, nodules are forming at a slow rate of a one to a few tens of millimetres per million years (Ku,1977; Cronan, 1980; Calvert, 1978). Their formation appears to be related to active tectonic belts such as spreading ridges and deep-ocean trenches. They are found chiefly below the carbonate compensation depth in areas with low clastic sedimentation and high biological activity in overlying surface waters (Cronan, 1980, 2000). Nodules with high nickel and copper contents are found in some of the deep ocean basins at depths of 4000 to 5000 metres.

Figure 11 shows the distribution of all known manganese nodules and crusts for which there are quantitative chemical analyses and where estimates of their abundance have been mapped. These data have been compiled from sites where dredges, cores, submersibles and bottom photographs have been taken. Although the chemical analyses cover wide regions, the same is not true for the abundance of nodules and/or thickness of crusts which are less well documented. Therefore, the analyses presented here is only preliminary and should not be taken as anything other than a guide to this resource.

Figures 12 (a) and (b) shows the density of nodules and crusts (in kg/m^2) on the seafloor (compiled from extensive reports in the literature (reference to NOAA and MMS CD-ROM data base; McKlevey and Wang, 1969; Rawson and Ryan, 1978).

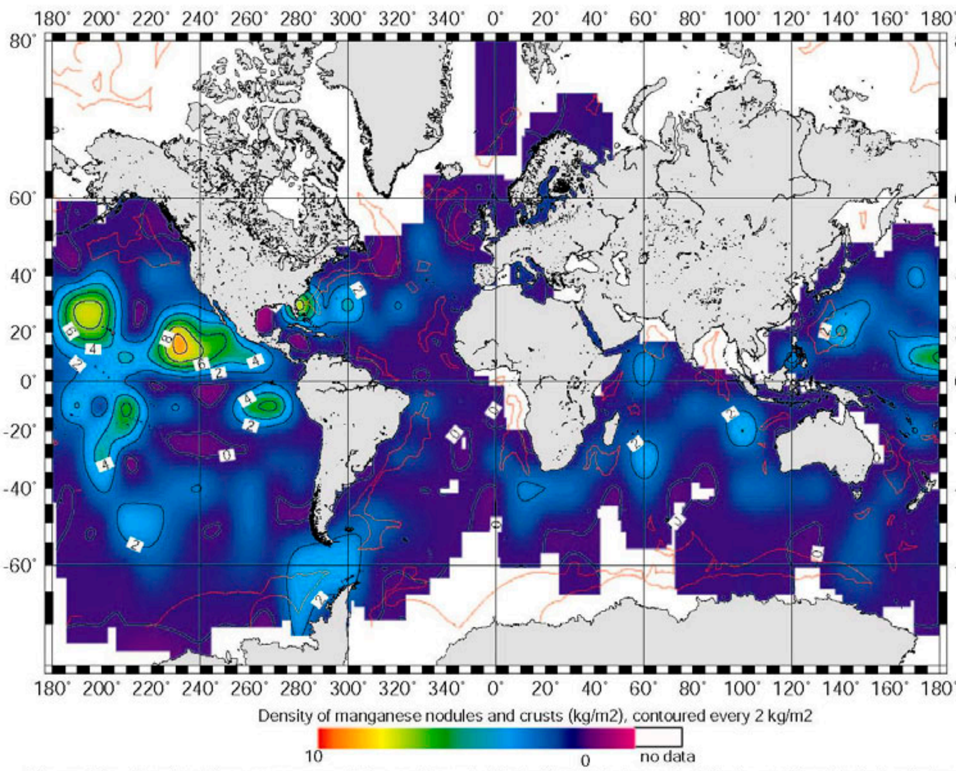

Figure 12a. Density of manganese nodules and crusts (kg/m2) gridded on a 1 latitude and longitude basis from data compiled from the same sources cited on figure 11.

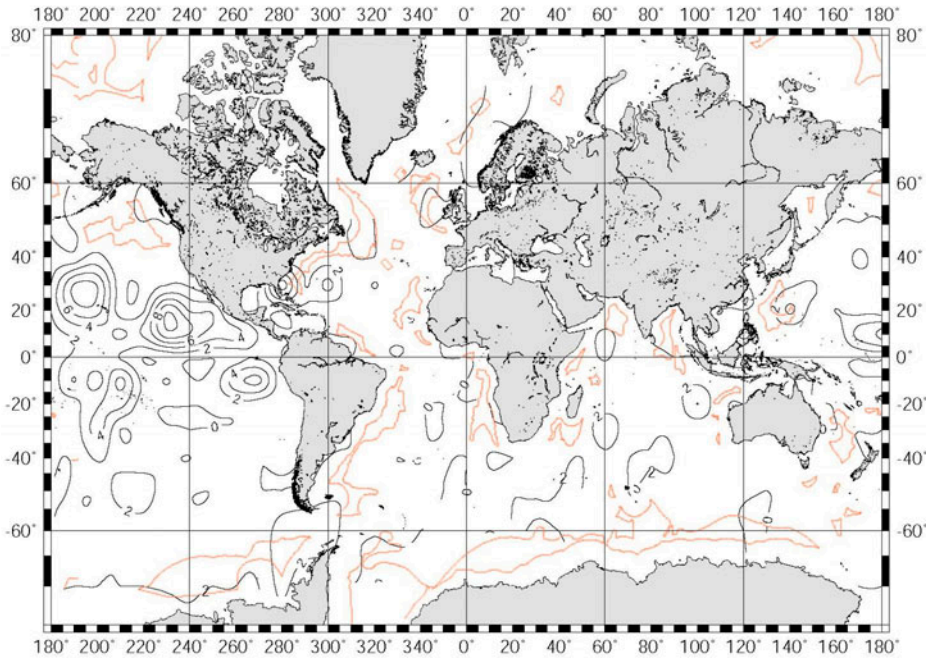

Figure 12b. Density of manganese nodules and crusts (kg/m2) contoured every 2 kg/m2 from a 1 latitude and long grid based on data compiled from the same sources cited on figure 11.

There are four elements are of economic importance in these deposits: manganese, copper, nickel and cobalt. Figures 13 to 20 show the composition of these elements in nodules and crusts, as well as the density of these elements (mass/unit area) on the seafloor. Estimates for the density of these four important elements (in mass per unit area) has been derived by multiplying the elemental compositions of the nodules and crusts (in dry wt. %) with their density on the seafloor (mass/unit area). These data have been compiled and contoured on a 1° latitude and longitude grid. Areas lying beyond 10° in either latitude or longitude are not contoured since extrapolation beyond these ranges is considered unreliable here.

Important areas where cobalt-bearing manganese crusts have been found in the Pacific include the Northwest Hawaiian Ridge, Johnston Island, Huwland-Baker Islands, Marianas Island, Guam, Marshall Islands, Central Seamounts, Palmyra-Kingman, Micronesia and Wake Island (Manheim 1986). Clark et al., (1984, 1985) state that "the area around the Federated States of Micronesia and the Marshall Islands appear to have a much larger resource potential for cobalt, nickel, manganese and platinum than other island areas". Cobalt bearing manganese-iron crusts cover thousands of square kilometres in the Atlantic Ocean and are found on the Blake Plateau, Sierra Leone Rise, and the east flank of the Mid-Atlantic Ridge. Here crusts have a cobalt content of up to 1 wt. %. The mean content of cobalt in 77 samples of crusts from depths to 2,500 m in the Atlantic Ocean is 0.5 wt. % and the total content ranges from 0.5 to 0.85 wt. %, while the mean content of manganese is 20.15 wt. % and the total ranges from 17.9 to 22.28 wt. % (Manheim, 1986). The average metal content in crust samples from the Hawaiian Archipelago and Johnston-Palmyra Region in the Pacific is: 0.90 wt. % cobalt, 0.50 wt. % nickel, 0.06 wt. % copper, and 24.7 wt. % manganese (Clark et al. 1984). The average thickness of the crusts is 2.4 to 2.8 cm.

The composition of nodules and crusts is strongly effected by their geologic environment. Nodules and crusts containing appreciable amounts of nickel, copper and cobalt are distributed in a belt within 300 km of the equator in the Pacific and Indian oceans and in a large region of the south, central and south-eastern Pacific.. A region of special economic interest lies in the central north-east Pacific Ocean between the Clipperton and Clarion fracture zones (bounded by latitude 5° N and 25°N and longitude 270°E to 210°E). Here, abundant nodules have a up to 30 wt. % manganese, 1.5 wt % copper, 10,000 ppm cobalt and 2 wt % nickel. They have a combined content of nickel and copper of up to 3.5 wt %. Nodules in this region are more concentrated than in most other areas, with averages up to 10kg/m^2. However, nodule abundance varies considerably within local areas, and in isolated sites ranges up to 30 kg/m^2 (Hayes et al.,1985; Frazer, 1977). Our estimates of the elemental concentration on the seafloor in this region are up to 3kg/m^2 for manganese, 80 g.m^2 for copper, 25 mg/m^2 for cobalt and 0.2 kg/m^2 for nickel.

A large area in the Central Pacific Ocean (north of 28°N and between 180-200°E) has widespread concentrations of nodules with average densities up to 10kg/m^2 (Figure 12). These contain elemental concentration up to 20 wt. % manganese, 1 wt. % copper, 4000 ppm cobalt and 1% nickel, with combined nickel and copper concentrations of up to 2 wt. %. The elemental density on the seafloor range up to 1.5 kg/m^2 for manganese, 60 g/m^2 for copper, 40 mg/m^2 for cobalt and 0.75 kg/m^2 for nickel.

A number of locations south-west of Hawaii (within an area 5°N to 10°N and 180°E to 195°E) have concentrations of nodules and crusts averaging $2kg/m^2$. These contain elemental concentrations and densities on the seafloor of up to 10 wt. % manganese but with less than 1 kg/m^2, up to 1 wt.% copper with less than $10g/m^2$, up to 4000 ppm cobalt with a maximum of 10 mg/m^2, and 0.5 wt. % nickel with less than 0.025 kg/m^2. The combined nickel and copper concentration is up to 2 wt. %.

Because of a number of factors including depth of water and sedimentation rates, the pattern of nodule distribution seen to the north of the equator is not found in to the south (Halbach,1983).

Table 2. Average abundance of Mn, Fe, Ni, Co and Cu in manganese nodules and crusts from different environments (in weight per cent) (after Cronan 1977).

	Seamounts	**Plateaux**	**Active ridge**	**Other ridge**	**Continental margin**	**Marginal seamounts**	**Abyssal plains**
Mn	14.62	17.17	15.15	19.74	38.69	15.65	16.78
Fe	15.81	11.81	19.15	20.08	1.34	19.32	17.27
Ni	0.351	0.641	0.306	0.336	0.121	0.296	0.540
Co	1.15	0.347	0.400	0.570	0.011	0.419	0.256
Cu	0.058	0.087	0.081	0.052	0 082	0.078	0.370
Mn/Fe	0.92	1.53	0.80	0.98	28.8	0.81	0.97
Depth	1872	945	2870	1678	3547	1694	4460

Nodules densities of up to 8 kg/m^2 are found in the Pacific southern equatorial belt at the edge of the calcareous zone between 180°E and 220°E. However, occurrences are infrequent throughout much of the area. An exception is an area between the East Pacific Rise and South America densities of up to $6kg/m^2$ are reported.

Manganese nodules with up to 2 wt. % of combined nickel and copper and up to 4000 ppm cobalt contents are found in an area in the Indian Ocean (Figures 1, 15, 17, 19) that extends from 10°S to 25°S and 70°E to 86°E, but have concentration of less than 1 kg/m^2 (Frazer and Wilson, 1980).

Other areas south-west of Australia (between 40-60°S and 70-95°E) and north-west of Austalia (between 10-25°S and 95-105°E) have scattered concentrations of nodules up to 2 kg/m^2. However, their metal content appears to be generally low (Cronan, 1980, 2000; Haynes et al.,1985; Gross and McLeod, 1987) with combined copper and nickel of only 2 wt. %. A more significant field of nodules lies in the western Pacific, between 20°N and the equator and 160-200°E where average densities are up to 6 kg/m^2. Here combined copper and nickel comprises 2-3 wt. %, and cobalt concentrations are up to 8000 ppm. This translates in to elemental abundance of copper, cobalt and nickel of up to 50 kg/m^2, 25 mg/m^2 and 0.05 kg/m^2 respectively (Figures 16, 18 & 20).

Nodules are sparsely and irregularly distributed through broad areas of the Atlantic. Probably the most economically interesting concentrations are found on the Blake Plateau, in shallow water east of Florida. Here, nodules and crusts with high Mn/Fe ratios make them economically attractive as a manganese resource (Manheim, 1972). Nodules off the west coast of Italy are of special interest for similar reasons. Good possibilities for finding nodules in other areas near continental margins where they have high Mn/Fe ratios (Cronan, 1980; 2000; Glasby, 1977) include areas such as the southern and south-western African continental margin.

4.5.7 Resource potential of manganese nodules and crusts

Although the mineralogy, composition and origin of manganese nodules are relatively well known, assessments of their resource potential are not well documented. Potential resources estimates for copper, nickel and cobalt in nodules were made during the 1960s and 1970s and are summarised in Volume I of the United Nations Seabed Mineral Series. However, most of the estimates of resource potential were based on a minimum abundance of 10 kg/m^2 and a minimum combined grade of 1.76 wt. % copper and nickel. However, the abundance of nodules remains a major source of uncertainty and any global estimates must be subject to an order of magnitude error. Despite this, potential world-wide resources of nodules range from 14 to 99 billion tonnes (Gross and McLeod, 1987). Mero (1977) states that "assuming an average concentration of 9 kg/m^2 of ocean floor over 6 million km^2, the high-grade area of the Clarion-Clipperton region in the north Pacific comprise a resource of about 38 billion tonnes of dry nodules, containing about 110 billion tonnes of manganese, 115 million tonnes of cobalt, 650 million tonnes of nickel, and

520 million tonnes of copper". In a more recent estimate, Morgan (2000) calculates the nodule potential in the Clarion-Clipperton zone as 34 billion tonnes containing elemental resources of 7500 million tonnes of manganese, 340 million tonnes of nickel, 265 million tonnes of copper and 78 million tonnes of cobalt.

Accepting the uncertainties and limitations of past and present resource estimates, and using the methods described in this report, it is possible to assess the resources held by manganese nodules and crusts within potential "extended legal continental shelf" (ELCS) regions. Table 3 gives the results of this exercise. Coastal states are listed against the area of their potential ELCS, the average concentration on the seafloor (mass/area) of elements found in manganese nodules and crusts, the total resource of that element.

The top ten countries, ranked in descending order, that have the greatest resource potential of nodules and crusts in their ELCSs are: the United States of America, Madagascar, Brazil, Antarctica, Argentina, Japan, South Africa, Canada and India, ranging from 1.86 billion tonnes to 0.33 billion tonnes. In contrast, the bottom ten countries that have potential ELCS resource of nodules and crusts are: Guyana, Mauritania, Kenya, Congo, Zaire, Gambia, Sierra Leone, Guinea Bissau, Guinea, Venezuela, ranging from 15.3 million tonnes to 0.28 million tonnes respectively.

- ***Table 3a**:* Global distribution, concentration and abundance of manganese nodules and crusts. Values obtained from averages for each ELCS, or portion of, potentially calimed by each coastal state.
- ***Table 3b***: Global distribution, concentration and abundance of elemental manganese in nodules and crusts.
- ***Table 3c***: Global distribution, concentration and abundance of elemental copper in nodules and crusts.
- ***Table 3d***: Global distribution, concentration and abundance of elemental nickel in nodules and crusts
- ***Table 3e***: Global distribution, concentration and abundance of elemental cobalt in nodules and crusts.

Country	Area No.	Area (sq. km)	Total Area (sq. km)	Conc. Mn nod (kg/sq.m)	Total Mn nods (tonnes)	Total Mn nods for country
Angola	23	251,305	251,305	0.25	62,826,138	62,826,138
Antarctica	26	15,187	5,418,265	0.25	3,796,673	1,484,701,297
	27	1,235,520		0.68	840,153,314	
	28	1,113,819		0.5	556,909,560	
	29	1,376,905		ND		
	31	1,676,835		0.05	83,841,750	
Argentina	24	239,319	239,319	1	239,319,000	239,319,000
Australia	32	250,116	728,342	0.5	125,058,150	363,262,670
	33	23,100		1	23,100,210	
	34	29,776		1	29,775,750	
	35	56,215		1	56,214,560	
	36	48,230		ND	0	
	37	37,650		ND	0	
	38	25,027		ND	0	
	39	258,228		0.5	129,114,000	
Bangladesh	15	969,982	969,982	ND	0	0
Brazil	24	1,675,235	1,964,494	0.5	837,617,500	922,099,185
	25	240,591		0.25	60,147,710	
	42	48,668		0.5	24,333,975	
Burma	15	46,203	46,203	ND	0	0
Canada	1	19,778	2,193,712	ND	0	436,144,640
	2	57,143		ND	0	
	4	872,289		0.5	436,144,640	
	5	1,244,502		ND		
Congo	23	14,652	14,652	0.25	3,663,000	3,663,000
Denmark	7	237,431	237,431	ND	0	0
Equitorial Guir	22	15,566	15,566	ND	0	0
France	30	34,653	258,768	ND	0	336,172,110
	39	224,115		1.5	336,172,110	
French Guiana	25	140,980	140,980	0.25	35,244,915	35,244,915
Gabon	23	136,752	136,752	0.25	34,188,000	34,188,000
Gambia	20	10,662	10,662	0.25	2,665,582	2,665,582
Ghana	22	25,943	25,943	ND	0	0
Greenland	5	103,312	103,312	ND	0	0
Guinea	21	27,897	27,897	0.05	1,394,871	1,394,871
Guinea Bissau	21	38,359	38,359	0.05	1,917,947	1,917,947
Guyana	25	61,003	61,003	0.25	15,250,628	15,250,628
Iceland	6	2,800	84,937	1	2,799,980	23,334,315
	7	82,137		0.25	20,534,335	
India	15	150,457	1,011,832	ND		646,031,250
	17	861,375		0.75	646,031,250	
Ireland	7	176,511	176,511	0.1	17,651,100	17,651,100
Japan	14	339,701	339,701	2	679,402,580	679,402,580
Kenya	18	20,782	20,782	0.5	10,390,995	10,390,995
Madagascar	19	2,087,434	2,087,434	1	2,087,434,000	2,087,434,000
Mauritania	20	53,312	53,312	0.25	13,328,000	13,328,000
Mauritus	45	321,039	321,039	1.5	481,558,500	481,558,500
Morocco	20	824,562	824,562	0.25	206,140,415	206,140,415
Mozambique	19	123,258	123,258	1	123,258,000	123,258,000
Namibia	23	1,111,735	1,111,735	0.25	277,933,750	277,933,750
New Zealand	36	48,230	617,808	0.5	24,114,750	321,417,670
	37	37,650		0.5	18,824,770	
	38	25,027		1	25,027,030	
	39	506,902		0.5	253,451,120	
Nigeria	22	103,772	103,772	ND	0	0
Norway	8	92,181	158,920	ND	0	0
	9	49,231		ND	0	
	10	17,508		ND	0	
Oman	17	375,295	375,295	0.75	281,471,250	281,471,250
Pakistan	17	41,255	41,255	0.75	30,940,905	30,940,905
Phillippines	14	564,725	564,725	2	1,129,449,420	1,129,449,420
Portugal	43	61,738	123,476	1	61,738,000	123,476,000
	44	61738		1	61,738,000	
Russia	1	48,608	430,369	ND	0	0
	3	52,488		ND	0	
	11	218,421		ND	0	
	12	75,397		ND	0	
	13	35,456		ND	0	
Senegal	20	69,924	106,650	0.25	17,481,000	19,317,290
	21	36,726		0.05	1,836,290	
Seychelles	45	321,039	321,039	0.25	80,259,750	80,259,750
Sierra Leone	21	51,030	51,030	0.05	2,551,518	2,551,518
Somalia	18	242,676	242,676	0.5	121,337,985	121,337,985
SOPAC	39	224,115	324,192	ND	0	100,077,000
	40	79,365		1	79,365,000	
	41	20,712		1	20,712,000	
South Africa	19	123,258	184,863	1	123,258,000	138,659,250
	23	61,605		0.25	15,401,250	
Sri Lanka	15	768,758	768,758	ND	0	0
Suriname	25	89,110	89,110	0.25	22,277,450	22,277,450
Tanzania	18	55,681	55,681	0.5	27,840,520	27,840,520
Togo	22	15,566	15,566	ND	0	0
United Kingdc	7	243,679	243,679	0.25	60,919,750	60,919,750
United States	1	248,260	1,212,653	ND		1,860,660,625
	4	214,889		0.5	107,444,500	
	5	508,417		2.5	1,271,042,125	
USA (Guam)	14	241,087		2	482,174,000	
Uruguay	24	53,182	53,182	0.5	26,591,000	26,591,000
Venezuela	25	1,141	1,141	0.25	285,208	285,208
Zaire	23	13,431	13,431	0.25	3,357,750	3,357,750
Total			25,137,321		7,416,422,221	12,856,203,226

Country	Area No.	Area (sq. km)	Total Area (sq. km)	Conc. Mn (kg/sq.m)	Total Mn (T) (tonnes)	Total Mn (T) for country
Angola	23	251,305	251,305	0.05	12,565,228	12,565,228
Antarctica	26	15,187	5,418,265	0.0005	7,593	156,216,951
	27	1,235,520		0.08	98,841,566	
	28	1,113,819		0.05	55,690,956	
	29	1,376,905		ND		
	31	1,676,835		0.001	1,676,835	
Argentina	24	239,319	239,319	0.25	59,829,750	59,829,750
Australia	32	250,116	728,342	0.1	25,011,630	51,642,810
	33	23,100		0.1	2,310,021	
	34	29,776		0.1	2,977,575	
	35	56,215		0.15	8,432,184	
	36	48,230		ND	0	
	37	37,650		ND	0	
	38	25,027		ND	0	
	39	258,228		0.05	12,911,400	
Bangladesh	15	969,982	969,982	ND	0	0
Brazil	24	1,675,235	1,964,494	0.1	167,523,500	181,986,440
	25	240,591		0.05	12,029,542	
	42	48,668		0.05	2,433,398	
Burma	15	46,203	46,203	ND	0	0
Canada	1	19,778	2,193,712	ND	0	130,843,392
	2	57,143		ND	0	
	4	872,289		0.15	130,843,392	
	5	1,244,502		ND		
Congo	23	14,652	14,652	0.05	732,600	732,600
Denmark	7	237,431	237,431	ND	0	0
quitorial Guin	22	15,566	15,566	ND	0	0
France	30	34,653	258,768	ND	0	11,205,737
	39	224,115		0.05	11,205,737	
French Guiana	25	140,980	140,980	0.01	1,409,797	1,409,797
Gabon	23	136,752	136,752	0.05	6,837,600	6,837,600
Gambia	20	10,662	10,662	0.05	533,116	533,116
Ghana	22	25,943	25,943	ND	0	0
Greenland	5	103,312	103,312	ND	0	0
Guinea	21	27,897	27,897	0.01	278,974	278,974
Guinea Bissau	21	38,359	38,359	0.01	383,589	383,589
Guyana	25	61,003	61,003	0.1	6,100,251	6,100,251
Iceland	6	2,800	84,937	0.1	279,998	4,386,865
	7	82,137		0.05	4,106,867	
India	15	150,457	1,011,832	ND		86,137,500
	17	861,375		0.1	86,137,500	
Ireland	7	176,511	176,511	0.02	3,530,220	3,530,220
Japan	14	339,701	339,701	0.2	67,940,258	67,940,258
Kenya	18	20,782	20,782	0.05	1,039,100	1,039,100
Madagascar	19	2,087,434	2,087,434	0.2	417,486,800	417,486,800
Mauritania	20	53,312	53,312	0.05	2,665,600	2,665,600

Country	Area No.	Area (sq. km)	Total Area (sq. km)	Conc. Mn (kg/sq.m)	Total Mn (T) (tonnes)	Total Mn (T) for country
Mauritus	45	321,039	321,039	0.4	128,415,600	128,415,600
Morocco	20	824,562	824,562	0.05	41,228,083	41,228,083
Mozambique	19	123,258	123,258	0.2	24,651,600	24,651,600
Namibia	23	1,111,735	1,111,735	0.05	55,586,750	55,586,750
New Zealand	36	48,230	617,808	0.05	2,411,475	82,831,991
	37	37,650		0.05	1,882,477	
	38	25,027		0.1	2,502,703	
	39	506,902		0.15	76,035,336	
Nigeria	22	103,772	103,772	ND	0	0
Norway	8	92,181	158,920	ND	0	0
	9	49,231		ND	0	
	10	17,508		ND	0	
Oman	17	375,295	375,295	0.1	37,529,500	37,529,500
Pakistan	17	41,255	41,255	0.1	4,125,454	4,125,454
Phillippines	14	564,725	564,725	0.2	112,944,942	112,944,942
Portugal	43	61,738	123,476	0.1	6,173,800	12,347,600
	44	61738		0.1	6,173,800	
Russia	1	48,608	430,369	ND	0	0
	3	52,488		ND	0	
	11	218,421		ND	0	
	12	75,397		ND	0	
	13	35,456		ND	0	
Senegal	20	69,924	106,650	0.05	3,496,200	5,332,490
	21	36,726		0.05	1,836,290	
Seychelles	45	321,039	321,039	0.05	16,051,950	16,051,950
Sierra Leone	21	51,030	51,030	0.01	510,304	510,304
Somalia	18	242,676	242,676	0.05	12,133,799	12,133,799
SOPAC	39	224,115	324,192	ND	0	15,011,550
	40	79,365		0.15	11,904,750	
	41	20,712		0.15	3,106,800	
South Africa	19	123,258	184,863	0.2	24,651,600	27,731,850
	23	61,605		0.05	3,080,250	
Sri Lanka	15	768,758	768,758	ND	0	0
Suriname	25	89,110	89,110	0.02	1,782,196	1,782,196
Tanzania	18	55,681	55,681	0.05	2,784,052	2,784,052
Togo	22	15,566	15,566	ND	0	0
United Kingdom	7	243,679	243,679	0.05	12,183,950	12,183,950
United States	1	248,260	1,212,653	ND		182,134,120
	4	214,889		0.15	32,233,350	
	5	508,417		0.2	101,683,370	
USA (Guam)	14	241,087	241,087	0.2	48,217,400	48,217,400
Uruguay	24	53,182	53,182	0.1	5,318,200	5,318,200
Venezuela	25	1,141	1,141	0.01	11,408	11,408
Zaire	23	13,431	13,431	0.05	671,550	671,550
Total			25,378,408			2,033,288,915

Country	Area No.	Area (sq. km)	Total Area (sq. km)	Conc. Cu (g/sq.m)	Total Cu (T) (tonnes)	Total Cu (T) for country
Angola	23	251,305	251,305	3	753,914	753,914
Antarctica	26	15,187	5,418,265	1	15,187	21,338,635
	27	1,235,520		15	18,532,794	
	28	1,113,819		1	1,113,819	
	29	1,376,905		ND	0	
	31	1,676,835		1	1,676,835	
Argentina	24	239,319	239,319	12	2,871,828	2,871,828
Australia	32	250,116	728,342	5	1,250,582	2,639,762
	33	23,100		8	184,802	
	34	29,776		8	238,206	
	35	56,215		8	449,716	
	36	48,230		ND	0	
	37	37,650		ND	0	
	38	25,027		ND	0	
	39	258,228		2	516,456	
Bangladesh	15	969,982	969,982	ND	0	0
Brazil	24	1,675,235	1,964,494	8	13,401,880	14,512,996
	25	240,591		3	721,773	
	42	48,668		8	389,344	
Burma	15	46,203	46,203	ND	0	0
Canada	1	19,778	2,193,712	ND	0	4,797,591
	2	57,143		ND	0	
	4	872,289		5.5	4,797,591	
	5	1,244,502		ND	0	
Congo	23	14,652	14,652	2	29,304	29,304
Denmark	7	237,431	237,431	ND	0	0
uitorial Gui	22	15,566	15,566	ND	0	0
France	30	34,653	258,768	ND	0	1,120,574
	39	224,115		5	1,120,574	
rench Guian	25	140,980	140,980	3	422,939	422,939
Gabon	23	136,752	136,752	2	273,504	273,504
Gambia	20	10,662	10,662	2	21,325	21,325
Ghana	22	25,943	25,943	ND	0	0
Greenland	5	103,312	103,312	ND	0	0
Guinea	21	27,897	27,897	2	55,795	55,795
uinea Bissa	21	38,359	38,359	2	76,718	76,718
Guyana	25	61,003	61,003	3	183,008	183,008
Iceland	6	2,800	84,937	4	11,200	93,337
	7	82,137		1	82,137	
India	15	150,457	1,011,832	ND	0	1,722,750
	17	861,375		2	1,722,750	
Ireland	7	176,511	176,511	1	176,511	176,511
Japan	14	339,701	339,701	10	3,397,013	3,397,013
Kenya	18	20,782	20,782	2	41,564	41,564
Madagascar	19	2,087,434	2,087,434	5	10,437,170	10,437,170
Mauritania	20	53,312	53,312	2	106,624	106,624

Country	Area No.	Area (sq. km)	Total Area (sq. km)	Conc. Cu (g/sq.m)	Total Cu (T) (tonnes)	Total Cu (T) for country
Mauritus	45	321,039	321,039	10	3,210,390	3,210,390
Morocco	20	824,562	824,562	2	1,649,123	1,649,123
Mozambique	19	123,258	123,258	5	616,290	616,290
Namibia	23	1,111,735	1,111,735	7	7,782,145	7,782,145
New Zealand	36	48,230	617,808	8	385,836	1,901,053
	37	37,650		8	301,196	
	38	25,027		8	200,216	
	39	506,902		2	1,013,804	
Nigeria	22	103,772	103,772	ND	0	0
Norway	8	92,181	158,920	ND	0	0
	9	49,231		ND	0	
	10	17,508		ND	0	
Oman	17	375,295	375,295	2	750,590	750,590
Pakistan	17	41,255	41,255	2	82,509	82,509
Phillippines	14	564,725	564,725	8	4,517,798	4,517,798
Portugal	43	61,738	123,476	4	246,952	493,904
	44	61738		4	246,952	
Russia	1	48,608	430,369	ND	0	0
	3	52,488		ND	0	
	11	218,421		ND	0	
	12	75,397		ND	0	
	13	35,456		ND	0	
Senegal	20	69,924	106,650	2	139,848	139,848
	21	36,726		ND	0	
Seychelles	45	321,039	321,039	5	1,605,195	1,605,195
Sierra Leone	21	51,030	51,030	2	102,061	102,061
Somalia	18	242,676	242,676	2	485,352	485,352
SOPAC	39	224,115	324,192	ND	0	500,385
	40	79,365		5	396,825	
	41	20,712		5	103,560	
South Africa	19	123,258	184,863	5	616,290	1,109,130
	23	61,605		8	492,840	
Sri Lanka	15	768,758	768,758	ND	0	0
Suriname	25	89,110	89,110	3	267,329	267,329
Tanzania	18	55,681	55,681	2	111,362	111,362
Togo	22	15,566	15,566	ND	0	0
United Kingdor	7	243,679	243,679	1	243,679	243,679
United States	1	248,260	1,212,653	ND	0	8,999,262
	4	214,889		7	1,504,223	
	5	508,417		10	5,084,169	
USA (Guam)	14	241,087	241,087	10	2,410,870	
Uruguay	24	53,182	53,182	8	425,456	425,456
Venezuela	25	1,141	1,141	3	3,422	3,422
Zaire	23	13,431	13,431	1	13,431	13,431
Total			25,378,408			100,082,574

Country	Area No.	Area (sq. km)	Total Area (sq. km)	Conc. Ni (kg/sq.m)	Total Ni (T) (tonnes)	Total Ni (T) for country
Angola	23	251,305	251,305	0.005	1,256,523	1,256,523
Antarctica	26	15,187	5,418,265	0.01	151,867	26,460,333
	27	1,235,520		0.01	12,355,196	
	28	1,113,819		0.005	5,569,096	
	29	1,376,905		ND	0	
	31	1,676,835		0.005	8,384,175	
Argentina	24	239,319	239,319	0.0075	1,794,893	1,794,893
Australia	32	250,116	728,342	0.01	2,501,163	5,347,823
	33	23,100		0.005	115,501	
	34	29,776		0.005	148,879	
	35	56,215		ND	0	
	36	48,230		ND	0	
	37	37,650		ND	0	
	38	25,027		ND	0	
	39	258,228		0.01	2,582,280	
Bangladesh	15	969,982	969,982	ND	0	0
Brazil	24	1,675,235	1,964,494	0.005	8,376,175	8,473,511
	25	240,591		ND	0	
	42	48,668		0.002	97,336	
Burma	15	46,203	46,203	ND	0	0
Canada	1	19,778	2,193,712	ND	0	8,722,893
	2	57,143		ND	0	
	4	872,289		0.01	8,722,893	
	5	1,244,502		ND	0	
Congo	23	14,652	14,652	0.005	73,260	73,260
Denmark	7	237,431	237,431	ND	0	0
uitorial Guii	22	15,566	15,566	ND	0	0
France	30	34,653	258,768	ND	0	4,482,295
	39	224,115		0.02	4,482,295	
rench Guian	25	140,980	140,980	ND	0	0
Gabon	23	136,752	136,752	0.002	273,504	273,504
Gambia	20	10,662	10,662	0.001	10,662	10,662
Ghana	22	25,943	25,943	ND	0	0
Greenland	5	103,312	103,312	ND	0	0
Guinea	21	27,897	27,897	0.001	27,897	27,897
uinea Bissa	21	38,359	38,359	0.001	38,359	38,359
Guyana	25	61,003	61,003	0.001	61,003	61,003
Iceland	6	2,800	84,937	0.001	2,800	413,487
	7	82,137		0.005	410,687	
India	15	150,457	1,011,832	ND	0	4,306,875
	17	861,375		0.005	4,306,875	
Ireland	7	176,511	176,511	0.001	176,511	176,511
Japan	14	339,701	339,701	0.002	679,403	679,403
Kenya	18	20,782	20,782	0.0005	10,391	10,391
Madagascar	19	2,087,434	2,087,434	0.005	10,437,170	10,437,170
Mauritania	20	53,312	53,312	0.001	53,312	53,312

Country	Area No.	Area (sq. km)	Total Area (sq. km)	Conc. Ni (g/sq.m)	Total Ni (T) (tonnes)	Total Ni (T) for country
Mauritus	45	321,039	321,039	0.05	16,051,950	16,051,950
Morocco	20	824,562	824,562	0.001	824,562	824,562
Mozambique	19	123,258	123,258	0.005	616,290	616,290
Namibia	23	1,111,735	1,111,735	0.005	5,558,675	5,558,675
New Zealand	36	48,230	617,808	ND	0	5,319,293
	37	37,650		ND	0	
	38	25,027		0.01	250,270	
	39	506,902		0.01	5,069,022	
Nigeria	22	103,772	103,772	ND	0	0
Norway	8	92,181	158,920	ND	0	0
	9	49,231		ND	0	
	10	17,508		ND	0	
Oman	17	375,295	375,295	0.005	1,876,475	1,876,475
Pakistan	17	41,255	41,255	0.005	206,273	206,273
Phillippines	14	564,725	564,725	0.01	5,647,247	5,647,247
Portugal	43	61,738	123,476	0.001	61,738	123,476
	44	61738		0.001	61,738	
Russia	1	48,608	430,369	ND	0	0
	3	52,488		ND	0	
	11	218,421		ND	0	
	12	75,397		ND	0	
	13	35,456		ND	0	
Senegal	20	69,924	106,650	0.001	69,924	106,650
	21	36,726		0.001	36,726	
Seychelles	45	321,039	321,039	0.05	16,051,950	16,051,950
Sierra Leone	21	51,030	51,030	0.001	51,030	51,030
Somalia	18	242,676	242,676	0.001	242,676	242,676
SOPAC	39	224,115	324,192	ND	0	3,002,310
	40	79,365		0.03	2,380,950	
	41	20,712		0.03	621,360	
South Africa	19	123,258	184,863	0.005	616,290	924,315
	23	61,605		0.005	308,025	
Sri Lanka	15	768,758	768,758	ND	0	0
Suriname	25	89,110	89,110	0.001	89,110	89,110
Tanzania	18	55,681	55,681	0.001	55,681	55,681
Togo	22	15,566	15,566	ND	0	0
United Kingdon	7	243,679	243,679	0.001	243,679	243,679
United States	1	248,260	1,212,653	ND	0	12,186,013
	4	214,889		0.01	2,148,890	
	5	508,417		0.015	7,626,253	
USA (Guam)	14	241,087	241,087	0.01	2,410,870	
Uruguay	24	53,182	53,182	0.01	531,820	531,820
Venezuela	25	1,141	1,141	0.001	1,141	1,141
Zaire	23	13,431	13,431	0.005	67,155	67,155
Total			25,378,408			142,877,873

Country	Area No.	Area (sq. km)	Total Area (sq. km)	Conc. Co (mg/sq.m)	Total Co (T) (tonnes)	Total Co (T) for country
Angola	23	251,305	251,305	5	1,257	1,257
Antarctica	26	15,187	5,418,265	2	30	4,178
	27	1,235,520		2	2,471	
	28	1,113,819		ND	0	
	29	1,376,905		ND	0	
	31	1,676,835		1	1,677	
Argentina	24	239,319	239,319	4	957	957
Australia	32	250,116	728,342	1	250	720
	33	23,100		3	69	
	34	29,776		1	30	
	35	56,215		2	112	
	36	48,230		ND	0	
	37	37,650		ND	0	
	38	25,027		ND	0	
	39	258,228		1	258	
Bangladesh	15	969,982	969,982	ND	0	0
Brazil	24	1,675,235	1,964,494	3	5,026	5,412
	25	240,591		1	241	
	42	48,668		3	146	
Burma	15	46,203	46,203	ND	0	0
Canada	1	19,778	2,193,712	ND	0	1,745
	2	57,143		ND	0	
	4	872,289		2	1,745	
	5	1,244,502		ND	0	
Congo	23	14,652	14,652	1	15	15
Denmark	7	237,431	237,431	ND	0	0
uitorial Guin	22	15,566	15,566	ND	0	0
France	30	34,653	258,768	ND	0	2
	39	224,115		0.01	2	
rench Guiana	25	140,980	140,980	2	282	282
Gabon	23	136,752	136,752	1	137	137
Gambia	20	10,662	10,662	2	21	21
Ghana	22	25,943	25,943	ND	0	0
Greenland	5	103,312	103,312	ND	0	0
Guinea	21	27,897	27,897	1	28	28
uinea Bissau	21	38,359	38,359	1	38	38
Guyana	25	61,003	61,003	1	61	61
Iceland	6	2,800	84,937	2	6	88
	7	82,137		1	82	
India	15	150,457	1,011,832	ND	0	12,921
	17	861,375		15	12,921	
Ireland	7	176,511	176,511	1	177	177
Japan	14	339,701	339,701	8	2,718	2,718
Kenya	18	20,782	20,782	0.5	10	10
Madagascar	19	2,087,434	2,087,434	5	10,437	10,437
Mauritania	20	53,312	53,312	2	107	107
Mauritus	45	321,039	321,039	8	2,568	2,568
Morocco	20	824,562	824,562	2	1,649	1,649
Mozambique	19	123,258	123,258	5	616	616
Namibia	23	1,111,735	1,111,735	3	3,335	3,335
New Zealand	36	48,230	617,808	1	48	2,189
	37	37,650		1	38	
	38	25,027		3	75	
	39	506,902		4	2,028	
Nigeria	22	103,772	103,772	ND	0	0
Norway	8	92,181	158,920	ND	0	0
	9	49,231		ND	0	
	10	17,508		ND	0	
Oman	17	375,295	375,295	4	1,501	1,501
Pakistan	17	41,255	41,255	4	165	165
Phillippines	14	564,725	564,725	2	1,129	1,129
Portugal	43	61,738	123,476	2	123	185
	44	61738		1	62	
Russia	1	48,608	430,369	ND	0	0
	3	52,488		ND	0	
	11	218,421		ND	0	
	12	75,397		ND	0	
	13	35,456		ND	0	
Senegal	20	69,924	106,650	2	140	213
	21	36,726		2	73	
Seychelles	45	321,039	321,039	1	321	321
Sierra Leone	21	51,030	51,030	1	51	51
Somalia	18	242,676	242,676	2	485	485
SOPAC	39	224,115	324,192	ND	0	300
	40	79,365		3	238	
	41	20,712		3	62	
South Africa	19	123,258	184,863	2	247	370
	23	61,605		2	123	
Sri Lanka	15	768,758	768,758	ND	0	0
Suriname	25	89,110	89,110	1	89	89
Tanzania	18	55,681	55,681	1	56	56
Togo	22	15,566	15,566	ND	0	0
United Kingdon	7	243,679	243,679	1	244	244
United States	1	248,260	1,212,653	ND	0	5,409
	4	214,889		3	645	
	5	508,417		7	3,559	
USA (Guam)	14	241,087	241,087	5	1,205	
Uruguay	24	53,182	53,182	2	106	106
Venezuela	25	1,141	1,141	1	1	1
Zaire	23	13,431	13,431	1	13	13
Total			25,378,408			62,307

Elemental resources for the top ten ranked countries held by the nodules and crusts in their ELCS range from: 330 million tonnes of manganese (for Antarctica) to 44.5 million tonnes (for India); 28.3 million tonnes of copper (for Antarctica) to 0.9 million tonnes (for India); 35.7 million tonnes of nickel (for Antarctica) to 2.2 million tonnes (for India); and 4458 tonnes of cobalt (for the USA) to 445 tonnes (for India). For the bottom ranked countries, with the lowest abundance of nodules and crusts present in their ELCS, the elemental resources range from: 2.7 million tonnes of manganese (for Mauritania) to 11,408 tonnes (for Venezuela); 0.18 million tonnes of copper (for Guyana) to less than 1,500 tonnes (for Zaire); 0.15 million tonnes of nickel (for Guyana) to 2,852 tonnes (for Venezuela); and 107 tonnes of cobalt (for Mauritania) to about 20 tonnes (for Gambia).

At the scale of this global study, it is not possible to determine specifically where resources contained in nodules and crusts occur at grades above or below economically viable cut-off limits (e.g. when considering recovery, transport and production costs against commodity prices). However, it may be useful to rank countries according to the average grade of manganese nodules and crusts in their ELCS. This does not give the maximum grade of occurrence (which may be as much as ten times greater), and hence is not an indication of exactly where the highest grades may occur.

It is useful to identify those ELCS areas where, on average, high grades are found and that may in future have selected locations exploited for manganese nodule and crust recovery. The top ten countries with the highest average grades of nodules and crusts (in tonnes per km^2) are: the Philippines, Japan and Guam (~2,000), the USA (~1,500), Madagascar, Mozambique, Argentina, Fiji (~1,000), and South Africa (~900). The Yemen, Pakistan, and Oman all have equal grades of ~750 tonnes per square kilometre. The Marshall Islands, Johnston Islands (U.S. EEZ), Kiribati, the Federated States of Micronesia, and French Polynesia are the Pacific Island areas with probably the greatest manganese crust resources (Gross and McLeod, 1987; Kesler, 1994). However, at present, only the Marshall Islands EEZ has been the area most extensively studied.

It is generally considered that a cut-off limit for grades to be considered a viable resource is at 10 kg/m² (or 10,000 tonnes per km²) (Mero, 1977). On this basis, there are no obviously viable resources within any of the ELCS areas, and hence, at a regions scale, all nodules and crusts in these regions must be considered para-marginal.

4.6 Marine hydrocarbon deposits

4.6.1 What marine hydrocarbon deposits comprise

Oil and natural gas are hydrocarbon deposits that occur naturally within thick sedimentary sequences. These are largely confined to the continental shelves, continental slopes, continental rises, and small ocean basins. Hydrocarbons provide the major part of the energy source for modern civilisation, providing power for heating, lighting, telecommunications, industrial and agricultural machines, as well as all forms of transport. It also forms the raw material for numerous products ranging from plastics to fertilisers.

4.6.2 How marine hydrocarbon deposits are formed

Hydrocarbons are formed over millions of years, mainly in marine sedimentary basins. These geologic environments contain strata comprising mineral and biochemical elements including, importantly, unoxidised organic matter. Over millions of years, the sedimentary sequences are subjected to high pressures and temperatures during burial. These conditions fractionate the unoxidised organic matter, forming liquid (oil) and gaseous hydrocarbons (natural gas). Oil may comprise between 50 to 90 percent hydrocarbons, with oxygen, nitrogen and sulphur in minor quantities.

Generally, large quantities of hydrocarbons can be formed only at depths within sedimentary sequences greater than 1,000 - 2,000 meters. Formation of exploitable reservoirs of hydrocarbons requires migration (from their source rocks), to geological traps comprising a porous reservoir rocks overlain by an impermeable horizon. Common geological traps for hydrocarbons include: shales, salt domes (evapotites), and anticlinal folds of permeable and non-permable rock layers. In addition to liquid hydrocarbons, natural gas is commonly formed in association with crude oil. However, because of its lower viscosity, gas is often found separate from oil reservoirs. Sedimentary sequences in excess of 1,000 m thick, in areas of high-heat flow, and comprising organic-rich layers at depth overlain by porous rocks that are in turn overlain by domed impermeable strata provide ideal environments for hydrocarbon formation and retention.

4.6.3 Where marine hydrocarbon deposits are found

Table 4 (with references to Figure 21) shows the "proved" reserves of oil and gas (in billions of barrels and trillions of cubic feet) in offshore fields around the world (Klette, 1997).

Province number	Oil BB	Gas TCF	NGL BB	Total BBOE
1	1.6	6.6	0	2.7
2	<0.1	4.7	0	0.8
3	0.3	0.1	0	0.4
4	30.2	129.7	0.7	52.6
5	0.1	0	0	0.1
6	<0.1	0.9	0	0.1
7	<0.1	<0.1	0	<0.1
8	<0.1	<0.1	0	<0.1
9	0.1	0.2	<0.1	0.2
10	0.6	0.9	<0.1	0.8
11	0.7	1.4	<0.1	0.9
12	1.5	2	<0.1	1.9
13	<0.1	0.1	<0.1	<0.1
14	0.1	0.2	<0.1	0.2
15	10.1	6.2	<0.1	11.2
16	0.3	1.1	<0.1	0.5
17	3.3	3.6	<0.1	3.9
18	<0.1	0.1	<0.1	<0.1
19	0.1	3.3	0.1	0.7
20	<0.1	6	0	1
21	14.5	12.2	0.1	16.6
22	34.8	93.9	2.8	53.3
23	0.2	1.9	<0.1	0.6
24	<0.1	<0.1	0	<0.1
25	<0.1	<0.1	<0.1	<0.1

26	<0.1	0.1	0	<0.1
27	1.3	2	<0.1	1.6
28	2.7	15.7	0.7	6
29	0	0.1	0	<0.1
30	0	0.2	0	<0.1
31	0	70	0.1	11.8
32	0	8.1	0	1.4
33	<0.1	0.3	<0.1	0.1
34	0	0.1	0	<0.1
35	<0.1	0	0	<0.1
36	0	0.1	0	<0.1
37	0.1	1.4	<0.1	0.3
38	0.5	13.3	0.4	3.2
39	0	0.1	0	<0.1
40	0	<0.1	0	<0.1
41	<0.1	0	0	<0.1
42	<0.1	0.7	<0.1	0.1
43	<0.1	0.1	0	0.1
44	1.1	56.7	1	11.6
45	<0.1	18	0.2	3.2
46	0.7	25.6	0.9	5.9
47	0.1	10.3	0.1	2.5
48	<0.1	14.3	0.1	2.4
49	0.2	1.4	<0.1	0.4
50	0.1	0.4	<0.1	0.1
51	8.4	24.2	0.3	12.7
52	0.2	79.6	<0.1	3.5
53	<0.1	0	0	<0.1
54	8.4	1.8	0	0.3
55	0.2	0.1	<0.1	<0.1
56	<0.1	1.8	0	0.3

Offshore hydrocarbon provinces with identified reserves of oil, gas and natural gas liquid in billion barrels of oil equivalent.

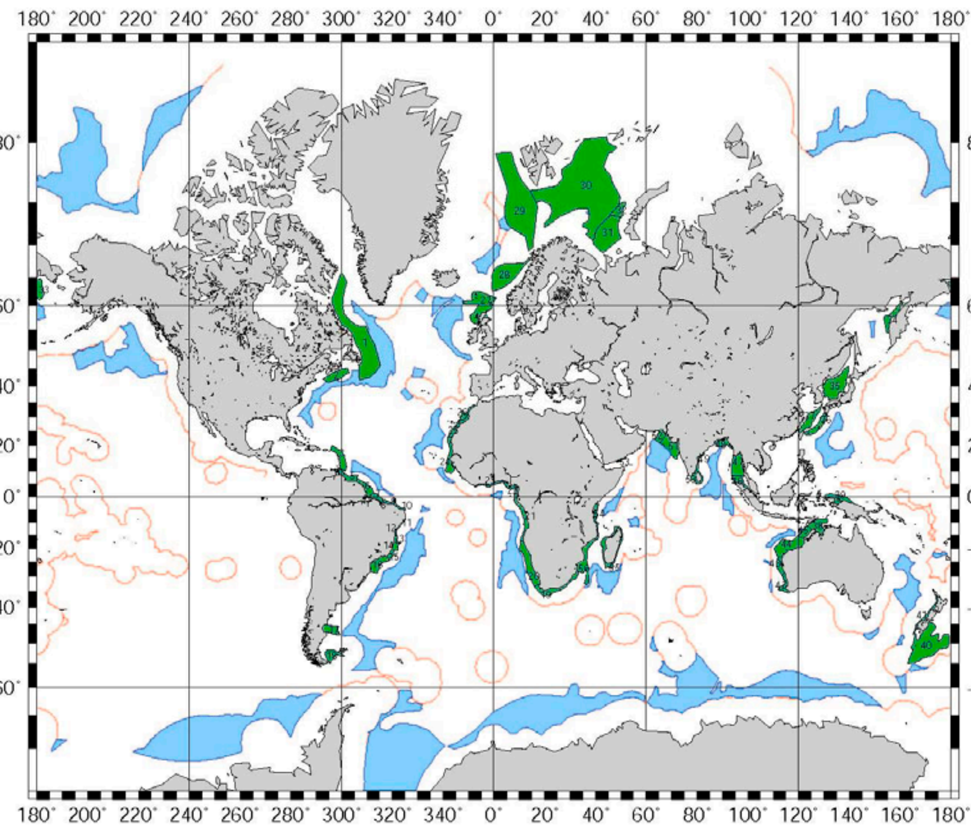

Figure 21. Oil and Gas provinces of the world, with identifying numbers referred to in the text (after Klett et al.,1997)

These areas are almost exclusively on the continental shelves and contain sedimentary sequences greater than 1,000 m in thickness. Proved reserves are those that are currently available under present technology, and do not include those areas where favourable conditions for hydrocarbon formation and preservation occur. The location of fields ranges from the continental slopes of northern Alaska to Tierra del Fuego and from the South China Sea to the Gulf of Mexico. With the exception of a small area off central western Africa, none of these areas lie within the ELCS regions.

According to the International Energy Agency (IEA, 1996): "The concentration of oil reserves and production is as pronounced in the offshore areas as onshore. The top ten offshore fields accounted for 25% of estimated 1995 world offshore production and the top 25 fields over 40%."

Table 5. World's twenty five largest off-shore producing oil fields* (in: thousand barrels per day), from: "Global Offshore Oil Prospects to 2000" International Energy Agency, 1996).

	Field	**Country**	**Area**	**1995 Production**	**2000 Production**	**Expected Change**
1	Safaniya-Khafji	Saudi Arabia/NZ	Persian Gulf	956	1210	254
2	Canterell	Mexico	North America	878	822	-56
3	Bern	Saudi Arabia	Persian Gulf	800	750	-50
4	Statfjord (+N. & E.)	Norway/UK	North Sea	634	255	-379
5	Oseberg (+W., E. & S.)	Norway	North Sea	499	496	-3
6	Upper Zakum	Abu Dhabi	Persian Gulf	485	500	15
7	Gullfaks (+W. & S. Satellites)	Norway	North Sea	484	270	-214
8	Tapis Area **	Malaysia	East Asia	329	427	98
9	Bombay High	India	Arabian Sea	320	275	-45
10	Zuluf	Saudi Arabia	Persian Gulf	300	250	-50
11	Abkatun	Mexico	Gulf of Mexico	285	280	-5
12	Ekoflsk (+ satellites)	Norway	North Sea	279	221	-58
13	Rashid	Dubai	Persian Gulf	275	250	-25
14	Tia Juana	Venezuela	Lake Maracaibo	250	180	-70
15	Lower Zakum	Abu Dhabi	Persian Gulf	219	300	81
16	Umm Shaif	Abu Dhabi	Persian Gulf	199	180	-19
17	Snorre	Norway	North Sea	196	186	-10
18	Brent	United Kingdom	North Sea	187	165	-22
19	Bachaquero	Venezuela	Lake Maracaibo	185	155	-30
20	Abu Safah	Saudi Arabia	Persian Gulf	180	180	0
21	Scoff	United Kingdom	North Sea	180	140	-40
22	Takula	Angola	Gulf of Guinea	175	155	-20
23	Ku	Mexico	Gulf of Mexico	170	150	-20
24	Belayim	Egypt	Red Sea	168	134	-34
25	Salman/ABK	Iran/Abu Dhabi	Persian Gulf	161	155	-6

**Based on average 1995 crude oil production figures.*
*** includes: Seligi, Guntong, Semangkok, Tinggi, Tiong, Pulai, Belkok, Irong, Barat, Palas, Tabu.*

Table 5 (with reference to Figure 22), shows the current state of offshore hydrocarbons production.

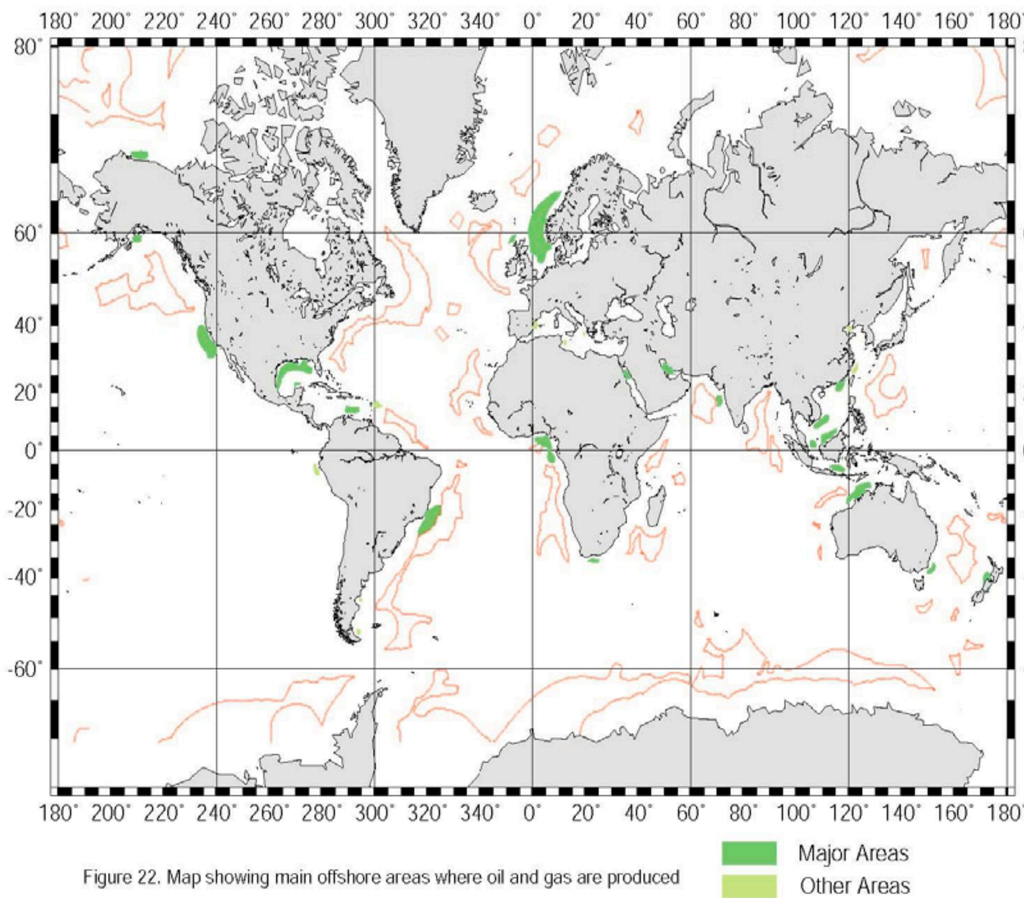

Figure 22. Map showing main offshore areas where oil and gas are produced

This is currently dominated by the Persian Gulf and the North Sea. Of the twenty five largest production fields, eight are in the Persian Gulf and eight others are in the North Sea. The remaining nine smaller ones are located in the Gulf of Mexico, East Asia, South Asia, South America, West Africa and North Africa. The IEA identify fifteen fields that produced in excess of 200 kb/d (thousand barrels of oil equivalent per day) in 1995. Another thirty fields are estimated to have had production levels of more than 100 kb/d.

Offshore oil supply growth is expected to come increasingly from areas outside the North Sea and the Persian. "By 2005, five fields, two off Brazil and one each in West African waters, the Gulf of Mexico and the Norwegian Sea, are expected to move into the top 25, and several other potential major producers off West Africa and in the deep-water Gulf of Mexico could be approaching similar production levels in the next decade" (IEA, 1996).

4.6.4 Resource potential of marine hydrocarbon deposits

According to the International Energy Agency (IEA, 1996), "world-wide offshore oil production in 1995 is estimated to have been 21.3 million barrels per day (mb/d) or just over 30% of total world supply of crude oil and natural gas, representing an increase of 3.9 mb/d versus 1990." The IEA also consider current offshore reserves "to be of the order of 200 billion barrels or about 20% of the world total. However, much of the undiscovered economically recoverable resource base is believed to lie offshore."

Much of the offshore hydrocarbon resource also lies within strata that does not allow production due to excessive water depth and/or difficulties in extraction. However, technological improvements in recovery efficiency and greater access to deep-water areas are increasing the range of economically recoverable resources offshore.

Thus the estimated proved reserves of oil world-wide at the beginning of the 21st Century is about one trillion barrels. Of this amount, about 252 billion barrels (25 per cent) are estimated to lie in sub-sea environments. Similarly, the total world-wide proved resources of natural gas is estimated as about 4,000 trillion cubic feet, of which about 26 percent are estimated to be sub-sea. However, these offshore resources may be as much as ten times larger, in which case they will provide the majority of future hydrocarbon production (IEA, 1996).

Here, we describe the offshore hydrocarbon resources that potentially lay within the ELCS areas of the world. The term "resource" is used here to include all the conventional hydrocarbons (oil and gas) that in areas where conditions for hydrocarbon formation and accumulation are favourable. As with the term "resource" used elsewhere in this report, these are neither proved nor indicated, and their future exploitation is subject to exploration, discovery and prevailing economic conditions.

Reference to the global sediment thickness model (compiled by NGDC, based on work by: Mathhias et al., 1988; Ludwig and Houtz, 1979; Hayes and LaBrecque, 1991; Divins and Rabinowitz, 1991; Divins, D.L., and Eakins, in prep; and gridded on a 1° basis) shows that the continental margins contain the greatest thickness of sediment, of up to 20 km (Figure 5), and hence have the greatest potential for hydrocarbon reservoirs (Figure 23).

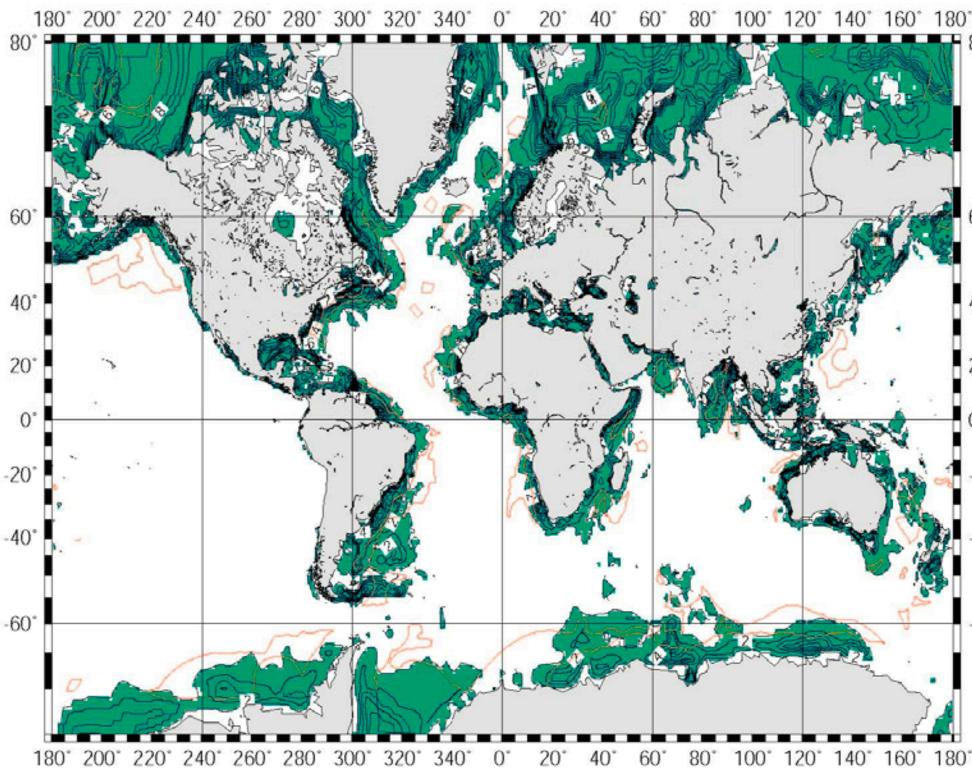

Figure 23. Map showing sediment thickness (contoured every 1 km - from the world sediment thickness model, Figure 5) for areas on the seafloor containing greater than 1 km sediment thickness and with reference to ELCS regions (outlined in red).

The continental rises also contain considerable accumulations of sediment (often in excess of 1 km), and probably include organic-rich source rocks deposited when the proto-ocean basins were narrow and had restricted circulation (Rona, 1969; Schneider, 1969). The abyssal plains probably contain insufficient thickness of sediments (less than 1 km) to yield hydrocarbon accumulations. Parts of the deep trenches may be more favourable, as may some foundered remnants of continental blocks broken off during continental rifting.

Areas that contain wide continental shelves with sediment thickness in excess of 1 km (Figure 24), and hence are favourable for hydrocarbon deposits occur throughout the sub-arctic (north of 60°N) including the coasts of: Greenland, Norway, Alaska, northern Canada and Russia. In the Arctic Ocean, sedimentary thickness often exceed 4 km.

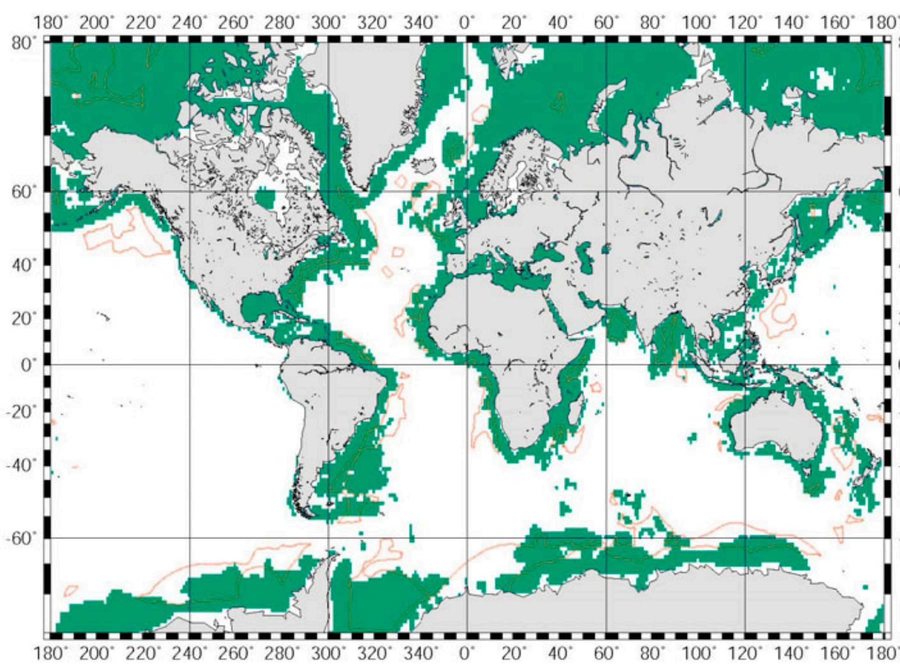

Figure 24. Map showing areas of the seafloor with greater than 1 km thickness of sediment accumulation with reference to ELCS regions (outlined in red).

Similarly, much of the continental margin of Antarctica also contains sediment in excess of 2 km thick. Elsewhere, favourable offshore conditions occur along the Atlantic seaboards of North, Central and South America (including Mexico, Trinidad-Tobago, Venezuela, Guyana, Surinam, French Guiana, Brazil, Uruguay, Argentina), western Europe and Africa, Eastern Africa, the northern margin of the Indian Ocean, Indonesia and around Australia, New Zealand, off mainland China, Korea, Taiwan, and the Pacific seaboard of Russia (Sea of Okhotsk).

Small sub-sea basins that have a thick sedimentary sequences and hence large petroleum resources include the Gulf of Mexico and the Caribbean Sea (2-6 km thickness), the Mediterranean Sea (up to 8 km), the Black Sea and Caspian Sea (4 km), the Bering Sea, the Sea of Okhotsk, the Sea of Japan, the South China Sea, and the seas within the Indonesian Archipelago (all 2-4 km) (Figure 24). However, several of these favourable areas have water depths of as much as 5,500 meters and extend 1,500 km or more from shore, making hydrocarbon production difficult.

Table 6: Coastal States with ELCS regions that coincide with offshore sedimentary sequences thickness in excess of 1 km.

Country	Area No.	Area (sq. km)	% area with >1 km sed thickness	Area with >1km sed thickness (sq. km)	Total area
Angola	23	251,305	65	163,348	163,348
Antarctica	26	15,187	0	0	2,133,702
	27	1,235,520	40	494,208	
	28	1,113,819	80	891,055	
	29	1,376,905	30	413,072	
	31	1,676,835	20	335,367	
Argentina	24	239,319	70	167,523	167,523
Australia	32	250,116	10	25,012	174,640
	33	23,100	20	4,620	
	34	29,776	0	0	
	35	56,215	98	55,090	
	36	48,230	0	0	
	37	37,650	0	0	
	38	25,027	0	0	
	39	102,675	80	82,140	
	39	155,553	5	7,778	
Bangladesh	15	969,982	100	969,982	969,982
Brazil	24	1,675,235	40	670,094	862,567
	25	240,591	80	192,473	
	42	48,668	0	0	
Burma	15	46,203	100	46,203	46,203
Canada	1	19,778	100	19,778	948,072
	2	57,143	100	57,143	
	4	872,289	0	0	
	5	1,244,502	70	871,151	
Congo	23	14,652	100	14,652	14,652
Denmark	7	237,431	55	130,587	130,587
uitorial Guin	22	15,566	100	15,566	15,566
France	30	34,653	0	0	112,057
	39	224,115	50	112,057	
rench Guian	25	140,980	70	98,686	98,686
Gabon	23	136,752	90	123,077	123,077
Gambia	20	10,662	0	0	0
Ghana	22	25,943	80	20,754	20,754
Greenland	5	103,312	50	51,656	51,656
Guinea	21	27,897	40	11,159	11,159
uinea Bissau	21	38,359	65	24,933	24,933
Guyana	25	61,003	90	54,902	54,902
Iceland	6	2,800	0	0	53,389
	7	82,137	65	53,389	203,847
India	15	150,457	100	150,457	968,764
	17	861,375	95	818,306	880,085
Ireland	7	176,511	35	61,779	61,779
Japan	14	339,701	0	0	0
Kenya	18	20,782	100	20,782	20,782
Madagascar	19	2,087,434	30	626,230	626,230
Mauritania	20	2,962	100	53,312	53,312
	20	50,350	0	0	
Mauritus	45	321,039	0	0	0
Morocco	20	824,562	40	329,825	329,825
Mozambique	19	123,258	100	123,258	123,258
Namibia	23	1,111,735	25	277,934	277,934
New Zealand	36	48,230	0	0	228,106
	37	37,650	0	0	
	38	25,027	0	0	
	39	506,902	45	228,106	
Nigeria	22	103,772	100	103,772	103,772
Norway	8	92,181	50	46,090	68,522
	9	49,231	10	4,923	
	10	17,508	100	17,508	
Oman	17	375,295	100	375,295	375,295
Pakistan	17	41,255	100	41,255	41,255
Phillippines	14	564,725	0	0	0
Portugal	43	61,738	0	0	0
	44	61738	0	0	
Russia	1	48,608	98	47,636	408,124
	3	52,488	100	52,488	
	11	218,421	100	218,421	
	12	75,397	100	75,397	
	13	35,456	40	14,182	
Senegal	20	69,924	40	27,970	53,678
	21	36,726	70	25,708	
Seychelles	45	321,039	0	0	0
Sierra Leone	21	51,030	75	38,273	38,273
Somalia	18	242,676	100	242,676	242,676
SOPAC	39	224,115	45	100,852	100,852
	40	79,365	0	0	
	41	20,712	0	0	
South Africa	19	96,515	75	72,386	108,537
	19	26,743	20	5,349	
	23	61,605	50	30,803	
Sri Lanka	15	768,758	85	653,445	653,445
Suriname	25	89,110	55	49,010	49,010
Tanzania	18	55,681	100	55,681	55,681
Togo	22	15,566	100	15,566	15,566
United Kingdo	7	243,679	35	85,288	85,288
United States	1	248,260	98	243,295	751,711
	4	214,889	0	0	
	5	508,417	100	508,417	
USA (Guam)	14	241,087	0	0	0
Uruguay	24	53,182	100	53,182	53,182
Venezuela	25	1,141	100	1,141	1,141
Zaire	23	13,431	100	13,431	13,431
Total		25,137,321			13,170,814

Although this is not an assessment of the resource volume of hydrocarbons, the table serves to identify those coastal states with ELCS areas that have some hydrocarbon resource potential.

The top ten ranked countries, according to those with the greatest ELCS areas (cited in brackets by million km^2) containing sedimentary sequences in excess of 1 km thick and hence having potential hydrocarbon resources are: Antarctica (2.23), Canada (0.95), Brazil (0.95), USA (0.75), Sri Lanka (0.65), India (0.58), Argentina (0.52), Madagascar (0.49), Russia (0.41) and Morocco (0.33). The bottom ranked countries are: Kenya (0.02), Sierra Leone (0.02), the Congo Republic (0.015), Zaire (0.013), Guinea (0.012), Bangladesh (0.005), Mauritania (0.003), Equatorial Guinea, Tonga and Venezuela (each with ~0.001).

In their report (Ranking Of The World's Oil And Gas Provinces By Known Petroleum Volumes), Klett *et al*., (1997), identify hydrocarbon resources for forty-one offshore provinces that contain known reserve volumes. These areas are shown on Figure 21 in green and listed on Table 4, which also show their oil and gas volume potentials. Although none of these provinces coincide with the ELCS regions, their proximity to those regions, accumulated thickness of sediment, and the basement type are combined to indicate hydrocarbon potential from high to low (Figure 25).

On the basis of known hydrocarbon volume reserve, the top ten ranked offshore provinces identified by Klett *et al*. (1997) are identified in Table 7 below (by province number – referred to on Figure 21, and billion barrels oil equivalence (BBOE) of oil and gas). Also identified are the ELCS regions (by number, referred to on Figure 7) and their coastal states, that lie closest to each of the USGS identified hydrocarbon provinces. The top ten ranked provinces are given in Table 7.

Table 7 gives an <u>indication</u> of the relationship between known reserve volumes and the adjacent ELCS regions where there is significant hydrocarbon potential.

Table 7. The top ten ranked offshore provinces ranked according to their combined oil and gas reserves in BBOE (billion barrels of oil equivalence).

USGS Province	**Location**	**ELCS**	**BBOE**	**Coastal State(s)**
22	(central west Africa)	22	53.3	Togo Equatorial Guinea Gabon Ghana
4	(N.E. Venezuela)	25	52.6	Venezuela Suriname Guyana French Guiana Brazil
21	(west Africa)	23	16.6	Angola, Congo Gabon
51	(Indus Fan)	17	12.7	India Pakistan
31	(Barents Sea)	10	11.8	Norway
44	(N.W. Australia)	32	11.6	Australia
15	(Amazon Fan)	24	11.2	Brazil
28	(N.E. Atlantic)	8	6	Norway
46	(Indonesia)	16	5.9	Indonesia
17	(Argentina)	24	3.9	Argentina

A qualitative indication of resource potential, and hence a qualitative ranking of ELCS regions and their coastal states, can be made by comparing the known reserve province against the location of those countries with significant sedimentary sequence thickness. However, it does not indicate the estimated resource volume.

The hydrocarbon resource potential, based on sediment thickness, crustal age and basement type is shown on Figure 25. High resource potential that coincides with ELCS regions are found throughout the Atlantic seaboard of North and South America (including the Labrador Sea); Antarctica; northern and western Norway; south and west of the United Kingdom and Ireland; parts of north-west Africa; south-west Africa, south-east Africa and East of the Horn of Africa; South of Pakistan; East and West of India; South of Tasmania (Australia); North of New Zealand and East of Australia; the Sea of Okhotsk; and the Alaskan Arctic seaboard. In all of these areas, conventional hydrocarbon resources are considerable and of high potential value.

In many of the ELCS areas identified as having hydrocarbon resource potential, the seafloor lies beyond 500 m depth and 200 nautical miles from shore. In high latitudes there is both seasonal and permanent ice shelf cover. For these reasons, hydrocarbon resources in the ELCS regions are mostly sub-marginal to para-marginal. What can not be indicated or predicted is the size of individual oil fields, or whether sedimentary sequences that a have high potential for hydrocarbon resources have adequate geological traps. However, there is considerable potential for exploitation in the future when technology and economic conditions make exploration, proving, and ultimately exploiting of these resources viable.

4.7 Marine gas hydrate deposits

4.7.1 What marine gas hydrate deposits comprise

Gas hydrates occur widely in nature mainly beneath the seafloor in deep-sea sediments but also close to the seabed in shallow arctic seas. This is because the compound is stabilised by a pressure – temperature relationship. In water depths greater than 300 m it can form at temperatures well above freezing and cement loose sediments into a hard layer several hundred metres thick before natural processes provide that rigidity.

Gas hydrate is a crystalline compound composed of gas molecules, normally methane (Kvenvolden, 1993), en-caged within water molecules to form a solid similar to ice. It forms within the sediment spaces cementing the grains together. This dramatically changes the physical properties of the sediment. One volume of hydrate also stores 164 volumes of un-pressurised methane – a measure of the value of the resource.

The methane in gas hydrate forms naturally by organic decay in the thick sediments normally found in the deep water adjacent to continental margins. The deep-sea pressures (> 500 m depth) and intra sediment temperatures (increasing with depth) determine the gas hydrate stability. At depth in the sediment the temperature becomes too high for hydrate to be stable and the abrupt change of physical properties inherent with free gas in the sediment pore spaces generates a seismic reflect – the Bottom Simulating Reflector (BSR).

BSRs have been used to identify gas hydrate on seismic reflection profiles for some time. They are a useful way to identify the presence of hydrate, although other seismic characteristics also occur. The BSR at the base of the hydrate stability zone is to date is poorly mapped world-wide (Max, 1990; Lee et al, 1994; Miles, 1995).

Gas hydrates are currently considered as hydrocarbon resources. They are also being exploited as methane reserves by Japan. Whether the methane in the hydrate or the free gas beneath the hydrate is targeted, they represent up to 10 times the fuel value of current conventional hydrocarbon reserves. (Gornirz & Fung, 1994). The distribution of potential gas hydrate resources continues to drive national research strategies as evidenced by the new US$27M USA initiative, and current research programmes in India and Japan.

4.7.2 How marine gas hydrate deposits are formed

Gas hydrates form and accumulate where marine sediments contain suitable and sufficient dissolved gas and where the geothermal (sub-surface temperature gradient) conditions are within the stability field of the hydrate. The source of the dissolved gas is from the breakdown of organic matter trapped within the sediment. Therefore, the un-oxidsed organic carbon content of the sediment is a significant factor in determining the potential for gas generation.

The methane hydrate pressure (depth) - temperature stability field (Figure 26) shows that these conditions may be met at water depths greater than about 500m on the continental slope (dependant on bottom water temperature) reaching some depth beneath the deep seafloor (determined by the geothermal gradient).

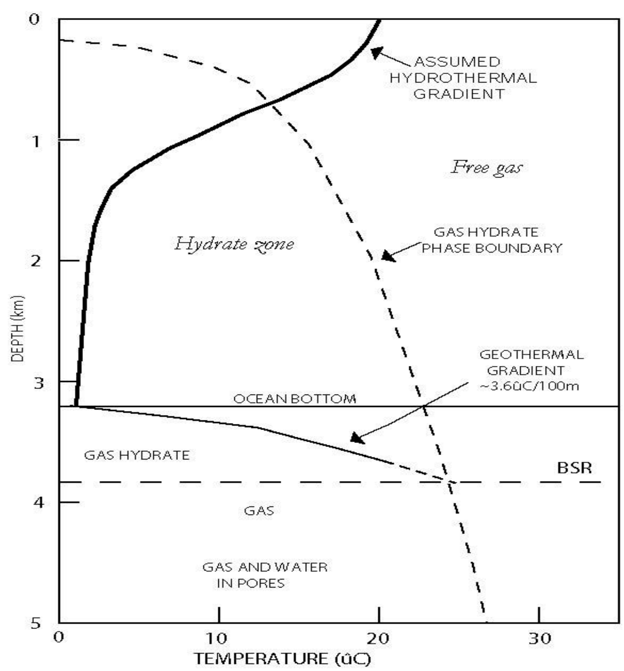

Figure 26. Phase equilibrium diagram for gas hydrate stability with pressure and temperature (after Prensky, 1995).

The introduction of higher molecular-weight gases (ethane or propane) to the methane allows hydrate gas mixture to form at lower pressures and therefore to be stable in shallower water or at higher temperature (Kvenvolden, 1993). However, the presence of salts in pore water shifts the gas hydrate phase boundary to the left and decreases the gas hydrate stability area, requiring deeper and or colder conditions for formation and accumulation in marine environments.

4.7.3 Where marine gas hydrate deposits are found

Figure 27 shows the world wide locations of known all known gas hydrates (Max, 1990; Lee *et al*., 1994; Kesler, 1994).

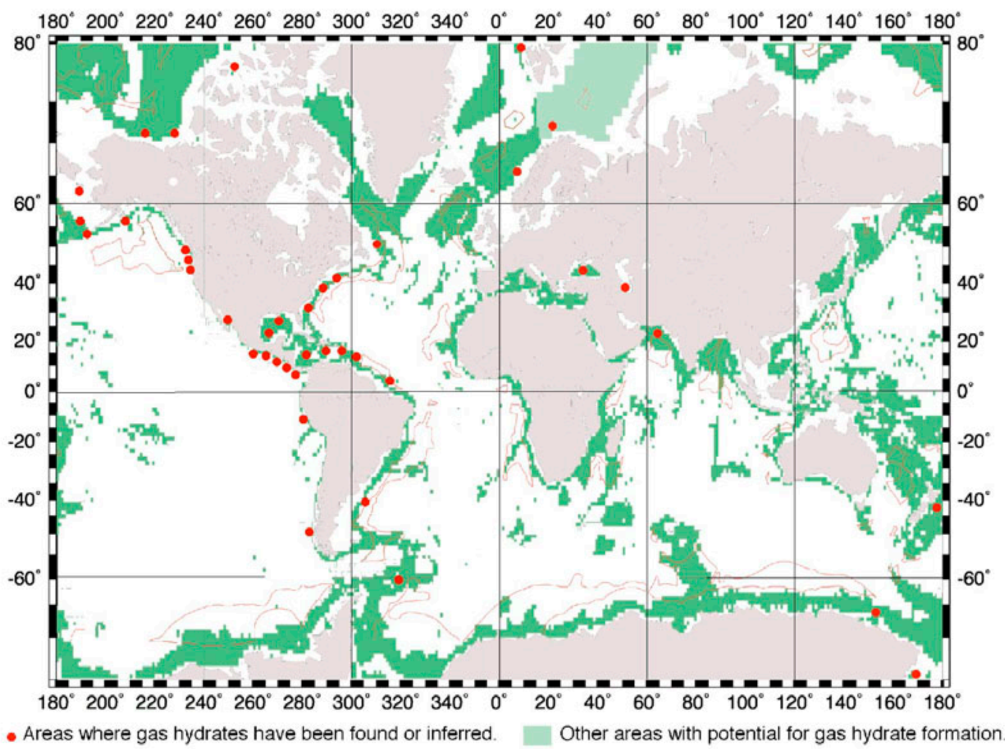

Figure 27. Location of known and indicated gas hydrate occurrences world wide, but excluding areas where bottom simulating reflectors are found (after Max, 1990; Lee et al, 1994; Kesler, 1994; Kvenvolden et al., 1993).

However, this does not include the world wide occurrence of BSRs, for which seismic data are not compiled. The figure also shows the areas where water depths range from 500 to 4000 m on seafloor that is older than 30 Ma. These depths are appropriate for gas hydrate formation and the age of the underlying oceanic lithosphere is such that heat flow, based on plate cooling models, is expected to be low enough for hydrate stability (Miles, 1995).

Known hydrates are found on the Atlantic and Pacific margins of both North and South America, especially at equatorial latitudes. They are also found around off the coast of Canada, Alaska, off the West coast of Norway, the Black Sea and off the coast of Pakistan. Isolated occurrences are also found off New Zealand and Antarctica.

Production of gas from hydrate fields are currently limited to Japan and Russia. The Messoyakha field is a continental gas field in the permafrost region of Western Siberia (Krason and Finley, 1992). Because of the permafrost conditions, and low temperature gradient in the subsurface, part of this shallow gas reservoir is believed to be in the gas hydrate stability zone (Makogon, 1971). During the mid-1970s, over two million cubic metres of gas per day were produced (Makogon, 1984, 1988). Although on land, the Messoyakha field serves as an example of production from a gas hydrate reservoir that will be useful in developing future offshore technologies for gas hydrate exploitation. In Japan, gas hydrates are being exploited from the Nankai Trough, but as yet little information about this activity is available in the public domain.

4.7.4 Resource potential of marine gas hydrate deposits

BSRs indicate only the presence of a gas hydrate layer and not the total volume of hydrate or the volume of free gas in the sediment beneath the layer. It is not possible, yet, to estimate the potential resource that gas hydrates offer with any certainty. Instead, it is only possible to estimate the areas where conditions for hydrate formation are favourable (Kvenvolden et al., 1993 and others – see below). Table 8 below shows a compilation of current estimates for global methane gas and carbon resources in oceanic and continental settings.

Table 8. Estimates of methane gas and methane carbon resource contained in continental and marine gas hydrate accumulations (modified from Kvenvolden, 1993, by Prensky, 1995).

Methane gas m^3 x10^{15}	**Methane gas Tcf x 10^5**	**Methane carbon kg x 10^{15}**	**Reference**
Oceanic sediments			
3.1	1.1	1.7	McIver (1981)
5-25	1.8-8.8	2.7-13.7	Trofimuk *et al*. (1977)
7600	2700	4100	Dobrynin *et al*. (1981)
17.6	6.2	11	Kvenvolden (1988)
19.5	6.9	11	MacDonald (1990)
26.4-139.1	9.3-49.1	----	Gornitz and Fung (1994)
Continental sediments			
0.014	0.005	7.5	Meyer (1981)
0.057	0.011	17	McIver (1981)
0.057	0.02	31	Trofimuk *et al*. (1977)
34	12	1800	Dobrynin *et al*. (1981)
----	----	400	MacDonald (1990)

Although considerable uncertainty exists about the total gas resource potential of hydrates, it is clear that the oceanic potential is far greater than the continental one.

The know locations of gas hydrates is very likely to underestimate the total world wide occurrence. From considerations of the stability condition for hydrate, it is likely to occur everywhere that the seafloor exceeds 500 m (or 300 m in high latitudes), and where there is a source of unoxidsed organic carbon in marine sediments. The greater the thickness of marine sediments, the greater the likelihood of there being suitable source material for the production of biogenic methane (the key fuel element in gas hydrates).

Figure 28 shows the location of areas favourable for gas hydrate formation, and hence with potential for hydrate resources.

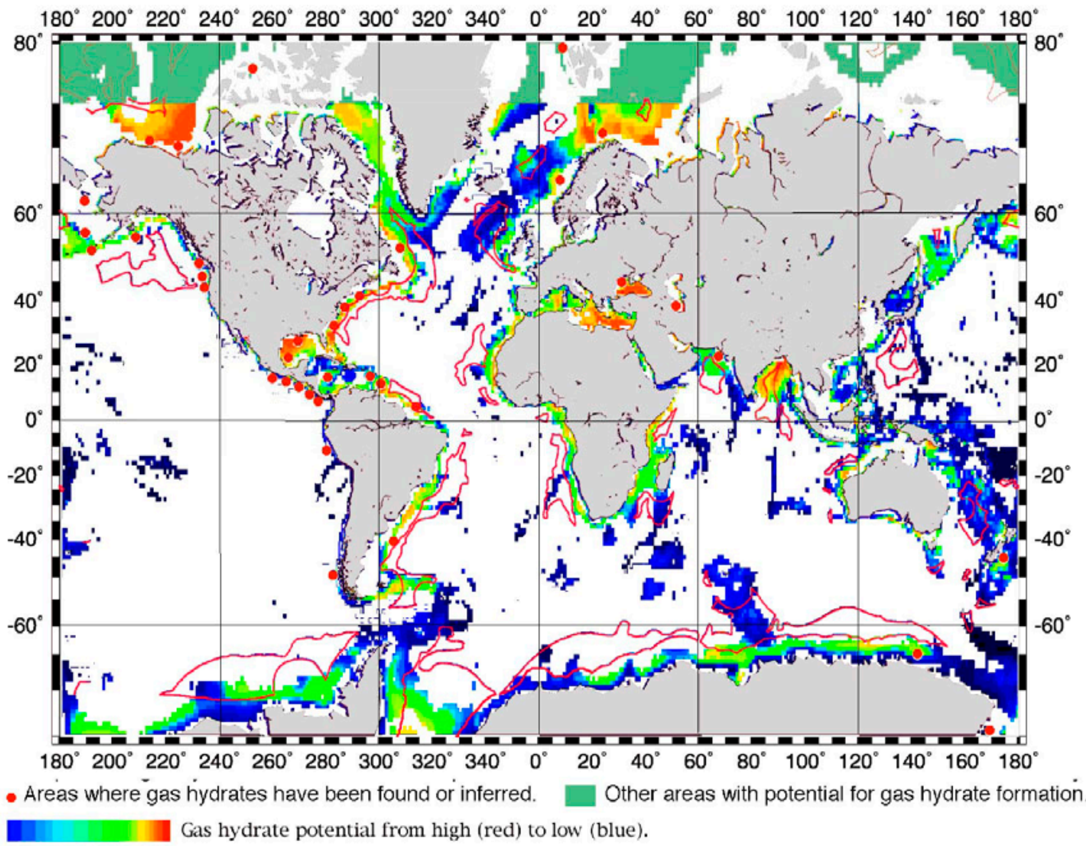

Figure 28. Map showing conventional gas hydrate potential (qualitative and relative only) based on water depths between 500 m and 4,000 m, seafloor greater than 30My old and sediment thickness.

These areas lie in water depths greater than 500 m, on crust less than 30 Ma old and include data on sediment thickness. Areas with relatively high gas hydrate potential are coloured red, and those with low potential are coloured blue. These are relative indications of hydrate potential and are not indicative of actual known or indicated volumes. Areas where sediment thickness data are missing, but lie below 500 m and on crust more than 30 Ma old are coloured green. These regions lie in high northern latitudes, where bottom water temperatures are low. Thus they probably also have high gas hydrate potential, with possible hydrate resources at the seafloor.

The areas identified on Figure 28 as having high gas hydrate potential coincide with those localities where gas hydrates have been found already. Elsewhere, high potential exists in the Arctic and Antarctic, Bearing Sea, Barents Sea, Labrador Sea, eastern margin of North and South America, the African margin, Mediterranean Sea, Black Sea, off Pakistan and eastern India, north-west Australia, south-west New Zealand and the Sea of Okhotsk, Japan and the western European Margin. The ELCS (extended legal continental shelf) regions that coincide with these areas of high gas hydrate potential are ranked, from high to low, on Table 9 below.

Table 9. ELCS regions that coincide with areas of high gas hydrate potential, ranked from high to low potential.

ELCS region	Location	Hydrate potential	Coastal States
1.	Arctic Ocean	High	Canada Russia USA
2.	Arctic Ocean	High	Canada
9.	North-East Atlantic	High	Norway
10.	Barents Sea	High	Norway
15	Bay of Bengal	High	Burma India Sri Lanka
13.	Sea of Okhotsk	High	Russia
12.	Bering Sea	High	Russia
18.	Arabian Sea	High	Kenya Somalia Tanzania
5.	North-west Atlantic	Moderate	USA Canada Greenland
24 (southern	South-West Atlantic	Moderate	Argentina
27 & 28	Southern Ocean	Moderate	Antarctia
7(east)	North-East Altantic	Low	United Kingdom Iceland
23 (central)	West Africa	Low	Namibia Angola

ELCS region	Location	Hydrate potential	Coastal States
19	Southern Madagascar	Low	Madagascar Mozambique South Africa
35	Southern Tasmania	Low	Australia
39	Tasman Sea	Low	Australia Mew Zealand (French Caledonia)

Elsewhere, the potential for gas hydrate formation is probably negligible as a resource, although much research is needed to establish the occurrence of BSRs or other indicators of hydrate presence.

Exploitation of gas hydrates has potential hazards, since the stability of hydrates has been implicated in the stability history of continental slopes. Any activity that may uncontrollably destabilise gas hydrate layers through changes of pressure and temperature must be viewed with caution until the technology for safe exploitation of hydrates is in place. Until such technologies are developed, all gas hydrate resources must be considered sub-marginal.

5. Conclusions

This report examines the non-living resource potential within the extended legal continental shelf (ELCS). These areas lie beyond the 200 nautical mile jurisdiction of nation states' exclusive economic zones, and their outer limits are defined by the criteria established by the United Nations Convention on the Law of the Sea, Article 76.

The offshore non-living resource potentials described in this report are based on a statistical evaluation of known occurrences and reserves, the geologic environments favourable for their formation, models for sediment type and thickness, and basement composition. The result is an assessment of the potential for non-living resources to occur.

Eight different types of non-living resource are assessed. These all occur on the seafloor. Table 10 gives a summary of these resources, their quantity, and estimated value (exclusive of recovery and production costs) for the nation states that have potential claim to ELCS regions.

Placer deposits comprising heavy minerals, gold and diamonds are limited to near-shore areas and have negligible resource potential in the ELCS regions. Similarly, phosphorites occur in the equatorial oceans, mainly between 400 m and 1,500 m depth, but have limited resource potential in ELCS areas. Evaporite deposits occur on many continental margins. However, they only overlap with ELCS regions off eastern North America and western central Africa, where their resource potential is low. Polymetalic sulphides (PMS) are formed at active plate boundaries. With the exception of the West Pacific and off the western coast of North America, PMS resources are low in the ELCS regions.

The major resource potential within the ELCS regions is held in iron-manganese nodules and crusts, oil, gas and gas hydrates. Four elemental metals are the main components of value in manganese nodules and crusts: manganese, copper, nickel and cobalt. World-wide, the total value of these metals within the ELCS regions is: US$ 4,534,487 millions of manganese; US$ 196,677 millions of copper; US$ 1,131,278 millions of nickel, and US$ 690 millions of cobalt. Conventional oil and gas comprise an estimated US$ 2,984,800 millions with a similar estimated value of US$ 3,085,600 millions for gas hydrates. In total, the resource potential (excluding recovery and production costs) contained within the ELCS regions of the world amounts to an estimated US$ 11, 934 trillions.

Table 10*:* Summary of offshore resources in extended legal continental shelf (ECLS) areas and their commodity values at current (June 2000) prices. Prices are quoted from: (LME) London Metal Exchange, (USGS) United States Geological Survey and the (OGJ) Oil and Gas Journal. Prices for gas hydrates are based on conventional oil and gas prices at a barrel equivilence.

Country	Total area (sq. km) (ELCS)	placer deposits	phosphorite deposits	evaporite deposits	Total Mn nodules for country (tonnes)	nodule + crust grade tonnes/sq.km	Total Manganese for country (tonnes)	value millions US$ metal (LME) US$2000/mtu	value millions US$ ore (USGS) US$2.4/mtu	Total Copper for country (tonnes)	value millions US$ metal (LME) US$1739/mtu	Total Nickel for country (tonnes)	value millions US$ metal (LME) US$9298/mtu	Total Cobalt for country (tonnes)	value millions US$ metal (LME) US$25.24/kg	oil & gas (BBOE)	value millions US$ per BOE (OGJ) US$28/brl	gas hydrate (BBOE)	value millions US$ per BOE (OGJ) US$28/brl
Angola	251,305	ND	ND	ND	62,826,138	250	12,565,228	25,130	30	ND	ND	1,256,523	11,683	ND	ND	0	2,800	0	2,800
Antarctica	5,890,075	ND	ND	ND	899,640,943	153	330,809,982	661,620	794	28,256,376	49,138	35,703,904	331,975	2,471	62	20	560,000	30	840,000
Argentina	239,319	ND	P	ND	741,706,550	1,000	185,426,638	370,853	445	8,900,479	15,478	5,562,799	51,723	1,483	37	6	168,000	9	252,000
Australia	758,341	ND	P	P	311,924,985	505	77,465,555	154,931	186	2,639,761	4,591	5,347,819	49,724	617	16	1	28,000	1	28,000
Bangladesh	969,962	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	1	28,000	ND	ND
Brazil	194,493	ND	P	ND	1,025,211,585	472	190,579,378	381,159	457	16,162,795	28,107	9,407,299	87,469	4,052	102	10	280,000	ND	ND
Burma	46,203	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	2	56,000	4	112,000
Canada	2,173,934	ND	ND	ND	436,144,640	199	255,293,551	510,587	613	8,219,970	14,295	11,211,896	104,248	2,367	60	3	84,000	10	280,000
Congo	14,652	ND	ND	ND	3,663,000	250	732,600	1,465	2	1,465	3	73,260	681	1	0	0	2,800	ND	ND
Denmark	237,431																		
Equitorial Guinea	15,566	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	1	28,000	ND	ND
France	258,768	ND	ND	ND	ND	ND	35,349,852	70,700	85	482,882	840	2,241,147	20,838	224	6	ND	ND	0	1,400
French Guiana	140,980	ND	ND	ND	35,244,915	250	ND	ND	ND	422,939	735	ND	ND	141	4	0	2,800	ND	ND
Gabon	136,752	ND	ND	ND	34,188,000	225	6,837,600	13,675	16	ND	ND	683,760	6,358	ND	ND	1	28,000	ND	ND
Gambia	10,662	ND	ND	P	2,665,582	250	533,116	1,066	1	21,325	37	26,656	248	21	1	0	2,800	ND	ND
Ghana	25,943	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	8	224,000	ND	ND
Greenland	103,312	ND	ND	ND	ND	ND	ND	ND	ND	51,656	90	ND	ND	ND	ND	1	14,000	1	21,000
Guinea	27,897	ND	ND	ND	1,394,871	50	1,394,871	2,790	3	55,795	97	69,744	648	28	1	0	1,400	ND	ND
Guinea Bissau	38,359	ND	ND	ND	1,917,947	50	1,917,947	3,836	5	76,718	133	95,897	892	38	1	0	1,400	ND	ND
Guyana	61,003	ND	ND	ND	15,250,628	250	1,220,050	2,440	3	183,008	318	152,506	1,418	61	2	0	2,800	ND	ND
Iceland	84,937	ND	ND	ND	20,534,335	242	4,106,867	8,214	10	84,937	148	410,687	3,819	ND	ND	ND	ND	0	1,400
India	1,011,812	ND	ND	ND	333,618,585	560	44,482,478	88,965	107	889,630	1,547	2,224,124	20,680	445	11	2	56,000	4	112,000
Ireland	363,278	ND	ND	ND	90,819,590	250	ND	ND	ND	1,089,835	1,895	ND	ND	ND	ND	3	70,000	ND	ND
Japan	339,701	ND	ND	ND	679,402,580	2,000	67,940,258	135,881	163	3,397,013	5,907	3,397,013	31,585	1,019	26	ND	ND	ND	ND
Kenya	20,782	ND	ND	ND	10,390,995	500	1,039,100	2,078	2	41,564	72	51,955	483	1	0	0	8,400	1	28,000
Madagascar	1,641,073	ND	ND	ND	1,641,072,790	1,000	328,214,558	656,429	788	8,205,364	14,269	8,205,364	76,293	1,641	41	1	14,000	1	14,000
Mauritania	53,312	ND	ND	P	13,327,910	250	2,665,582	5,331	6	106,623	185	133,279	1,239	107	3	0	2,800	ND	ND
Morocco	824,562	ND	ND	ND	206,140,415	250	41,228,083	82,456	99	1,649,123	2,868	ND	ND	1,649	42	0	2,800	ND	ND
Mozambique	24,430	ND	ND	ND	24,429,660	1,000	4,885,932	9,772	12	122,148	212	122,148	1,136	24	1	1	14,000	1	14,000
Namibia	1,111,735	ND	ND	ND	277,933,650	250	55,586,730	111,173	133	7,782,142	13,533	5,558,673	51,685	2,223	56	0	1,400	0	1,400
New Zealand	617,808	ND	ND	ND	321,417,670	520	80,420,516	160,841	193	1,901,053	3,306	5,319,293	49,459	570	14	0	5,600	ND	ND
Norway	158,920	ND	ND	ND	ND	ND	ND	ND	ND	141,411	246	ND	ND	ND	ND	2	56,000	4	112,000
Oman	268,672	ND	ND	ND	201,504,045	750	26,867,206	53,734	64	537,344	934	1,343,360	12,491	269	7	2	56,000	ND	ND
Pakistan	41,255	ND	ND	ND	30,940,905	750	4,125,454	8,251	10	82,509	143	206,273	1,918	41	1	1	14,000	ND	ND
Philippines	564,725	ND	ND	ND	1,129,449,420	2,000	112,944,942	225,890	271	5,647,247	9,821	5,647,247	52,508	1,694	43	ND	ND	ND	ND
Russia	430,369	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	10	280,000	15	420,000
Senegal	106,623	ND	ND	P	19,310,660	181	5,331,164	10,662	13	213,247	371	ND	ND	177	4	0	1,400	ND	ND
Sierra Leone	51,030	ND	ND	ND	2,551,518	50	2,551,518	5,103	6	102,061	177	127,576	1,186	51	1	0	1,400	ND	ND
Somalia	242,676	ND	ND	ND	121,337,985	500	12,133,799	24,268	29	485,352	844	ND	ND	ND	ND	2	42,000	3	84,000
South Africa	604,827	ND	ND	ND	558,623,260	924	111,724,652	223,449	268	3,208,950	5,580	3,024,135	28,118	666	17	0	5,600	0	5,600
Sri Lanka	768,758	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	0	7,000	1	14,000
Suriname	89,110	ND	ND	ND	22,277,450	250	ND	ND	ND	267,329	465	ND	ND	89	2	5	140,000	ND	ND
Tanzania	55,681	ND	ND	ND	27,840,520	500	2,784,052	5,568	7	111,362	194	ND	ND	ND	ND	3	70,000	5	140,000
Togo	1,232	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	1	28,000	ND	ND
United Kingdom	502,362	ND	ND	ND	125,590,490	250	25,118,098	50,236	60	502,362	874	ND	ND	ND	ND	2	42,000	2	42,000
United States of America	1,212,653	ND	ND	ND	1,860,660,805	1,534	182,134,150	364,268	437	8,952,336	15,568	12,186,015	113,306	4,458	113	10	280,000	20	560,000
Uruguay	35,936	ND	ND	ND	17,968,125	500	3,593,625	7,187	9	287,490	500	179,681	1,671	72	2	1	14,000	ND	ND
Venezuela	1,141	ND	ND	ND	285,208	250	11,408	23	0	3,422	6	2,852	27	1	0	5	140,000	ND	ND
Yemen	106,623	ND	ND	ND	79,967,453	750	10,662,327	21,325	26	213,247	371	533,116	4,957	107	3	4	112,000	ND	ND
Zaire	13,431	ND	ND	ND	3,357,750	250	671,550	1,343	2	1,343	2	67,155	624	1	0	0	5,600	ND	ND
Totals					11,711,780,715		2,267,243,380	4,462,701	5,355	113,097,870	193,901	27,339	1,121,089	27,339	677		2,984,800		3,085,600

TOTAL VALUE (June 2000)
(billions US$) 11,849

The value of the non-living resources in the ELCS regions depends on the technological developments that will allow their extraction and production. Because of this, with perhaps the exception of conventional gas and oil, and possibly gas hydrates, many resources on the ELCS will remain uncompetitive with onshore resources.

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Placer deposits

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Gas hydrate deposits

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General

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SUMMARY OF PRESENTATION AND DISCUSSIONS ON THE EVALUATION OF THE NON-LIVING RESOURCES OF THE CONTINENTAL SHELF BEYOND THE 200 MILE LIMIT OF THE WORLDS MARGIN

Presentation

Dr. Lindsay Parson, a Government Scientist of the United Kingdom at the Southampton Oceanography Centre, Southampton, the United Kingdom, made the presentation on "An evaluation of the non-living resources of the continental shelf beyond the 200-mile limit of the world's margin". He informed participants that his presentation would be divided into four parts. He said that in the first part, he would define the geographic area covered in the presentation using criteria contained in the United Nations Convention on the Law of the Sea. Dr. Parson said that in the second part of the presentation, he would focus on the mineral resources that are known to occur or that may occur in the continental shelf beyond the 200-mile limit, and that in the third part of his presentation he would examine some of the difficulties that have to be overcome to exploit these resources, as well as ongoing efforts to transform some of these resources into reserves of mineral commodities. He said that the fourth part of his presentation would focus on economic and marketing issues in developing some of these resources.

Dr. Parson said that the definition of the 200-mile limit is contained in Article 76 of the 1982 United Nations Convention on the Law of the Sea. He said that the article provides a series of criteria and parameters through which a coastal state can legitimise its claim to an area that it believes is a natural prolongation of its landmass extending beyond 200 nautical miles. He said that at the present time, very few coastal states had presented their claims to the Commission on the Limits of the Continental Shelf as required by the Convention. He informed participants that although the provisions of the Convention require coastal states that intend to establish the outer limits of their continental shelf beyond 200 nautical miles to submit particulars to the Commission within 10 years of the entry into force of the Convention for the concerned state, very few coastal states had made the necessary submissions. He said that he was of the opinion that many states were in the process of compiling the necessary particulars along with the supporting scientific and technical data to meet the deadline. He informed participants that upon receipt of a submission, the Commission, which was established in 1996, determines if there is positive proof that the landmass, which extends into the deep ocean, essentially into the area, the ISA's jurisdiction, is a natural prolongation

Dr. Parson said that once the natural prolongation has been established, the outer limits are established by one of two criteria. He said that the first criterion is that the outer limit of a coastal state's continental shelf, where that shelf extends beyond 200 nautical miles from the baselines from which the territorial sea is measured, is delineated by straight lines not exceeding 60 nautical miles in length from the foot of the continental slope, connecting fixed points defined by coordinates of latitude and longitude. He said that in the second criterion, the fixed points used for delineation are based on the thickness of sedimentary rocks, which have to be at least 1 per cent of the shortest distance from the outermost fixed point to the foot of the continental slope. He said that if a coastal state has a particular development of a sedimentary section on its margin, it could extend its the limit of the continental shelf out to the point to where it thins out to one percent of the distance from the foot of the slope. He observed that a coastal state like Canada, obtains a nice big shelf under this criterion because it has the Grand Banks. He also observed that coastal states such as Nigeria and Congo have got it made because of the criteria.

He informed participants that in order to make sure that this is not an expansionist programme, there are cut-offs. He said that there are two cut-off criteria. First, he said that a coastal state could not establish a distance that is more than 350 nautical miles from its baselines, and secondly that the coastal state could not extend its shelf further than 100 nautical miles beyond its 2500 metre isobath. He said that the coastal state could use either of the criteria that result in the maximum extension of the shelf.

With slides, Dr. Parson provided a summary of the areas that are purported to have extended continental shelves. He pointed out that the illustration included indications of the locations of the exclusive economic zones of coastal states (200 nautical miles), and informed participants that these areas cover something like 25 million square kilometres. He described this total area as a very small percentage of the actual ocean but said that many parts of the extended continental shelf are closer to some areas of potential resources such as hydrocarbons. Using his illustration, Dr. Parson said that there are only about 35 to 40 countries that have potential claims of extended continental shelves.

With a map, Dr. Parson showed participants the mid-ocean ridge system, pointing out that since they were devoid of any sediment, they would not contain resources that are normally associated with sediment basins such as hydrocarbons and phosphorites. He showed participants the location of the abyssal plains, pointing out that these were the areas with the potential for accumulating nodules and manganese crusts. He also showed participants the locations of the continental margins, indicating that these were the areas with immediate to near term market resource potential.

Recalling an earlier presentation and discussion about resources and reserves, Dr. Parson said that a resource is something that evolves, or can evolve, into a reserve in response to, inter alia, the amount of progress or advances in exploration technology, market forces, and economic forces around the deposit itself. He also recalled discussions on indicated and inferred resources, and said that when an inferred resource is realised, it becomes a reserve. He noted however that an inferred resource can be further subdivided Para-marginal or sub-marginal resources. Dr. Parson said that a reserve is essentially something that has a present day marketing and technological feasibility. He said that Para- marginal and sub-marginal resources are deposits that might cost as much as two or three times the present day marketable value of the resource. While stating that these resources are fairly useless in relation to current market conditions, Dr. Parson said that they may be viewed in a qualitative way, in terms of whether they will come on line in 5, 10 or 50 years in terms of exploitation technology.

Dr. Parson undertook a review of marine mineral deposits to evaluate whether they is a potential for them to occur on the extended continental shelf and hopefully, in the areas of the study as well. Starting with placer deposits, Dr. Parson noted that while the workshop had heard presentations on placer deposits of diamonds offshore south-west Africa, it was to be kept in mind that there are a variety of placer deposits, that range from heavy minerals/metals (cassiterite, platinum and gold), to light heavy minerals (monazite, zircon, ilmenite, rutile, magnetite, diamond). He said that some of these are actively being mined in coastal areas. He also said that during the workshop, participants had heard of diamonds being mined in water depths of 150 metres or more, with licenses being granted or offered for deeper water situations. He pointed out that in order for any of these deposits to occur beyond 200 nautical miles, significant reworking and redistribution of these deposit have to take place. Even then, he said that if any of these deposits were found beyond 200 nautical miles, they would have to be considered as very marginal or sub-marginal resources. With a slide, Dr. Parson showed participants a map of the world that indicated known locations of marine placers as well as locations of marine placer mines. He informed participants that all of the deposits and mines are well within 200 nautical miles of coastal baselines.

Turning his attention to chemogenous deposits, namely submarine deposits of phosphorite, Dr. Parson said that they deposits created when phosphate forms compounds either as sedimentary cement or in nodular horizons. He said that the criteria for their formation include, areas of up-welling, medium water depths, and in tropical or subtropical environments. He also said that there are huge reserves of phosphorite, with estimates of hundreds of billions of tonnes of phosphorite in coastal areas and distant areas from the coasts. He said that the downside of this picture that phosphorite is a low value commodity. He said that there are plenty of phosphatic ores that can be used for, inter alia, the fertilizer industry, the chemicals industry, and in pharmaceuticals. He pointed out that there are significant phosphorite deposits on land that are accessible and rich, making it difficult to imagine its exploitation on the extended continental shelves. With the use of a slide containing a map showing the distribution of marine phosphorites, he did, however, point out that some of these deposits are very close to the extended continental shelves. He gave the extended continental shelf of Argentina as an example of an area where phosphorites are known to occur.

With regard to evaporates, saline minerals formed from the evaporation of seawater, Dr. Parson said that they widespread in the continental margins. He mentioned potash, anhydrite, natural salt and gypsum as common evaporates and said that they were not related or restricted to any latitude controls. He pointed out however that like phosphorites, these were low value mineral commodities that are abundant in land deposits. He also said that none of the marine deposits in EEZs are being seriously exploited, making those on the continental margins sub-marginal resources.

Regarding polymetallic sulphides, Dr. Parson described the conditions for their occurrence as at mid-oceanic ridge volcanoes, in friable and slurriable chimneys and in very localized areas. He said that current knowledge of these deposits is at the model testing stage, and that much more input is required from academia and industry to prove them.

Dr. Parson said that he wanted to bring across is that there are sites that have geographic interests in the extended shelves. In this regard, he pointed out that Iceland has a claim to the Reykjanes Ridge that has at least one hydrothermal site on it. He also pointed out that the Rainbow field in the Azores is within the 350 nautical mile limit of Portugal. He also said that this field is the biggest, most active, and robust field in the Atlantic. Finally he pointed out another site in the Galapagos, to which he said Ecuador has every right to claim.

In relation to hydrothermal systems, he described these as the resources with the greatest access. He said that the normal figure for the length of the mid-ocean ridge system is about 50-60,000 kilometres. He said that if less than a 2 percent of it lies within the exclusive economic zones or claimable areas for states, 45,000 kilometre of the system is available for activities in the Area.

Dr. Parson spoke about Ferro-manganese crusts. He said that based on the discussions that had been held at the workshop, the following may be said about these mineral resources: (i) they are not unique and not widespread; (2) they occur in layers, up to several tens of centimetres thick, in areas of low sedimentation and biological activity, and (3) would be relatively easy to mine with tractors, scrappers and crushers.

With regard to manganese nodules he pointed out that since their discovery 130 years ago, there has been a significant amount of analyses done on them. He said that their distribution is probably better known than the distribution of other resources. With a map, he showed locations where manganese nodules and crusts have been recovered. He showed that the Clarion-Clipperton zone is the area with the highest concentration of recovered samples followed by the central Indian Ocean basin. He pointed out that they had contoured the published data on abundance and said that the data could be used to determine the number of nodules that actually occur within a one-degree grid. He said that on their map, they had highlighted the areas of greatest concentration this way.

He said that by combining the distribution of nodules in terms of the weight of nodules per square metre, with the composition of each of the nodules, maps of the distribution of the cobalt or any other metal per square metre could be created. He said that the end result is a map containing a weight per square metre metal representation for nodules. He described this as an incomplete database that should be used a guideline. He noted that the actual algorithm used for contouring needs to be carefully examined. He said that contouring permits quantitative or semi-quantitative estimates of what may be found within the extended continental shelves. He said that similar estimates could be made for all of the metals of economic interest to be found in nodules. Based on these estimates, Dr. Parson said that in terms of dry weight nodules, the biggest winners in terms of what lies in the extended continental shelves are the United States, Brazil, Antarctica, Argentina, Japan, South Africa, Canada and India. He said that for these countries, estimates of the metal tonnage in nodules on the extended continental shelf range from 1.86 to 0.4 billion tonnes

With respect to estimates of the gas hydrate potential within the extended continental shelves, starting with Dr. Desa's presentation he made the following observations as to criteria for occurrence: a particular pressure/temperature stability, water depths ranging between 500 and 3,500 and an adequate amount of biogenic gas in the sediments. Dr. Parson said however that in the absence of suitable technology that would allow these resources to be extracted even when they occurred close to land made estimates of this resource tenuous. He pointed out there is a pilot programme off Nankeen, Japan, and that there is also land based extraction of methane from a plant that was established in the 1970s in Russia. Noting that there is a form of demonstration technology available for extracting this material, Dr. Parson expressed doubts that this technology would be adapted from land to significant depths of water.

With a map, Dr. Parson showed participants sites where gas hydrates have been sampled and analysed. Some of the sites that he identified were in areas of the extended continental shelf. He pointed out some sites where he said there is sufficient sediment, an appropriate water column structure and that are unaffected by anomalous heat flow. He said that using a combination of these parameters; they have made comments on the potential for hydrates at some of these sites. He said that these sites could be used to identify areas in the next phase of the exploration. In this regard, Dr. Parson said that the countries that could benefit from development of hydrate potential on the extended continental shelves are Canada, Norway, Russia, the United States, Namibia and Australia. He described this list of countries as being the most comprehensive based on the present day understanding and knowledge of hydrates. He described the gas hydrate potential as a marginal resource. He also said that for coastal states interested in claiming an extended continental shelf, this is one of the resources that might justify their efforts.

With regard to offshore hydrocarbons, Dr. Parson said that because the price of oil and gas allows the resources to be marketable from production in fairly extreme conditions, it is pushing the industry deeper and deeper into the ocean basins. While noting that there are still very significant deposits that are being exploited on land, he said since the late 1990s the top ten offshore hydrocarbon provinces are producing something like 25 percent of the world's consumption. He also said that the conditions for the occurrence of offshore hydrocarbons are sufficient sediment accumulation, somewhere between 1 and 2 kilometres or more, the right maturation process, temperature and pressure, and the required overburden. He said however that for the purposes of prediction, the best parameter to use is sediment thickness.

Referring to Table 10 of his paper, Dr. Parson said that it was developed using published data from the geophysical data centre in

Colorado, USA, and the International Energy Authority. He said that there is very little chance that hydrocarbons will be found in the Area, but indicated the potential for these resources within the extended continental shelves.

He said that the estimates of resources in his paper are broken down by country. He said that this has been done for nodules, crusts, gas hydrates and hydrocarbons. He described these estimates as based on the best-case scenarios. He also said that the identified deposits will not be exploitable for the next fifty years and would only be exploitable based on progress in economic conditions and technology.

SUMMARY OF THE DISCUSSIONS

The discussions that followed Dr. Parson's presentation focussed on his vision of sulphides and phosphorites as potential resources on the continental shelf, the deadline for coastal states' submissions to the Commission on the Continental Shelf, the sizes of exploration areas for manganese-manganese cobalt crusts deposits, and why the potential for aggregates on the extended continental shelf was not addressed in his presentation.

The observation was made by a participant that in both his paper and presentation, Dr. Parson did not appear to have that much confidence in the exploitation of seafloor polymetallic sulphides in the near to medium term. He was also asked which of the three mineral deposits, polymetallic nodules, seafloor polymetallic sulphides or ferromanganese crusts deposits he thought would come on stream first.

In response to the question on his confidence in the exploitation of seafloor polymetallic sulphides, Dr. Parson said that his paper was written before he heard two presentations at the workshop. He said that based on the presentation of the extraction technique used by De Beers Marine for diamonds and following discussions with Dr. Peter Herzig on the applicability of these techniques to seafloor polymetallic sulphides, he has been happily persuaded in the other direction in terms of whether they are recoverable or not.

With regard to the mineral deposit that he thought would come on stream first, Dr. Parson said that he would have very little hesitation to say that it would be the cobalt-rich ferromanganese crusts deposits. While noting that in all three cases, serious steps have to be taken in order for mining to take place, Dr. Parson said that the crusts deposits seem to be the easiest of the three to mine.

Another participant made the observation that in Dr. Parson's presentation he had said that given the availability of land-based phosphorite deposits he did not see significant efforts being made to develop marine phosphorites. This participant pointed out that within the next couple of years the United States would see a change in its position as a net exporter of phosphorites to a net importer of phosphorites. This participant said that while it did not mean that the United States would be mining marine phosphorites immediately, the situation rewarding these deposits may not be quite as pessimistic as indicated. This participant pointed out that there are extensive phosphorite deposits, for example on the Blake Plateau in offshore Florida in North America, so that offshore exploitation could have some potential in the medium term. This participant pointed out that in addition to the insular or atoll phosphorites on the continental shelf, in most of the seamounts of the world that have been studied, a different type of phosphorite deposit has been found on them.

In relation to Dr. Parsons's comments on the deadline for submitting applications for extended continental shelves, another participant pointed out that during recent discussions at the Commission, 1996 and not 1994 is the year taken as the commencement of the Commission's work. As a result the deadline would be 2006.

With regard to the sizes of exploration areas for exploration for seafloor polymetallic sulphides deposits, one participant said that listening to the talks over the last few days, he is of the opinion that these are small deposits with fragmented continuity. He said that from an industry point of view, large areas have to be provided for in exploration licences so that the resource base at an inferred level is sufficient for mining organizations grounds to secure the funding to develop these resources. He asked Dr Parsons why he had indicated 150 square kilometres on his map for exploration areas.

In response, Dr. Parson said that the 150 kilometres that is mentioned is with respect to the length of ridge. He said that this is significantly more that 150 square kilometres and might contain three ridges.

Finally, Dr. Parson was asked why he made no mention of aggregates since the current trend is to discourage the extraction of aggregate in coastal areas. This participant suggested that the extended continental shelf should be viewed as a potential source of aggregates in the future.

Pointing out that aggregates are mentioned in his paper, Dr Parson said that he did not focus much attention on them, because it is unlikely that they would not be found within the 200 nautical miles. He concluded by stating that aggregates on the extended continental shelf would represent a resource that "below sub-marginal".

Part 4

REGULATORY AND PROMOTIONAL FRAMEWORKS

CHAPTER 18

STATUS REPORT ON THE DATA AND REPORTING REQUIREMENTS OF NAMIBIA'S OFFSHORE MINING POLICY AS IT RELATES TO PROSPECTING AND EXPLORATION (INFORMATION AND DATA REQUIREMENTS DURING PROSPECTING AND EXPLORATION AND DEGREES OF COMPLIANCE)

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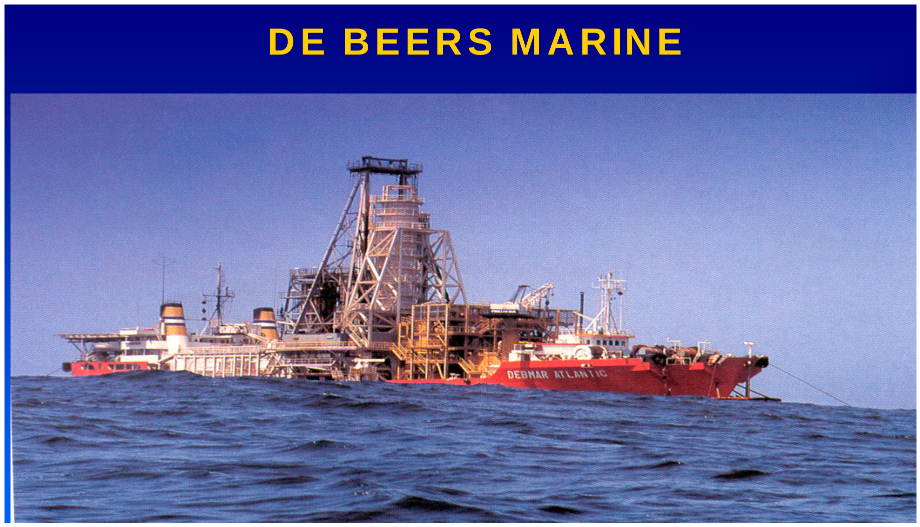
1. Introduction

Namibia is endowed with an abundance of mineral resources, being particularly well known for its history of high quality diamond mining spanning a period of over 100 years. There are several foreign companies exploiting the mineral wealth of Namibia. It is generally not Government policy to participate in the development of mineral resources and investors are therefore not required to give free equity to Government. However, of late, the trend among multinationals is to engage in "smart partnership" development of the resources with locally owned entities. Diamond exploration attracts the greatest interest and currently, the whole coastline from south to north is taken up by exclusive prospecting and mining licences for this mineral, as shown in the map below.

Offshore diamond exploration started in the early 1960's. A Texan entrepreneur, Sammy Collins of Marine Diamond Corporation, using a steam tug with a 20" airlift, first mined diamonds. Subsequently, the use of barges became more popular. The first of these was Barge 77, converted from a submarine pipe-laying rig, equipped with a 30cm airlift feeding a 30-tph-recovery plant. Today there are approximately twenty-three (23) exploration and mining vessels operating in the territorial sea and the Exclusive Economic Zone (EEZ) of Namibia. The bulk of these vessels operate at depths in excess of 200 m and eight belong to De Beers Marine, working under contract for Namibia's premier diamond mining company, Namdeb Diamond Corporation, while three belong to the NASDAQ – listed company NAMCO. The Government of the Republic of Namibia and De Beers Centenary jointly own Namdeb. In addition, there are several diver-assisted boats operating within shallower waters in the Namdeb concessions as contractors.



For the purpose of this workshop, this paper will summarize the salient features of the legislative framework governing mineral prospecting and exploration in Namibia, with special emphasis on provisions requiring submission of information, reports and returns by mineral license holders. We will begin with a general review of the applicable legislative provisions of the Minerals (Prospecting and Mining) Act of 1992 (hereinafter referred to as "the Minerals Act"). We will then go on to discuss how companies comply with the provisions of the Act, and highlight some measures put in place by the country's Ministry of Mines and Energy to ensure compliance. We will conclude with an analysis of the practicality of some of the requirements, and of the storage and use of the data by the Ministry.

2. General Background

Since independence 10 years ago (March 1990), the Government of the Republic of Namibia has committed itself to creating an enabling investment climate for the mineral resource sector, including the diamond industry. To this end, the Government has put in place an all-embracing and competitive legislative framework to guide and regulate the industry in a manner, which makes optimum use of the non-renewable resource, which remains key to economic development, while ensuring an equitable return for all stakeholders (Ministry of Mines and Energy, Directorate of Mines Paper, March 2000).

The existence of a modern, transparent and competitive framework is critical in attracting scarce exploration dollars into any country. This has become especially important during the last decade, when most countries liberalized their economies in order to attract foreign investment. The main legislative framework for regulating the industry is to be found in the Minerals Act and the Mines and Works Ordinance of 1968. The latter regulates the health and safety aspects of the industry. In addition to these pieces of legislation, the Diamond Act of 1999 provides, amongst other things, for control measures in respect of the possession, purchase, sale, processing and export of diamonds and incidental matters connected thereto.

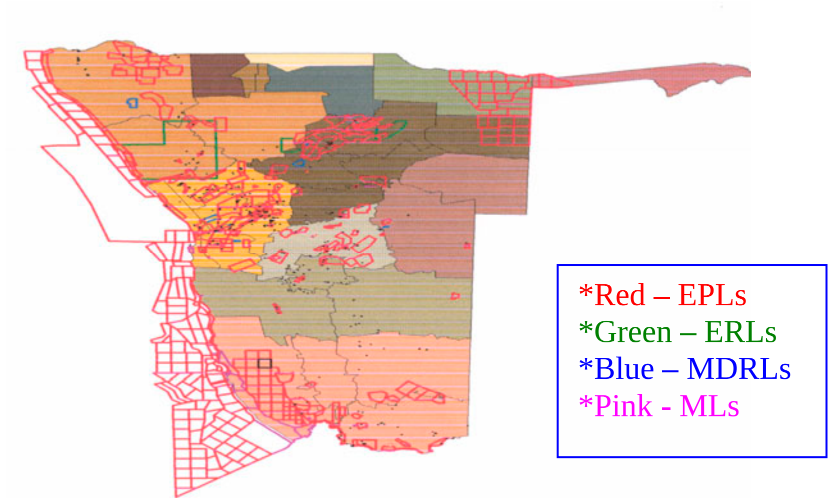
As a first step, immediately after independence the Namibian Government promulgated the Minerals Act in order to supplant those parts of the 1968 Ordinance regime, which inadequately catered for modern requirements and circumstances.

The stated purpose of the Minerals Act is "to provide for reconnaissance, prospecting and mining for, and disposal of, and the exercise of control over, minerals in Namibia; and to provide for incidental matters". The ownership of minerals in relation to any land on or under which any mineral or group of minerals is found is vested in the State, notwithstanding any right of ownership of any person in relation to any land (section 2). The Act also makes provision for the applicant if it so wishes, before the relevant license is issued, to request the Minister "to enter into an agreement not inconsistent with the provisions of this Act containing such terms and conditions upon which the license will be granted" (section 49). This is typically more pertinent to the mining phase. A draft model Mineral Agreement exists, while one mineral agreement has been entered and two are under negotiation.

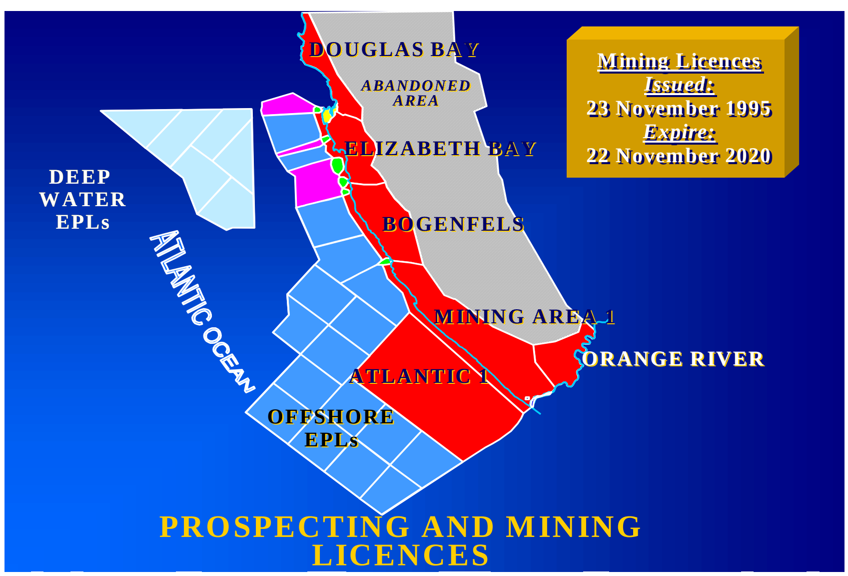
The Minerals Act makes no distinction between prospecting and exploration whether onshore or offshore. It covers three main conventional phases, namely reconnaissance, prospecting and mining. Prospecting is defined as the "intentional searching whether by way of excavations or otherwise, for any mineral or group of minerals with a view to delineating or evaluating deposits or concentrations of any such mineral or group of minerals, but does not include mining"(section 1 (1)). For the purpose of this presentation we will confine ourselves to the prospecting phase only.

Prospecting licenses may be non-exclusive or exclusive. Most serious prospectors normally would apply for an Exclusive Prospecting Licence (EPL), which is granted for an initial period of 3 years with a right to renewal for further periods, not exceeding two (2) years at a time (section 71 (1)).

Currently there are 404 EPLs issued of which 239 are for diamonds, 127 of these being offshore. The maximum acreage is generally 100 000 ha.



NAMDEB'S offshore mineral licenses including EPLs extending approximately 65 km into the sea from the shore. Some of the land-based licenses extend about 5 km into the sea as well, as suggested by the Namdeb mineral licenses map below.



The grant of a licence confers upon the holder thereof certain rights and obligations that include but are not limited to the right to carry on prospecting within the area granted, subject to an approved prospecting programme and specified minimum expenditure. In addition, the holder of an EPL is obliged to submit quarterly and annual reports setting out the progress made and to keep relevant records at the registered office, which the regulatory authority may inspect.

The returns must give amongst other things information regarding the location and results of all photo geological studies, imaging, geological mapping, geochemical sampling, geophysical survey, drilling, pitting and trenching, sampling and bulk sampling carried out during each quarter or annually. The licence holder must also report on the results of all analytical, metallurgical and mineralogical work incidental to such prospecting.

Interpretation and assessment of studies, surveys and work relating to the period of review must also be provided (section 76 (1)). Furthermore, the licence holder must submit information regarding the nature, mass or volume and value of any mineral sold or otherwise disposed of and the full names and addresses of any person to whom such mineral or group of mineral was sold or otherwise disposed of. It must also provide information regarding the expenses incurred during the period under review and such other relevant information as the Mining Commissioner (a statutory post) may require. At the expiry of the first tenure of the EPL or on application for renewal application, a report evaluating the prospects of a discovery must be submitted.

The Mining Commissioner is responsible for licensing, and for monitoring performance of the industry in terms of the Minerals Act. He has devised a special format (spreadsheet) in which data are submitted to the Ministry (see Annex A). The Ministry has a computerised Title Management System through which it is able to monitor the status of all mineral licences and the due date for submission of returns.

Annex A: Format for data submission to the Namibian Ministry of Mines and Energy

Ministry of Mines and Energy **Quarterly Report EPL No**	**Issued to**………………………………………… **Quarter from** …………..to…………………………

1) PHYSICAL EXPLORATION DONE #	**Expenditure 1)[A to E]+ 2) = N$**

A) GEOPHYSICAL SURVEYS		**Expenditure = N$**			
PROSPECT/FEATURE	*TYPE OF SURVEY**	*SURVEY SPECS*	*AREA COVERED (ha, km², etc.)*	*DURATION*	*CONTRACTOR*

B) GEOTECHNICAL SURVEYS		**Expenditure = N$**			
PROSPECT/FEATURE	*TYPE OF SURVEY***	*NO. OF SAMPLES TAKEN*	*SAMPLES LOGGED*	*DURATION*	*CONTRACTOR*

C) BULK SAMPLING (to recover diamonds)		**Expenditure = N$**				
PROSPECT/FEATURE	*SAMPLE METHOD****	*SAMPLE SIZE (footprint area in m²)*	*NUMBER OF SAMPLES*	*DIAMONDS*	*CARATS*	*GRADE (cts/m², cts/m, cts/100tons, cts/hr)*

D) OTHER FIELDWORK (TRENCH BULK SAMPLING, TRIAL MINING, ETC.)		**Expenditure = N$**			
PROSPECT/FEATURE	*METHOD****	*AREA (Sampled or mined)*	*DIAMONDS*	*CARATS*	*GRADE (cts/m², cts/m, cts/100tons, cts/hr)*

E) GEOLOGICAL MAP INTERPRETATION AND GIS CAPTURE, MODELLING, SEDIMENT DYNAMICS, ETC.			
PROSPECT/FEATURE	*AREA (ha, km², etc.)*	*WORK DONE (Method and deliverables)*	**Expenditure = N$**

*	*BATHYMETRY, SIDE SCAN SONAR, SEISMIC, RESISTIVITY, ETC.*
**	*VIBROCORES, GRABS, CPT'S, ETC*
***	*SAMPLING OR MINING TOOL, AIRLIFT, ETC.*
#	*COORDINATE LIST AND REFERENCE MAPS TO BE ATTACHED FOR SURVEY AND SAMPLING LOCATIONS*
##	*ENGINEERING AND DESIGN, MARKET STUDIES, GENERAL COSTS ETC*

2) OTHER EXPENDITURE ##	**Expenditure = N$**
Non-specific portion of salaries, consultants, legal fees, audits and accounting, communications, rent, travel, insurance, security, training, conferences, meetings, etc.	

3. Compliance With Legislative Requirements

All serious prospectors take their obligations as imposed by section 76 seriously and keep the required records at their registered offices and submit returns to the Mining Commissioner, containing summaries of work done for the period under review. The Minerals Act requires submission of the returns "within 30 days after the end of each quarter"(section 76 (1) (d)). The Ministry's interpretation of this section is that such quarter is to be calculated from the date of issuance of the EPL. The industry through the Chamber of Mines Prospecting Committee has put forward a different interpretation based on practical realities. To this end, a request has been made to the Ministry to allow submission of returns as per calendar quarters. The Ministry maintains that quarters calculated from the commencement date of the EPL is the correct interpretation of the Minerals Act and that this enables them to give proper attention to each operator's reports, as they are not inundated with quarterly returns all at once. However, the provision remains problematic for those companies with a large number of licences, all commencing on different dates.

The Minerals Act regime does not differentiate between onshore and offshore operators and as such, the latter are inhibited by a lack of flexibility in the application of the Act. In particular, section 76 does not cater for modern technology in the area of offshore geophysical surveys. The Ministry requires that all raw data collected during geophysical surveys be submitted to them. Most of the operators offshore use contractors based outside Namibia and the data is normally taken to Cape Town and processed there using very specialised proprietary computer systems. The raw data usually amount to large volumes of Gigabytes on tapes and CDs. The licence holder is then presented with the contractor's interpretation of the data.

Since the Ministry insists that raw data must be submitted to it, the licence holder has to ensure that its contractor returns all raw data to Namibia, resulting in costly administrative processes to retrieve the raw data. The raw data is of very little use to the Ministry, as they do not have the technical capacity (computer systems) to properly interpret such data at this point in time.

4. Storage and Utilization of Data Submitted to the Ministry of Mines and Energy (Mme)

The Geological Survey and the Mines Directorates of the Ministry are the custodians of all data submitted to the Ministry. The latter, as indicated earlier, use the data for monitoring performance. During the currency of the licence, the information and data submitted are kept confidential in closed files. This information is kept confidential until such time as the license area is relinquished or abandoned. Upon relinquishment, the information and data is transferred to an open file and is used by the Geological Survey for investment promotion.

Any interested third party can have access to the open files, free of charge. The rationale used by Government in allowing free access to data on an open file, is that a new company/investor interested in an area that has been looked at previously need not re-invent the wheel. Government's interest is to promote the discovery of a deposit in the shortest possible time. Most companies, however, feel that in today's competitive environment, new entrants should not benefit, free of charge, from data collected by others and should preferably be left to their own devices when prospecting over the same area.

The Ministry requires that information be submitted in an SEG-Y format. However, the bulk of the information remains uncollated and stored at the Geological Survey. The Geological Survey is understaffed and at the moment, is not in a position to collate/interpret the data into a useful format. Previously, before the advent of technology caught up with Namibia, the data used to be stored in the raw format as received from the license holders and was not compiled or collated in a user friendly format. We understand, however, that the Ministry has put together a project as part of 2nd National Development Plan (NDPII) to build its capacity in this regard.

Summary and Conclusions

The Minerals Act provisions related to submission of data and information to the regulatory authority are comprehensive. The data requirement exists to enable the authority to monitor the operations and thereby discourage land locking. Prior to the commencement of the Act, land locking was one of the factors discouraging new entrants as speculators controlled most of the prospective areas and sold the areas at prohibitively high prices. The Ministry is severely understaffed and in need of support in building its capacity to effectively monitor the industry. Collation of raw data thus presents a tremendous challenge to the regulatory authority. The collection of raw data and storage in that format is almost useless to any one except the gatherer thereof. If the regulatory authority is not in a position to make effective use of the data, it should not be necessary to require the licence holder to submit information in the raw format, as this imposes a burden that is discouraging to prospective foreign investors without any offsetting benefit.

The objective should rather be to facilitate the submission of readily accessible information by the licence holder, which the authority can use for evaluation purposes in monitoring the industry, and also for creation of a database for later usage. However, making data collected by other parties available to a third party free of charge serves as a disincentive to those companies who have invested substantial funds to generate such data. It might, therefore, be useful to consider charging a reasonable fee to subsequent data users, as is currently the case in the offshore petroleum industry. This possibility has been raised with the authority, albeit not yet favourably considered.

Notwithstanding these issues, the importance of providing detailed information on one's activities cannot be over-emphasised. It is in the interest of the operator to ensure that the authority is kept informed. Similarly, the authority must ensure that information and data submitted is kept confidential throughout the duration of the license. In our experience, this is not always easy. Unscrupulous elements do from time to time make use of such confidential information to the detriment of the licence holders. This threat is greatest during renewal, when third parties, having learned of the prospectivity of the area, wish to stake claims over the same area.

Finally, the reporting requirements of the Minerals Act in the current format do not adequately address the needs of offshore operators especially with regard to geophysical data. Moreover, since there are not yet any regulations implementing the Act, administrative issues that ought to be addressed through such regulations, these issues must be handled through ambiguous provisions of the Act, which is cumbersome and contributes to uncertainty. The Minerals Act is presently under review, and hopefully these latter concerns, at least, will be addressed.

Summary of Presentation and Discussions on the Status Report on the Data and Reporting Requirements of Namibia's Offshore Mining Policy as it relates to Prospecting and Exploration Information and Data Requirements during Prospecting and Exploration and Degrees of Compliance

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Presentation

Ms. Inge Zaamwani, Managing Director of Namdeb Diamond Corporation of Namibia, and a member of the Authority's Legal and Technical Commission noted at the beginning of her presentation that like Papua New Guinea, under Namibian legislation, there is no distinction made between onshore and offshore mining operations. She said that the regime for onshore mining applies to offshore mining, creating problems for offshore operators because of its lack of flexibility. She also said that despite the introduction to Namibia by Ian Corbett she would provide a brief background on the country. In this regard, she stated that she often got asked whether Namibia is in Arizona in the USA. She said that her presentation would consist of a background on Namibia, including information on its location, population and the various minerals that are mined there, and Government policy for the minerals sector.

With the use of slides, Ms Zaamwani illustrated Namibia's location in relation to other African countries. She said that Namibia is located on the Southwestern coast of Africa, bordering South Africa to the south, Angola to the north, and Botswana to the east. She said that most of the onshore diamond mining operations are carried out in an area called "Diamond Area no. I." She informed participants that from the day that diamonds were first discovered in Namibia (when Namibia was a colony of Germany) until now, this area has been declared a "no-go" area, or a prohibited and restricted area. She indicated that extending down the coast to the mouth of the Orange River, there are other offshore activities.

Ms. Zaamwani informed participants that the capital city of Namibia is Windhoek with a population of about 270,000 people. She said that the Government of Namibia subscribes to free market economic policies, and that as far as the development of mineral resources is concerned, the trend since the 1990s is for their development to be in the form of partnership between foreign investors and locally owned entities. She said that is in this context that the joint partnership between the Government of Namibia and De Beers evolved. She said that diamond exploration attracts the greatest interest and for entities interested in marine minerals development, and that the whole coastline is dotted with various licenses. With regard to the types licenses issued by the Government of Namibia, Ms Zaamwani said that the only two types of licenses are issued. These are prospecting and mining licenses. She also said that under the license, prospecting includes exploration.

Through the use of a slide, Ms. Zaamwani showed participants marine diamond concessions off the coast of Namibia. These she said, extended all the way up to Meob Bay, which is the northern port of Namibia. She also said that the bulk of the concessions are owned by NAMDEB, and that a few of them belong to another company, a NASDAQ listed company called NAMCO.

Through the use of other slides, Ms. Zaamwani showed illustrations of the types of barges that were first used to mine diamonds offshore Namibia.

She pointed out that the first barge used by Sammy Collins was a converted submarine pipe-laying rig.

As concerns the technology used then, she said barges were equipped with a 30 cm airlift feeding a 30-tph-recovery plant on board the barge Since then, Ms Zaamwani said that those types of barges have been replaced by more conventional types of vessels adapted to offshore mining.

Ms. Zaamwani informed participants that twenty-three exploration and mining vessels operate in Namibia's territorial waters and its Exclusive Economic Zone (EEZ). She said that De Beers Marine owns the majority of vessels. She also said that De Beers Marine works under contract for NAMDEB. Ms. Zaamwani informed participants that NAMDEB has been mining diamonds for over 75 years essentially onshore. She said that its expertise and core competency is in onshore operations, where it mines large alluvial deposits and operates one of the largest earth-moving fleets in the world. She said that the decision to move operations offshore was made because NAMDEB's onshore concessions extended about 5 kilometres into the offshore waters of Namibia. She said that as was apparent from Mr Corbett's presentation, that decision has paid dividends.

Ms. Zaamwani told participants that the main player in Namibia's offshore diamond industry is Namdeb, which is jointly owned by the Government of Namibia and De Beers. In addition she said that NAMCO, listed on the NASDAQ stock exchange, was another player. She informed participants that during the 1990s, the Government of Namibia decided to open the industry to more players. Since then other players such as Diamond Fuels International have joined group. She said that in addition to this company, which is in the final stages of test mining, there are several other companies engaged in exploration or prospecting.

With slides, Ms. Zaamwani showed participants photographs of the ceremony when the joint venture agreement between De Beers and the Government of Namibia was signed. They showed Mr. Thompson, then the Chairman of de Beers and therefore Chairman of Namdeb, and the President of the Republic of Namibia. Ms. Zaamwani said that the joint-venture partnership was born out of the historical circumstances prevalent at the time of independence. She said that De Beers, having operated in Namibia for over 75 years, decided to offer fifty per cent equity in its operations to the new Government at independence. She also said that Namibian law does not prescribe state participation in mining operations.

Ms. Zaamwani then turned her attention to the legislative framework for offshore mining in Namibia. She informed participants that at independence there was virtually no legislative framework applicable to the mining industry that had been structured to meet the needs of Namibia. She said that all activities were regulated under the South African mining legislation. She said that the new Government set about the task of creating an enabling investment climate within a competitive legislative framework. She pointed out that in the early 90's when Namibia gained its independence a lot of countries were opening up their economies and investors had a lot of places to choose from. She said that countries that offered the most attractive package got the scarce exploration dollars.

Ms. Zaamwani said that the main legislative framework is contained in the Minerals Act, whose full title is the Minerals Act: Prospecting and Mining Act of 1992. She also said that there is an ordinance called the Mines and Works Ordinance of 1968 that regulates the health and safety of workers in the industry, and the Diamond Act of 1999 that deals with the possession, sale, trade and dealing in diamonds. She pointed out that although licensing is through regulations contained in the Minerals Act, once diamonds are found the provisions of the Diamond Act apply. She also said that under the Minerals Act there are provisions on environmental protection applicable to the mining industry, and that there is also a draft Environmental Management Act under the Ministry of Environment and Tourism that will also regulate some aspects of mining.

Ms. Zaamwani said that under the Namibian Minerals Act ownership of minerals is vested in the State. Landowners just own surface rights. She said that the State could license a qualified applicant to exploit or extract those resources even if they are under private land, subject to compensation for the loss of the use of rights. She emphasized that compensation is not for the value of the minerals that might be in your land, but for surface rights. She described the confidentiality of data during the currency of licenses as an important element for most investors. She said that the Act guarantees that once data and returns are submitted, those data are kept confidential and used by the regulatory authority for the purposes as stipulated. When a license expires, Ms Zaamwani said that those data are transferred to an open file system and can be accessed by anybody who is interested in that area. She said that the confidentiality of data provisions is applicable to both onshore and marine mining.

With regard to the types of licenses, Ms. Zaamwani said that there is a non-exclusive prospecting license that is basically a regime for small miners who want to take a look around to see what is available, the exclusive prospecting license, the reconnaissance license and the mining license. Ms. Zaamwani said that the exclusive prospecting license is the more popular type of license used by serious prospectors and foreign investors. She said that the reconnaissance license comes in two types: The non-exclusive reconnaissance license that is similar to the non-exclusive prospecting license but on a larger scale; and the exclusive reconnaissance license that obtains exclusivity to the area for the operator for the duration of the license. She also said that these licenses vary in duration from 6 months to three years. As regards the mining license, Ms. Zaamwani said that its tenure is either determined by the life of the deposit or 25 years whichever is relevant.

To cater to a situation where the development of a deposit is affected by a drop in the market price for the commodity to be produced from it, Ms. Zaamwani said that under Namibian law, a mineral deposit retention license is offered. With this law, rather than the loss of the deposit, the contractor gets to keep the deposit for a period of 5 years while the market is improving or whatever the circumstances are that created the *force majeure* are being addressed. Ms. Zaamwani said that at the present time, the Ministry of Mines and Energy of Namibia has issued a total of 404 exclusive prospecting licenses. She said that of this number, 239 are for diamonds of which 127 are offshore licenses. She remarked that was a very significant number, given the size of Namibia's population and the fact that other kinds of licenses have also been issued.

Ms. Zaamwani said that exclusive prospecting licenses provide the contractor certain rights and obligations. She said that one of the contractor's obligations is to carry out prospecting work in the licensed area.

Ms. Zaamwani said that a holder of a prospecting license has the right to minerals found during prospecting. She said a holder of a prospecting license could have this license for one or more types of mineral commodities, except for diamonds as well as base metals. She said that the commodities have to be won from a single type of mineral deposit. She said that a work programme, which is submitted along with the application, forms the basis for prospecting work. Ms. Zaamwani said that the minimum expenditure is based on the amount of work specified in the three-year exploration programme. She said that it is very important for holders of prospecting licenses to strictly adhere to good prospecting and mining practices, particularly in the diamond industry where "high grading" is a big temptation for investors who may wish to recover their investment quickly. She also said that "high grading" is against Namibian law and that it could result in the loss of one's license.

Ms. Zaamwani told participants that license holders are required by law to keep certain records of the activities conducted in their exploration areas. She said that license holders are required to submit annual and quarterly reports containing sufficient details regarding listed activities, location, the results of all photo geological studies that we carried out, imaging, geological mapping, geochemical sampling, geophysical survey, drilling, pitching and trenching, and bio-sampling. In addition, Ms. Zaamwani said that license holders are required to provide the results of all analytical, methodological and mineralogical work carried out during the specified period. She said that interpretation and the assessment of these studies must be provided, together with surveys, related work, and any other information relating to the nature, mass, volume, and the value of any mineral that you discover during prospecting. If the license holder removes any minerals from the license area, the names and addresses of any persons to whom the minerals were sold have to be provided. She said that expenses incurred during the period under review are also required.

Because of the nature of the information required, Ms. Zaamwani said that the Ministry of Mines and Energy has made it easier on license holders by providing them with a format to submit these details. She also said that the Ministry now has a computerized title management system into which this information is fed and which is utilized to monitor activities.

Ms. Zaamwani noted that as part of the presentation, she had been requested to provide an assessment of the degree of compliance. She pointed out that for a serious investor, compliance is not a problem because that is the price you pay when you go searching intentionally for minerals in any surface, or place. She said that the degree of compliance is high, close to 90% among the more serious operators. She said that reports must be submitted within 30 days after the end of each quarter, starting with the commencement date of the license. She said that this basis for determining the end of the quarter is a bit problematic. This was because for those operators with more than 50 licenses issued on different dates, for example this would mean engaging two full-time staff to take care of reports. Ms. Zaamwani said that the industry through the chamber of mines has now made a request to Government for quarters to be defined with reference to the calendar year.

Ms. Zaamwani said that one of the problems and that was clearly identified in Mr. Wanjik's presentation is that when an onshore regime is extended to an offshore regime; it creates some problems because the requirements for offshore operators are different insofar as geophysical surveys are concerned. Ms. Zaamwani said that under Namibian law, all the data collected during geophysical surveys as well as the interpretation of these data must be submitted to the Ministry. She said that the requirement for interpreted data is the source of the problem. She pointed out that is since the offshore industry is relatively new most operators use very specialized proprietary computer systems and that data are processed outside Namibia. She said that this lack of flexibility makes it onerous for operators in the marine environment. She said that the matter was currently under review by the Ministry, and that in due time the two regimes might be separated. She also said that the requirement to submit the raw data has also meant that all data must be retained, resulting in costly administrative processes to retrieve the data and then submit it to the Ministry.

Storage and utilization of data.

Ms. Zaamwani said that the Ministry of Mines and Energy through its directorates, the Geological Survey and the Mines and Energy Departments are the custodians of the submitted data. She said that at the Geological Survey, one finds piles and piles of raw data as well as the interpreted data since submitted data are filed there. She said that these data are not collated, and in the industry's view are of no use to the Ministry in that form. She informed participants that the Ministry is now undertaking a project to develop the capacity to collate and interpret those data that they receive from operators.

With regard to the open file system, as a result of which upon expiration of a prospecting license, the data and information gathered by an operator are made accessible to anyone interested in the area free of cost, Ms. Zaamwani said that the industry is uneasy about this approach. She said that the rationale of the Ministry is that this would facilitate mineral development and encourage investment. She said that industry was of the opinion that this provided a free ride to latecomers. Industry is also of the view that perhaps the Ministry could benefit, as is currently the practice in the petroleum industry, by charging a fee for the use of that data. She said that there is an ongoing dialogue with the Ministry on this issue as well as with the Chamber of Mines.

Environmental protection.

Ms. Zaamwani said that she is of the opinion that the Minerals Act is very rigid with regard to environmental protection because along with an application, a potential operator is expected to submit an environmental impact assessment statement. She said that without an opportunity to scout the area, this was a very difficult task for any potential operator. She said that the Act requires the applicant to provide an indication of the condition of the environment, what the applicant expects the condition to be after mining, and the measures that the applicant proposes to take in order to minimize the impact of its activities on the environment. She said that offshore operators are subject to the same requirements, incurring costs to meet these requirements. She also said that once the environmental impact assessment statement has been approved, it is transformed into an environmental management plan, which becomes part of the license.

Ms. Zaamwani said that as part of the environmental impact assessment study a lot of public meetings are held and views are solicited from the public on impact of the proposed mining operation in their geographic area. She informed participants that in some cases public opinion prevails against the application. She said that in these cases Government rejects the application. She noted that in the case of NAMDEB, it is in the process of being audited for accreditation to ISO 14001, and with final auditing completed was waiting for the outcome.

With slides, Ms. Zaamwani stated that the management of waste on board vessels is an important concern of all operators. She said that operators go to elaborate lengths utilizing different processes to separate the various wastes that they generate.

Health and safety

With regard to the health and safety of workers, Ms. Zaamwani said that this part of operations is regulated by the 1968 Ordinance. She said that most of the companies operating offshore have a zero-tolerance policy towards injuries at work, resulting in initiatives to encourage both employees and managers to ensure that the operations are conducted above reproach.

In summary, Ms. Zaamwani said that the Minerals Act has comprehensive provisions relating to the submission of the data and information that it requires. She said that the Act also prescribes the type of information that the Government would like to have. She said that by prescribing the format of the data and information that it requires, the work of the operator has been simplified.

Ms. Zaamwani said that although the confidentiality of data is guaranteed during the currency of the license there have been s individuals who have benefited from the use of confidential data especially during the renewal stage. She said that generally such data are revealed to competitors. She said that efforts are underway by the industry to ensure that confidentiality is operative in practice and that it is not just a piece of legislation. She said that the authorities use the data to monitor performance and it is particularly relevant during renewal because in the past, many license holders would not undertake any work until shortly before the due date of their reports when they would go and drill three or four holes. They would then go to the Ministry and claim that this was work done during the previous three years, and request additional time on their licenses. She said that the Ministry is now applying this provision in a serious manner, scrutinizing each and every detail of operators' work programmes and expenditures to ensure that they have actually carried out the work.

Ms. Zaamwani informed participants that the principle of use it or lose it is becoming very prominent in the Namibian industry, as well as in South Africa. Ms. Zaamwani said that this principle is encouraging operators to take their licenses seriously and ensure that they are carrying out the required work.

In relation to the raw data requirements of the Act, Ms. Zaamwani's opinion is that since the regulatory authorities because of lack of capacity and understaffing do not currently utilize these data, a representative sample of the data obtained by the operator along with its interpretation of the acquired data should suffice. She also said that she was refreshed to hear from Mr. Wanjik that his Government had managed to secure some funding from the World Bank to facilitate capacity building for this purpose.

Ms. Zaamwani said that the main problem with the Minerals Act of Namibia is that it is not flexible. She said that this is because matters that are supposed to be in regulations are contained in the Act itself. She said that any time a problem arises with a procedure and variations are proposed, to incorporate such proposals requires an amendment to the Act. She also said that the Ministry is now reviewing the Act with a view to separating administrative issues and placing these in regulations. Policy guidelines would be left in the Act.

With regard to the work of the Authority, Ms. Zaamwani pointed to the need for flexibility. She said that flexibility is very important in creating an enabling legislative environment. She said that this is especially so for deep sea mining with the amount of finance required, the risk involved and the technological solution that has to be found. She said that in order for the Authority to encourage the development of the resources in the Area, it has to make sure that the framework put in place by Legal and Technical Commission is flexible and encourages the development of the resources.

In this regard, she said that for environmental management, the requirement should be for a comprehensive environmental impact assessment to be submitted towards the end of the exploration phase because, as had been said by others, during the exploration or prospecting phases there is really minimum impact on the marine environment. Ms. Zaamwani said that the cost of environmental management is part of total project cost. She said that formulating the problem in a way as to acknowledge that it is the mining or extraction of the resource that is intrusive on the environment makes the message is clearer. She pointed out that like everything else, in making policy and legislation, a balance must be struck between environmental protection and the extraction of resources. Equally important she said is striking a balance between the experts involved in this type of work. She said that in drawing up the Namibian Minerals Act for example there was heavy representation of geologists and very little legal input. She said that the person brought in to draft the Act was basically told by the geologists what the thinking was behind a provision and very little consideration was given to issues such as flexibility.

Ms. Zaamwani ended her presentation by recalling that someone had asked her which entity she represented on the Legal and Technical Commission, her company or her Government. She said that she told the person that she had been appointed in her individual capacity and that she hoped that she was mature enough to maintain that balance between professional, company or country commitment. She said that often in the LTC, despite the fact that its members are professionals, such lines are drawn suggesting that the views that they express are not their own. Ms Zaamwani thanked participants for the opportunity to make her presentation.

SUMMARY OF THE DISCUSSIONS

The discussions that followed Ms. Zaamwani's presentation focussed five matters. The first topic was on license holders who do not conduct prospecting or exploration work as required. The next, on the problems faced by the Government of Namibia that arise from the large volumes of data and information that it requests from license holders. The third topic focussed on how the Government is able to monitor activities in offshore diamond concessions that are so closely bunched together. The fourth and fifth addressed questions on the Environmental Impact Assessment reports required of license holders, and decommissioning equipment following the completion of an offshore diamond mining operation.

Ms. Zaamwani was asked why a holder of a prospecting license would sit on the license for three years and do nothing about developing it. Ms Zaamwani said that the reasons included speculation and land locking. She said that this was the case for both onshore and offshore operations, pointing out that the situation has improved with new legislation.

One participant recalled that Ms. Zaamwani had mentioned the problems the Government has with data storage, with the use of proprietary software by companies and with proprietary software being used outside Namibia for processing data. This participant also said that Ms. Zaamwani had spoken about changes in the Minerals Act to allow the Government to deal with this situation. This participant suggested that a possible solution would be to request that data are presented in pdf format. The same participant also suggested that with regard to is the stack of data that already exists, historical data that is less than useful as it stands now, one approach would be to turn them over to researchers.

In response, Ms. Zaamwani said that the Geological Survey of Namibia now has a project in place to interpret the data and input it into software that has wider application than is currently the case. With respect to the comment attributed to her for a change in the Minerals Act to enable greater flexibility in data submission, Ms. Zaamwani indicated that because of the close relationship between license holders and Government such flexibility presently exists. She said that there is a need for a provision to be included in the legislation to allow various types of solutions to be applied by the industry.

Mr. Ian Corbett of De Beers Marine made a comment about the common data format. He said that De Beers Marine had enormous problems with that concept because the data that are acquired are not normal in many cases. He also said that De Beers Marine had problems in loading data particularly scientific data on to systems such as Geoquest or landmark. He added that what seems common from an oil industry perspective has not been common when carried across to other types of resources.

Another participant suggested that a possible solution to the problem of large quantities of data and lack of capacity to interpret these data might be to increase the periodicity of reporting from quarterly report to yearly, and for the Ministry to use the mining code as a basis for training staff of the Ministry.

Ms. Zaamwani said that under Namibia's Affirmative Action Act, there is new legislation on training that also affects the mining industry. She said that under the Mining Act, there is no explicit requirement although there is a provision that you must make use of Namibian goods and services, including labour. She reminded participants of the points made by Mr. Corbett in this regard, in particular, the amount of self-imposed obligations by the diamond industry to train local personnel. She also reminded participants that NAMDEB awards about 10 scholarships in various fields each year, which costs the company about $3.5 million every year.

A number of participants were interested in how the Government of Namibia monitors so many, closely packed offshore diamond concessions.

While pointing out that the question was best answered by the regulator, Ms. Zaamwani said that from the diamond miners perspective, they were concerned that other operators intrude in their concessions. She said that there have been rumours of submarines and boats being used in unauthorized areas. She invited Mr. Kennedy Hamutenya from Namibia's Ministry of Mines and Energy to respond the question.

Mr. Hamutenya said that the Namibian Government does not have the capacity to monitor offshore activities. He described the existing situation as a problem for the Government because it did not have vessels or helicopters, but relied on operators to transport Government officials to operations. With regard to the number of concessions and monitoring, Mr. Hamutenya however pointed out that many of them have been awarded to smaller operators who are still engaged in prospecting. He said in many of the concessions, activities have therefore not advanced, making less to monitor.

Another participant informed the workshop that in the Pacific, the Fisheries agency responsible for licensing fishing companies has a novel way of monitoring based on the licensed vessels. In this system, he said that of any two vessels belonging to an operator, one is an observing system while the other is used as a vessel monitoring system that uses satellite reporting. He wanted to know whether this remote-sensing method could not be used to monitor the diamond concessions.

Ms. Zaamwani informed the workshop that before she left the Ministry, it was working on a similar type of project. She said that at the time it appeared to be very costly. She also pointed out that on each of the mining vessels there are sophisticated security systems, and that operations are mostly hands-off with no contact with the product. She said that two years after leaving Government she did not know whether the situation has changed or not.

Commenting on Ms. Zaamwani's statement, Mr. Hamutenya said that the proposals that were given to Government of Namibia were extravagant. He said that the companies that undertook the research also exaggerated the possible losses to the Government in order to justify these proposals. He said that the Government is working on a simpler system that meets its needs without spending so much money.

Another participant noted the similarity between the mining codes of Belize, Namibia and Papua New Guinea with respect to requesting and mandating an Environmental Impact Assessment (EIA) statement at the start of prospecting. This participant mentioned that such a request results in costly front-end payments when the viability of a deposit has not been established. This participant stated that this requirement, depending on the scale of operations could be a serious deterrent to investment

Ms. Zaamwani said that through the flexible way in which work is done in Namibia, in particular by the Government not only understanding that such front-end payments are not desirable and agreeing that operators can submit this report before they proceed to the next stage, many problems are overcome. She noted however, the law requires EIAs to be submitted much earlier on. In that regard, she said that if anyone were to challenge the current practice then it could become a problem. She said that as long as the same people run affairs in the Ministry, and as long as their practice is consistent then the system works. The main point she thought was to adjust the law to make the practice legal.

It was pointed out by the participant from Belize that the situation could become critical even if the same people run the stated affairs in Government. This participant said that it was when a strong green lobby exists that the situation becomes critical. The participant informed others that in Belize, an offshore drilling project was delayed almost nine months because the lobby wanted a full blown environmental impact statement even though the law required something less. This participant therefore said that the existence of a strong lobby could be more important than flexibility within the Government. In response, Ms. Zaamwani turned the assertion over to any of the environmentalists gathered at the workshop.

The representative of Greenpeace said that as a practical environmentalist, he recognized the problems that arise by insisting on a full-blown Environmental Impact Assessment before any surveys or work had been carried out. On his own behalf, he said that this requirement was not practical.

Ms. Zaamwani was asked about the level within the company at which the decision on the environmental impact assessment is given. This participant pointed out that in the United States environmental analyses are treated in a different way than full-blown Environmental impact assessments. This participant said that there are certain specified activities that lead to an automatic request for an environmental impact assessment because the activities are of public interest or there is a specific issue at stake. He said that otherwise, if the local mining manager decides that there is no need to go on the full-blown EIS immediately, the manager provides a statement to that effect. He said that the license would be granted on that basis. He also said that every time the mining company moves on to a different set of activities it is required to provide an EIA. He said that when it appears that there is a potential for damage, the full-blown EIA is then requested. This participant wanted to know if the current practice in Namibia considered this approach.

Ms. Zaamwani said that she thought that the Act imposes the obligation on the senior management of the company to make the decision because if anything went wrong the directors would be held responsible. She said that in most cases, companies contract an independent consultant to make that assessment and submit these findings to the Ministry.

It was suggested that since there are different levels at which one could assess what is about to happen to the environment, and that this approach is utilized in the UK for example, the Government of Namibia could consider this approach, thereby alleviating the scale of the EIA.

Ms. Zaamwani was asked about regulations under the Minerals Act related to decommissioning. It was mentioned that the Law of the Sea Convention contains a number of requirements in this regard. It was mentioned that under the Laws of Papua New Guinea this requirement is addressed through references to the Law of the Sea Convention.

Ms. Zaamwani said that in offshore diamond mining, no infrastructure is installed on the seafloor and that all equipment used is on board the mining vessel. She said that when mining operations are discontinued, the departure of the vessel is the removal of all equipment. Ms. Zaamwani's statement was supported by Mr. Corbett who said that the only equipment used by De Beers Marine for which some seafloor infrastructure is required have been acoustic compacts for positioning. He said that the compacts are deployed on a concrete weight at the seafloor. Mr. Corbett said that because the compacts are expensive pieces of equipment, they are recovered, leaving small blocks of concrete. He said that the only types of equipment that are periodically lost from the De Beers Marine fleet are anchors, anchor chains or anchor wires.

Another participant commented on the process for enacting offshore mining legislation. This participant pointed out that the private sector adapts to new situations, obtaining the required expertise, technology and methods to achieve the desired results. This participant said that on the other hand it would appear that when it comes to enacting legislation, Governments are fixed in time and space.

With regard to the marine environment, the participant said that while this new environment is not strictly for minerals exploitation but includes fisheries, recreation and tourism, when it comes to drafting legislation for mining for example, the experts involved are still from the Department of Mines and Geology. He said that there is a need for a new approach, a more integrated approach whereby an integrated ocean policy is decided upon and put in place, before sectoral matters are considered. This way, the participant suggested that the regulations governing individual sectors would be more consistent.

Ms Zaamwani offered two comments to this observation. She said that in Namibia when the Minerals Act, as it relates to offshore minerals was enacted the country did not have an integrated oceans policy. She said that two weeks ago, a symposium was convened in Namibia on the core management of coastal resources. She said that the symposium turned out to be the fishing industry against the mining industry. She said that most of the papers that were presented focussed on the impact of mining on one activity or the other. She said that when a question was asked about the impact of the bottom trolley on the seafloor, most of the fisheries personnel were shocked because such impacts had never been addressed within the fisheries sector.

CHAPTER 19

STATUS REPORT ON THE DATA AND INFORMATION REQUIREMENTS OF THE NORWEGIAN OFFSHORE LICENSING POLICY AS IT RELATES TO PETROLEUM ACTIVITIES

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Stavanger, Norway

1. Introduction

This paper gives a short introduction into legislation, licensing policy, data requirements and data management as it is introduced on the Norwegian continental shelf (NCS). The topics addressed are all related to petroleum activities. Figure 1 shows Norway and its offshore areas including the island of Jan Mayen and the Svalbard archipelago.

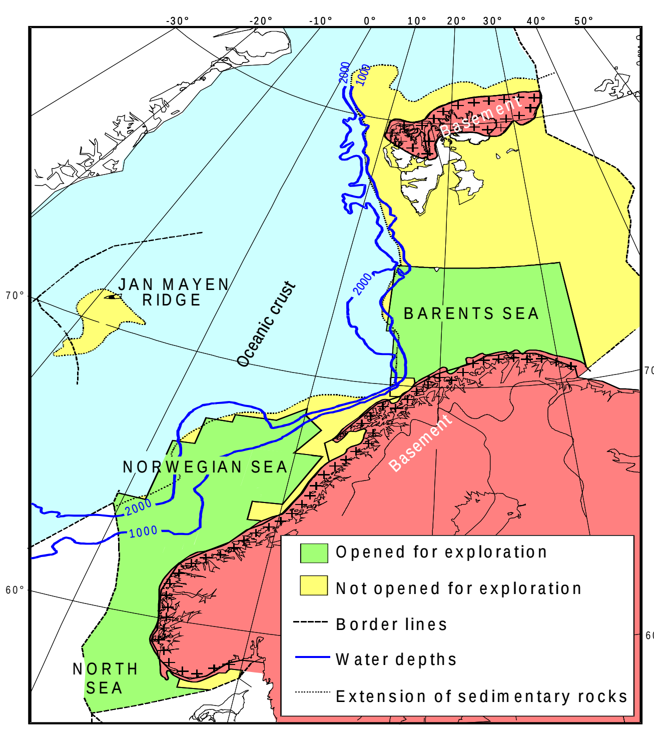

Figure 1. The Norwegian Continental Shelf

The Norwegian offshore sedimentary basins cover about 1.4 million km^2. About 60 per cent are opened for petroleum activities, but only around 10 per cent are licensed. The areas not opened are coastal areas with important fishing activities and the northern part of the Barents Sea, mainly due to environmental reasons. This paper does not cover activities and regulations related to the Svalbard archipelago where exploration for petroleum also has been conducted but without success. So far, coal mining has been the main activity on Svalbard.

Petroleum operations play a substantial role in Norway's economy, and contribute considerable revenues to the state. Norway's sovereignty over the NCS in respect of exploration for and production of sub-sea natural resources was proclaimed on 31 May 1963. A new statute determined that the state owns any natural resources on the shelf, and that the Crown alone is authorized to award licenses for exploration and production. In the same year, companies were granted permission to carry out preparatory surveys and reconnaissance.

Agreements on dividing the North Sea in accordance with the median line principle were reached by Norway with the UK in March 1965 and with Denmark in December of the same year. The border towards Russia north in the Barents Sea is still under negotiations.

The NCS is divided into quadrants, each comprising 12 blocks covering 15 minutes of latitude and 20 minutes of longitude. The average area of a North Sea block is about 600 km^2. A licensee can cover more than one block.

Norway's first offshore licensing round was announced in 1965. The first well was drilled off Norway in the summer of 1966. The first discovery was made in 1967, and the first production of oil came in 1971. Today 46 fields are producing while production has ceased in 10 fields.

So far 16 licensing rounds have been conducted in addition to some awards outside the regular rounds. 975 exploration wells have been drilled and 230 discoveries have been made. A total of 264 licensees have been awarded up through the years and 185 licensees are still active today. A total of 9.6 billion Sm^3 oil equivalents (o.e.) have been proven. Production to the end of 1999 totaled 2.7 billion Sm^3 o.e, which is about 21% of the total resources. About 3.7 billion Sm^3 o.e. are expected found through further exploration. This gives a resource estimate totaling 13.2 billion Sm^3 o.e. (about 51 per cent gas and 49 per cent oil).

Norwegian oil and gas production has increased substantially over the past ten years, and Norway ranks today as the world's second largest exporter of crude oil after Saudi Arabia. The production is in the order of 2.9 million barrels of oil per day, ranking Norway as number seven among the world's largest producers. Only seven per cent of oil production is for national consumption. Norway is also among the world's ten largest exporters of gas, and produces ten per cent of Western Europe's consumption. Most of the gas produced is exported or injected back to the reservoirs in order to enhance oil recovery.

2. State Organisation of Petroleum Operations

Key goals for Norwegian oil and gas policies since the early 1970s have been national management and control, building a Norwegian oil community and a state participation in the activity. The Petroleum Act specifies that the proprietary right to sub sea petroleum deposits on the NCS be vested in the state. This constitutes the legal basis for Government regulations of the petroleum sector.

Parliament determines the framework for petroleum operations in Norway. Overall, administrative responsibility for petroleum operations on the shelf rests with the Ministry of Petroleum and Energy (MPE). Its job is to ensure that these operations are pursued in accordance with the guidelines laid down by Parliament. The Norwegian Petroleum Directorate (NPD) is administratively subordinated to the MPE. Primary functions of the NPD are to exercise administrative and financial control to ensure that exploration for and production of petroleum are carried out in accordance with legislation, regulations, decisions, licensing terms and so forth. In addition, NPD will advise the MPE on issues relating to exploration and production of submarine natural resources.

On issues relating to the working environment, safety and emergency response, however, the NPD reports to the Ministry of Local Government and Regional Development (KRD).

3. Licensing Policy and Legislation

The Petroleum Act (Act No 72 of 29 November 1996) pertaining to petroleum activities provides the overall legal basis for the licensing system, which regulates petroleum operations in Norway. The Act and the provisions of the Act, authorise the grant of permits and licences to explore for, produce and transport petroleum and so forth. The Norwegian offshore licensing system comprises a number of documents, which go into more detail on the rights and duties of the various parties. The Norwegian licensing system complies with the requirements of the European Union's directive 94/22/EC on granting and using licensees to explore for and produce hydrocarbons (the licensing directive).

All the different kinds of geological and geophysical surveys conducted on the shelf require that permission be granted by the authorities (NPD). Before permission is granted, the companies/institutions have to give certain information (survey methods, area covered by the survey, time, etc) to avoid conflict of interest with other activities in the area.

In areas not opened for exploration activities the NPD has been given the exclusive responsibility on behalf of the landowner (the state) to undertake regional geophysical and geological investigations in order to generate basic understanding of geological conditions and describe the hydrocarbon potential of these areas. However, other institutions and companies are allowed to undertake geological and geophysical surveys in these areas on a scientific basis.

A scientific research license may be granted to Norwegian or foreign scientific institutions, scientists and others having a need for conducting scientific research. The permit is usually granted for one particular investigation. The license is normally free and entitles the licensees to carry out different geophysical and geological surveys. The permit does not give any exclusive right to undertake research in the areas covered by the license.

Nor does it give rights or priority to exploit possible natural resources. After the termination of the research, a report must be submitted concerning the extent and the execution of the research. In addition, within a reasonable period, a detailed report on the results of the research must be submitted and published.

When an area has sufficient regional data coverage and after environmental assessment studies, Parliament can open the area for industry. In areas opened for general exploration activity, companies can apply for a reconnaissance license to undertake geological, petrophysical, geophysical, geochemical and geotechnical surveys, including shallow drilling. This license grants no exclusive rights in the areas covered and does not entitle the holder to conduct regular exploration drilling. Areas covered by production licenses are closed for exploration under a reconnaissance permit. As soon as possible after the individual activities the licensee shall submit data, records and results from the activity to NPD.

By far the most important license to obtain is the production license. The license confers an exclusive right to the license holder for exploration, drilling and production of petroleum. The licensed area is granted to oil companies for a certain period. A production license permits the holder to drill exploration wells. Before a production license can be awarded, the area in question must have been opened for exploration. That can only happen after the environmental, economic and social impact of such operations on other industries and adjacent regions has been assessed. A phased opening of the continental shelf to exploration and restrictions on the number of blocks awarded in each licensing round have been used to maintain a moderate pace in the activity level.

Production licenses are normally awarded through licensing rounds. The Government invites applications for a certain number of blocks. Areas to apply for are announced by the Ministry based on recommendation from NPD and the industry. Criteria for announcing areas are that they cover several play types in order to increase the probability of discovery, have favourable geological conditions, are representative of neighbouring areas and have sufficient size. Production licenses are awarded on the basis of objective, non-discriminatory and published criteria. The announcement specifies the terms and criteria on which awards will be based.

On the basis of applications received, the MPE generally puts together a group of companies for each license and appoints an operator for this partnership. The operator is responsible for the daily conduct of operations in accordance with the terms of the license. From 1973 to 1991, state participation held a minimum of 50 per cent in each license awarded in that period. The state's average direct financial interest has declined since then and are now is generally between 20 – 30 per cent.

The production license regulates the rights and duties of the licensees in relation to the state. The document supplements the provisions of the Petroleum Act and specifies detailed terms covering each license. A production license entails an exclusive right to explore for and produce petroleum within its specified geographical area. Ownership of the petroleum produced rests with the licensees.

Each license is awarded for an initial exploration period, which can last up to ten years. A specified work obligation must be met during this period. The work commitment plays an important role as the controlling instrument. The licensees accept a commitment consisting of acquiring seismic (2D or 3D) data and drilling a certain number of wells. Providing the work obligation has been completed by the end of the initial period, the licensees are generally entitled to retain up to half the acreage for a period of up to 30 years. An area fee is then charged per square kilometer for the area kept. There is no area fee in the initial period. Providing all the licensees agree, a license can be relinquished. When areas, or parts of areas, are relinquished, they are again considered as open acreages.

The Act requires licensees to submit a plan for development and operation (PDO) to the MPE for approval before they can start developing petroleum deposits. The MPE is also authorized to approve plans for installation and operation (PIO) of facilities for transport and utilization of petroleum. The Petroleum Act also requires licensees to submit a decommissioning plan before a license expires or the use of a facility is terminated. The MPE will then decide on the disposal of these facilities.

4. Data Management

All data relating to geological, geophysical and reservoir characteristics, which have been obtained by national and international oil companies, must be regarded as a valuable asset for the nation in that area. This recognition is one of the key elements in the data management strategy on the NCS. High exploration efficiency and at the same time securing the long term national interest is the main objective of this strategy. Available information of high quality is a prerequisite for good decisions and an important element for increased efficiency in exploration, development and operations. Another important element is the idea that a complete and accurate data set is very important both for the industry, NPD, the public and other authorities involved for making right decisions and reducing costs. An element in the licensing strategy is that data by themselves are not a competitive element but how the data are used to document the applicants understanding of the regional geology in their application for new production licenses introduce the competitive element. Secrecy related to data gives poor co-operation between companies and authorities, forces companies to acquire their own data and increase costs and gives an incentive to hide negative information. Openness will create trust and co-operation, give a comprehensive evaluation of all data, promote participation and provide for cost efficient exploration.

The data requirements are detailed in the regulations and their guidelines. They cover cultural data, physical data, prognosis and plans, reported events, permits and agreements, statistics and different reports related to the activity. There are also guidelines related to data quality, media readability, format, archival efficiency, electronic reporting, administrative information and so on.

The NPD is entitled to all information the oil companies have regarding their activity in Norway. The Petroleum Act allows the NPD to formulate detailed routines for reporting, including physical form, medium and structure. The NPD also holds a seat on all licence committees as an observer. The NPD gives permission for drilling, to perform seismic surveys and for shallow coring. If the information received is not sufficient, additional reporting can be requested by the NPD.

The operator is obliged to collect all necessary information for its licensed activity. All these data are forwarded to the NPD or to the entity that the NPD has appointed to keep the data. The NPD is responsible for storing all information in central files. Storing facilities in the NPD are:

- Archives for general reports, well data and geophysical data. Core storage for storing cores and cutting samples from all wells drilled
- Electronic archives for geophysical and geological data and administrative data
- Freezer to store oil samples

After two years or more, all raw data are released. On an annual basis, the NPD publishes reports giving information on well logs, cores, samples, etc from raw data that have been released. Based on this, oil-companies, universities and other institutions can order a copy of the released samples. The price is set to cover administrative costs. The released data also includes seismic surveys. The release of core materials and fluid samples are regulated in the same way as the release of well data. The NPD must receive a written application that is handled by its release committee. The conditions for requesting core samples are that all reports from studies based on released material have to be submitted to the NPD as soon as completed. All palynological and micropaleontological preparation produced from the released material shall also be submitted to NPD.

Data that is not owned by a licence group is confidential for five years, while marked available data, is confidential for ten years. The NPD may shorten or extend this period on application. Sensitive information (interpretations etc) is confidential for 20 years. Data from areas relinquished or surrendered is no longer confidential. This also applies to data from an area where only parts of a licensed area are relinquished. All navigation data is public.

In relation to further exploration activity, there are two purposes for submitting a copy of all collected data to the NPD. The NPD gets the possibility to evaluate the results of each well and correlate these results with others. This provides an optimal basis for the authorities' regional understanding of the petroleum potential in order to prepare for new licensing rounds. By releasing data after two years, the oil companies are also able to carry out evaluations of the resource potential within an area.

5. The Norwegian National Data Set – DISKOS

The most important tool for offshore exploration is seismic data. Acquisition of seismic data in the North Sea started in 1962. Since then about 4.3 million line kilometres of seismic data have been acquired on the Norwegian continental shelf. Through the years, petroleum activity has generated increasingly higher amounts of data due to the numbers of wells, and to new technology. There has been an explosive development in the use of 3D seismic, which is now the sole method used for mapping discoveries and fields and is dominant in an exploration context. Nearly 1000 exploration wells and more than 2000 production wells have been drilled. Experience show that the petroleum industry has a great challenge in managing it's own data; a typical development project produces up to 30,000 drawings, 300,000 documents and uses more than 1.5 million sheets of paper!

Modern exploration techniques generate huge quantities of information, but the logistics of traditional data storage are often inefficient and costly. People involved thus spend too much time searching for data and collecting data of often-uncertain quality. This was the main concern when NPD took an initiative to establish a common national data repository for exploration and production related data called DISKOS. By means of this repository, data may be transferred directly to workstations at high speed and low costs, and data may be traded by easily changing owner rights to data in the data store. This is also a practical way to make data public after the required confidentiality period.

The software solution for the DISKOS data repository, called PetroBank, has been designed to provide users with rapid access to all data to which they hold a legal right of access. The company that pays for its initial acquisition owns the data. The NPD has access to all data by law, but ownership of the data does not change. Copyright is still held by the original purchaser of the data.

The project was conceived in 1992 and made available for the industry in 1995. Its use is expected to result in lower operational costs and more effective exploration programs, thus strengthening the competitive ability of the Norwegian petroleum industry. A common database like this ensures minimum duplication of stored data, quick and efficient data access and simplifies data trade and data release. Just the seismic data volumes in DISKOS are today in the order of 31810 Gigabytes.

A study to determine the business value of the DISKOS project from 1999 concluded that there were a number of positive cost benefits in DISKOS. Time taken to source and access 2D data is reduced from weeks to hours and the values added based on estimated costs savings is of the order of 30 – 40 million NOK per year (about US $ 5 million) per company. The costs of developing this data repository have been shared between NPD and the majority of the oil companies present on the Norwegian continental shelf.

6. Resource Classification

For all Governments it is important to have an overview of the total petroleum resources. The efficiency in exploration (timing and costs) and the total amount of petroleum resources to be found in a geological province is very dependent upon how exploration is planned and performed. The purpose of resource assessment and a resource classification system is to get a reliable estimate of the total petroleum resources of a nation or any other defined area in order to establish strategies for further exploration, development and production of these resources. The authorities will benefit from knowing certain critical factors regarding petroleum resources in their planning of how to manage the resources in such a way that they will be of maximum benefit to the nation. Important issues to focus on are what are the expected total resources present, the ratio between oil and gas, the distribution of the resources, timing and what is to be expected in the future.

One of the tasks of NPD is to keep an overall account of the petroleum resources at any time. This account forms the basis for the authorities planning of future activities. The total resources provide an indication of the resource base, and each field or groups of discoveries and prospects may be the basic assumptions upon which new developments are decided. Most of this is reported on an annual basis from the industry and is a part of the national budget reporting. In addition, the geological data reported to NPD is used in making their prognosis regarding the undiscovered resources and as a planning tool for future exploration activities. Figure 2 shows the classification system of petroleum resources used for the resource account on the Norwegian continental shelf.

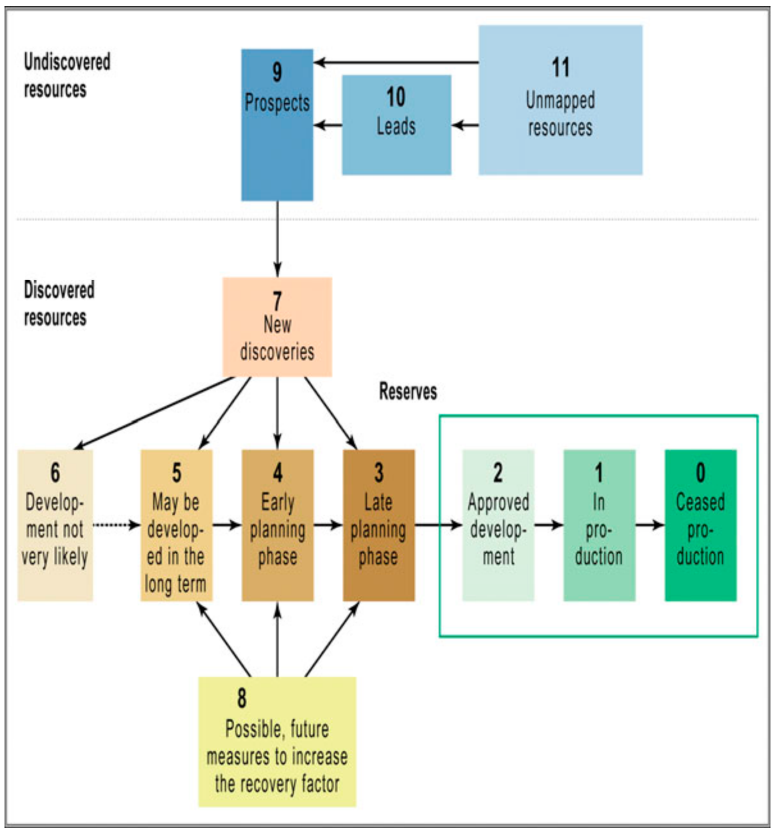

Figure 2. Classification of petroleum resources on the Norwegian continental shelf

NOTES AND REFERENCES

This paper is based on presentations made by NPD staff on licensing policy and data management. Most of this is not published but some of the material presented can be found on the NPD Internet homepage. More information regarding the activities on the Norwegian shelf and related topics can be found on the following Internet homepage addresses:

The Ministry of Oil and Energy: http://www.oed.dep.no
The Norwegian Petroleum Directorate: http://www.npd.no
Publications
The Ministry of Oil and Energy (2000), Fact Sheet 1999
The Norwegian Petroleum Directorate (2000), Annual report 1999
The Norwegian Petroleum Directorate (1999), Petroleum resources on the Norwegian continental shelf 1999.

The Norwegian Petroleum Directorate (1997), Classification of petroleum resources on the Norwegian continental shelf.

SUMMARY OF THE PRESENTATION ON THE STATUS OF DATA AND REPORTING REQUIREMENTS OF NORWAY'S OFFSHORE LICENSING POLICY AS IT RELATES TO PETROLEUM EXPLOITATION.

Dr. Bente Nyland of the Resource Management Department in the Norwegian Petroleum Directorate, Stavanger, Norway, presented her paper entitled " Status report on the data and information requirements of Norway's offshore policy as it relates to petroleum activities". She thanked the International Seabed Authority for the opportunity to participate in the workshop, stating that as a trained Geologist it had been interesting to hear about all the geological research that was taking place on the deep seabed.

Dr. Nyland informed participants that her presentation would consist of several interrelated topics. She said that she would start with a short introduction to the history of the Norwegian continental shelf, to show how over a period of thirty years her little country had been transformed into the second largest oil exporter in the world. She said that this would be followed with an introduction to the role of the Government of Norway, through its National Petroleum Directorate, in the development of offshore oil and gas. She informed participants that she would provide them with a resume of the legislative framework for offshore oil and gas in Norway, and an overview of Norway's the licensing policy. She stated that since Norway's data management philosophy is integral to its licensing policy, she would speak about the cooperative approach taken by Governmental authorities and industry in data management. She said that her presentation would be concluded with a description of the resource classification system used by Norwegian authorities.

With a map of Norway, including its offshore areas, Dr. Nyland pointed out the Norwegian continental shelf, and said that the Norwegian mainland consists of basement rocks with no petroleum activity and with no potential for petroleum, except for the Svalbard peninsula. She said that the Svalbard peninsula is treated differently from offshore basins.

Dr. Nyland pointed out the offshore sedimentary basins of Norway and informed participants that the Norwegian offshore area is divided into two areas: those open for exploration and those that are closed for this purpose. She said that about sixty per cent of the Norwegian area is open for exploration. She said that the forty per cent that is not open is because of environmental issues. In the northern part of the Barents Sea, Dr. Nyland told participants that the reason for not including this area is the important fisheries and fishing activities that take place there. She pointed out that in the southern part of the Norwegian offshore, the area is closed to accommodate the recreational activities that take place there. She said that the extreme northern part of the Barents Sea is closed to exploration activities for environmental reasons, particularly because of the ice cap, and lack of knowledge about the impact of petroleum activities on it. She said that the western part of the offshore area contains oceanic crust where lava masks features and makes it difficult to map sedimentary basins. She said that sedimentary basins have been identified near the Jan Mayen ridge. She said that water depth varies between 1500 and 2000 metres for most of the area and increases to 3,000 metres in other areas.

Dr Nyland said the petroleum industry in Norway started in 1958 following a major discovery of natural gas in a place called Groningen on the Netherlands shelf. This led people to believe that there might be hydrocarbons on the Norwegian continental shelf. She said that there were no maps at the time, or seismic surveys to confirm this. She said in 1968, Phillips Petroleum, an American oil company, made a proposal to the Government of Norway that it would pay a lump sum for a license covering the southern part of the Norwegian offshore. She said that happily, the Government of the time turned down the offer in order to investigate the matter.

Dr. Nyland informed participants that in 1963, Norway's sovereignty over its continental shelf was proclaimed. As a result, a new statute determined that the state owns all natural resources of the shelf, and that only the Crown is authorized to award licenses for exploration and production.

Dr. Nyland also said that agreements on dividing the North Sea in accordance with the median line principle were reached with the United Kingdom in March 1965 and with Denmark in December 1965. She said that in the Barents Sea there is still a dispute between Norway and Russia. While Norway is claiming the median line principle, Russia is claiming the sector line principle. In that area therefore, no exploration is permitted for either Norway or Russia by agreement between the two states.

Dr. Nyland said that the first offshore licensing round was announced in 1965, and the first offshore well was drilled in 1966. She said that the well was drilled in the southern part of the North Sea where every one was looking for the same analogy as the Groningen gas field. She said that the first discovery of an oil field was made in 1967, followed by the first production of oil in 1971. She said that the discovery and subsequent production was because of a mistake. She said that the effort that had been undertaken was to discover a formation like the Groningen field. She said that prior to the discovery, the 40 wells that were drilled in the same area yielded neither gas nor petroleum. She said that through an accident, someone drilled one hundred metres deeper resulting in the discovery of the Ekofisk field, which is one of the largest fields in production. She said that the field contains about 600 million cubic metres of oil, started producing in 1971, and remains one of the largest contributors to the Norwegian economy.

Dr. Nyland said that there are 46 fields in production, and that production from 10 other fields has ceased. She said that 975 exploration wells have been drilled, and 230 discoveries made. She said that a large number have not been approved for development for a variety of reasons. She said that some of the discoveries are rather small and some are a combination of gas and oil that have not been proven economically viable for development.

She said that exploration for oil on land has only taken place in the Svalbard peninsula. She reported that 20 wells have been drilled here, and that small traces of gas have been found. She informed participants that there is coal mining on the peninsula.

Dr. Nyland showed participants a map of the seafloor topography. She pointed out the Norwegian trench, which she said was a major issue in the debate on the median line principle. She said that this was because it was felt that the Norwegian continental shelf stopped at the trench since the trench is about 300 metres deep. She reported that happily all the major discoveries occur along the median line, working in Norway's favour.

Dr. Nyland said that from 16 licensing rounds, 264 licenses have been awarded, with 185 of these licenses still active. She said that the Norwegian continental shelf is divided into quadrants, and that each quadrant comprises 12 blocks covering 15 minutes of latitude and 20 minutes of longitude. She said that the typical North Sea block has an average area of between 500 to 600 square kilometres, decreasing in a northerly direction.

Dr. Nyland said that the total resource potential offshore Norway is 13.2 billion cubic metres of oil equivalent, with an almost fifty/fifty share between oil and gas. She said that most of the oil is in the North Sea (37 and 28 per cent respectively) with more gas in the Norwegian deep-sea.

With regard to production, Dr. Nyland said that oil and gas production has increased through the years. With regard to oil, Dr. Nyland said that production has peaked and presently amounts to almost 3 million barrels of oil per day, ranking Norway as the seventh largest oil producer in the world, and the second largest exporter. She said that only seven per cent of the oil produced satisfies domestic demand. She said that this is the case because Norway has a lot of water that is used to generate electricity.

In terms of natural gas production, Dr. Nyland said that this too has been increasing, and that Norway is among the ten largest producers of this commodity in the world. She also said that most of the gas is exported to Europe. She said that a large proportion of the gas produced is injected into the petroleum reservoirs to enhance oil recovery. She said that natural gas production in 1999 amounted to 227 million cubic metres of oil equivalent. She said that Norwegian forecasts are that it has seventeen years of oil production left, and ninety-three years of gas production.

She said that the tax rate consists of a 28 per cent corporate tax and a 50 per cent special petroleum tax. She said that Norway's income from oil and gas in 1999 was 5.7 billion dollars. She said that there is a royalty on production related to some of the older oil fields on the order of 8 to 60 per cent of the gross production value. She said that after the initial exploration period that can last up to ten years, the licensee has to pay an area fee that increases from 7,000 to 70,000 Norwegian kroner per square kilometre over a ten-year period. Dr. Nyland said that the exchange rate of the Kroner to the US$ is 8 to 1. She said that there is also a carbon dioxide emission fee, and a carbon dioxide emission policy. To conduct gas flaring, she said that an application must be submitted, and a fee paid for the emission. She said that Norway's income from petroleum and natural gas in 1999 was 94.2 billion kroner, and in addition, interest payments amounted to 26 million kroner. She said that the interest payments are placed in the Petroleum Foundation that now has accumulated an amount equal to 18 per cent of Norway's GNP.

With regard to roles and responsibilities within the sector, Dr. Nyland said that the two main actors were the Ministry of Petroleum and Energy that handles the petroleum policy of Norway, and the industry that conducts the business. She said that in addition there are supervisory authorities that advice the Ministries and the industry, as well as performing supervisory functions. She described the Norwegian Petroleum Directorate (NPD) as one such authority.

She said that the Norwegian Parliament determines the framework for petroleum operations in country, and that this framework has to be approved by the King of Norway. Dr. Nyland said that the Royal Ministry of Petroleum and Energy handles everything related to petroleum and natural gas, and that the Norwegian Petroleum Directorate is the technical wing of the Ministry. She said that the Royal Ministry of Local Government and Regional Development handles all matters related to safety, the working environment and health on the continental shelf. Dr. Nyland said that the primary responsibility of the Norwegian Petroleum Directorate is to exercise administrative and financial controls to ensure that the exploration for and production of petroleum and natural gas are carried out in accordance with the legislation of Norway, and its regulations, decisions, licensing terms and so on. She said that the total compliment of staff at the Norwegian Petroleum Directorate is about 350 persons, most whom are technical staff. She said that the NPD supervises all the other national authorities that work in the sector, and functions as a one-stop shop for the industry through its coordinating role.

Dr. Nyland said that the legislative structure of Norway's petroleum industry derives from about ten Acts, with only one that is directly related to petroleum. She said that there are a number of regulations related to the Act that are stipulated either by the Royal Ministry or by NPD. She also said that there are guidelines that specify what the regulations mean. She said that the law was last revised in 1996. She said that within Norway it is felt that the revision of the law should be a continuous process that reflects conditions within the industry. She said that the Act also contains provisions that deal with safety, work environment, resource management, environment and so on.

Dr. Nyland said that the Petroleum Act provides the legal basis for the licensing system, specifying the proprietary rights to sub sea petroleum resources on the Norwegian continental shelf, as well as in the Norwegian state.

Dr. Nyland said that data management is also a very important element in Norway's petroleum legislation. She said that the national view is that all data relating to geological, geophysical and reservoir characteristics, which have been obtained by national and international oil companies, are regarded as valuable national assets. She said that this view motivates all of the Norwegian authorities to formulate a data management strategy. Dr. Nyland said that in Norway it is thought that a better idea of the available data leads to exploration that is more efficient and at the same time secures the long-term national interest.

Dr. Nyland noted that the availability of high quality is a prerequisite for good decision-making. She said that it is recognized by Norwegian authorities that a large amount of data is generated during the conduct of petroleum activities.

Dr. Nyland informed participants once again that the continental shelf of Norway is divided into two. In one case, the areas are open for exploration activities by industry while other areas are not open for these activities. She said that in the closed areas, the NPD has been given exclusive responsibility on behalf of the state to undertake regional geophysical and geological investigations in order to develop a basic understanding of the geological conditions in these areas, as well as to assess their hydrocarbon potential. She said that the data acquired are packaged and sold to industry to provide all concerned with a minimum data set. Dr. Nyland said that in addition to NPD, the closed areas are open to institutions and scientists to undertake investigations under a scientific research license. She said that the license is free of charge, carries no exclusivity for research or provide its holder any rights to exploit possible natural resources. She said that a licensee is required to submit a report immediately after its research is completed informing the authorities of what has taken place, and within three years or a reasonable time to publish the data and the results of its research.

Dr. Nyland said that after an area has been opened up to industry, companies might apply for a reconnaissance license to conduct geological, geophysical, geochemical and geotechnical surveys. She said that this license in not exclusive. Dr. Nyland said that the reconnaissance license is the same as a prospecting license and that the licensee cannot conduct exploration drilling. She said that if there is a seismic expedition, the licensee has to have a representative of the Norwegian fisheries specialist on board the vessel. She said that all data collected has to be submitted to a company called PetroData within and no later than three months. She said that PetroData is the company that NPD has appointed to store all such data.

Dr. Nyland said that some of the other data, which if collected, have to be reported to NPD include gravity data and all data analysis. Dr. Nyland said that before an area can be open, there is a need for environmental impact assessment studies to investigate the impact of petroleum activities on the environment and for determine the risk of pollution to the sea or air, to ascertain the precautions that need to be taken prior to the onset of activities, and the economic and social effects of the activities in the affected region. Dr. Nyland said that by making this determination before any production licenses are issued, the licensee will know the basis for production work in that area and will not be surprised by restrictions when they become necessary.

Dr. Nyland said that the production license, which provides the licensee with exclusive exploration and production rights, is by far the most difficult license to obtain. She said that the Government after licensing rounds normally awards production licenses. Dr. Nyland informed participants that applications are invited for a certain number of blocks based on recommendations by NPD and the industry. She said that the licenses are awarded based on certain criteria. She said that following the announcement by the Government, applicants submit a geological evaluation report on the nominated area. She also said that this report forms an important basis for the evaluation of the applicant, and for settling the state's participation in the project.

Dr. Nyland said that criteria for the award of a license include, relevant technical expertise, financial capacity, an understanding of the geology of the area, experience on the Norwegian shelf and other continental shelves and previous performance, particularly in the region.

Dr. Nyland said that the license terms negotiated include the initial period, which is normally six years but which in difficult areas could be for up to ten years, the work commitment consisting of seismic data acquisition and on term and contingent well. In addition, Dr. Nyland said that the extension of the license period and partial relinquishment of areas are included in the license terms. She said that until 1985 STATOIL, which is the national petroleum company, handled the state's participation. She said that this was at a minimum fifty per cent and could rise to seventy per cent. In 1985, Dr. Nyland said that there was a split of STATOIL and the SDFI was created. She said that today STATOIL's share could be zero per cent, while the SDFI normally gets thirty per cent.

Dr. Nyland said that the drilling programme is a minimum requirement. She said that after the initial period, fifty per cent of the area has to be relinquished. After this period, Dr. Nyland said that the area fee kicks in. She said that this fee is to encourage companies to complete exploration rather than sitting on the area.

Dr. Nyland said that the release of data is also covered in the legislation. She said that the Act has also been changed so that reporting requirements apply to everyone generating information through petroleum activity. She said that the operator assumes responsibility for information when a production license is surrendered. Under the law, all material must be surrendered to the Royal Ministry of Petroleum and Energy or to anyone designated by the Ministry. She said that the Ministry has designated NPD to receive the data and information.

She said that as result, NPD has formulated a detailed routine for reporting. She said that NPD holds a seat on every licensing committee as an observer. She said that NPD gives operators permission to perform seismic surveys and drilling among other activities, and that if it is not satisfied with the information that is submitted, it can request additional reports.

With regard to data and information that are routinely reported to NPD, Dr. Nyland said that these included the application, the results of marine scientific research, production, plan for development, period of production, continuous activity progress report, information on flared gas, records and results, and fiscal terms.

Dr. Nyland said that in relation to storing facilities, NPD has an archive system, an electronic archive and a core store. She said that the archive system is where general reports, all the well data and all the geophysical data are stored. She said that the electronic archive is where geophysical, geological and administrative data are stored. She also said that the core store is where all the cores from the continental shelf and cut samples are stored. She pointed out that NPD also has a freezer where all the oil samples are stored.

She said that typically, an exploration well core is divided into five pieces. Half of the core remains with the licensee; NPD is provided with a quarter of the core, and the remaining quarter is stored for reference. With regard to cores from production wells, Dr. Nyland said that half of the core is given to NPD while the licensee keeps the remaining half.

Dr. Nyland said that the objective of data release is to increase the understanding of the Norwegian shelf with regard to efficiency in all phases of activity, and to increase safety during drilling operations. As an example, she said that if someone had problems during drilling, the information is passed on to other drillers to ensure that they are aware of the problem and are able to address it during any drilling that they might undertake.

Dr. Nyland said that information that is received by NPD that is not confidential by law is organized in a way to facilitate rapid distribution and to encourage greater use of it. She emphasized that the NPD is working very hard to establish high quality data sets and to put most of it in digital format.

In relation to the release of seismic and well data, Dr. Nyland said that under the Norwegian regulation, license data are considered confidential for two years, data not owned by a license group are considered confidential for five years, and market available data are considered confidential for ten years. She said that however, NPD may shorten or extend the period of confidentiality of market available data. In this respect, she said that sometimes NPD arranges for the pre-release of such data if it makes an area more attractive or interesting to applicants.

Dr. Nyland said that sensitive information such as data interpretation is confidential for twenty years. She said that data from relinquished areas are not considered confidential. She also said that all navigation data are considered public.

She said that a primary consideration in Norway's policy on data release is for the data to be used in a manner that the total exploration cost is reduced as much as possible and for resources to be discovered in a speedy fashion. She pointed out that drilling for petroleum on Norway's continental shelf is expensive, and that to drill a well costs about 30 to 100 million US dollars. She also pointed out that since Norway is an active player in the activities, the state would like as much as possible to reduce associated costs. She said that in Norway it is felt that release of data and sharing information is very important to achieve this objective. She emphasized that data in and of itself does not provide a competitive advantage in obtaining a production license, but that the award of a license validates the use of the data. She further pointed out that the release of data reduces the need to duplicate data, and said that Norway has areas where three different companies have acquired data without gaining any more information.

Dr. Nyland said that the role of NPD is to serve as a catalyst for standardization and cooperation, to increase data circulation, and to organize statistics and trend analysis on behalf of the authorities. Based on the large quantity of data involved in the industry, Dr. Nyland said that NPD was obliged to propose a system that could take care of the data in an efficient manner. She said that the objectives of the DISKOS database that NPD subsequently established were: to establish a common databank that ensures a minimum of duplication in stored data, and rapid and efficient data access and data trade. She said that the challenge for NPD was to reduce the physical data volume, and to get direct access to data from workstations and to perform sufficient quality control. She said that DISKOS is called the national repository and that its framework is that all data of common interest on the Norwegian continental shelf should be stored in this database. She also said that the cost of developing DISKOS has been shared by NPD and the majority of companies working on the Norwegian continental shelf.

Dr. Nyland illustrated the amount of data emanating from a single development project in Norway. These data consisted of 30,000 drawings, 300,000 documents, and about 5 million sheets of paper. Referring to this quantity as representing the documentation on the project, she said that in addition, there were also seismic and well data. She informed participants that since NPD started collecting seismic data in 1962, about 4.3 million line kilometres of such data have been acquired. She said that since 1999, the use of 3-D seismic has become the sole method used for mapping discoveries and fields, and is the prominent method for exploration.

Dr. Nyland described the data flow relating to DISKOS. She said that data are digitally reported to the database by licensees, and from the database, companies and partner customers of NPD can then retrieve what they require as per procedures. She said that NPD uses the database to store data reported from companies, for its own use, and for the release of the public data.
Dr Nyland said that the software used to develop DISKOS is PetroBank, which was developed by IBM.

Dr. Nyland said that a study to determine the value of the DISKOS project concluded that it had a number of cost benefits. She said that this study noted that the time required to access 2D data is reduced from weeks to hours, and that the value added was approximately thirty to forty million kroner per year per company.

Dr. Nyland said that another useful type of information is resource classification. She said that it is important for the Norwegian authorities to have an overview of the total resources in an area. She said that the purpose of resource assessments and a resource classification system is obtaining the most reliable estimate of the resources of a nation, in order to establish strategies for exploration and production. She said that by having these types of information, the authorities would benefit by knowing certain critical factors. For petroleum resources, Dr. Nyland said that these are the total resources expected, the ratio between oil and gas in an area, the distribution of resources, and the timing of when these resources would become available. She said that one of the tasks of NPD is to keep an overall account of the resources at any time, which forms the basis for planning activities on the continental shelf. She said that these accounts are reported as part of Norway's national budget since petroleum is very important for Norway's economy.

She said that a resource classification would differ between the landowner and the companies. She said that companies would work off the economic principle to determine what resources can be classified as reserves, while the nation would work towards moving all resources to the category of reserves.

Dr. Nyland said that the classification system comprises eleven different classes, including undiscovered resources, discovered resources and reserves. She said that under the category undiscovered resources, sub–categories include unmapped resources, leads and prospects. Dr. Nyland said that unmapped resources are determined through geostatistical methods, and those resources that are considered, as leads are better known than unmapped resources. Dr. Nyland described prospects as mapped resources, either by a licensee in a licensed area or by NPD in other areas. She said that when a discovery is made from a prospect, it is included under the category new discoveries, and depending on the type of oil that it contains, the size of the deposit, the discovery could be moved into another class. As an example, she said that a deposit in class six is one whose development is unlikely. She said that other classes are "may be developed in the long-term", "discovery in the early planning phase" and "discovery that is in the late planning phase". Dr. Nyland informed participants that the plan for development and operation (PDO) is normally prepared during the late planning phase. She also said that at this stage, since a certain quantity of oil has been earmarked for production, reserves are established. She said that following approval of the PDO, the deposit is then worked to produce the oil. Dr. Nyland pointed out that even after production stops in a field, there are still resources and reserves of petroleum in it. Dr. Nyland said that NPD continuously works at improving oil recovery in fields on the shelf. She said that it has a goal of ensuring fifty and seventy per cent recovery in oil and gas fields respectively, depending on reservoir quality. She said that currently recovery in oil fields is about forty-five per cent.

Dr. Nyland said that the current challenges for Norway are to maintain a high production level through finding new resources, and increasing exploration efficiency, to develop small discoveries, to increase the recovery rate, and to ensure that the marine environment is protected from offshore oil and gas production.

In her concluding remarks, Dr. Nyland said that she had tried to convey three messages to participants, which she said could be applied to resources other than petroleum. She said that the first of these was the need for a close connection between the legislative framework, the licensing policy and data management. She said that the second message was the need to establish a trustworthy relationship between the national authorities and the industry concerned. In this regard, she pointed out that the system that has been implemented in Norway is based on trust. She said that the Norwegian authorities have had no reason to believe that any company is trying to cheat the state. Thirdly, Dr. Nyland emphasized that data is very important to the landowner for an understanding of the geology and the resource potential in an area, and the value of what is present. In this regard, she also said that the landowner has to be directly involved in the activities that are taking place. Finally, she said that it is important that if resources are found and proven economically viable, the industry is there to produce these resources. She pointed out that there would always be complaints from industry about the level of taxation and the framework within which it is to operate. She said that it is important for the authorities to listen to what the industry has to say because of the need to ensure that conditions are acceptable to both parties. She further pointed out that even though Norway's taxation of seventy-eight per cent is among the highest in the world, all the major oil companies are working on Norway's continental shelf. She stated that this means that the business is good or acceptable to them even at these taxation rates. She once again emphasized the benefits of Norway's data sharing principle, in particular its role in attracting business, promoting cost efficient exploration, and building on acquired data and information. She pointed out that in comparison with the UK that has the same resource growth as Norway, in the absence of information sharing, it has taken much more time to achieve this level of growth.

SUMMARY OF THE DISCUSSIONS FOLLOWING DR. NYLAND'S PRESENTATION ON THE STATUS OF DATA AND REPORTING REQUIREMENTS UNDER NORWAY'S OFFSHORE POLICY FOR PETROLEUM RESOURCES.

The discussions following Dr. Nyland's presentation focussed on Norway's data release and sharing policies, the role of STATOIL in Norway, and how the Norwegian Petroleum Directorate (NPD) is involved in the protection of the marine environment from petroleum exploration and production.

One participant recalled that in connection with Norway's data release policy, Dr. Nyland had said that data not owned under a license is confidential for five years. This participant wanted to know who owned this data. Dr. Nyland responded that under a reconnaissance license as well as an exclusive license to gather seismic data for a company, data may be held for five years. She said that if a company acquires seismic data on a non-exclusive basis for sale to companies in the industry, then the data may be held for ten years. This is to protect the business of the seismic companies. Dr. Nyland was asked for how long an exploration license is awarded. She said that the duration of an exploration or reconnaissance license is one year and that the license is awarded for a specific study. She said that the data acquired in the course of the study might be held for five years. She said that under a production license, two years after a well has been drilled, the associated data has to be released. In response to a question on what happens to the data when an area is relinquished, Dr. Nyland responded that data on that area immediately becomes public.

Another participant observed that the role of STATOIL seems to have changed. This participant asked Dr. Nyland to provide some information on the drivers behind that change. Dr. Nyland said that STATOIL and NPD were both created in 1972. She said in the case of STATOIL, the objective of the Kingdom of Norway was to have a state-owned oil company to participate in petroleum activities. In the case of NPD, Dr. Nyland said that the Kingdom decided to create a regulatory body that was not involved in petroleum development activities. She also said that they were designed in such a way that the relationship between them was as with other oil companies on the Norwegian shelf. She said that from its formation, and to assist it to grow, STATOIL was given a fifty per cent share in all blocks. Additionally under Norway's petroleum legislation, oil companies were required to train STATOIL staff. Dr. Nyland said that during this period, STATOIL also handled the state's direct financial interest in other petroleum activities, including the economic and financial sides of SDFI. Under the circumstances, Dr. Nyland said that the costs of STATOIL were carried, because the license paid for its interest. Dr. Nyland also said that over the years, STATOIL grew and as it became more competitive, the legislation created for it started to cause problems. She said that in 1985, the issue of what constituted the state's direct share and STATOIL's share in a license became very confusing. The state therefore decided to separate the shares by fixing its direct interest and making STATOIL's share more transparent.

The same participant recalled that Dr. Nyland had said that for data sharing, trust between the regulator and the companies was an absolute necessity. This participant asked Dr. Nyland how Norway had been able to achieve this. In response, Dr. Nyland said that the Norwegian authorities had worked very closely with the companies. She said that from the beginning for example, the framework conditions and regulations were sent to industry members for their evaluation. On the part of the industry, Dr. Nyland said that it established a coordinating body to deal with the authorities. Dr Nyland said that during the concession round, the Norwegian authorities concentrated on the use of the data, and convincing those concerned that their data were not being shared with other companies but were only for the use of the authorities. She said that presently, the industry is eager to provide data as well as to discuss their interpretation and evaluation of their data. She commented that the large, technical staff members of NPD helps in this process because it is as qualified as their counterparts in industry are. One participant suggested that the model utilized by NPD would be useful not only for the International Seabed Authority but also for other nations trying to develop such an industry. Dr. Nyland pointed out that a number of countries have expressed interest in Norway's approach. She said that interest has been shown in the data management side as well as in the licensing policy. She said that NPD has collaborations with the United States Bureau of Mines, Australia, India, Namibia, Tanzania, Mozambique, South Africa, Angola, Mexico, Brazil and Venezuela.

Dr. Nyland was asked if NPD had an administrative role in environmental management. Dr. Nyland said that NPD coordinates the inputs of the national pollution agency as well as those of the Department of Environment. She said that in this regard NPD is to try to ensure that the environment is fully protected during offshore petroleum development. She said that for example if flaring is to occur, or substances discharged into the sea, it is reported to NPD, which in turn directs the request to the concerned environmental agency.

CHAPTER 20

STATUS REPORT ON THE DATA AND REPORTING REQUIREMENTS OF BRAZIL'S OFFSHORE MINING POLICY AS IT RELATES TO PROSPECTING AND EXPLORATION

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This paper presents a brief summary on the occurrence of mineral resources offshore Brazil, the country's experience with exploration and production of oil and natural gas – the only relevant mining activity on the seabed, and a panorama of the legal framework regulating the industry.

Brazilian offshore mining activities, up to now, are restricted to the exploration for and production of oil and natural gas. Some other minerals have been prospected or even produced, but this activity has been limited and has not been of economic significance. Before discussing the oil and natural gas offshore industry, a brief description of the other offshore minerals will be presented.

1. Mineral Resources to be found offshore Brazil

In several countries, such as Denmark, France and Canada, for instance, offshore sand and gravel supplies are added to onshore supplies to meet the demand for this resource. Japan is the main producer of offshore sand and gravel with 35 % of its needs coming from offshore sources. Offshore sand and gravel are the most important superficial sedimentary deposits, economically speaking, and the easiest ones to exploit among the mineral resources existing offshore Brazil. Since they are low-unitary-value minerals, transportation is a significant portion of its final cost; hence, economic exploitation is restricted to areas close to shore. Thus, sand and gravel do not have significance in this study. Additionally, there are no regulations governing its exploration and mining.

Similar to sand and gravel, limestone is also a relatively low-unitary-value mineral whose transportation cost is significant, although not as important as in the case of the former. Nowadays, national limestone demand is supplied by onshore production, but, in the medium term, exploitation of offshore resources is anticipated. Offshore Brazil is considered the longest and most continuous carbonaceous environment in the world, extending from the Pará River in the north of the country (5° S). It is relatively narrow, shallow, at warm (25 to 39°C), high salinity (30 % to 38 %) waters. Its width varies from 8 km, in front of Salvador, to 113 km, in the northeast of the country. For the purposes of the workshop, limestone does not have significance in this study.

Phosphate, a sedimentary mineral whose main component is a variety of apatite called flourapatite carbonate, often occurs as nodules. Offshore phosphates supply, presently, 70 to 80 % of the world demand, and are the biggest known resources in the world. In general, the phosphate content of Brazilian offshore sediments is very low. Known deposits are considered economically insignificant, and the industrial utilisation of this resource is minimal, compounded by the water depths at which deposits occur and the lack of technology. The production of sub-sea phosphates is not foreseen for the next few decades, in Brazil.

Sub-sea placers are exploited around the world. The main examples are cassiterite in Southeast Asia and diamonds in Namibia. In Brazil, some heavy metals occur along the coast from Pará, in the north of the country, up to Rio Grande do Sul, in the extreme south. Offshore mining activity is restricted to coastal deposits.

Polymetallic nodules, or manganese nodules, generally occur at ultra deep waters, around 4,000 meters of water depth, in oceanic basins In Brazil, there is only one record of polymetallic nodules off the northeast coast, at a depth of 2,200 meters.

Polymetallic sulphides were only found onshore two decades ago. In 1977, the first offshore discovery occurred next to the Galapagos Islands. Generally, the known deposits are found on meso-oceanic mountain ranges, at about 2,500 meters of water depth. In Brazil, the only place where polymetallic sulphides may occur is at the meso-oceanic mountain ridge close to the St. Peter and St. Paul rocks.

All the above-mentioned minerals occur at the surface of the sea bottom. Among sub-surface mineral resources, one may state that evaporite, sulphur, and coal are the main ones.

The Brazilian marginal evaporite basin, which consists of deposits of anhydrite, gypsite, and sodium, potassium, and magnesium salts, extends from São Paulo, in the southeast, to the Alagoas Basin, in the northeast. Its largest extension is at the southern end, opposite Santos, in São Paulo State, where it is 650 km wide. These deposits however are relatively small and are not considered large enough to be exploited economically.

Sulphur has been produced as a by-product of natural gas, of petroleum refining, of pyrite processing and metal smelting. Brazil does not produce primary sulphur. The country imports approximately 80 % of its consumption. Thus, for trade balance and balance of payments, sulphur is an important issue. Under such conditions, considering the Brazilian dependence on imported sulphur and favourable geologic reality, this is a key mineral for offshore exploration. On the other hand, there is a world tendency to decrease the production of mined sulphur, and to increase the production of sulphur as a by-product. Furthermore, due to the globalisation of the economy, the trend is to drive imported sulphur more competitive than national primary production. So, offshore sulphur exploration has not properly been evaluated.

In some countries, such as England and Canada, there is coal mining from offshore resources. In Brazil, coal is found in the Rio Bonito formation, in the Paraná basin. Nevertheless, due to the amount of land-based coal reserves (more than 20 billion tons) and to the difficult circumstances of the national coal industry that arises through competition from high-quality, relatively-cheap imported coal, sub-sea coal resources it is not foreseen good perspectives for the economic utilisation of possible sub-sea coal reservoirs.

2. Petroleum and Natural Gas

Undoubtedly, petroleum and natural gas are the most significant minerals that are obtained from the offshore in Brazil. The country is widely known as the number one offshore petroleum and natural gas producer in the world. The technology used for exploration and production is state-of-the-art.

In terms of the history of its oil industry, Brazil saw as milestones the first oil strike in Lobato, in Bahia state, in 1939, the creation of Petrobrás, in 1953, the first offshore production, in the coast of the state of Sergipe, in 1968, the first discovery in Campos basin, Garoupa field, in 1974, the installation of the first offshore early production system off the Brazilian coast, in 1977, also in Campos basin, and the first deepwater discovery, the Marlin field, in 1985.

Since 1953, there is a state monopoly on the activities related to the petroleum and natural gas in Brazil. Petrobrás – Petróleo Brasileiro S.A. was created in order to undertake the activities of the monopoly. Because of that, talking about petroleum and natural gas, in Brazil, means talking about Petrobrás.

Petrobrás, according to the December 20th, 1999 edition of Petroleum Intelligence Weekly, is classified as the 14th Petroleum Company in the world. If one takes into account only public companies, its rank increases to the sixth place. The Company holds the concession for the fourth largest reserve of oil equivalent among public companies. Oil equivalent represents the sum of the oil plus the equivalent to oil in terms of the energy contained in natural gas. Petrobrás is ranked only behind Shell, Exxon, and BP. The Company is the fifth biggest oil producer, among public oil companies, and occupies the same rank in refining capacity.

Undoubtedly, Petrobrás is a leader in offshore operations, and, it is also the leader in technology for deep-water operations. In fact, this position is a natural consequence of its exploration success in offshore areas (mainly in the Campos Basin and offshore Rio de Janeiro State). Because of this success, Brazilian hydrocarbon reserves have significantly increased, especially in deep waters. Total reserves are presently estimated to be 17.27 billion barrels of oil equivalent, with 12.98 billion barrels of oil equivalent in deep waters.

While the total reserves of oil equivalent add up to 17.27 billion barrels, 9.52 billion barrels are proved, that is, there are no doubts about their existence or about the possibility of their being produced. More than 50 per cent of the total lies in deep and ultra deep waters. Deep waters are taken to be water depths between 400 and 1,000 metres and ultra deep waters are water depths deeper than 1,000 metres.

If one only considers liquid hydrocarbons reserves, that is, oil and condensate, the figures go to 14.32 billion barrels, 8.08 billions of which are proved. Approximately, 82 % of these reserves are found in deep and ultra deep waters.

Natural gas reserves amount to 468 billion cubic meters (16.53 trillion cubic feet), almost half of which are proved. Different from oil, the reserves of which are located mainly offshore, almost half of the natural gas reserves are found onshore. This makes it easier to produce that gas.

Natural gas reserves may have two origins: gas associated with oil, and non-associated gas. The larger associated gas reserves are found in the Campos Basin, and offshore Rio de Janeiro State, where the Roncador field deserves a special mention since it contains the largest natural gas reserves in Brazil. With reference to non-associated natural gas, the Solimões Basin, in the Amazonas State (onshore), is the basin with the largest reserves. Leste do Urucu field and Rio Urucu field, both in the petroleum province of Urucu, contain the two largest onshore gas reserves.

Considering the evolution of the oil and natural gas production, it may be viewed that the significant increase that occurred recently is a direct consequence of the production from the new fields, especially from Campos Basin giant fields.

Last April, Petrobrás' average oil production was 1 million and 203 thousand barrels per day, 79.1 % of which came from offshore fields. It is widely known that Rio de Janeiro State is the main producer, followed by Rio Grande do Norte State, the main onshore producer.

Natural gas production, as of last April, reached 35.5 million cubic metres per day (382 million cubic feet per day), being offshore fields responsible for 59.5 % of the total. Similarly to the oil, Rio de Janeiro State is also the main natural gas producer, chiefly associated gas. The main onshore gas producer is the Amazonas State.

Geologists foresee that Brazil has a great potential for new discoveries of oil and natural gas. Deep and ultra deep waters shall contain 60 % of this potential.

Campos Basin occupies a relevant position relatively to the geologic potential of the country because of the fact that 60 % of it shall be in deep and ultra deep waters. But if one separates the potential according to the type of fluid, different tendencies will be seen. While the liquid (oil and condensate) shall be discovered mainly in Campos Basin, the natural gas of the future shall come from other basins.

Due to present forecasts, exploratory activities face several challenges. Regarding technology, they require the intense use of 3D seismic survey and the drilling of special wells. Until recently, investments in exploration were directed for the search of oil. Nowadays, because of the new guidelines to increase the share of natural gas in the Brazilian energy matrix, the search for non-associated natural gas in already explored plays has begun, both onshore and offshore. Associated gas is going to be searched in deep waters in other basins than Campos, and in ultra deep waters, chiefly in Campos Basin. As a policy of Petrobrás for the new scenario of the petroleum industry in Brazil, many exploration projects will be implemented in partnerships with companies that bring value to them.

3. Framework for Brazil's Regulations

The new legislation of the Brazilian petroleum and natural gas sectors, which reached its inaugural landmark with the Constitutional Amendment number 9, dated November 9, 1995, was introduced into the national juridical arrangement with the objective of consolidating, within the activities it deals with, the modernisation of the Brazilian State. Such modernisation aims at qualifying the Brazilian society to quickly make use of the world technological, economical and social advances, thus, improving the quality of life of the Brazilian people. Therefore, we avoid the domestic isolation in a world where the barriers among the nations are gradually being fragmented and where there is a disorder between the progress of Brazil and the one of the develop countries.

As far as the Government is concerned, such goal will be reached by means the opening of the economy, which will allow the attraction of capital for the development via incentives to the private sector. Such modernisation is needed to increase the competitiveness of the Brazilian economy in the international market and to foster a decrease in the size of the state.

Although it is new, the legislation of the oil sector is very broad, since it is made up by an impressive number of regulations issued by the regulatory agency, the National Petroleum Agency (ANP - Agência Nacional de Petróleo). The basic law of this particular industrial segment is Law number 9,478, dated August 6, 1997, popularly known as "the law of the petroleum", which disposes on the country energy policy and on the activities related to the state oil monopoly, with the creation of the National Council of Energy Policy and the National Petroleum Agency, and takes other measures. The ANP was established by a presidential decree on January 14, 1998 (Presidential Decree number 2,445) as an autarchy under a special regimen, which also approved its regimental structure and the demonstrative picture of temporarily assigned positions as well as functions of trust.

Once established, as expected, ANP began an intense regulatory activity, reason why it was created in the first place. Thus, following is a list of the most relevant items produced by ANP:

- Ordinance number 80, of May 28, 1998, which establishes the term for the companies that owes equipment and facilities for the transportation of petroleum, natural gas and their by-products through pipelines or by vessels to send required information;

- Presidential Decree number 2,705, of August 3, 1998, which gives the basic technical definitions to be used in all regulations regarding petroleum taxation to be followed by ANP. This includes the signature bonus, royalties, special participation fees and rentals;

- Ordinance number 155, of October 21, 1998, which establishes the method to be used to calculate petroleum reference prices;

- Ordinance number 169, of November 26, 1998, which regulates the use of gas pipelines by companies other than the owner ("transport rights"). The owner communicates to the ANP its "available capacity" (maximum capacity less gas supply contracts). Within this available capacity, the owner is obliged to permit the transport of gas of other operators, at "market prices". ANP will determine tariff if the owner of the pipeline and the company requiring to use it can not agree;

- Ordinance number 170, of November 26, 1998, which establishes that all new oil and gas operations need to be authorised by the ANP;

- Ordinance number 188, of December 18, 1998, which regulates the activities of petroleum prospecting companies. Surveys are subject only to ANP authorisation. The data acquired can be freely used by the spec company;

- Ordinance number 200, of December 23, 1998, which establishes, for those who hold concession, authorisation, and register to exert activities related to the petroleum industry and to supply fuels in the country, the obligation to adequate their computer systems and electronic devices, aiming at avoiding the millennium bug, in order to guarantee the correct performance of the facilities and the supply of petroleum, natural gas, their by-products and fuel alcohol;

- Ordinance number 10, of January 13, 1999, which establishes the procedures for the calculation of the special participation established by article 50 of Law number 9,478. The deductions and depreciation allowed in the calculation of the net revenue are detailed;

- Ordinance number 174, October 25, 1999, which approves the regulation about the procedures to be adopted in for exploration and production Concession Agreements;

- Ordinance number 176, of October 27, 1999, which approves the Regulation about well abandonment procedures;

- Ordinance number 195, of December 24, 1999, which establishes the criteria to be adopted from January 1, 2000 on, in order to distribute the 7.5 % share of the quota of the royalties to be paid due to the production of petroleum or natural gas that exceeds 5 % of such production, to those municipal districts affected by the embarkment or disembarkation of petroleum or natural gas;

- Ordinance number 14, of February 1, 2000, which establishes the procedures for operational accidents and accidental pollutants spill reporting, to be followed by the concessionaires and other companies authorized to conduct activities related to oil and gas exploration and production;

- Ordinance number 40, of March 1, 2000, which establishes the rules for the activity of the domestic transport of petroleum and its by-products by sea;

- Ordinance number 75, of May 3, 2000, which approves the Regulation that deal with the procedure for the Codification of Wells drilled for the exploration or the production of petroleum and/or natural gas; and

- Ordinance number 76, of May 3, 2000, which approves the Regulation that deal with the procedures for the Reclassification of Wells drilled for the exploration or production of petroleum and/or natural gas.

Besides the legal diplomas and a broad scale of regulations setting the activities, the concession contracts also impose a series of obligations to the concessionaires. Thus, restricting ourselves only to the major responsibilities conceived at the concession contracts for exploration, development and production of petroleum and natural gas, during the production stage, we can mention the following obligations:

- To notify the starting date of production until 24 hours after it occurs;

- To prepare a monthly production bulletin, until the 15th day of the month, pointing out the reasons for deviations bigger than 15 % in relation to the estimated output;

- To notify any problem that may avoid the measurement of the production;

- To previously notify the drilling of wells;

- To notify about the progress and the results of the works;

- To notify any oil spill incident or any loss of natural gas;
- To pay the participation fee accordingly and within the established deadlines;

- To previously notify the end of the production phase due to economic reasons;

- To present annually proofs of bookkeeping, inventory of assets and equipment, list of hired services, etc.;

- To prepare an annual work plan and budget by October 31 of the previous year; and

- To prepare an annual production plan by October 31 of the previous year.

Regarding tributary matters, the new oil and natural gas legislation has introduced innovations. Specific taxes were either created or altered for the sector, such as the tax for the retention of areas, the taxation over the royalties, the special participation and the participation of landowners. These takes were conceived at Section VI, Chapter V of the "petroleum law".

The tax for the retention of areas or the payment for the occupation or retention of the area, which is its legal denomination, is inserted in the list of Governmental takes as mentioned in article 45 of the petroleum law, and is specified in article 51 of the same legal text. The criteria for the calculation and the collection of the tax area are determined in accordance to article 28 of the Presidential Decree number 2,705, of August 3, 1998.

This tax must be paid up to January 15 of the year that follows the one of the owed amount, according to what was verified.

The values to be paid are calculated in accordance to the phase of the work (exploration, development, or production), taking into consideration the geological characteristics, the location of the sedimentary basin where the concession is situated, and other aspects. The tax varies between R$ 10,00 and R$ 5.000,00 (approximately US$ 5.00 to US$ 2,500.00) per square kilometre.

The royalties derive from articles 47 and 49 of the petroleum law. The criteria for their calculation and collection are determined in article 11 and in the aforementioned Presidential Decree number 2,705. The incidence of royalties varies between 5 % and 10 % over the total volume of the oil and natural gas production multiplied by the reference price, with the exact fee being set by each concession contract.

The definition of the total volume of production appears in clause XI of article 3 of the Presidential Decree number 2,705/98. In general terms, one may say the total volume of production is equivalent to the overall output, deducting the volume of natural gas re-injected in the reservoir as well as the volume of natural gas whose burning is authorised by ANP.

Payment of royalties must occur every month, until the last working day of the month that follows the one whose production is under consideration.

Another example of Governmental take on the withdrawal of the oil and natural gas industry is the special participation, which is supported on article 45 of the petroleum law, and specified in article 50 of the same law. The long chapter VII of the Presidential Decree number 2,705/98 sets the criteria for calculation and collection of the tax, whilst ANP Ordinance number 10/99 introduces a formula for its verification. The verification must be carried out every three months, in line with each three-month period of the calendar year, with payment due until the last working day of the month that follows the one of the verification.

Article 22 of the Presidential Decree number 2,705/98 presents a series of tables with progressive indexes to be applied over the net revenue of the production in the three-month period. These ones vary according to the location of the concession (onshore, offshore up to 400 metres of water depth, and offshore at waters deeper than 400 metres), and to the production time of the concession.

The net revenue of the production over the three-month period must be verified to each field, one by one, taking into account the production of oil equivalent to the three-month period. Calculation of the net revenue of the production in the three-month period starts from the gross revenue, of which deductions are made as estimated in chapter IV of ANP Ordinance number 10/99, and including the addictions described in chapter VII of the same regulation.

In the beginning of the production of an oil field, there may be exemption of the payment of the special participation. The limits for exemption, as established by the Presidential Decree number 2,705/98, decrease from the start of the first year of production until the fourth year following the start.

The first concession contracts were signed on August 6, 1998. In their majority, these contracts referred to producing fields. In order to deal with them, ANP Ordinance number 10/99 has a specific chapter – Chapter VIII – that defines the type of appropriation of previous expenses.

A fourth kind of payment, which does not apply to offshore activities and that is similar to the taxes, is the participation to be paid to landowners, conceived in article 52 of the petroleum law. Such non-Governmental participation is regulated by ANP Ordinance number 143/98. It is paid following a taxation that varies from 0.5 % to 1 % over the production of oil and natural gas, taking into consideration a calculation basis similar to the one that is applied to royalties.

The beneficiary is the landowner in whose land the wellhead is located. The volume of natural gas that is re-injected into the reservoir and the one whose burning is authorised by ANP are proportionally divided amongst the wells, in accordance to the output of natural gas of each well.

A specific contract between the landowner and the concessionaire must be signed, with a copy for ANP, so that payment may begin. Such payment must come through until the last day of the second month following the one of the production. ANP must receive, until 30 days following the payment, a document proving that the payment was actually made.

All payments to be made by the concessionaires shall be calculated based on reference prices, as set by the Presidential Decree number 2,705/98. For the oil, it will be the highest value between the sale price actually practised by the concessionaire and a price set by ANP, for each current flow, based on Brent oil price, more or less a differential that is established according to the oil refining profile. Whilst the concessionaire must notify ANP, until the 15th day of the following month, the volume of oil sold and the respective sales price, ANP will publish monthly in the Union Official Journal the prices set for each field. The highest between the two figures will be the reference to calculate the payments to be done by the concessionaire.

For natural gas, reference price is equivalent to the average sale price practised by the concessionaire, free of taxes, deducting transportation costs. However, transportation costs may only be deducted if the gas sale contract contains such a specific clause.

Regularly published ANP regulations set the reference prices both for the petroleum and for natural gas.

As stated before, there are several rules in the regulations and in the concession contract concerning environmental matters. But, in Brazil, the Conama – Conselho Nacional do Meio Ambiente (National Council on Environment) has its specific resolutions dealing with environment protection. One resolution deserves special attention for those who work in the petroleum and natural gas industry: Conama Ordinance number 23, of December 7, 1994.

This resolution establishes specific criteria on the licensing of activities related to drilling and production of oil and natural gas. It also determines that all activities must be licensed by Ibama (the federal agency to deal with environmental matters) or by the correspondent state environmental agency, depending upon the scope of each one.

Brazilian authority requirements regarding environmental issues tend to be tighter and tighter since this matter is a major concern nowadays.

4. Requirements for Prospecting and Exploring Offshore Brazil

Several requirements must be accomplished by prospecting or exploring companies to be authorised to operate in Brazilian waters. ANP, as already mentioned, is the proper authority to give such operation authorisation.

In the case of data acquisition, which is dealt by Ordinance number 188 of 1998, the authorisation is intuito personae, that is, for the specific company that requested it. The authorisation cannot be negotiated with any other company, unless ANP previously and explicitly agrees to that. Otherwise, more than one company may be authorised to prospect at the same area.

Concessionaires do not need to require authorisation for data acquisition at its own concession, but they must register all the operations. A series of information shall be presented to ANP until 20 days before the beginning of the work.

The prospecting company must present information on the company itself, such as legal constituent documents, proofs of technical and operational capability, previous experience etc. Additionally, it has to apply information on the proposed acquisitions like what will be prospected, where it will occur, a detailed schedule of the works, a summary of geologic information of the area, and the reasons for the data acquisition is interesting for exploration and production of petroleum and natural gas, besides other usual or relevant information. If any of this information is altered or updated, the company must present the new one in a 30-day period to ANP.

ANP may send a representative to follow the operations on the expenses of the prospecting company.

The data are non-exclusive of the authorised company. The company is obliged to sell the data to any interested company, as soon as to inform the identity of any buyer of such data in a 30-day period after the sale.

The company must send monthly reports on the operations to ANP, and, if there is any delay on the initial schedule, it must be justified. All the reports and any other document relating to the data must be freely yielded to ANP within 60 days after the closing of the works.

If an authorised company defaulted on a previous authorisation, it will not receive a new authorisation, unless ANP accepts the company justification.

Concessionaires must acquire exclusive data. Such data are not marketable, but they can be changed by other company's data. ANP shall receive, free of charge, these data within a 60-day period.

Both exclusive and non-exclusive data have a confidentiality period varying from two to tem years, depending on the sort of data. Only bathymetry data do not have a confidentiality period.

For a company to take part on a bid for exploration, development or production of petroleum or natural gas, it must fulfil a series of requirements that are established in Ordinance number 174 of 1999. Such a company shall receive, from ANP, qualifications under the technical, the economical and financial, and the juridical aspects, and it ought to pay the participation fees.

In order to be technically qualified, the company must prove its previous experience, or that it has employees who are experienced, in the following issues:

- Produced volume of oil equivalent;
- Onshore exploration and production operations;

- Offshore exploration and production operations;
- Deep and ultra-deep-water exploration and production operations;
- Adverse environment exploration and production operations;
- Experience in operating at environmentally sensible areas; and
- Experience in international operations.

According to the proved experience, the companies will be classified in one of the following categories: qualified to operate at any block of the bid; qualified to operate at some blocks of the bid, which will be defined by ANP; and non-operators.

Several duties and requirements are established by the concession agreement, since it is specific for the operation under consideration. But there are some general issues that are contained in every agreement.

It is clear to the concessionaire that it has not any rights over other natural resources that may exist in the concession area. The concessionaire is prohibited from using, making good use of or disposing, and under any title, totally or partially, of such resources, except when duly authorised in accordance with applicable Brazilian legislation.

The concessions have as objective the performance, by the concessionaire, of the operations specified in the work and investment program – which is annexed to each agreement – and any other additional activities of exploration that it may decide to undertake within the concession area. The exploration phase will be divided into a certain number of periods, called exploration periods. During the exploration phase, the concessionaire shall, in each exploration period, complete in its entirety the previewed minimum exploration program. If it fails to do so, ANP may draw on a stand-by letter of credit provided by the concessionaire, without prejudice to other legal and contractual remedies.

Any discovery of oil, natural gas, other hydrocarbons, minerals and, in general, any natural resources, within the concession area, shall be notified, exclusively and in writing, by the concessionaire to ANP after, in the maximum, 72 hours of the discovery. In the case of discovery of any natural resources other than oil or natural gas, it will be obliged to comply with the instructions and allow the performance of the relevant measures as determined by ANP or other competent authorities. While waiting for such instructions, the concessionaire shall refrain from taking any measures that could put at risk or in any way impair the discovered resources.

During the effective period of the concession, the concessionaire shall have the exclusive right to perform the operations in the concession area, except in the case of data acquisition, as mentioned in ANP Ordinance number 188 of 1998, for this purpose being obliged to, at its own account and risk, make all investments and bear all necessary expenses, supply all necessary equipment, machinery, personnel, service and proper technology and, to the extent required by the applicable law, assume and respond for losses and damages caused, directly or indirectly, by the operations and their performance, independently of pre-existing fault, before third parties, ANP and the Federal Government.

In the case that the concessionaire is a consortium of companies, one of them shall be designated operator. The operator will carry out and execute all operations and activities on behalf of the concessionaire and will submit all plans, programs, proposals and other communications to ANP, and will receive all responses, requests, solicitations, proposals and other communications from ANP, on behalf of the concessionaire. The operator shall be responsible for the full and timely performance of all obligations of the concessionaire with respect of any aspect of the operations. The concessionaire may nominate another operator other than the original one, provided that it can demonstrate adequate experience, qualifications and financial capacity. Such nomination is subject to prior approval by ANP.

The concessionaire shall provide ANP with prior written notice concerning the commencement of drilling any well in the concession area, giving a work program with detailed information about the expected drilling operations, as well as about the equipment and the materials to be used.

ANP, directly or through agreements with other entities, will follow-up and oversee the operations performed in the concession area with the purpose of assuring that the concessionaire is fully and rigorously complying with its obligations under the terms of the concession agreement and applicable Brazilian legislation.

The concessionaire shall keep ANP constantly informed about the progress and results of the operations, in accordance with oil industry best practice including regarding timing and format. Based on such principles and without limiting its application, the concessionaire shall always have ready for ANP disposal, in addition to other documents required in the concession agreement, copies of maps, sections and profiles, geological and geophysical data and information, including interpretations, data, wells records and test, as well as reports and other documents defined in specific regulations, which contain the necessary information for the characterisation of the work process, obtained as a result of the operations.

As long as within the limits of its attributions and competence, ANP may, upon the receipt of a written request of the concessionaire, authorise the location or construction of installations or equipment outside the concession area, in order to complement or optimise the logistics or infrastructure related to the operations.

The planning and performance of any abandonment operations, including with regard to the areas, wells, structures, fields, transfer lines, parts or units of surface and subsurface installations, in land and in the sea, shall be done in accordance with applicable Brazilian legislation and oil industry best practice, as well as in observance of the provisions related to environment protection.

The concessionaire shall adopt, at its own cost and risk, all the necessary measures for the conservation of reservoirs and other natural resources and for the protection of the air, soil and water in the surface or in the subsurface, subject to the Brazilian legislation and rules about environment and, in their absence or lack, adopting oil industry best practice with this regard. Within this principle, and without limiting its application, the concessionaire is obliged to, as a general rule, and with respect to the execution of the operations, as well as the relinquishment and abandonment of areas and removal and reversion of assets, to preserve the environment and protect the harmony of the ecosystem in the concession area, to avoid the occurrence of damage to the fauna, flora and the natural resources, to attend to the safety of persons and animals, and to repair or indemnify the damages resulting from the concessionaire's activities and to perform the environmental remediation acts determined by the competent agencies, all as required by applicable law and oil industry best practice. The concessionaire shall also take care that the operations do not cause any damages or losses that affect other economic or cultural activities in the concession area, such as exploration of renewable natural resources, mining, biological and oceanographic research, and tourism.

5. Closing Considerations

Offshore mining activity is a very recent one in Brazil. Rules and regulations related to it have just come into force, as soon as rules and regulations regarding environment protection. The legislation is very dynamic, as it uses to be when we deal with a new branch of the law. It improves day-by-day.

This paper gives a simple view, a vol d'oiseau over the legislation on petroleum and natural gas exploration and exploitation in Brazilian waters. Obviously, if one confronts such requirements to other country requirements, one may establish a more complete set of rules and regulations. Surely, Brazilian experience will help to have, as a result of this workshop, the initial framework of an international regulation for offshore mining activities.

SUMMARY OF THE PRESENTATION ON THE STATUS OF THE DATA AND REPORTING REQUIREMENTS OF BRAZIL'S OFFSHORE MINING POLICY AS IT RELATES TO PROSPECTING AND EXPLORATION.

Dr. Roberto Viera de Macedo, Adviser to the President of Petrobras S.A. of Brazil presented this paper, which he co-authored with Mr Walter Leitão of the Maritime and Environmental Law Sector of Petróleo Brasileiro S.A., and a member of the Authority's Legal and Technical Commission. Dr. Viera de Macedo informed participants that his presentation would consist of a description of the minerals that may occur offshore Brazil, the achievements of Petrobrás in offshore exploration and production of oil and gas, and conclude it with a presentation of the Brazilian legislation for the exploration and production of petroleum and natural gas.

Through slides, Dr. Viera de Macedo provided the workshop with information on the marine mineral deposits of Brazil. Dr. Viera de Macedo said that sand and gravel deposits are the main superficial sedimentary deposits in offshore Brazil. He said that because these deposits contain low unitary value commodities, and transportation costs play a significant role in the feasibility of their development, none of Brazil's coastal deposits is presently exploitable. He said that the same conditions apply to limestone deposits that are found in abundant quantities offshore Brazil. He said that current demand is met from land-based sources, and that marine mining of limestone is not expected in the near future. Dr Viera de Macedo said that offshore phosphates are often found as nodules in Brazil. He said that the phosphate content of nodules and in offshore sediments in Brazil is very low, making offshore phosphate mining uneconomic now. With regard to sub-sea placer deposits, he said that deposits of heavy metals have been found along the coast in Brazil, from Para in the north of the country to Rio Grande do Sul in the south. He also said that offshore mining activities are restricted to coastal deposits of sub-sea placers.

Dr. Viera de Macedo said that in relation to polymetallic nodules, the only chance of finding these kinds of deposits is close to the Saint Peter and Saint Paul rocks. He noted however that no such deposits have yet been found offshore Brazil. With regard to polymetallic sulphides, he said that no deposit has been found in Brazilian offshore waters. He pointed out that all these minerals are found on the seabed.

Dr. Viera de Macedo said that the Brazilian marginal evaporate basin extends from the northeast of the country in the Alagoas basin to the southeast of the country near Santos in Sao Paulo State. He said that at the southeastern end the basin is 650 kilometres wide. He also said that although the basin contains deposits of anhydrite, gypsite, and potassium, magnesium and sodium salts, a considerable amount of prospecting and exploration will be required for any of the deposits to be mined. Dr. Viera de Macedo turned his attention to sulphur. He said that Brazil does not produce primary sulphur but that sulphur for domestic consumption is imported and is produced as a by-product of pyrite processing. He said that while imports account for eighty (80) per cent of consumption, he did not foresee a change to primary production. Finally, he said that sub-sea coal deposits have been discovered in the Rio Bonito formation in the Paraná basin. He noted that the quality of Brazilian coal is not competitive with imported coal. He therefore said that he did not envision that Brazil would be mining these deposits in the near future.

Dr. Viera de Macedo said that the only meaningful marine mineral resources in Brazil are petroleum and natural gas. He said that the state owned Oil Company of Brazil, Petrobrás, is known to have achieved several milestones in the exploration for and production of offshore oil and natural gas. He said that technology for this purpose has been entirely developed in Brazil, and that this technology is among the most advanced for offshore oil and gas exploration and production. He said that the first commercial oil strike occurred in 1939 in Lobato in Bahia state. He said that in 1953, Petrobrás was created by the Brazilian Government to carry out all activities related to the oil industry in the country. These activities were the exploration, production, refining, transportation, and the commercialisation of petroleum and natural gas in Brazil. He also said that in 1968, the first offshore oilfield was discovered in the state of Sergipe at a water depth of 70 metres. Dr. Viera de Macedo said that the main petroleum province of Brazil, the Campos basin was discovered in 1974 with production starting in 1977 using the first oil production system. He said that this event was followed in 1985, by the discovery of the first deepwater oilfield, the Marlin Field.

Dr. Viera de Macedo said that when Petrobrás was created in 1953 it had a daily production of 60,000 barrels, three small refineries and a fleet of ten (10) oil tankers. In 1999, Dr. Viera said that Petrobrás had gross sales of US $2.5 billion, daily production of 1.36 million barrels of oil and 39 million cubic metres of natural gas. He said that Petrobrás has 74 fixed platforms and 27 floating platforms. He also said that the ratio between proved reserves and production is 20 years. Petrobrás has eleven (11) refineries with a total capacity of 1.8 barrels per day, and a field fleet of 64 owned vessels and 31-chartered vessels. In 1999, Dr. Viera de Macedo said that Petrobrás invested US$1.3 million in research and development. He said that according to the Petroleum Investment Weekly publication of 20 December 1999, Petrobrás is the fourteenth largest petroleum company in the world. He said that unlike most state oil companies, the Government of Brazil does not own 100 per cent of Petrobrás. He said that shares of the company are traded on the Brazilian stock exchange and on the New York Mercantile exchange. He also said that among all public companies, Petrobrás is the sixth largest in the world.

He said that in terms of proven reserves, Petrobrás ranks as the company with the fourth largest reserves in the world, trailing only Exxon, Shell and BP-Amoco. In terms of production, he said that Petrobrás is the seventh largest producer in the world.

With slides, Dr. Viera de Macedo provided participants a briefing of developments in the Campos basin. He said that the Campos basin is found in offshore areas in the Southeastern part of Brazil. He said that the basin has yielded the largest offshore fields in the country. He said that the Campos basin is 115,000 square kilometres and contains fields at water depths ranging from 30 to 3,000 metres. He said that in this area, Petrobras has 27 floating production systems (Floating, Production, Storage and Offloading tankers), and 14 fixed production platforms. He said that 79 producing fields in the basin account for 77 per cent of the national output of oil, and 47 per cent of the national output of natural gas. He said that Petrobras maintains a 3,600-kilometre network of pipelines in the basin.

Dr. Viera de Macedo said that very important oil strikes have been made in the Campos basin. He said that since 1984, 9 huge oil fields have been discovered in the basin, including the Marlin, the Roncador, the Barracuda, the South and East Marlin, and the 539. He described the latter as the largest field discovered in the Campos basin, with one well drilled so far. He said that presently, Brazil's proven oil reserves are estimated at 9.5 billion barrels of oil equivalent, with total reserves estimated at 17.3 billion barrels of oil equivalent. He also said that 40 per cent of the proven reserves are found in water depths ranging between 400 and 1,000 metres, and 31 per cent are found in water depths in excess of 1,000 metres or in ultra deep waters. He said that over 50 per cent of the total reserves of the company are found in ultra deep waters.

With a graph, Dr. Viera de Macedo explained to participants the potential for undiscovered oil and natural gas resources in Brazil. He pointed out that based on current information, it is estimated that 49 and 12 per cent of the total potential resources are in ultra deep and deep waters respectively. Based on this consideration, Dr. Viera de Macedo said that Petrobras would have to continue to develop its offshore production technology if it wished to be able to take advantage of this potential. He said that on 17 March 2000, Petrobras achieved a daily production rate of 1.26 million barrels that was made up of 55 per cent from deep-water fields, 25 per cent from water depths below 400 metres, and 20 per cent from terrestrial sources.

Dr. Viera de Macedo informed participants that because oil deposits in deep water fields in the world have different characteristics, operators in these regions have developed different approaches to exploration and production. He said that in the Campos basin, Petrobras faced challenges arising from shallow reservoirs and therefore relatively cold oil and gas in the reservoirs, and unconsolidated sandstones that caused many problems during drilling. He pointed out however that despite high currents, the environmental conditions are mild. He said that in the Campos basin Petrobras found steep slopes on the seabed where the biggest fields were found, including canyons. He also said that several coral mounds that result in difficulties in placing equipment on the seafloor were also found. He informed participants that available infrastructure that was relatively close to the fields helped the company to overcome these difficulties. He said that presently Petrobras has 5 exploration rigs in the Campos basin, and 19 rigs for production.

Due to reservoir characteristics and environmental conditions, Dr. Viera de Macedo said that Petrobras utilizes sub sea equipment and floating production units to develop its fields in deep water. He said that well development is in phases because Brazil as a developing country does not have the funds to completely develop a field in a single step. He said that as revenue is generated from a field, this applied to the completion of a phase in another field. As a result, Dr. Viera de Macedo said that Petrobras has a lower capital exposure, an early cash flow and a high level of flexibility. He said that this was achieved in partnership with Petrobras' main suppliers and some sub sea companies, without the help of any other operators.

Dr. Viera said that Petrobras has set a number of world records in well completions, including the 1997 well completion in Campos basin at a water depth of 124 metres. He also said that the company had set records in drilling depths, including in the 1982, a well at 5,600 feet water depth, in 1999, two wells below 8,000 feet, and in 2000 an exploratory well at 9,150 feet water depths. He said that deepest field in Campos basin is the Roncador field, which was started with an early production system consisting of two wells. He said that this field was developed less than ten months after discovery. He said that the two wells have been in production since January 1995, and produce more than 20,000 barrels a day. Dr. Viera de Macedo said that at Roncador, Petrobras has its deepest well completion and production. He said that the FPSO is positioned above the well, which is at a water depth of 1,877 metres. He said the production system is the only dynamically positioned FPSO in the world. Designed for 2,000 metres water depth, he said that this unique technology has made significant contributions to the world's oil industry.

Dr. Viera said that based on Petrobras' current technology, the deepest fields that can be exploited can only to be down to 2,000 metres of water depth. He said that for deeper fields, Petrobras is looking at alternatives that include using dry completion units with the wellheads on top of the units, instead of on the seabed. He said that Petrobras has discovered that a heavier type of oil, around 15 to 20 degrees API, occurs in the deeper fields.

In terms of reservoir management, he said that Petrobras realizes that improvements are required in its methods and the stimulators that it uses to enhance oil recovery. He said that new drilling technology is also required. He said that the continuity of well flow has to assured, and that Petrobras has to mitigate the presence of hydrates in their pipes. He said that new boring systems, anchor systems, risers, umbilicals and sub sea connections among other equipment have to be developed for ultra deep waters. He said that in 1993 Petrobras established a programme for technology self sufficiency named PROCAP 2000 with an objective of being able to produce oil at 2000 metre depth by the year 2000. He said that this objective was met. He said that the new objective of the company is to produce oil at water depths of 3,000 metres without waiting until the year 3000. He said that this new programme was approved by the Board of Petrobras in June 2000. He said that the new programme is to be a cooperative one, dedicated to the exploitation of deep-water exploitation systems. He said that scenarios for the application of technology for this purpose have already been identified. He said that these scenarios included work to be undertaken, inter alia, in the second phase of the development of the Roncador field that is to include drilling at 1,500 and 2,000 metres, in the second module of the development of the South and East Marlin fields, and several prospects at water depths up to 3,000 metres. He also said that the scenarios included work in deep water fields in the Gulf of Guinea and the Gulf of Mexico in fields that Petrobras had acquired with joint- venture partners for work in these geographic areas.

Dr. Viera de Macedo said that the strategy of the new programme is selectivity, focussing on the stage of technology development, funding, by linking with Governmental agencies, sharing efforts with the Brazilian technological community and through linkages with the international technological community. Dr. Viera de Macedo said that the primary goals of the programme are to provide technological solutions that make the production of oil and gas from water depths up to 3,000 metres economically viable, to reduce the capital expenditure for future field development, and to reduce the lifting costs of the currently producing fields. Dr. Viera de Macedo then showed participants a video of the Roncador field including the programme for its total development.

With regard to the legislative framework for oil and natural gas, and its reporting requirements, Dr. Viera de Macedo informed participants that from 1953 until 1995, Petrobras formally known as Petróleo Brasileiro S.A was the state organ set up to exclusively exploit the petroleum and natural gas resources of the country. In order to take advantage of technological and other advances in the global community, Dr. Viera de Macedo said that in 1995, the Government of Brazil enacted a constitutional amendment (number 9) whose objective was to modernize the country. As part of this process, Dr. Viera de Macedo said that new regulations were enacted for the petroleum and natural gas sector. He said that the basic law in this regard, popularly known as " the Petroleum Law ", or Law number 9478 was enacted on 6 August 1997. Under this law, he said that the previous regime, consisting of a state monopoly on petroleum and natural gas activities was discarded and replaced with an entity called the National Council on Energy Policy, and a National Petroleum Agency.

Dr Viera de Macedo said that the Agência Nacional de Petróleo (ANP) or the National Petroleum Agency was established by Presidential decree number 2445, on 14 January 1998, to control the development of petroleum and natural gas, and to promulgate legislation to govern the sector, including participation by other companies. He said that since Brazil did not have petroleum legislation at the time, ANP had to promulgate a series of legislation in this regard. He provided participants with some of the legislation (ordinances) that were promulgated by this body in respect of offshore petroleum exploration. These included, inter alia,

a. Ordinance number 80 that deals with equipment and facilities for the transportation of petroleum and natural gas;
b. Presidential decree number 2705 of 1998 that regulates the Government take in the oil industry;
c. Ordinance number 155 that provides criteria for use in determining petroleum reference prices;
d. Ordinance number 169 that regulates the use of gas pipelines;
e. Ordinance number 170 that establishes the ANP as the body to authorise new oil and gas operations;
f. Ordinance number 188 that regulates the activities of petroleum prospecting companies;

Ordinance number 200 that regulates the millennium bug in the industry;

g. Ordinance number 10 that regulates the special participation of the Government as part of its take;
h. Ordinance number 174 that establishes the procedures for exploration and production concession agreements;
i. Ordinance number 176 that establishes abandonment procedures;
j. Ordinance number 195 that establishes the criteria for distributing excess royalties to municipal districts;
k. Ordinance number 14 of 2000 that regulates the treatment of accidents and oil spills;
l. Ordinance number 40 of 2000 that establishes rules for the transport of petroleum and its by-products by sea;
m. Ordinance number 75 of 2000 that regulates the codification of wells, and
n. Ordinance number 76 of 2000 that regulates the reclassification of wells.

Dr. Viera de Macedo described some of the ordinances and the teething problems of implementing the petroleum law, especially from the perspective of Petrobras. These included the lack of personnel to analyse environmental impact assessment studies, and other matters including the application of Government takes etc. He said that for the purposes of the workshop, the most relevant ordinances were 188, 174, and the requirements contained in the concession agreement.

He said that ordinance number 188 of 1998 is that which regulates data acquisition. He said that the ANP, the body that authorizes prospecting and exploration in Brazilian waters, is the depositary for data and information from prospectors and concessionaires. He said that to acquire data on any area, the authorization is given to a specific company.

He said that a company that receives authorisation to prospect an area is required to provide information such as legal documents on its establishment and proof of its technical and operational capabilities. He said that the company has to indicate where prospecting will take place and the commodity that it is interested in. In addition, he said that the company has to submit a detailed schedule of the work it proposes to carry out, a summary of the geologic information and data that it has on the area, the reasons for data acquisition, and the company's previous experience. He said that prospecting is not exclusive, and that more than one company can prospect an area.

Dr. Viera de Macedo said that companies are required to send reports on their operations to ANP. He said that depending on the type of survey conducted there is confidentiality of the data submitted for periods ranging from 2 to 10 years. He however said that bathymetric data are not considered confidential.

He said that concessionaires do not need authorisation for data acquisition in their concessions.

Dr. Viera de Macedo said that ordinance number 174 of 1999 contains the requirements for companies to tender bids for blocks of offshore areas. He said that the company must provide proof of its technical, financial and legal qualifications. The company must provide proof of its experience in the work to be undertaken or of the experience of its employees in this regard. He said that companies are classified to operate any block, some blocks, or as companies eligible to participate in an operation but not as an operator.

Dr. Viera de Macedo said that the Brazilian concession agreement contains several interesting exploration provisions. He said that a concessionaire has no rights over any other minerals in the area except petroleum and natural gas. The concessionaire has to implement a minimum exploration programme. Any discovery is to be reported within 72 hours. While the concessionaire has exclusive rights to operate in the concession area, except for data acquisition. He said that if the concessionaire is a consortium of companies, Dr. Viera de Macedo said that the law requires that one of the companies will have to be nominated as the operator. The operator then acts on behalf of the consortium. He said that ANP has to be notified of drilling operations, and ANP oversees all operations in the concession area. He also said that the concessionaire has to maintain all information on the concession area for ANP to inspect at all times. Dr. Viera de Macedo said that ANP might authorize the construction of facilities outside the concession area, for the logistical operations of the concessionaire.

He said that the environment has to be protected at all times during the tenure of the concession.

As part of his concluding remarks, Dr. Viera de Macedo pointed out that offshore mining in Brazil is very recent phenomenon. He noted that the regulations for offshore prospecting, exploration and exploitation of petroleum and natural gas have only recently come into force.

He said that environmental regulations for offshore mining in Brazil are considered very stringent and among the most advanced in the world. He noted however that the concerned institutions are not that well prepared to deal with them. He said that Petrobras works within this legal framework like any other authorised company with no privileges that result from it being state owned. He said that Petrobras sees itself as having an educational role in the development and establishment of the new legal framework.

In conclusion, Dr. Viera de Macedo presented the International Seabed Authority with the offshore regulations of Brazil.

SUMMARY OF THE DISCUSSIONS

The discussions that followed Dr. Viera de Macedo's presentation focussed on the environmental impact of fixed versus floating platforms, the length of time required to deploy the pipeline from the vessel to the Christmas tree, and the competitiveness of its offshore policy for petroleum and natural gas.

A participant asked about the nature of environmental impacts of fixed and floating platforms on the seabed. Dr. Viera de Macedo explained that fixed platforms were utilized in shallower waters near the coast while floating platforms were used in deeper waters. He said that not much impact has been observed in either case. He said that fish appear to be attracted to the platforms. He said that in general along with the frequent gas flares, the surrounding waters are heated slightly. This does not appear to impact the fish around the platforms. He said that the major problem has been fishermen in their vessels that come after the fish. He said that these vessels sometimes get in the way of operations. In response to another question about the impact of the platforms on the seabed in deeper waters, Dr. Viera pointed out that since the platforms are floating, the only equipment in contact with the seabed are the Christmas trees.

One participant wanted to know the length of time required to deploy the pipeline from the vessel to the Christmas tree. Dr. Viera de Macedo said that he was not sure what the answer is. He suggested that it could be two or three days.

In view of the number of ordinances relevant to the petroleum industry that Dr. Viera de Macedo had referred to, another participant wanted to know if they came under the jurisdiction of a single agency. If not, this participant wanted to know how investors were facilitated through the process. It was also pointed out that because of provisions in the regulations on the Government's take, that included items such as special participation, deductions and fees, the overall take of companies would be relatively small for the operator and investor. In this light, it was suggested that perhaps the framework is not as competitive and attractive as one might want, in particular since Petrobras still appeared to be a state monopoly. Dr. Viera de Macedo was asked what incentives were provided to investors other than Petrobras, and what the Government of Brazil actually obtained from operators.

With regard to the ordinances relevant to the petroleum industry, Dr. Viera de Macedo said that two agencies were involved in the process. These were ANP and the environmental agency. He said that ANP falls under the jurisdiction of the Minister of Mines and Energy, and that the environmental agency was under the Ministry of the Environment. He said that ANP was responsible for concessionaires.

Dr. Viera de Macedo reiterated that Petrobras is no longer a monopoly. He said that there had been two rounds of bidding since the new law entered into force. He pointed out that several companies entered bids in both rounds. In 2000, for example, Dr. Viera de Macedo said that 44 companies submitted bids. These comprised five Brazilian companies and thirty-nine international companies that included some of the majors. He said that 21 bids were accepted, suggesting that the Government's take is not prohibitive. With regard to the Government's take, Dr. Viera de Macedo also pointed out that part of the bidding process included questions relating to the use of the goods and services of local Brazilian companies. He said that the Government's take was not what it appeared to be but that rather was an indirect take, meant to help to create linkages with the Brazilian economy. He said that the take from a concession varied according to the stage of development, and that the amount is fixed in the agreement. Another participant was of the view that since the Brazilian economy is being opened up, many of the bidders might have entered the process to position themselves.

CHAPTER 21

OFFSHORE MINERAL POLICY: THE INDONESIAN EXPERIENCE

By: Prof. Dr. Hasjim Djalal
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1. Legal Basis

Article 33 of the 1945 Constitution of Indonesia (which is now in force) stated that:

a) The Indonesian economy is organized as a common endeavor based on the principle of commonality (kekeluargaan). The branches of production, which are important for the state and which control the livelihood of the common people, are controlled by the state.

b) Land and water (sea) and the natural resources contained therein are controlled by the state and shall be used for the utmost prosperity of the people.

The Government Declaration of 13 December 1957 adopted the archipelagic state principles, which was enacted into Law number 4/1960, and stated that the archipelagic waters of Indonesia and the 12-miles territorial sea around them were parts of Indonesian national territory and therefore were placed under the national sovereignty of Indonesia. Consequently, all resources contained in those waters and their seabeds were also appertained to the Republic of Indonesia.

Subsequently, law number 44 / 1960 on Oil and Gas mining in the country reflected the new situation. Immediately thereafter, Indonesia also ratified the 1958 Geneva Convention on the Continental Shelf by Law number 19 / 1961.

After oil exploration gained momentum and intensity in the continental shelf beyond the 12-mile territorial sea outside the archipelagic waters, Indonesia declared on February 17, 1969 its continental shelf beyond the territorial sea up to the limit of "exploitability" in conformity with the 1958 Geneva Convention. This was reaffirmed in Law no. 1 / 1973, which in Article 2 declared that all natural resources on and in the Indonesian continental shelf belong to the state and are fully controlled by the state, which has exclusive rights over the natural resources.

UNCLOS 1982 extended the continental shelf of a coastal state "throughout the natural prolongation of the land territory to the outer edge of the continental margin, or to a distance of 200 nautical miles from the baselines". Indonesia codified the UNCLOS by Law no. 17 / 1985. Indonesia has delineated most of its continental shelf boundaries by agreements with its neighbors, although some of the boundaries are still being negotiated at the moment. Consequently, the Government of Indonesia controls all scientific research, exploration, exploitation, construction of installations and structures on the continental shelf. All the installations and equipment on the Indonesian continental shelf used for exploration and exploitation of the natural resources of the shelf are regarded as being within Indonesian customs area. The exploration and exploitation of the natural resources must take into account the policy and interests of other activities, particularly those of defense and national security, communications, telecommunications and underwater cables, fisheries, oceanographic and other scientific research and nature reserve. Violations of all the rules regarding these matters are punishable by imprisonment and / or a fine.

2. Law No. 44 / 1960

Law 44 / 1960 regulates the following:

Mining of oil and natural gas in Indonesia, including in all islands, in the seabed of the archipelagic waters, territorial sea and continental shelf, and can only be done by the state through a state company (article 3 paragraph 1 and 2). This is because oil and gas are regarded as vital to the life of the common people, and national defense and security. Oil and natural gas are regarded as "strategic materials". Law no. 44 / 1960 replaced the law enacted before independence, namely the law number 214 / 1899 as amended by the law number 434 / 1906 which was regarded no longer suitable for Indonesia because they were considered "liberalistic", "capitalistic" and "individualistic".

Mining efforts include exploration, exploitation, processing / refining, transportation and marketing (article 4). Carrying out any of these activities without licenses are violations punishable by jail and / or fines (Article 18).

The Government, on the basis of proposals by the Department of Mines, determines the boundaries of mining areas. The Minister of Mines can appoint a contractor to carry out mining activities that cannot be carried out by the state company, and the contract must be approved by Parliament (article 6 paragraph 3).

A mining area does not include land rights on the earth 's surface.

Mining cannot be carried out: 1) in an area closed for public purposes; 2) graveyards, holy places, public works and roads, railroads, water pipes, electric and gas pipes etc; 3) around the defense establishment; 4) other military areas; 5) building, residential areas and all lands appertaining thereto, except with the permission of the relevant parties.

In extreme urgency, those places can be removed at the cost of the contractor and after getting permission from the Government authority.

The state company may relinquish parts or all of the contract area after being approved by the Minister. Relinquishment terminates obligations for the relinquished area.

The state company must transfer to the Minister all maps and cliché as well as all land measurements, etc in connection with the mining efforts (article 10).

Those who are entitled to the land (other than state land) must let the mining works on the land to take place if they have been properly informed of the license and have been properly and fairly compensated.

The Minister of Mines and Energy decides the amount of compensation once formality for the devolution of the right has taken place. If the owner of the land disagreed with the amount decided by the Minister, the amount shall be determined by the relevant district court and all those costs shall be borne by the company (article 12).

The owner of the land is obliged to let the mining works proceed. The company must pay to the state a fixed fee, exploitation fee, and other fees (article 15). The amount of the fees is determined by the Government Regulations. The Department of Mines and Energy regulates and supervises the implementation of oil and gas exploration and exploitation (article 16) including determining the conditions for permission to use foreign experts / personalities to be employed in the oil and gas companies (article 17).

Oil and gas companies are obliged to report their compliance with all the guidance issued by the Department of Mines and Energy (article 17 paragraph 3). All mining rights of the oil and gas companies (which are not state companies) granted before the entry into force of Law 44/ 1960 were respected during a period of transition (which was decided by Government Regulation). The titleholders were given priority in considering them as contractor for the concession area. The mining rights of the state company that already existed before the entry into force of the Law 44 / 1960 became a new authorized mining right for the area concerned.

Some violations of the provisions of this law are punishable by imprisonment and / or fine.

3. Pertamina State Oil Company / Law No. 8 / 1971

Indonesian oil and gas exploration gained momentum by the consolidation of state oil company Pertamina under Law number 8 / 1971. In fact, the Law number 8 / 1971 already established Pertamina under Government Regulation number 27 / 1968 which was later reconfirmed.

The purpose of the company is to develop and to carry out business in oil and gas in its broadest sense for the utmost prosperity of the people and the state, as well as to develop national resilience (article 5). The company was therefore given more importance than simply a business entity; it has also some national functions.

The company's activities are in the field of oil and gas, which includes exploration, exploitation, processing and refining, transportation and marketing. With the approval of the President of the Republic of Indonesia, the company can also expand its business activities to other related businesses (article 6 paragraph 2). This was the beginning of the expansion of Pertamina's activities to all areas that were remotely related to oil and gas, which in the end stretched the capacity of the company very thin. In fact, the company almost collapsed in the 1970's.

The capital of the company belongs to the state, and originates from the state budget. The company is not authorized to have "silent funds" or "secret funds". In practice, this rule is suspected to have been largely ignored.

All Indonesian mining areas are reserved for Pertamina as far as oil and gas are concerned. The area for its direct operations is decided by the President of the Republic upon the recommendation of the Minister of Mines and Energy. This was regarded as the origin of a strong Presidential influence in the daily affairs of Pertamina.

Pertamina can enter into production-sharing contracts with other companies (article 12 paragraph 1) and the President must approve the agreement or contract to this effect (article 12, paragraph 3). This was again widely regarded as the source of a strong Presidential role in Pertamina.

In principle, Pertamina should deliver 60% of its income to the state, while the remaining 40% could be used for operational and other developmental purposes.

The Government has the right to place at least 3 Ministers as members of the Board of Commissioners of Pertamina. These Ministers are appointed and replaced by the President, and all of them are responsible to the President. If the Government Commissioners cannot agree on specific issues among themselves, the matter will be brought to the President for decision; again, enlarging the power of the President in Pertamina.

Government Regulation determines the salaries of the board of Commissioners, while the Board of Commissioners determines the salaries of the Board of Directors. All expenses of the Board of Commissioners are to be paid by Pertamina. Members of the Board of Directors are appointed and dismissed by the President, each supposedly for 5 years. This provision again strengthens the power of the President.

The Pertamina legislation is still applicable up to this moment. There have been a lot of attempts recently in Parliament to revise Law 8 / 1971, particularly an attempt to reduce the power of the President in the business affairs of Pertamina and the attempt to eliminate the exclusive power of Pertamina over oil and gas. Many people make the argument in the context of globalization of trade and economy and the development of a market economy. They make the argument that the monopoly of Pertamina should be abandoned, and that the management and the marketing of oil and gas products and industries should also be liberalized and left to market forces.

On the other hand, there is a sufficiently large opinion in the country that, in accordance with the 1945 constitution, oil and gas belongs to the state and should be used for the benefit of the common people. Moreover, it is argued that since oil and gas are not renewable resources, if left simply to market forces the resources would be depleted very soon. According to this view, the application of the principles of liberalization and market forces to non-renewable resources would not be appropriate, at least for countries like Indonesia.

4. Government Regulation No. 17 / 1974

On the basis of the Law no. 8 / 1971, the Government, through regulation no. 17 / 1974 further regulates the control of exploration and exploitation of oil and gas in Indonesian offshore areas. Under this regulation, the state oil and gas company, Pertamina, and its contractors are obligated to submit to the Director General of Oil and Gas of the Department of Mines and Energy, among others, the following:

1. Annual programme of works and approved budgets for those works;

2. An operational programme of oil and gas mining, 3 months before the works begin.

3. All data, samples, maps, reports and other documents obtained or produced by the company from the exploration and exploitation of oil and gas, which are regarded as Government property. (Article 4).

4. After obtaining permission from the Director General, the company can send the samples and data abroad for assessment / evaluation.

5. The company is obligated to give correct information to Government inspectors and provided inspectors with the necessary facilities to carry out their responsibilities.

Except as approved by the Minister of Mines and Energy, exploration and exploitation cannot be carried out in the following places:

(i) Defense /military bases, sealanes of navigation, or ports installations;
(ii) Religious, cultural, natural reserves or touristy areas;
(iii) Less than 250 meters from the boundary of its mining areas;
(iv) Fishing grounds or spawning areas;
(v) Areas with underwater installations, pipelines, and underwater cables; and
(vi) In areas under scientific research or investigation.

Companies are obligated to prevent pollution of the sea, rivers, coastlines or air space and to fight and eliminate pollution when it occurs.

The construction of installations and structures at sea must meet the following requirements:

(i) Assure the safety of workers;

(ii) Assure the safety of navigation;
(iii) Prevent damage to underwater cables or pipelines; and
(iv) Prevent the possibility of slippage, seabed landfall or moving of the installations or structures, either due to current, waves, ocean power, wind, or otherwise.

Companies must also:

Completely dismantle the disused installations or structures to assure safety of navigation and the sealanes and to report on the works done on dismantling and removal of the disused installations and structures,

Report on the construction of pipelines and on the repair of any damage to the pipelines,

Report on geological and other basic research in the area,

Report before carrying out exploratory, development and evaluation drillings and the results thereof as well as the progress of activities including information on reservoirs as well as resources that are found.

Not to abandon any well before precautionary measures are taken.

Report on production and any plan for secondary production.

Violations of some of the rules and regulations are also subject to imprisonment and / or fines.

5. Production Sharing Contract

On the basis of all these legislation, Pertamina has formulated a model of production sharing contract/agreement that has been widely used and revised since 1977. The contracts clearly state that all mineral oil and gas existing within the statutory mining territory of Indonesia are national riches controlled by the state (Note: This basic constitutional provision is now being challenged by the increasing desire for regional autonomy in which the provinces are now claiming substantial control over the mining resources in their province). Moreover, Pertamina has an "exclusive authority" to mine, while the contractor would assist Pertamina in accelerating the exploration and development of the resources within the contract area. The contracts further elaborate the following points.

Scope and definitions: In the production-sharing contract, Pertamina shall have and be responsible for the management of the operation contemplated in the contract. The contractor shall be responsible to Pertamina and is appointed and constituted the exclusive company to conduct petroleum operations in the contract area. The contractor shall:

> Provide all the financial and technical assistance for such operations,
>
> Carry the risk of operating costs,
>
> Share an economic interest in the development of petroleum deposits in the contract area,
>
> Such cost shall be recoverable as provided in contract,
> Generally the contractor will not incur interests expenses to finance its operations,
>
> The total production achieved shall be divided in accordance with a scheme as decided in the contract.

Terms of contract: The term of the contract is 30 years from the effective date. At the end of the initial 6 years, the contractor shall have the option to request for a 4-year extension, the approval of which shall not be unreasonably withheld. If at the end of the initial 6 years or the extension thereto no petroleum in commercial quantities is discovered, then the contract shall generally automatically terminate in its entirety. If petroleum is discovered within the initial 6 years or the extension thereof and can be produced commercially, then development will commence in that portion of the contract area immediately. In other portions of the contract area, explorations may continue concurrently without prejudice to relinquishment provisions.

Relinquishment: On or before the end of the initial 3 years as from the effective date, the contractor shall relinquish 25 % of its original contract area. On or before the end of the initial 6 years, the contractor shall relinquish a further 25 % of the original contract area. On or before the end of the 10th year, the contractor shall relinquish another area so that thereafter the area shall not be more than. Km2 (subject to negotiation), or 20 % of the original contract area, which ever is less. In the remaining area (the 20 % or less) Pertamina and the contractor "shall maintain a reasonable exploration effort". If contractor during the 2 consecutive years does not submit exploration programs, Pertamina may require the contractor either to submit an exploration program or to relinquish such part of the contract area. The contractor and Pertamina shall maintain close consultations with regard to the relinquishment of any portion of the contract area.

Work programme and expenditures: The contractor shall commence petroleum operations not later than 6 months after the effective date. The contractor shall declare the minimum amount to be spent on the programme of explorations to be carried out for the first 6 years and petroleum operations for the further next 4 years, altogether specifying programme and minimum expenses for the 10 years (firm commitment) in US dollar. The actual amount spent each year can be calculated for the next year. 3 months prior to the beginning of each calendar year, the contractor shall submit to Pertamina a work programme and budget for that calendar year. Pertamina, within 30 days, may request or propose revisions to the programme and the budget after which Pertamina and the contractor shall consult to reach agreement. Changes in the detail programme are allowed during the year provided they do not change the general objective of the work programme. Approval of the work programme and the budget will not be unreasonably withheld.

Rights and obligations of the parties: During the first. Contract years (negotiable), the contractor shall not have the right to sell, assign, transfer, convey or otherwise dispose of all or any part of its rights and interest to other than its affiliated company. The contractor shall have the following obligations:

Advance all the necessary funds and purchase or lease all the required equipments, supplies and materials,

Furnish all technical aids, including foreign personnel,

Furnish such other funds, including to the relevant foreign third parties,

Be responsible for the preparation and execution of the work programme,

Conduct an environmental baseline assessment at the beginning of the activities,

Take the necessary precaution for the protection of ecological system, navigation and fishing and shall prevent extensive pollution of the area, sea or rivers and others.

After the contract expires, remove all equipments and installations from the area in a manner acceptable to Pertamina and perform all the necessary site restoration activities,

Include in the annual budget of operating costs the estimates of the anticipated abandonment and site restoration costs,

Include an abandonment and site restoration programme in any development for each commercial discovery.

Submit to Pertamina copies of all such original geological, geophysical, drilling, well, production and other data and reports as it may compile during the term of the contract.

Prepare and carry out programs for industrial training and education of Indonesians for all job classification.

Appoint an authorized representative who shall have an office in Jakarta.

After commercial production commences, fulfill the obligation to supply domestic market in Indonesia under a strict formula as indicated in the contract.

Give preference to goods and services that are produced in Indonesia or rendered by Indonesian nationals provided they are equally advantageous with respect to quality, price, availability and quantities required.

Pay income tax to the Government of Indonesia and comply with Indonesian income tax laws and regulations, including keeping and showing of books and records,

Comply with all applicable laws of Indonesia and not to conflict with Indonesian obligations under international law,

Not to disclose geological, geophysical, petrophysical, engineering, well logs and completion, status reports and any other data to third parties without Pertamina written consent, even after the termination of the contract.

The contractor shall have the following rights:

To sell or transfer the rights and interests to affiliated company with notification to Pertamina.

To sell or transfer rights and interests to non-affiliated company with prior consent of Pertamina and the Government of Indonesia.
Retain control to all leased property and be entitled to freely remove them.

Have the right of ingress and egress from the contract area.

Have access to all geological, geophysical, drilling, well, production and other information held by Pertamina or Governmental agencies relating to the contract area.

Freely lift, dispose of and export its share of crude oil, and retain abroad the proceeds obtained there from.

Rights and obligations of Pertamina:

Pertamina is responsible for the management of the operation while the contractor is responsible for the work programme.

Pertamina assumes and discharges all other Indonesian taxes, except contractor's income tax.

Pertamina assists contractors in the execution of the work programme by providing facilities, supplies, and personnel with the necessary visas, work permits, etc.

The contractor shall advance at least US dollars 75,000 a year for the purpose of enabling Pertamina to meet local currency expenditures.

Pertamina shall ensure that at all times during the term of the contract the Rupiah funds are available to cover Rupiah expenditure for the execution of the work programme.

Pertamina has the title to all original data resulting from the petroleum operation; however, they shall not be disclosed to third party "without informing the contractor and giving the contractor the opportunity to discuss the disclosure of such data if the contractor so desires." The contractor should also not disclose the data to third parties.

Pertamina has the right to use the equipment which becomes its property solely for the petroleum operations envisaged under the contract; otherwise Pertamina shall first consult the contractor.

Recovery of operating costs. The contractor is authorized and obligated to market all crude oil produced and saved from the contract area subject to the following:

The contractor will recover all operating costs (as clearly defined) in the form of crude oil and shall be entitled to freely export them, except those destined for the domestic market of Indonesia.

The remaining crude oil shall be apportioned in graduated level of production as follows:

If the first production is from a "marginal field", Pertamina will get 64.2857 % and the contractor 35.7143 %. "Marginal field" is the first field capable of producing not more than 10,000 barrels daily average for 24 consecutive production months and represents a separate segment from the others.

Similar partition for "tertiary recovery" of "enhanced oil recovery" (E.O.R.) project and also represents a separate segment from the others (64.2857 % and 35.7143 % respectively).

From the "pre-tertiary reservoir rocks" (which were deposited or formed in pre-tertiary time):

> 64.2857 % for Pertamina and 35.7143 % for contractor, for production of up to 50,000 barrels daily average for the calendar year.
>
> 73.2143 % for Pertamina and 26.7857 % for contractor, for production of 50,000 to 150,000 barrels daily for the calendar year.
>
> 82.1429 % for Pertamina and 17.8571 % for contractor, for production of more than 150,000 barrels daily average for the calendar year.
>
> Other than the above, 83.2143 % for Pertamina and 26.7857 % for contractor.
>
> Each of the above is a separate segment of production.
>
> The title will pass to the contractor at the point of export and to Pertamina at the port of delivery.

Both parties can take and receive the respective portions in kind (subject to 90 days prior notification to the contractor for each of the semester of such calendar year).

The contractor may recover an investment credit up to 15.7800 % of the capital investment cost or production facilities in a new field producing from tertiary reservoir rock before recovering operating cost.

Natural Gas:

Natural gas <u>may be flared</u> if the processing and utilization thereof is not economical or if they cannot be used for secondary recovery operation (repressurizing and recycling).

If they are economical, then the construction and installation of facilities for such processing and utilization shall be under an approved work programme similar to crude oil, except that the split is 37.5000 % for Pertamina and 62.5000 % for contractor.

The contractor may recover an investment credit amounting to 102.1400 % of the capital investment for production facilities.

Pertamina may take and utilize the uneconomical natural gas for the sole count and risk of Pertamina.

<u>First Tranche Petroleum</u>: The parties shall be entitled to first take and receive each year 20 % of the production of petroleum and natural gas of that year (called "first tranche petroleum") before any deduction for recovery of operating costs and handling of production to be calculated and apportioned as indicated above.

<u>Valuation of crude oil:</u> Valuation shall be at the <u>net realized price FOB Indonesia</u>, unless Pertamina finds a more favourable net realized price, and in such a case it can give option to contractor whether the contractor will pay the more favourable price or let Pertamina market the oil.

<u>Compensation and production bonus</u>: The contractor shall pay to Pertamina as compensation for information now held by Pertamina the sum

of US dollar... (negotiable) within 30 days after the effective date of the contract.

The contractor shall provide Pertamina 30 days after being requested with equipment and service in amount not more than US Dollar.... (negotiable) for exploration and production activities in Indonesia.

The contractor shall pay Pertamina different amount of bonus (negotiable) within 30 days after the cumulative petroleum production has reached different or certain level of production... (negotiable) within 30 days. Such bonus shall not be included in the operating costs.

Payment: Any payment to Pertamina shall generally be made in US dollar except those from proceeds of local sale, within 30 days following the end of the month in which the obligation occurs.

Title to equipment: Equipment purchased by the contractor pursuant to the work programme becomes property of Pertamina (in case of import, when landed at the Indonesian ports of import) and will be used in such petroleum operations except the leased equipments belonging to third parties that may be freely exported from Indonesia.

Consultation and arbitration: The parties shall meet to discuss matters periodically and will make every effort to settle amicably any arising problem. If a dispute arises which cannot be settled amicably, it shall be submitted to arbitration with the possibility of the President of the International Chamber of Commerce appointed an arbitrator and the rules to be applied will be the rules of conciliation and arbitration of the International Chamber of Commerce. The decision of the majority of the arbitrators shall be final and binding upon the parties.

Training: Contractors agree to employ qualified Indonesian personnel and after commercial production commences will undertake the schooling and training of Indonesian personnel for labour and staff positions including administrative and executive management positions and will consider programme of assistance for training of Pertamina personnel. Cost and expenses of training Indonesian personnel shall be included in the operating costs.

Termination: The contract cannot be terminated during the first... contract year (negotiable) as from the effective date, except by a 90 days written notice if a major breach of contract is committed by the other party which has been conclusively proven by arbitration.

After….years (negotiable) as from the effective date of the contract, the contractor decides that circumstances do not warrant the continuation of the operations, and after due notice and consultation, the contractor may relinquish its rights and be relieved of its obligations.

If during the first.... contract years (negotiable), the contractor has not completed the work programme and spent less than the amount required to be so expended as agreed, and after consultation the contractor relinquish its rights, the contractor shall transfer the remaining amount of the initial ... (negotiable) years firm expenditures commitment to Pertamina.

Book and Accounts: Pertamina shall keep complete books and accounts reflecting all operating costs as well as services received from the sale of crude oil but will delegate this function to contractor until commercial production commences.

Contractor shall have the right to inspect and audit Pertamina books and accounts relating to the contract.

Pertamina and the Government of Indonesia also have the right to inspect and audit contractor's books and accounts relating to the contract and engage independent accountants whose costs shall be included in the operating costs.

Applicable Laws: The laws of the Republic of Indonesia shall apply to the contract. Any failure or delay in the performance of the contract is excused to the extent attributable to "force majeure".

Processing of products is subject to another contract, but the contractor agrees to refine 28.57 % of its share of crude oil in Indonesia. If there is no such refining capacity in Indonesia, then the contractors agree, "to set up a corresponding refining capacity for that purpose" under the following conditions:

Pertamina has first requested contractor thereto,

The contractor portion of crude oil is not less than.... barrels per day (negotiable); and

If both parties think that such refining capacity is economical. Otherwise, the contractor may make an equivalent investment in another project related to petroleum or petrochemical industries in Indonesia.

Indonesian Participation: Pertamina has the right to demand 10 % of undivided interests in the contract for itself or for other Indonesian interests (Indonesian participants). This is intended to give opportunity to Indonesian companies to take share in the exploitation of oil and gas production.

This right shall lapse after 3 months of the discovery of petroleum in the contract area if Pertamina does not use this option.

If Indonesian participant uses this option, he/she/it will be offered standard operating agreement and if he/she/it does not accept the offer within 6 months, the contractor is released from the obligation to offer participation to Indonesian participants.

If Indonesian participant acquires the 10% undivided interests, he/she/it will reimburse the contractor 10 % of the operating costs which the contractor has so far spent, 10 % of the compensation paid initially to Pertamina for information, and 10 % of the amount paid to Pertamina for equipments and services during the first contract year.

The Indonesian participant has the option to reimburse the same amount, either: a) in cash within 3 months; or b) by way of a "payment out of production" of 50 % of his production entitlement under the contract, equal in total to 150 % of the said amount commencing as from the first date of the production.

Operating Cost: "Operating cost" would include current year non-capital costs which can include operations, office services and general administration, production drilling, exploratory drilling, surveys, other exploration expenditures and training.

It would also include current year's depreciation of capital costs, such as construction utilities and auxiliaries, construction of housing and welfare, production facilities and moveables. Current year allowed recovery of prior year's unrecovered operating cost may also be included.

Depreciation of capital costs are divided into 3 groups, depending on expected useful life of the capital goods, namely group 1 = 50 %, group 2 = 25 %, and group 3 = 10 %. Interest on loans and insurance premium and fees as well as all expenditures incurred in the abandonment of all exploratory wells and the restoration of the drilling sites may also be recoverable as operating costs. This amount however is paid every year to Pertamina on the basis of calculation of costs and the lifespan of the project or installation.

6. Conclusions

The Indonesian mining legislation treats oil and gas somewhat differently from the hard minerals. While the exploration and exploitation of oil and gas are largely based now on production sharing system, the exploration and exploitation of hard minerals is still largely based on licensing system, in which the licensed mining companies are obliged to pay mining fees and tax/ royalties to the Government. This difference is basically because it is relatively easier to delineate the oil and gas reserve and resources in comparison with delineation of the hard mineral reserves and resources, particularly deep underground.

The production sharing system in Indonesia has given quite a substantial power to the Government or the President to participate in the management of oil and gas as well as in the oil company (Pertamina). There are more than 30 articles in the various Laws and Regulations that empower the Government / the President to deal with the Pertamina affairs. Consequently, after the political change in Indonesia recently, there is a strong opinion in the society to eliminate or reduce the power of the Government or the President in the oil and gas industries as well as the near monopoly of Pertamina in the oil and gas business. But substantial amount of opinion also opposes this new trend, primarily based on practicalities and national needs.

In fact, the production sharing contract as well as the previous arrangement has brought substantial benefits to all parties. From 1996 to 1999, the contractor has obtained a total of 14 % of the net gross revenue / production for the recovery of their costs and capitals, 19 % for profit / rate of return to their investments, while 67 % of the revenue / production has gone to the Government of Indonesia directly deposited by the contractors. Pertamina retains 5 % of the Government share, deducted by 60 % for tax, thus a net of 2 % from the total Governmental receipt.

During the life of the contract within the last several decades of the various companies operating in Indonesia, the oil and gas companies have generally complied with their obligations and the cooperation with Pertamina the Indonesian Government have generally been useful and profitable. Currently, some 50 oil companies, including most of the world's biggest and prominent companies are operating in more than 170 production sharing contract areas in Indonesia, onshore and offshore. In general, offshore mineral exploration and exploitation have been generally smooth and relatively freer from problems and conflicts, including provincial / regional, compared to exploration and exploitation of minerals, liquid and hard, onshore.

This paper does not deal with:

Joint Development Zone or Zone of Cooperation, although Indonesia does have substantial experience in this field in the Timor Gap Agreement between Indonesia and Australia. Although the possibility for Joint Development Zone concept may exist in the future for the border area between the national jurisdiction and the international seabed area, for the moment the possibilities may appear still remote.

Offshore hard mineral resources.

Although Indonesia does have some tin mines offshore, they are however still very close to the shorelines and in fact they are generally regarded as extension of mining on land.

SUMMARY OF THE PRESENTATION AND DISCUSSIONS ON INDONESIA'S OFFSHORE MINING POLICY AS IT RELATES TO EXPLORATION AND EXPLOITATION OF OIL AND NATURAL GAS.

Ambassador Djalal, Special Advisor to the Indonesian Minister for Oceans, Exploration and Fisheries informed participants that his presentation would be on Indonesia's offshore mineral policy with a focus on the oil and gas industry.

He described Article 33 of the Indonesian constitution as fundamental to activities in the sector, and said that this article indicates that the economy of Indonesia is based on the principle of kekeluargaan or the principle of commonality. He said that the article provides that the vital sectors of the Indonesian economy are to be controlled by the state, which is of course somewhat different from the old system, which was the basic western system of economy. By giving the state control of all sectors of the Indonesian economy, Ambassador Djalal said that all factors that control the lives of common people are protected.

Ambassador Djalal said that the second basic principle guiding the sector is the Archipelagic state principle. Ambassador Djalal said that when Indonesia declared Independence, the territorial sea was three miles with the high seas adjoining it. He observed that at the time, there were no clear provisions on who controlled the mineral resources in territorial seas or beyond. He said that upon Indonesia's declaration of the Archipelagic principle in 1957, it also declared that all the resources within its Archipelagic waters are part of Indonesian resources and therefore controlled by the state of Indonesia. Later, Ambassador Djalal said that the declaration was enacted into Law number 4/1960.

Ambassador Djalal said that the third point about Law number 44/1960 is that it provides that all mining areas for oil and gas in Indonesia are reserved for Pertamina. He described this law as facilitating Pertamina's monopoly over oil and gas in Indonesia. He said that this law covered all areas where oil and gas may be found, i.e., onshore and offshore. He said that as a consequence, Pertamina seeks production-sharing contracts with all oil companies. He explained this by stating that while on the one hand Pertamina reports to the Government, the contractor reports to Pertamina. In order for a foreign company to enter into a production-sharing contract with Pertamina, Ambassador Djalal stated that the contract has to be approved by the Government of Indonesia. He also said that in some cases, approval has to be granted by the Indonesian Parliament and ratified by the President of Indonesia. He made the observation that the role of the state in granting contracts in the oil and gas industry is therefore significant. He pointed out that many Indonesians are of the opinion that this is one of the reasons for the system of cronyism or favouring one company over another in Indonesia. He also suggested that this system manifests itself in other ways such as in corrupt practices.

He said that in principle Pertamina provides the Government with at least sixty per cent of all revenues from the oil and gas industry. He pointed out that after 30 years experience, Pertamina has been providing the Government with sixty-seven per cent. Ambassador Djalal said that the balance of revenues is shared under the contract. He said that in order to further strengthen the role of the Government in Pertamina, three members of Pertamina's Board of Commissioners are Ministers of Government. He said these included the Minister of Mines and the Minister of Finance. Ambassador Djalal also said that the President of Indonesia appoints all the Directors of Pertamina. He described the situation as a cozy kind of business, where the Government has a strong hand in Petamina's affairs, and not a regular kind of business.

Ambassador Djalal informed participants that lately a lot of groups within the country have submitted legislation to change this situation. He said that the prevalent opinion is that the Government has far too great a role in Pertamina, and that Pertamina's monopoly of the oil and gas industry has to be reduced. He pointed out that since most of the producing fields are located in Indonesia's provinces, another development has been that the provinces are requesting a larger share of the revenues accruing from oil and gas production. Ambassador Djalal said that the new legislation that has been passed by Parliament gives the provinces fifteen per cent of the oil revenues, and thirty per cent of the gas revenues. He pointed out however that the provinces have asked for a larger share. He further pointed out that the President of Indonesia, when asked by representatives of the provinces at a recent news conference in North Sumatra, his opinion of the appropriate share for the provinces, he responded that the provinces could get seventy-five per cent of the revenues if that was their wish. Ambassador Djalal said that this statement has created a tremendous problem in the country at the present time. He noted that with a law having been passed in Parliament on the appropriate share for the provinces, the statement of the President has created problems for the central Government. Additionally, Ambassador Djalal noted that the central Government has further problems with the provinces since another law has been enacted giving provinces authority over natural resources within twelve miles of their respective coastline. Ambassador Djalal said that this drastic new law is scheduled for implementation in two years, after regulations to implement it have been developed. He informed participants that when the draft law was submitted to the Ministry for Oceans Exploration and Fisheries, the Ministry advised Parliament that the Ministry would support the devolution of power to the provinces, in only three areas. These were for coastal zone management, control of land-based sources of pollution, and protection of traditional fishermen and fisheries. Ambassador Djalal said that the Parliament of Indonesia, being very apprehensive of regionalism and of discontent in the provinces, where people were claiming various rights in Parliament, or on the streets of Djakarta and in the media, somehow agreed to give the provinces the authority over natural resources within the twelve-mile zone. He said that this law has resulted in some of the provinces claiming rights over oil and natural gas resources within twelve-miles of the coastlines. He said that in one instance, a province is now requesting control over oil and gas, and all other resources within the 200-

mile economic zone. He described this development as scary for both the central Government and the business community, particularly the oil and gas industry. He said that with twenty-six provinces in Indonesia, if each decided to create its own legislation, confusion would be the order of the day. He said that the central Government is engaged in discussions with provincial Governments that this is not the way to proceed. He noted that while the central Government wanted to give a lot of power and authority to the provincial Governments, this desire did not include creating confusion in the economy as a whole.

In relation to the Government of Indonesia's regulations of 1974 (Law number 17/1974), Ambassador Djalal said that it is clearly stated that Pertamina and contractors have to submit an annual programme of work. He said that if the annual programme of work is not submitted, there would be consequences faced by the contractor. In addition, he said that an operational programme has to be submitted three months before the year of operation. In this regard, he said that all data, samples, maps, reports and other documents that are produced for an area, are considered as Government property, and must be submitted to the Director-General of Oil and Gas. He said that contractors are allowed to send samples for investigation abroad following approval of a request, by the Director-General. Additionally, Ambassador Djalal said that contractors must cooperate with Government Inspectors, including providing access to their activities and installations, and providing explanations to questions that the Government might have.

Ambassador Djalal noted that under this regulation, in specified offshore areas, no exploration or production is allowed, that contractors have an obligation to prevent pollution, and to completely dismantle disused installations. He emphasized that this third obligation has become a big problem in Indonesia because the law is not clear about the party that has to undertake dismantling. He noted that currently there are about 400 offshore installations in Indonesian waters. He said that some of them with twenty-year life spans have been in Indonesian waters for over twenty-five years. He projected that next year there would be about 18 to 20 disused installations. He said that the Government has been engaged in determining who would dismantle these installations and at what cost. Ambassador Djalal stated that the problem arose because initially, in their eagerness to ensure that the production-sharing contracts became viable, Pertamina and the Government insisted that all equipment brought into Indonesia became the property of Indonesia. He said that because all of the expenses of the contractors could be factored into operational costs, they normally complied with this provision. Now, he said that when the Government approached any of the contractors requesting that the installation be dismantled, it was informed that the equipment in question was the Government's property. With regard to Pertamina, he said that when the request is put to it to dismantle the installation, it would refer to the costs involved. He said that it has been determined that depending on the size of the installation and the water depth it is located in, dismantling it ranged between one and seven million dollars. He said that therefore to dismantle the 18 or 20 installations next year could cost up to 150 million dollars. Stating that it was unclear where this sum of money would come from, Ambassador Djalal informed participants that he undertook a review of some of the relevant contracts. He said that in so doing, he discovered that before contractors begin operations, they are required to incorporate a sum for dismantling their installations at the end of production. Pointing this out to Pertamina, Ambassador Djalal stated that its response revealed a major problem. Nevertheless, he said that the Government of Indonesia is keen to solve the problem. He said that it is examining the approach taken in Louisiana, USA, where disused oilrigs were moved into the reef zone and converted into reefs. He said that another alternative that is being examined is to refit them for use elsewhere.

Ambassador Djalal said that contractors are required to report on the construction of pipelines, on geological and other operations, exploratory development as well as evaluation drilling, and also if they are engaged in secondary production. He described secondary production as enhancing production from a well, by introducing steam into the well. He said that thirty per cent of production in some offshore areas in Indonesia is from secondary production.

With regard to the production-sharing system, Ambassador highlighted some of its significant components. He said that in this system, the contractor with exclusive rights in the contract area, reports to Pertamina. He said that the contractor has specific obligations, including the provision of all financial and technical assistance, bearing the risk involved in bringing the field into production single-handedly, sharing the crude oil it produced with the Government, and contributing to economic development. In this regard, he said that a lot of the oil companies establish schools, community centres and hospitals for local communities. He pointed out that there have been problems associated with this obligation, with companies seeking to ascertain why there are Ministries of Education, Health etc in Indonesia, and oil and gas companies are being asked to build schools and hospitals.

Ambassador Djalal explained that the aspect of the system that deals with the recoverable costs of the oil companies is the most difficult part. He said that every penny spent by the companies has to be invoiced, resulting in very meticulous bookkeeping and accounting. He said that the accounts are maintained by Pertamina. He said that contractors, the Government and Pertamina all have a right to audit the accounts. He said that the oil companies do not lose any money, because all the money that they spend for training, schools, hospitals etc, is recoverable under the production-sharing system. After recovery of costs, Ambassador Djalal said that the balance of production is divided under the scheme, which he described as complicated.

He said that the contract is normally for thirty years, but exploration is for six years. He said that an additional four years might be granted for exploration. He noted that for the four additional years to be granted, the contractor must have funds that are committed for the work envisioned during that period. With regard to relinquishment, Ambassador Djalal said that twenty-five per cent of the area has to be relinquished within three years, another twenty-five per cent within six years, and thirty per cent within ten years. In the end, he said that the area open to exploitation by the company is can only be up to twenty per cent of the original exploration area. He said that at the production stage, another obligation is that petroleum production has to start within six months of the contract date. Breach of this obligation, he said, could result in the contract being invalidated.

He pointed out that his paper clearly spells out the obligations of Pertamina and contractors. He emphasized the contractor has a right to recover all operating costs from its production of crude oil, and as defined in crude oil terms. He said that there is a separate agreement on how the recovery of operating costs is to be implemented based on oil production. He said that the remainder of the production is apportioned in graduated levels of production from sixty-four to eighty-three per cent for Pertamina, and with the company receiving between seventeen and thirty-six per cent. He said that the more the company produces crude oil, the less it gets. For natural gas, Ambassador Djalal stated that if it can be produced in liquefied form, the companies normally get up to seventy per cent of the profits accruing from processing the gas, with thirty per cent paid to Pertamina.

In addition to the above, Ambassador Djalal said that a most important consideration is the payment of compensation and production bonuses to the Government for companies that produce more oil than projected and therefore increase their incomes. Ambassador Djalal said that there are about five such bonuses. He described three such bonuses, starting with the bonus for information help by Pertamina. Ambassador Djalal said that under this scheme, every time that Pertamina supplies a company with information and new data on its specific area, the company pays for this information and data. A second bonus that is paid is in relation to the obligation of companies to help Pertamina develop its resources. In this regard, Ambassador Djalal said that the companies pay for goods and services required by Pertamina, whose costs are then recovered by the company as part of operating costs. Ambassador Djalal said that another bonus is the graduated level of production bonus, which is determined by the level of production of the company.

Ambassador Djalal pointed out that in addition to the obligation to turn over all equipment to the Government of Indonesia, contractors are also obliged to train Indonesians in all aspects of the contractor’s business, to purchase the goods and services that they require from local suppliers if available, and to refine up to 28.57 per cent of their share of the crude oil that they produce in Indonesia. If Indonesia does not have the refining capacity to process this amount of crude oil from the contractor, Ambassador Djalal pointed out that the law obligates the contractor to invest an amount of money that is equivalent to refining their share in other petrochemical or related industries in Indonesia. He gave as an example of these industries fertilizer plants. Ambassador Djalal informed participants about one other obligation whose purpose is to broaden Indonesian participation in the oil and gas industry. This provision of Indonesian law obligates contractors to provide an option for Indonesians to purchase up to 10 per cent of the undivided shares in the contract.

In conclusion, Ambassador Djalal said that the Indonesian mining legislation treats oil and gas somewhat differently from hard minerals. While the exploration for and exploitation of oil and gas is based on the production-sharing system, hard minerals are developed on the licensing system where contractors are required to pay fees and royalties. The basis for these two systems is that it is felt that it is relatively easier to delineate oil and gas reserves in comparison with reserves of hard minerals.

1. The production-sharing system has given substantial powers to the Government, in particular to the President of Indonesia to participate in the management of oil and gas, as well as in Indonesia's petroleum company (Pertamina). More than thirty articles in the various laws and regulations empower the Government and the President to deal in Pertamina's affairs. Following the recent political changes in Indonesia, there is a strong opinion in Indonesian society, of the need to eliminate or reduce the power of the Government and the President of Indonesia in the oil and gas industry, as well as the near monopoly enjoyed by Pertamina in the industry. Other sectors of society oppose this opinion in view of the fact that the constitution of Indonesia requires the Government of Indonesia's control of this industry. It is therefore unclear how the matter will resolve itself.

2. The production-sharing system has brought significant benefits to all parties involved. From 1966 to 1999, that is the period during which this system has been in effect, the contractor has received a total of 14 per cent of the net gross revenues for the recovery of their costs and capital, and a rate of return of 19 per cent on their investment. On its side, Pertamina, which is obligated to return to the Government 60 per cent of the oil revenues, has received 67 per cent. In the end under the system that has been devised, Pertamina retains 2 per cent of these revenues, with rest going to the Government.

3. During the lives of the contracts over the past several decades, the oil and gas companies have generally complied with their obligations,

and cooperation with Pertamina and the Indonesian Government has been useful. Currently, under the difficult circumstances in Indonesia, about 50 oil and gas companies are operating in Indonesia, through 170 production-sharing contracts. These include most of the world's biggest and prominent companies.

4. In general, offshore mineral producing operations have been smooth and free of conflicts compared to land-based exploration and exploitation of minerals.

Ambassador Djalal reiterated that his paper does not deal with joint development zones in which Indonesia has a lot of experience in the South China Sea (Malaysia and Vietnam) and Timor Sea (Australia), or with offshore mining of hard minerals.

SUMMARY OF THE DISCUSSIONS.

The discussions following Ambassador Djalal's presentation focussed on the types of contracts that are awarded for natural gas, the distinction between Pertamina and the Government of Indonesia, activities undertaken by Pertamina in oil and gas development, whether Indonesia's new oil and gas law contemplates the use of concession agreements, the adequacy of a rate of return of 19 per cent, and how Indonesia ensures that costs that may be recovered are not genuine.

One participant noted that during Ambassador Djalal's presentation, he had referred very quickly to contracts for the development of natural gas. This participant wanted to know the types of contracts entered into for natural gas production. Ambassador Djalal said that for natural gas, in Indonesia two possibilities are recognised. The first is to flare the gas for which approval is required, and the other is to process it to liquefied natural gas. He said that in the case of the latter, the natural gas is produced separately under conditions more favourable to the company. He also said that natural gas production occurs in many places in Indonesia, in particular off the Natuna Islands in the South China Sea, and in East Java. He informed participants that Indonesia is in the process of constructing a pipeline to transport natural gas from the southwestern part of the Natuna Sea near the border with Malaysia, to Singapore.

Another participant noted that sometimes Ambassador Djalal referred to revenues for the Government and at other times to revenues for Pertamina. This participant wanted to know whether the two entities were the same. Ambassador Djalal informed this participant that Pertamina is the agent of the Government of Indonesia in the oil and gas industry and a state company. Yet another participant wanted to know the role of Pertamina before a production-sharing contract was concluded, to find out which entity undertook seismic surveys and mapping of an area before a contract is signed, and also to find out the process used by Indonesia in awarding contract areas. Ambassador Djalal said that areas were awarded on an open tender basis. He said that Pertamina was actually an offshoot of an old company Permina. There was a Dutch oil company called Stantech that developed into Permina, which was also an oil company. This company produced and processed crude oil. Ambassador Djalal said that Pertamina still produces a small portion of Indonesia's oil and gas. With regard to awarded areas, he said that it is not through a tender process. Companies come forward and make proposals. He also said that most of Indonesia's offshore area is open to oil production, and that it is estimated that 60 per cent of Indonesia's oil and gas is produced in offshore areas, particularly in the Java sea, in Eastern Kalimantan waters as well as the southward part of the South China sea.

Another participant wanted to know where the detailed numbers on Pertamina's take came from, in particular numbers like 64.2837 per cent and 83.2134 per cent. Ambassador Djalal responded that these numbers are to be found in the contracts themselves. In response to a question about the tax system, Ambassador Djalal said that taxes are the responsibility of Pertamina. He pointed out however that since Indonesia runs a production- sharing system, most of the companies do not bother with tax, except income tax. He said that taxes such as production tax etc are factored into the system. He also pointed out that Indonesia has a double taxation arrangement with about 60 countries.

A participant wanted to know whether or not a rate of return of 19 per cent is considered a good rate of return in the petroleum industry. Ambassador Djalal said that his understanding is that a rate of return of 10 to 15 per cent is pretty good. He added that since all operating costs are factored into this rate, it would appear that a 19 per cent rate of return is good. He also added that companies cannot recover interest charges on loans under the scheme.

Finally on items of cost that are recoverable, one participant asked Ambassador Djalal that since a lot of unrelated costs may be submitted as costs related to the contract, how does the Government of Indonesia ensure that the costs that are submitted are bona fide. In response, Ambassador Djalal said that Pertamina records all costs and that in the regulations guidelines are provided for acceptable costs. He also said that the contractor, Pertamina and the Government of Indonesia are all allowed to audit the accounts.

CHAPTER 22

THE ROLE OF SOPAC IN PROMOTING EXPLORATION FOR MARINE MINERAL RESOURCES IN THE PACIFIC REGION

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1. Introduction

The South Pacific region comprising 22 Pacific Island countries [PICs] and territories collectively cover over 20 million square kilometres of the Pacific Ocean and is considered to be one of the most prospective regions in the world for offshore mineral resources. With ocean to land ratios in the Pacific being as much as 25, 000 to 1, the potential economic benefits to the region through development of these marine mineral resources could be enormous.

The region's potential prosperity has largely been determined through numerous marine scientific research [MSR] campaigns, which have identified key resource areas of polymetallic massive sulphides [PMS], manganese nodules and cobalt-rich manganese crust, within the 200 nautical mile exclusive economic zones [EEZs] of some PICs. In addition to these, other collaborative research programmes have established the potential for hydrocarbons, placer minerals, gas hydrates and precious corals in the region.

For many PICs, their living and non-living marine resources represent the only natural resources of any tangible economic significance or development potential. Consequently, the sustainable development and management of the region's marine environment and marine resources are of paramount importance to their long-term future.

In 1972, the Committee for Co-ordination of Joint Prospecting for Mineral Resources in South Pacific Offshore Areas [CCOP/SOPAC] was founded under the auspices of the United Nations Economic and Social Commission for Asia and the Pacific [ESCAP]. At the time, the primary focus of CCOP/SOPAC was to promote and develop the offshore hydrocarbon and mineral potential of the South Pacific region. It evolved to become an inter-governmental organisation in 1984 and changed its name to the South Pacific Applied Geoscience Commission [SOPAC] in 1989. It now has a membership of sixteen PICs plus two French Territories, who hold associate member status.

Although SOPAC's mandate has diversified to providing other technical services to its member country Governments, the promotion and development of both nearshore and deep-sea marine mineral resources remains a core function of its work. In this regard SOPAC continues to coordinate all MSR cruises related to minerals in the Pacific, to collect data and maintain extensive databases of marine mineral resources, and to provide other advice and support for marine mineral research and development. More recent initiatives of SOPAC's work programme include assisting some of its member countries to develop national, marine mineral resource policies.

This paper seeks to discuss SOPAC's activities and experiences in promoting deep-sea marine mineral exploration in the region, and identifies issues, which need to be addressed if SOPAC is to be effective in its efforts to promote exploration and development of marine mineral resources in the region.

2. SOPAC – Historical Brief

Prior to the inception of CCOP/SOPAC in 1972 as both promoter and watchdog for marine mineral resource exploration of Pacific Island Countries [PIC], research vessels from institutions and organisations of various countries periodically visited the South Pacific Region to carry out geosciences and other investigations. At the time, many PICs were unaware of the extent and nature of these marine research activities. As well, an inadequate or complete lack of national capacity prevented PICs from exercising their legitimate right to access the data, data assessments and resulting information from these research cruises.

The establishment of CCOP/SOPAC, sought to remedy this situation by providing a regional mechanism to co-ordinate and stimulate marine research in the region, and by so doing, promote and develop the offshore hydrocarbon and mineral potential of the South Pacific region.

Under the 1989 intergovernmental agreement establishing the South Pacific Applied Geoscience Commission [SOPAC], full membership[1] rights are extended to any independent island State of the South Pacific and any self-governing island country in the South Pacific, which is in free association with another State. Associate membership[2] to SOPAC, being accorded to any local administration of a non self-governing territory in the South Pacific region. The agreement articulates the purpose of SOPAC as being to:

- Promote, facilitate, undertake, coordinate, advise on and cooperate in the prospecting ofand, research into the non-living resources in the offshore, coastal and onshore areas of those countries whose Governments are members of the Commission as well as in the other oceanic areas of the South Pacific region.

- Assist in the development of such resources.

- Undertake such other activities related to prospecting, research and development of those resources, as the Governing Council shall determine.

SOPAC's Governing Council meets on an annual basis to review and discuss the organisation's work programme. There are two elements to the meeting, which provide advice on science to the Council members. A Technical Advisory Group [TAG] meets jointly with the Council. Immediately preceding this is the meeting of the Science, Technology and Resources Network [STAR], which is an open forum for reporting scientific research in the South Pacific and for exchanging ideas and information between scientists from SOPAC member countries and the international scientific community.

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[1] Full membership extends to governments of Australia, Cook Islands, Fiji, Federated States of Micronesia, Guam, Kiribati, Marshall Islands, Nauru, New Zealand, Nuie, Papua New Guinea, Samoa, Solomon Islands, Tonga, Tuvalu and Vanuatu.

[2] Associate membership extends to New Caledonia and Tahiti Nuie (French Polynesia).

STAR was founded in 1985 in collaboration with the Intergovernmental Oceanographic Commission [IOC] of UNESCO. STAR sessions are more than scientific and technical meetings where scientists present scientific papers and discuss results and implications, in that there is an expectation on participants to formulate advice to SOPAC concerning its work programme and to highlight technical and scientific issues of particular importance and urgency.

One of the great strengths of SOPAC is its ability to mobilise excellent science and bring it to bear to address the national needs to its member countries. The long established working relationship between SOPAC and the international research community is a vital element in this endeavour, which STAR is charged to nurture. This relationship stimulated an order of magnitude change in the geosciences database in the SOPAC region during the 1980's. Current working groups of direct relevance to marine mineral resources include: Benthic Habitats, Law of the Sea, Oceans, Tectonics and Ocean Drilling, Coastal and Nearshore Processes and Resources, and Ocean Basin Mineral Resources and Technology.

Although SOPAC's purpose has diversified to include technical services[3] beyond its initial focus to promote and develop offshore mineral resources, an offshore mineral resouces brief remains a core function and priority service area of its work programme. With donor funding finally secured for it's Ocean Unit's work programme, SOPAC has recently recruited a marine affairs adviser, with responsibilities to coordinate regional marine scientific research activities, maintain and update regional deepsea mineral and cruise databases, and advise on UNCLOS duties and obligations. Further, a decision has been reached to transfer the Maritime Boundaries Programme from the Forum Fisheries Agency [FFA] to SOPAC. This initiative will enable a more focussed regional effort toward delimitation of martime zones and boundaries for PICs.

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[3] The SOPAC Secretariat offers the following technical services to its member countries: Coastal Management, Coastal Engineering, Disaster Management, Energy, Environmental Services, Hazard Assessment, Human Resources Development, Hydrology, Mineral Resources, Ocean Management, Publication and, Information and Technology. SOPAC's member countries and technical advisers meet annually to review and direct the work programme for each of these technical services.

3. Marine Scientific Research - Cruise Co-Ordination

Although there is a requirement under the United Nations Convention on the Law of the Sea [UNCLOS] for all data of marine scientific research to be sent to the Governments of the coastal states in which the cruises have taken place, this has not always been the case. To ensure that SOPAC continues to meet its mandate to co-ordinate MSR cruises and, ensure that data and information acquired during the cruises are made available to its member countries, SOPAC has developed a consents protocol for the co-ordination of MSR in the Pacific region.

The protocol includes procedures to be followed by States who wish to carry out MSR on non-living marine resources in sea areas under the jurisdiction of a coastal State in the region. It also specifies required formats for the exchange of data between SOPAC and the researching organisation to ensure that data can be read and easily integrated into the cruise database. The procedures also provide SOPAC member countries with a clear administrative process for handling requests for consent to conduct MSR by foreign research organisations. The intent and wording of the protocol, borrows heavily from *The Law of the Sea: Marine Scientific Research – A Guide to Implementation of the Relevant Provisions of the United National Convention on the Law of the Sea*.

This considered, regional approach to coordinating MSR activity through SOPAC allows all of its member countries, irrespective of their size and technical capacity, to get individual and collective advice and assistance to:

- Evaluate MSR requests for consent to conduct MSR
- Advise on clearance and conditions of participation or representation
- Monitor post-cruise obligations
- Assist in assessment of research results and access data that would otherwise not be collected or used effectively.

Since 1972, SOPAC has, on behalf of its member countries, collected and processed large volumes of data and information acquired during MSR cruises in the region, which it stores and maintains in a cruise database.

Issues persisting include the non-compliance of some researching organisations to meet their post-cruise obligations or the use of incompatible formats of data being submitted to SOPAC, following completion of a cruise. These issues continue to be addressed at SOPAC Annual Sessions[4] through continually reinforcing the importance of MSR co-ordination for the region to representatives of international research organisations and SOPAC member countries. In addition, by re-stating the MSR obligations on the researching State to researchers and communicating SOPAC's requirements regarding data formats.

3.1 Marine Scientific Research Cooperation

Since its inception, SOPAC has consistently championed the promotion and co-ordination of MSR of non-living resources in the Pacific region. These efforts have led to numerous long-term co-operative offshore mineral programmes in the SOPAC region, by various research institutions from Australia, Canada, European Union, France, Germany, Japan, Korea, New Zealand, the former Soviet Union, the United Kingdom and the United States of America, with co-ordination being provided by SOPAC.

These research programmes have provided PICs with invaluable data and resulting information, which have identified offshore resources from which an economic benefit will accrue in the event of their development. The target mineral resources that remain the focus of research include manganese nodules, cobalt-rich crusts and polymetallic massive sulphides [PMS]. A sample of these co-operative research programmes, which identify the participating research States, the Exclusive Economic Zones [EEZ] in which research has been conducted and the types of mineral resources that have been targeted for study, are included in Table 1.

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4 SOPAC Annual Sessions provide an opportunity for international researchers [SOPAC's Technical Advisory Group] and SOPAC member country representatives to review, discuss and agree the SOPAC work programme.

Table 1: Co-operative deepsea mineral research programmes conducted in the SOPAC region .

Researching State	Research Programme	Duration	EEZ Area	Target Mineral Resource
France CCOP/SOPAC	EVA	1977-1987	Fiji, New Caledonia, Solomon Is, Tonga, Vanuatu	PMS
Germany	ICIME	1978	Cook Is, Fiji, French Polynesia, Tonga	Mn Nodules
USA CCOP/SOPAC	Machias	1978-1981	Cook Is, Fiji, French Polynesia, PNG, Samoa, Solomon Is, Tonga, Tuvalu, Vanuatu	Hydrocarbons Mn Nodules Precious Corals
USSR	Various	1978-1990	Cook Is, Fiji, Kiribati,PNG, Samoa, Solomon Is, Tonga, Vanuatu	Mn Nodules PMS
Germany	MIDPac	1981-1989	Cook Is, Fiji, French Polynesia, Kiribati, Marshall Is, New Caledonia, Solomon Is, Tuvalu, Tonga	PMS Cobalt-rich crust Mn Nodules
USA CCOP/SOPAC	Tripartite I	1982-1984	Fiji, PNG, Samoa, Solomon Is. Tonga, Tuvalu, Vanuatu	Hydrocarbon PMS
Japan/SOPAC	Natsushima	1983-1984	Fiji, PNG	PMS
USA CCOP/SOPAC	Tripartite II	1984-1986	Cook Is, Fiji, FSM, Kiribati, PNG, Samoa, Solomon Is, Tonga, Tuvalu, Vanuatu	Various
Australia SOPAC	SeaMap	1985-1989	Australia, Fiji, New Zealand, Samoa, Tonga, Vanuatu	

France	Seapso	1985-1986	Cook Is, Fiji, French Polynesia, Marshall Is, New Caledonia, Solomon Is, Tonga, Vanuatu	Various
USA	Papatua	1985-1986	Cook is, Fiji, French Polynesia, Guam, Kiribati, New Zealand, PNG, Solomon Is, Samoa, Tonga, Vanuatu	Various
Japan SOPAC	JPN-SOPAC DMRP[5]	1985-2000	Cook Is, Fiji, Kiribati, Marshall Is, FSM, PNG, Samoa, Solomon Is, Tonga, Tuvalu, Vanuatu	Manganese nodules Cobalt-rich crust PMS
Australia Canada SOPAC	Paclark	1986-1991	Australia, Cook Is, PNG	Mn Nodules PMS
France	Charcot	1986-1987	French Polynesia	Co-rich crust
USA UK	Crossgrain	1987	Cook Island, French Polynesia, Kiribati	Mn Nodules Cobalt-rich crust
France, Japan SOPAC	STARMER I	1987-1991	Fiji, New Caledonia, Solomon Is, Vanuatu	PMS
New Zealand UK	GloriaSurvey	1988	Fiji, New Zealand, Tonga	
USA	Roundabout	1988–1999	Cook Is, Fiji, French Polynesia, Guam, Kiribati, Marshall Is, Samoa, Tonga, Tuvalu	PMS Mn Nodules Precious Corals

[5] In response to a request by SOPAC, the government of Japan started the programme in 1985 as a five-year cooperative study project between Japan and SOPAC. The first stage of the programme has been extended twice and completed in March 2000. The purpose of the programme is to assess the potential of deep-sea mineral resources including manganese nodules, cobalt-rich manganese crusts and submarine massive sulphide deposits within the Exclusive Economic Zone (EEZ) of SOPAC member countries.

SOPAC	SOPAC Gloria	1989	Fiji, Samoa, Solomon Is, Tonga, Vanuatu	
France	Subpso	1989	New Caledonia, Tonga, Vanuatu	PMS
China	Geological Survey of the South Pacific	1990	Cook Is, Fiji, French Polynesia, PNG, Solomon Is, Tonga, Vanuatu	Various
UK	Swath Mapping	1992	Tonga	PMS
USA	SeaMARC	1992	PNG	PMS
Australia Canada SOPAC	PacManus	1993-2000	PNG, Solomon Is, Vanuatu	PMS
France SOPAC	ZoNeCo	1993-1994	New Caledonia	
Eurpoean Union	SOPACMAPS	1993	Fiji, Solomon Is, Tuvalu, Vanuatu	
China		1993-1994	Marshall Is.	Cobalt-rich crust
France, Japan SOPAC	STARMER II	1994-1999	Fiji, New Zealand, PNG, Samoa, Solomon Is,Tonga, Vanuatu	PMS

Deep-sea Mineral Resources Cooperation - SOPAC/Japan

The SOPAC/Japan Deepsea Mineral Resources Programme [SOPAC/Japan Programme] is one example of the types of long-term cooperative initiatives that have taken [and continue to take] place between international research organisations and SOPAC, in the region. Since 1985, the SOPAC/Japan Programme's main outputs have included numerous geological and geophysical research cruises in the EEZs of the Cook Islands, Fiji, Kiribati, Marshall Islands, Federated States of Micronesia, PNG, Samoa, Solomon Islands, Tonga, Tuvalu, Vanuatu, the development of an atlas on deepsea mineral resources in the South Pacific Ocean and the design and development of a deepsea mineral resources database.

Three types of offshore mineral deposits are currently the focus of their interest. They include manganese nodules, cobalt-rich crusts and polymetallic massive sulphides. The aim of the SOPAC/Japan Programme is to assess the resource potential of these mineral resources in the region. The programme has proposed future work to include, more detailed research in areas showing promise , conducting baseline environmental assessments and maintaining the GIS deepsea mineral database.

3.1.1.1 Manganese Nodules

Possibly the most explored deep-sea area in the world for manganese nodules is the Clarion-Clipperton Zone, located between the South West of Hawaii and the West Coast of California, and is reported to contain the world's largest occurrence of manganese nodules. However, the work by the SOPAC/Japan Programme has shown that the cobalt metal content and resource density of the manganese nodule reserves in the EEZ of the Cook Islands are significantly greater than that of the Clarion-Clipperton Zone.

The SOPAC/Japan Programme has also identified manganese nodule deposits in the EEZs of Kiribati and Tuvalu. Table 1 illustrates metal contents, abundance and nodule resources in the EEZs of the Cook Islands, Kiribati and Tuvalu. Figure 1 outlines the level of abundance of manganese nodules in the EEZ of the Cook Islands.

Table 2. Metal contents, abundance, and resource of manganese nodule in the survey area

Country [EEZ]	Average Co [%]	Average Ni [%]	Average Cu [%]	Average Abundance [kg/m^2]	Nodule Resource [metric tonnes]
Cook Islands	0.39	0.45	0.29	10.68	7,500,000,000[1]
Kiribati					
• Gilbert Islands	0.23	0.96	0.96	1.54	100,000,000[2]
• Phoenix Islands	0.22	0.66	0.60	4.55	630,000,000[2]
• Line Islands	0.20	0.84	0.57	4.37	670,000,000[2]
Tuvalu	0.20	0.54	0.47	2.74	914,000,000[3]

[1] *Estimated by Clark et al.,1995* [2] *Estimated by Kinoshita and Tiffin, 1993* [3] *Estimated by Kojima, 1999*

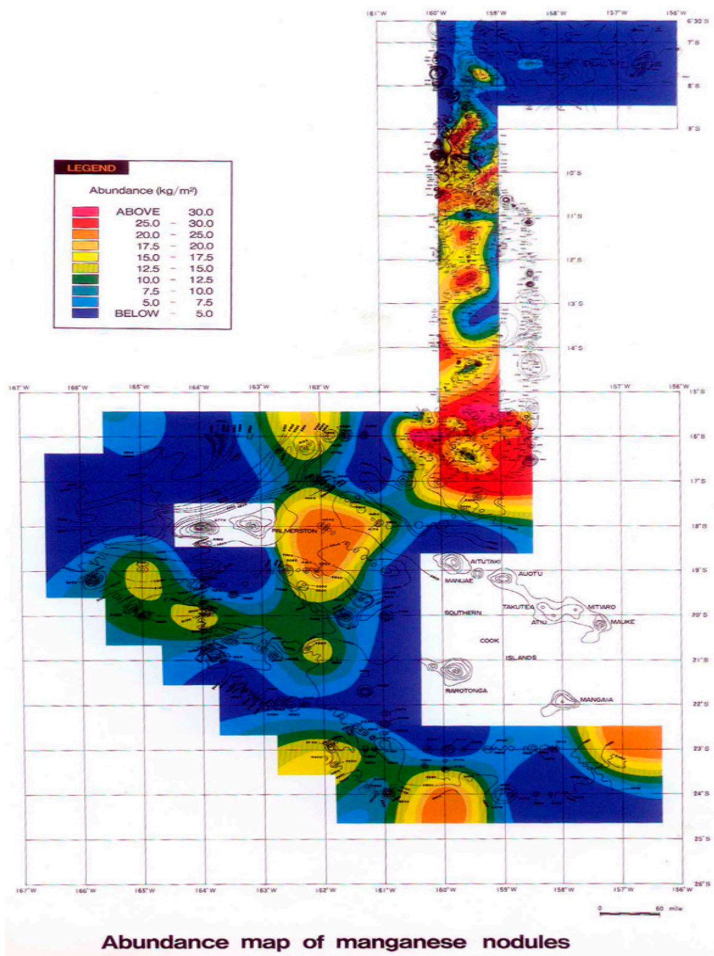

Figure 1. Abundance Map of Manganese Nodules within the EEZ of the Cook Islands

3.1.1.2 Cobalt-Rich Manganese Crusts

The Japan-SOPAC programme continues to investigate the locations of cobalt-rich manganese crusts. Various research initiatives have discovered deposits of cobalt-rich manganese crusts, up to 15cm thick, on terraces and submerged platforms in the EEZs of Kiribati, Tuvalu, Republic of the Marshall Islands, Samoa, Guam and the Federated States of Micronesia. Cobalt-rich crusts have also been found in areas in the western Atlantic and the Caribbean.

The chemical composition of the crusts is similar to that of manganese nodules, with the exception of the cobalt content, which is three to five times greater than that of the manganese nodules. Table 3 lists the metal contents and thickness of cobalt-rich crusts discovered in the Pacific area and Table 4 lists the estimated tonnage of some of these occurrences.

Table 3: Metal contents and thickness of cobalt-rich crusts*

Country [EEZ]	**Co [%]**	**Ni [%]**	**Cu [%]**	**Thickness [mm]**
FSM	0.42	0.33	0.06	
Kiribati				
• Gilbert Islands	0.69	0.58	0.10	12.4
• Phoenix Islands	0.78	0.66	0.11	17.0
• Line Islands	0.62	0.60	0.12	19.5
Marshall Islands	0.71	0.56	0.09	27.7
Samoa	0.41	0.23	0.08	3.4
Tuvalu	0.78	0.50	0.09	19.5

* Data derived from analytical work carried out on samples taken from seamounts during Japan/SOPAC Deep-sea Mineral Resources Programme research cruises.

Table 4: Resource assessment of cobalt-rich crusts in the western Pacific region

Country [EEZ]	**Cobalt [10^6t]**	**Nickel [10^6t]**	**Manganese [10^6t]**	**Platinum [10^6oz]**
FSM	17.76	9.96	496.0	34.7
Guam	0.55	0.31	15.5	0.68
Marshall Islands	10.55	2.49	281.3	21.5
Samoa	0.03	0.01	0.8	0.04

3.1.1.3 Polymetallic Massive Sulphides

Polymetallic massive sulphides [PMS], which are rich in Cu, Zn, Pb, Ag and Au, are currently creating the most excitement in the offshore mineral sector, with Pacific PMS deposits being heralded by some as potentially being "bonanza resources"[6], due to their high gold content.

PMS deposits were first discovered in the Pacific in 1984 in the Southern Lau Basin in water depths of 1800m. More discoveries of sulphide deposits were made in 1986, in the Manus Basin Woodlark Basin and Northern Lau Basin. In 1988 the North Fiji Basin deposits were discovered, east of Fiji.

Preliminary results of research cruises conducted in the EEZs of Vanuatu and the Solomon Islands suggest evidence of hydrothermal activity. More detailed exploration of these may result in further discoveries of PMS deposits. There are at least ten known locations of PMS deposits and hydrothermal sites in the Pacific, refer Figure 2.

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[6] The New York Times of 21 December 1997 reported Pacific PMS deposits as being the "richest volcanic deposits ever found at sea" and estimated their likely value to be in the order of "billions of dollars" if they were situated on-land.

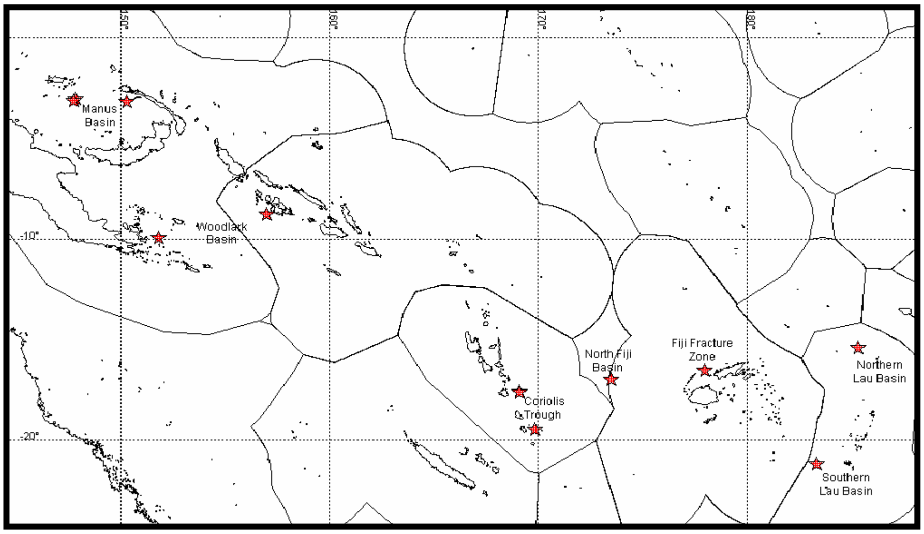

Figure 2: Location Map of Known Polymetallic Massive Sulphides Deposits and Hydrothermal Activity in the SOPAC Region

Table 5: Summary of polymetallic massive sulphides discovered in the Pacific region

	Manus Basin	**Woodlark Basin**	**North Fiji Basin**	**Lau Basin [Northern]**	**Lau Basin [Southern]**
Location					
• Latitude	3 ' 09	9 ' 54.1	16 ' 58	15 ' 23	21 ' 10
• Longitude	150'16.8	151'48.9	173'30	174'41	176'40
Water Depth	2500m	2346-2600m	2500-3000m	2100m	1820 m
Date Discovered	1986	1986	1988	1986	1984
Cruise Identification	Moana Wave 1986 Akademik Mstislav	RV Franklin 1986	RV Kaiyo 1988	SIO Papatua 1986	RV Sonne 1984
Type of Mineralisation	Black Smokers	Hydrothermal Fe-Mn oxides	White Smokers	Black Smokers	Black/White Smokers

Estimated Volume	Unknown [extend 150m]	Unknown	Unknown	Unknown	Unknown [approximately 100m x 20m]
Host Rock	Basalt-Andesite	Basalt-Andesite	Basalt-Andesite	Basalt-Andesite	Basalt-Andesite
Status	Active	Inactive	Inactive	Inactive	Active
Comments	Sulphides Rich in Cu, Zn, Au	Hydrothermal Sulphides	Pyrite rich with anhydrite	Sphalerite, pyrite, chalcopyrite	Sphalerite Pyrite Chalcopyrite Barite Gold

Manus Basin - Both et al (1986), Crook (1990)
Woodlark Basin - Binns et al (1986)
N Lau - Hawkins and Helu (1986), Malahoff and Falloon (1991)
S Lau - von Stackelberg at al (1989), Hawkins (1989), Fouquet (1991)

Although large amounts of PMS data are now available, to date there has been no successful drilling[7] undertaken to estimate volumes of known PMS deposits. Current estimates suggest that a cubic metre of PMS rock would be worth approximately USD 2 000 and would make mining such deposits extremely profitable. Currently, little is known about the costs to extract and process the ore. However, with PMS deposits being located in water depths averaging 2,500m, the costs to extract and process the ore could, for the moment, prohibit development. However, in contrast to the development of the mentioned target resource minerals, it is likely that PMS deposits will be exploited first.

In addition to the potential economic value of PMS deposits, it has been suggested that the potential pharmacological or genetic engineering uses of the diverse biota, associated with active hydrothermal vents, may be significant. As very little is known about these living marine resources, there

[7] A sea floor Boring Machine System was used during the SOPAC/Japan research cruise of the central spreading ridge of the North Fiji Basin, between May 20 and July 2, 1999. BMS core sampling of known mineralised zones was abandoned due to deterioration in the weather.

is currently no regional agency tasked to co-ordinate, monitor and advise on MSR issues relating to this diverse biota.

By identifying a regional agency, which has capacity to co-ordinate research cruise activities [which involve biological sampling], collect data and resulting information, promote and encourage biological sampling at known PMS sites, PICs will be able to encourage research organisations to work on the hydrothermal vent communities situated within their EEZs.

Further, such research will undoubtedly lead to a better understanding of the biota and determine their significance as a potential economic resource, as well as provide opportunities for PICs to benefit from data and resulting information that would otherwise be out of reach due to limited national capacity and funding constraints.

3.2 Marine Scientific Research – SOPAC Databases

3.2.1 MSR Cruise Database

SOPAC's mandate to coordinate MSR cruises extends to collecting, managing and distributing data, for its member countries. The SOPAC Regional Data Centre collates, maintains and continuously updates the database as new MSR data and information is received. Figure 3 shows the level of reported research cruise activity [based on density of ship tracks] in the SOPAC region.

The Data Centre is able to use the cruise database to produce [upon request] special reports, maps and data in a format that is user friendly for its member countries and other customers such as research organisations.

As custodians of large volumes of invaluable data, which SOPAC collects, maintains and stores for its member countries, SOPAC has deemed it pertinent to develop a GIS and Remote Sensing policy to establish a framework for the sound management of these databases. The Policy addresses all aspects of data standards, data confidentiality and data exchange, for the databases that SOPAC maintains for its member countries. Essentially, data is categorised as being either, confidential, regional, country or in the public domain. For country-specific data, the release of data to a third party is conditional upon advising and seeking permission from the country concerned that it is in order for SOPAC to release these.

With regard to post-cruise obligations under UNCLOS, the researching State is required to provide the coastal State with information resulting from the MSR, as well as make these available internationally. Essentially this renders all results of MSR to be open file and to be easily accessible in the public domain. Emerging issues with regard to data confidentiality will become more obvious as the region establishes commercial relationships with industry. These arrangements will inevitably place expectations upon the host country to honour the confidentiality of sensitive data collected within license areas, irrespective of whether they have been collected as part of MSR or as part of exploration.

SOPAC will need to manage this process with sensitivity, mindful of the fact that the activities of both researchers and industry are tantamount to the success of research, discovery, exploration and exploitation. It is widely acknowledged within the SOPAC region that MSR has and will continue to be a very important data collection and assessment mechanism for the region. Both to collect additional information on known deposits as well as to advance research into new and less chartered areas of the Pacific region.

Deep-sea Mineral Resources Database

As part of the SOPAC/Japan Programme initiative, a South Pacific seafloor atlas on deep-sea mineral resources in the South Pacific region was completed and published in 1995. This work summarised the results of the first 10 years of the SOPAC/Japan Programme.This co-operative programme has also resulted in design and development of a deep-sea mineral resources database of selected offshore areas in the SOPAC region[6]. The database is a synthesis of data acquired from databases of key researching organisations[8], which have worked in the Pacific region. The primary focus of the database is to collate existing data and information on manganese nodules, cobalt-rich crusts and hydrothermal deposits.

[8] Data included in the databases of the following research organisations are included the Deep-sea Mineral Resources database designed and developed by Japan and

The types of data that have been integrated into the database include geochemistry, structural characteristics, genetic environment, mineralisation characteristics and geographic position, for manganese nodules and cobalt-rich crusts, and geochemistry, geology and geological structure, morphology and environment, ore deposit and geographic position for deep-sea hydrothermal deposits [polymetallic massive sulphides].

The deep-sea mineral resources database will enable member countries [through SOPAC] to:

- Establish base-line survey databases for environmental assessment.

- Improve existing deepsea mineral resource databases.

- Produce maps, which show data and information based upon specific queries of the database.

- Produce special reports, which are in a format that can be easily understood.

- Publish mineral potential maps.

SOPAC: USGS, NOAA, IFREMER, UH SOEST, UCSD, SCRIPPS Institute, GEOLIS and JAMSTEC. Boring Machine System was able to penetrate 1.0 m

Table 6: Survey Area and Target Resources of the Japan –SOPAC Deepsea Mineral Resources Programme Between 1985 and 1999.

Phase	Year	Country	Survey Area	Target Resource
	1985	Cook Islands	North Penrhyn Basin	Manganese Nodules
	1986	Cook Islands	South Penrhyn Basin	Manganese Nodules
I	1987	Kiribati	Phoenix Islands Group	Nodules and Crusts
	1988	Tuvalu	Ellice Islands and Basin	Nodules and Crusts
	1989	Kiribati	Southern Line Islands	Nodules and Crusts
	1990	Cook Islands Samoa	Southern Cook Islands Samoan Islands	Manganese Nodules Nodules and Crusts
	1991	Kiribati	Gilbert Islands Group	Nodules and Crusts
I	1992	Papua New Guinea	Manus Basin	Hydrothermal Deposits
	1993	Solomon Islands	Woodlark Basin	Hydrothermal Deposits
	1994	Vanuatu	Coriolis Trough	Hydrothermal Deposits
	1995	Tonga	Tonga Rides and East Lau Basin	Hydrothermal Deposits
II	1996	Marshall Islands	Northern part	Cobalt-rich Crusts
	1997	FSM	Whole area	Cobalt-rich Crusts
	1998	Marshall Islands FSM	Southern part Whole area	Cobalt-rich Crusts
	1999	Fiji	North Fiji Basin	Hydrothermal Deposits

This long-term cooperative study has confirmed the resource potential of the Pacific region and it is very likely that this relationship will continue into a full fourth phase. The focus now being to continue research efforts on understanding the characteristics of the most promising areas that have been identified and [based on current knowledge and data] conduct research surveys of other potential areas.

Recently, SOPAC member countries [with offshore mineral resources] have requested that research organisations consider including an environmental management component relating to deep-sea mining in their research programmes. This will enable the region to start collecting some baseline data and information, before mineral development initiatives are struck.

A new agreement between Japan and SOPAC, which commenced in April 2000, covers marine research surveys to be carried out over a three-year period. Each MSR cruise is expected to consist of about five weeks of ship-time and will survey offshore waters of the Cook Islands, Fiji and the Marshall Islands. These areas have been selected based on the encouraging results of previous work conducted during the 15-year programme between SOPAC and Japan, and resulting information from research campaigns of other researching States. The research cruises will focus on detailed ore prospecting in possible mining sites and conducting baseline surveys for environmental purposes. The anticipated budget for this phase of the SOPAC/Japan programme has been estimated to be in the vicinity USD 20 millions, which is to be spent over three years.

4. Offshore Mineral Policy

An Offshore Mineral Policy [OMP] is important for a coastal state with offshore mineral resources in that it sets the legislative baseline and framework upon which the Government can sustainably develop and manage the resources. Policy also informs company's interested in mineral development of the rules, regulations and systems that it faces in host country.

An aspect of SOPAC's work programme is to assist some of its member countries to develop offshore mineral policies. The catalyst to develop national offshore mineral policy and legislation for Pacific Island Countries was precipitated by Nautilus Minerals Ltd.'s application to Papua New Guinea [PNG] for two offshore exploration licences in the Bismarck Sea. The absence of relevant policy and legislative frameworks for offshore mineral exploration, at the time of the application being made, prompted the PNG Government to formulate an Offshore Policy Green paper *ex post*.

In February 1999, at the request of the Government of PNG an international offshore mineral policy workshop was organised by SOPAC, and held in Mandang, PNG. International experts, representing all facets of offshore mineral development attended the workshop and actively participated to develop the guiding principles for policy formulation. SOPAC has developed these recommendations into a set of international offshore mineral policy guidelines, which have been called the *Mandang Guidelines* [Refer Annex I]

Although the *Mandang Guidelines* have been developed in the Pacific for Pacific issues, they might be applicable to developing marine mineral policy elsewhere in the world. The Guidelines cover all aspects of offshore mineral development namely the legal and licensing regime, fiscal regime, environmental guidelines, marine scientific research requirements, stakeholder issues, benefit distribution mechanism and dispute settlement.

Since the offshore mineral policy workshop in Mandang, SOPAC has started to work with the Fiji Mineral Resources Department toward development of an Offshore Mineral Policy. A *Green paper* has been drafted for the Fiji Government and it is currently undergoing extensive national, regional and international[9] stakeholder review. It is the intention of SOPAC to use the Fiji Offshore Mineral Policy as the blue print when working with other member country Governments who have offshore mineral potential, to develop their own mineral policy.

It is widely acknowledged that the scale of investment and technology required for offshore mineral development is beyond the inherent capacity of the small island states of the Pacific. Consequently, SOPAC intends to assist PICs to develop a sound policy and regulatory framework to ensure that exploration and exploitation is conducted in such manner that maximises the economic benefits, whilst at the same time ensuring the protection and preservation of the marine environment.

5. Long-Term Potential of Deep-Sea Minerals

Although the immediate potential for deep-sea mineral development in the SOPAC region, is not imminent, the long-term potential of deep-sea minerals remains promising and cannot easily be dismissed. Since its inception in 1972, SOPAC has been highly effective in promoting, encouraging and supporting [in-kind], MSR in the region.

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[9] Fiji's Offshore Mineral Policy Green paper has been circulated to a panel of international stakeholders comprising policy makers, lawyers, academics, oceanographers, economists and major mining companies, for comment and review.

SOPAC's continuing and relentless promotion for MSR in the region, over the last three decades, has been rewarded with widespread regional MSR activity, resultant discoveries of numerous deposits of deep-sea mineral resources from these, and the acquisition of significant amounts of invaluable data. These discoveries have been instrumental in stimulating interest from industry, which has already resulted in the granting of two deep-sea mineral exploration licenses in the SOPAC region.

SOPAC maintains a certain optimism that with the work that it has been completed in the region to date, as well as the development of a sound licensing and tenement regime, any initial developments of deep-sea mineral resources are likely to occur in the Pacific.

6. Research and Exploration Issues Impacting the SOPAC Region

It is widely acknowledged that, to date, all discoveries of potentially economic deepsea mineral deposits in the region have been a result of marine scientific research. Strong relationships have been developed and fostered between international research organisations and SOPAC, and volumes of invaluable data and information have been collected, analysed and disseminated. Encouraging results from these research campaigns have resulted in ongoing research activity in the region, as well as the commencement of commercial exploration.

Emerging issues facing SOPAC as the region moves toward accommodating commercial exploration of its marine mineral resources, include:

i. Attempting to answer the perplexing question of when marine scientific research ends and prospecting begins, as well as distinguishing between prospecting and exploration.

ii. Clarifying the roles and relationships between research and Government, industry and research and, industry and Government and ensuring that these are articulated in sound offshore mineral policy.

iii. Resolving the issues concerning data reporting and confidentiality. Of particular concern to industry are the issues of data access and, publication and intellectual property rights of commercially sensitive information. For researchers, their professional standing is dependent upon the freedom to publish information. As the views of industry and research are divergent on these issues, it is imperative that they are resolved through extensive consultation.

With regard to marine scientific research and obligations under UNCLOS, issues surrounding the non-compliance of some researching organisations to meet their post-cruise obligations or incompatible formats of data being submitted to SOPAC, following the completion of a cruise still remain.

These issues are slowly being resolved at SOPAC Annual Sessions through continually reinforcing the importance of MSR co-ordination for the region to representatives of international research organisations and SOPAC member countries, re-stating the MSR obligations on the researching State to researchers and communicating SOPAC's requirements regarding data formats.

SOPAC believes that there is a need to provide PICs with sound information and advice on the potential benefits of encouraging research of living marine resources associated with active hydrothermal vents. As there is currently no regional agency tasked to co-ordinate, monitor and advise on MSR issues relating to sampling the living marine resources associated with active hydrothermal vents, PICs are faced with having to make unilateral decisions, based on either limited or no information. Denial to sample results in a lost opportunity to collect invaluable data and limits the ability to determine the potential of the resource. Similarly, sampling without the consent and participation of the coastal state results in the loss of intellectual property by the unsuspecting PIC.

7. Conclusion

Although deep-sea mining may not be a reality for marine mineral deposits occurring within the jurisdictions of PICs in the short-term, it is almost certain that if global trends in metal demand continue to rise, these deposits will be mined at some point. As living and non-living marine resources represent, for many PICs, the only natural resources of any tangible economic significance or development potential, it is imperative that they not lose sight of the potential benefits to be gained from future marine mining developments. Consequently, there is no time for the SOPAC region to rest upon its laurels if it is to be effective in encouraging further research and to attracting industry to explore and develop the region's marine mineral resources.

To ensure that SOPAC does not lose the momentum that it has gained through it's continuing efforts since the early 1970's to promote, encourage, co-ordinate and co-operate in marine scientific research, within the region and to communicate the resulting information from these research in order to stimulate dialogue between PIC Governments, international researchers and key industry players, it must ensure that it continues to:

- Promote, co-ordinate and co-operate in marine scientific research activities within areas that are already the subject of international research to better understand, determine and define these resource sites and to encourage the collection of baseline environmental data and information [in the event of potential mineral development].

- Encourage and co-ordinate marine scientific research activities into new areas, which will result in additional baseline data and information being collected [in the region] and may result in further marine mineral discoveries being made.

- Provide advice and assistance to PICs to ensure that they adopt a considered approach to the sustainable development and exploitation of their deepsea minerals resources.

With the development of rational marine mineral policy and appropriate marine mining legislation, PICs will be in an enviable position to be able to enter into effective dialogue with industry. The development of sound baseline environmental assessment protocols are also being addressed to ensure that managing the marine environment is accorded equal consideration in the event of developing the resource.

It is widely acknowledged that the scale of investment and technology required for marine scientific research and, deepsea mineral exploration and development is well beyond the inherent capacity of individual small island states of the Pacific. However, by adopting a regional approach through SOPAC, PICs have been effective in promoting, co-ordinating and co-operating in marine scientific research within the region. This collective effort has enabled PICs to have access to and, collect and maintain data and information resulting from these research activities, which would otherwise be out of reach due to limited national capacity and resources.

Promising research results have already led to expressions of interest, and requests by several exploration companies for licenses to explore selected areas within the region. Such requests have given rise to new challenges for SOPAC and those PICs with marine mineral resources. To be able to respond effectively to these requests and to address emerging issues as promotion *to explore for marine mineral resources in the region* transcends into the commercial sector, PICs are looking to SOPAC to provide the relevant licensing and tenement advice. PICs are also seeking assistance to enable them to build and implement effective systems and procedures for deep-sea mineral exploration and development.

The regional effort accorded to marine mineral research, exploration and development has enabled countries in the SOPAC family to prepare for realising their development opportunities from deep-sea mining, as a considered collective.

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ANNEX I

The Mandang Guidelines

1. As appropriate, nations should take relevant measures to ensure the provisions of the 1982 Convention become fully implemented within their jurisdictions.

2. Nations should move forward rapidly to delineate the baselines from which the various jurisdictional zones under the United Nations Convention on the Law of the Sea (UNCLOS) ("1982 Convention") are measured and to deposit the appropriate charts and list of co-ordinates with the United Nations.

3. In the case of potential extensions of the continental shelf beyond 200 nautical miles, these data should also be gathered as soon as possible and the appropriate claims filed (bearing in mind the 10-year limit from the date of ratification by the coastal state).

4. Measures should be taken to designate archipelagic and other sea-lanes for the purpose of navigation in accordance with the 1982 Convention and other international conventions.

5. Nations should proceed to select their preferred dispute resolution mechanism as required under the 1982 Convention.

6. In the interests of consistency and simplicity of administration, the unique nature of offshore mineral development activities and the diverse nature of stakeholder interests, coastal states should develop a comprehensive `Offshore Mining Act,' where appropriate, as a distinct country-specific regime which is separate from their existing on land mining acts.
7. The "risk" components associated with the exploration and exploitation of offshore mineral resources should be assessed and considered in the development of an appropriate licensing and fiscal regime.

8. Individual nations should develop a fiscal regime specific for offshore mineral development that accounts for the unique economic aspects of such exploration and development, in particular the high costs of exploration, development and technology development.

9. Initial offshore mineral developments should be viewed as "pioneering efforts" and as such be granted appropriate economic incentives to promote investment and development.

10. Recognising the appropriate instruments within the 1982 Convention regarding the conservation and management of the living resources within coastal states' EEZs, measures should be taken to minimise adverse impacts to the marine environment and to traditional and non-traditional uses of the sea that may be caused by offshore mining.

11. Where appropriate, coastal states should consider making a declaration that the non-living resources beyond the 3-mile limit from the Provincial coastlines are a "Common Heritage of the Nation".

12. Coastal states should adopt a proactive approach in all significant decision making activities related to environmental concerns associated with offshore mineral exploration and exploitation.

13. The collection of baseline environmental data should be a condition of any marine exploration licence. Collection of baseline data should begin as early as possible followed by systematic data collection throughout the term of the exploration licence.

14. Stakeholder groups and their interest should be clearly defined during the formulation of any Offshore Mineral Development Agreement to ensure that the interests of the stakeholders are adequately considered and, where appropriate, incorporated into the agreement.

15. Appropriate programs will need to be developed for the assessment of, and compensation for, impacts of marine mineral development activities on traditional and commercial fishery activities.

16. To facilitate the development and sustainability of national fisheries Government and industry should consider joint development of

industrial support facilities that could service both industries and allow for additional development (mineral processing, fish canning).

17. Offshore mineral policy and legislation should ensure the confidentiality of corporate research and development data within their license area/s.

18. To ensure the long term capability of the coastal states to effectively monitor offshore mineral resources activities, relevant Government representatives should participate in all at-sea phases of MSR, exploration and evaluation and that provision be made, either through appropriation or the creation of special use funds within the responsible agency (ies), to provide adequate human and fiscal resources required for needed data collection and collation, monitoring and enforcement activities.

19. Recognising the unique nature of the biota associated with active hydrothermal zones, activities that ensure an adequate understanding of the biota communities and the impacts of any associated mineral exploration and exploitation should be undertaken by MSR and Industry.

SUMMARY OF THE PRESENTATION ON THE ROLE OF SOPAC IN PROMOTING EXPLORATION OF MARINE MINERAL RESOURCES IN THE PACIFIC.

On behalf of his co-authors, Mr. Alfred Simpson, Director of SOPAC made a presentation of the paper, "The role of SOPAC in promoting exploration of marine mineral resources in the Pacific". In preliminary remarks, Mr. Simpson asked participants how a paper on a regional organization fits into a workshop where scientists have addressed issues related to the development of mineral resources, and others have addressed the development of mineral resources from a national perspective. He noted that at the end of her presentation, Ms. Zaamwani had presented some information on how the Legal and Technical Commission of the Authority performs its functions. Mr. Simpson said that he wanted to address the matter of participation by the members of the Authority in the work of the Authority. He made the observation that in the four or five years of his attendance at sessions of the Authority, other than the approximately twenty or thirty member states who participated keenly in the Authority's work, for the others the situation appeared to be "the lights are on but nobody is at home". He said that he hoped that his presentation would provide a process or a way for this latter group of countries to more actively participate in the work of the Authority through formulating common goals.

Mr. Simpson acknowledged the contributions of his co-authors to paper. He pointed out that Ms. Pratt, with several years of experience working with the Fiji Mineral Resources Department and who had recently joined SOPAC was the primary author. He said that Ms. Pratt had participated in several marine scientific research cruises including the Offshore Drilling Programme (ODP), and had gone on a dive with a submersible in the North Fiji basin. He introduced Mr. Kojima as a Japanese Marine Geologist on assignment with SOPAC, and Mr. Koshy as SOPAC's Resource Economist.

He stated that his presentation would provide participants a background on SOPAC, what it is and where it does its work, its primary focus on marine scientific research on marine minerals, and past, current and emerging issues in its work.

Mr. Simpson said that SOPAC started at about the same time as the Norwegian oil industry in 1972. He said that the origins of SOPAC were initiated at a meeting in Bandung convened by the United Nations Economic Commission for Asia and the Pacific (ESCAP), following the discovery of the Tonga oil seeps. He said that three or four representatives of the Pacific region (Fiji, New Zealand, Tonga and Australia) who attended the meeting began to question how their countries could address issues such as the oil seeps in Tonga. He noted that at the time there was very limited capacity in any of those countries to undertake the work required. Subsequently, Mr. Simpson said that the Committee for Co-ordination of Joint Prospecting for Mineral Resources in South Pacific Offshore Areas [CCOP/SOPAC] was founded under the auspices of the United Nations Economic and Social Commission for Asia and the Pacific [ESCAP]. The Committee's headquarters was based in Suva, and its primary focus was to promote and develop the offshore hydrocarbon and mineral potential of the South Pacific region. Mr. Simpson said that CCOP/SOPAC started with five member States involved in the programme. He said that it grew to sixteen full members and two associate members. It evolved to become an inter-governmental organization in 1984 and changed its name to the South Pacific Applied Geosciences Commission [SOPAC] in 1989.

He described SOPAC'S evolution from a one-programme, long-term oriented institution until the mid-1980s, into a multi-programme institution addressing shorter and medium term issues of interest to member states. In this regard, Mr. Simpson said out that other programmes, including coastal, water resources, sanitation, human resources development, and information technology programmes were introduced. He pointed out that the coastal programme addresses development issues associated with the most important mineral resource in the Pacific region, which is sand and gravel. He said that the Mineral resources Unit within the Resource Development Group has a big role, and the Oceans programme, which was the core programme within SOPAC when it first started. He described the human resource development programme as the backstop for all the programmes, and the information technology programme as the biggest crosscutting programme of SOPAC.

With regard to the name of the organization, Mr. Simpson said that perhaps the use of "Geosciences" was dated. He said that the organization SOPAC had expanded its activities beyond the application of Geosciences in its work to the management of sustainable development. In relation to SOPAC's mission statement, he said that in future there might be a need to reflect this transformation. He described the membership as small island states with limited capacities in marine geosciences (geology, geophysics etc) with very large marine jurisdictions, bigger than the United States for example. He said that the raison d'etre of SOPAC was to pool resources. Mr. Simpson said that SOPAC has a Governing Council that meets on annual basis in different countries of the region. He said that in the absence of scientifically qualified personnel in member countries, the constitution of SOPAC requires a Technical Advisory Group (TAG) to drive the work programme. Mr. Simpson said that with the assistance of the Intergovernmental Oceanographic Commission (IOC), a science and technology resource network feeds into the TAG. He said that members of this network attend meetings and comment on the proposed work programme to ensure that it addresses inputs of relevance to the needs of the region. He said that the work of SOPAC comprises two elements: coordinating and promoting work that takes place in two or more countries, and the second in national programmes. In this absence of capacities to undertake research, Mr. Simpson pointed out that the need for promoting and coordinating marine scientific research in the region became paramount. He said that SOPAC's work is fundamental in this regard. He said that LOS Convention obligations play a crucial role in this regard, and that SOPAC has become a vehicle for implementing some of these obligations. He also said that SOPAC has developed strong links with the ISA and IOC, as well as with a number of marine scientific researching institutions. He mentioned that the Agreement between Japan and the countries of the region for cooperation in marine scientific research in the deep-sea environment since 1985 had been amongst the most successful.

Mr. Simpson informed participants of some of the results of marine scientific research in the region, including discoveries of polymetallic nodules and seafloor massive sulphides, and said that efforts are currently being made to orient SOPAC's work to exploration for these mineral resources. He emphasized the importance of regional cruise coordination in view of the cost of running cruises, and the need to avoid duplication of efforts. In this regard, he pointed out the function of SOPAC to advise member states. He said that 852 cruises have been conducted in the region. He pointed out the need to have common protocols for data acquisition and reporting. He also pointed out that since SOPAC belongs to its Member States, contentious issues with regard to confidentiality of data and information are limited.

Mr. Simpson described the process that had been utilized as one that had consisted of data collection and annual meetings until the discovery of seafloor massive sulphides in Papua New Guinea's marine jurisdiction. He said that the request from Papua New Guinea to SOPAC on how to proceed following this discovery served as a wake up call for the organization and the countries of the region. He said that with the discovery, Papua New Guinea, as well as other countries in the region realized that they did not have a policy for offshore mineral resources. As a result, Mr. Simpson said that SOPAC had begun to concentrate its efforts on assisting some of its members to develop such policies. He recalled that in Mr. Wanjik's presentation, he had described some of the efforts of SOPAC to assist the Government of Papua New Guinea to develop an offshore minerals policy, in particular through the workshop that produced the Mandang Guidelines. He said that it is hoped that these guidelines will be used throughout the region. He said that SOPAC was presently assisting the Government of Fiji to develop such a policy, and that a draft that had been produced was being commented on by all stakeholders. Mr. Simpson said that similar requests from Nuie and the Solomon Islands had been addressed by SOPAC.

Mr. Simpson emphasized that the lack of indigenous capacity by countries in the region results in almost total dependence on the results of the marine scientific research undertaken by other countries. He said that this was particularly true with regard to exploration for mineral resources. He reflected on the discovery in Papua New Guinea, pointing out that the discovery itself had as a basis the results of marine scientific research. He indicated some of the difficulties that occur, pointing out that in the case of Papua New Guinea, which has placed a portion of its seafloor under license, a previously agreed cruise by the Government of Japan had now been refocused to the North Fiji basin under the jurisdiction of Fiji. While noting the benefit that had accrued to the Government of Fiji, Mr. Simpson pointed out that for Papua New Guinea, it is necessary that the work under the license that it had granted proceed with due diligence. He pointed out that if the work under the license does not proceed for one or other reason, it would mean that the database on marine minerals being developed by Papua New Guinea would suffer. He emphasized that the countries of the region want to encourage exploration but were faced with the dilemma of what happens if areas under license are not adequately explored. He suggested that under those circumstances, marine scientific research might be a better option.

Mr. Simpson said that an outgrowth of this potential problem is that SOPAC is assisting member states through clarifying the roles of marine scientific researchers and marine mineral explorers. In the case of Papua New Guinea, Mr. Simpson said that an effort has been made to determine what each group will undertake. He pointed out that a coordinating committee for marine scientific research has been set up in Papua New Guinea, and stated that this was a good basis for developing a programme to clarify roles.

He gave examples of some of the teething problems, including the role of the Ministry of Foreign Affairs of Papua New Guinea in giving approvals for the conduct of marine scientific research.

He pointed out the differences between how data produced from marine scientific research and data obtained from exploration are handled by the parties concerned. In the former, he said that the researchers livelihood is based on publishing. Therefore, while sometimes it could take up to a couple of years to work the data and publish it, in general such data are available to the community as a whole. In the case of data obtained from explorers in areas under license, Mr. Simpson informed participants that invariably one is informed that the concerned stock exchange does not permit the explorer to make such data available.

Mr. Simpson said that a key objective of SOPAC is to encourage capacity building in the region. In this respect, he said that whenever there is a cruise, SOPAC always tries to get a Pacific Island representative on it. He said that when such a representative could not be identified within the region, outside scientists represent the region.

Regarding the potential of the activities undertaken by SOPAC, Mr. Simpson said that member countries are sold on the regional effort because they have no choice. He said that until some of the member countries developed the required national capacities, this would be the situation. He said that SOPAC was also looking at new areas of assistance to member states. He said that one area was with regard to article 76 of the United Nations Convention of the Law of the Sea, and that another was in relation to delimitation. With regard to delimitation, Mr. Simpson said that SOPAC was taking over the functions of the Forum Fisheries Agency in this respect.

He noted that a very important subject matter for the region is physical oceanography. He pointed out that it is necessary for the region to obtain a better knowledge base in order to know the possible impacts of mining and other activities on the water column. He noted that while other parts of the marine ecosystem in the region are being studied, very little data and information are available on this part of it. He informed participants that together with the IOC, SOPAC is trying to establish a Pacific coast global ocean observation system, and a workshop to develop pilot studies to obtain some of the necessary data and information.

In conclusion, Mr. Simpson said that the acquisition of data is the key thing for progress in the work of SOPAC. He said that SOPAC would continue in its efforts to acquire data and information on marine mineral resources, and to promote marine scientific research as the basis for the understanding of these resources. He said that it is hoped that this process would lead to further discoveries, which represents the future of a large number SOPAC's member states. He also said that in the near term, offshore mineral policy would be a key in the region, particularly policy that results in a revision of legislation and that encourages marine mineral exploration and eventual development. He said that for those that do not have the required national capacity, the regional approach is the way to go forward.

SUMMARY OF THE DISCUSSIONS

The discussions that followed Mr. Simpson's presentation focused on SOPAC's authority to issue permits for research conducted in areas that appeared to be part of the international area, and how it ensures that representatives of its member states participate in cruises organized by marine scientific organizations in the region. Before this, however, one participant recalled how in 1978 he was called by the United Nations to lead a team to Suva to CCOP/SOPAC to close the programme down. Dr. Cruickshank said that the opinion had been formed that CCOP/SOPAC was not doing anything. He said that when the team arrived, it was very impressed with the enormous amount of work that had been accomplished, and that was going on. While congratulating Mr. Simpson and SOPAC, he informed participants that the long term planning by SOPAC would prove beneficial in the not too distant future. In this regard, he said that the evolving knowledge of marine mineral resources suggests that on area-by-area basis, the seabeds contain a similar value of minerals as terrestrial areas. He pointed out that the Pacific Ocean contains about half of the seabeds, and that the Island States that form SOPAC have jurisdictions that cover half of these seabeds. He said that this group of states therefore control approximately one quarter of the world's mineral resources.

In his comments, Mr. Simpson spoke about the unique relationship that SOPAC has developed over the years with a group of Technical advisers who come to SOPAC annually at their own cost. He also said that together with the IOC, SOPAC developing a big database on the Pacific Ocean.

Another participant recalling a slide presented by Mr. Simpson that showed ship tracks illustrating cruises in the region, pointed out that some of the tracks traversed the international area. This participant wanted to know which body authorized the research in these areas.

In his response, Mr. Simpson pointed out that the illustration was misleading in that the cruises originated from places such as Hawaii. He said that the tracks showed the entire voyage of the concerned vessels.

Finally, Mr. Simpson was asked how SOPAC ensured that representatives of SOPAC countries participated in all cruises and that such cruises were not a niche of the few.

Mr. Simpson pointed out that information on cruises was obtained either from a member country that had received a request or by the interested party contacting SOPAC. He said that many of the cruises were brought before SOPAC's annual meetings where they were planned and agreed to.

About the International Seabed Authority

The International Seabed Authority is an autonomous international organization established under the 1982 United Nations Convention on the Law of the Sea and the 1994 Agreement relating to the Implementation of Part XI of the United Nations Convention on the Law of the Sea. The Authority is the organization through which States Parties to the Convention shall, in accordance with the regime for the seabed and ocean floor and subsoil thereof beyond the limits of national jurisdiction (the Area) established in Part XI and the Agreement, organize and control activities in the Area, particularly with a view to administering the resources of the Area.

The Authority, which has its headquarters in Kingston, Jamaica, came into existence on 16 November 1994, upon the entry into force of the 1982 Convention. The first Secretary-General of the Authority, Satya Nandan (Fiji) was elected in March 1996, and the Authority became fully operational as an autonomous international organization in June 1996, when it took over the premises and facilities in Kingston, Jamaica previously used by the United Nations Kingston Office for the Law of the Sea. Meetings of the Authority are held at the Jamaica Conference Centre in downtown Kingston.

The International Seabed Authority web site contains detailed information on the organs of the Authority, including the Assembly, Council, Legal and Technical Commission, Finance Committee and the Secretariat. The site also includes a full list of documents issued by the Authority at each of its sessions, and the full text of selected documents. Press releases are available for the latest session and links are provided to some of the most important law of the sea documents. The web site will be updated on a regular basis and it is the intention of the Authority eventually to provide access to non-confidential information relating to deep seabed exploration through these web pages.