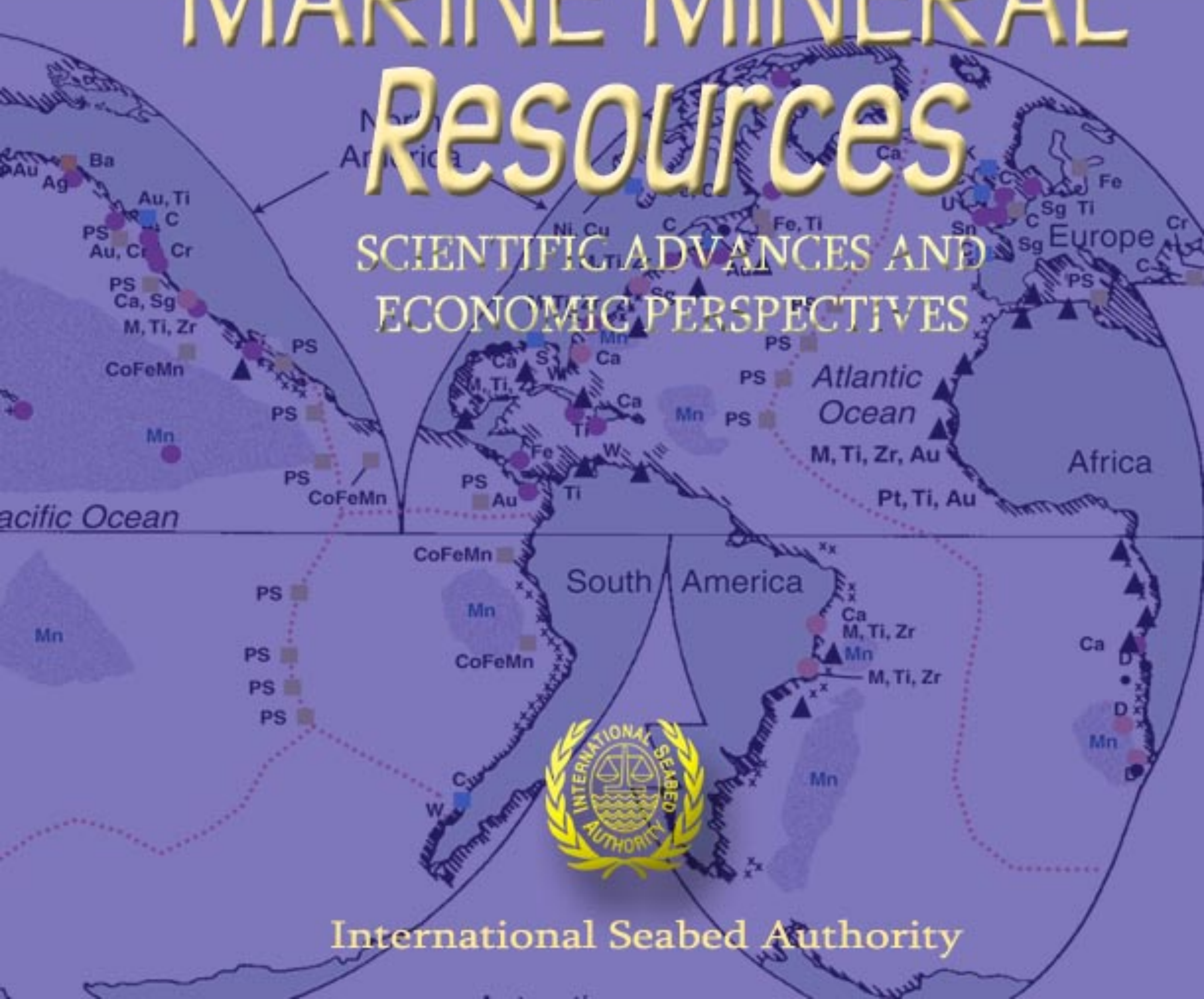
United Nations Division for Ocean Affairs
and the Law of the Sea, Office of Legal Affairs

MARINE MINERAL Resources

SCIENTIFIC ADVANCES AND ECONOMIC PERSPECTIVES



International Seabed Authority

Marine Mineral Resources

Scientific Advances and Economic Perspectives

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Foreword

The 1982 United Nations Convention on the Law of the Sea establishes an international legal regime for the world's oceans and seas. The comprehensive legal regime formed the basis of an international programme of action on the sustainable development of the resources and uses of the oceans and seas, as laid out in chapter 17 of Agenda 21.

The United Nations Division for Ocean Affairs and the Law of the Sea of the Office of Legal Affairs has developed a programme of activities for the realization by States of benefits under the legal regime and the programme of action established by the Convention and Agenda 21, respectively. One area where potential benefits assumed a critical role in the formulation of the legal regime in the Convention and its elaboration is that of marine mineral resources. The potential for the realization of benefits from these resources has expanded considerably both in areas within national jurisdiction and in the international area, as a result of scientific discoveries.

A significant need has been felt for further information about marine minerals, combined with the understanding of the implications of the new discoveries. An important step towards realization of benefits in respect of marine minerals is the acquisition and dissemination of information. To this end, in a joint project with the International Seabed Authority, the United Nations Division for Ocean Affairs and the Law of the Sea has prepared the present study, intended to provide information to member States and to their policy-makers on ocean affairs.

The International Seabed Authority is the organization entrusted, by the Convention, with the responsibility of administering the mineral resources of the international seabed area beyond national jurisdiction.

The United Nations Division for Ocean Affairs and the Law of the Sea, Office of Legal Affairs, and the International Seabed Authority acknowledge the contributions of *Professor Peter Rona* of the Institute of Marine and Coastal Sciences, Rutgers, The State University of New Jersey and of *Dr. Jean Pierre Lenoble*, former Chairman of the Authority's Legal and Technical Commission in the preparation of this publication.

Chapter 1: Introduction

Minerals from marine sources provide raw materials for the manufacturing and construction sectors, energy for industrial and domestic use, fertilizers for the agriculture sector, and importantly, freshwater for the very sustenance of life on earth. While the current contribution of marine mineral resources to the global economy is significant, more recent scientific discoveries suggest that the potential contribution of these resources to the global economy could be even greater.

The exploitation and utilization of marine mineral resources has a long history. Sand and gravel are dredged from the beach and the seabed worldwide. Oil and gas are intensively exploited offshore for several decades. Offshore production of tin in Southeast Asia is considerable. Gold has been mined offshore intermittently. Diamonds are currently extracted from the seabed offshore Namibia and South Africa (Corbett, 2004).

On the scientific side, the understanding of the Earth's processes and of their implications for marine minerals has undergone revolutionary changes over the past few decades. In the past thirty years there have been significant changes in the knowledge about and perception of marine mineral resources. It is commonly known that the globe is three-quarters covered by water. What is not so widely known perhaps is that the potential mineral resources of the seabed are hectare for hectare, equivalent in value to mineral resources on land. The seabed of the Pacific basin and rim alone equals half of the world's surface area, nearly half of which are in areas beyond the limits of national jurisdiction of any State (the Area). The development of the marine mineral resources contained in this basin would significantly affect the future world metals market. The utilization of marine minerals is driven by growing societal needs, which may be met by turning to the sea for materials that are in short supply on land and can be recovered more economically from the sea, or are unique to the sea.

At the beginning of the new millennium, there is already an international legal regime for the world's oceans and seas embodied in the 1982 United Nations Convention on the Law of the Sea ("the Convention"). This is a significant achievement of the international community.

The tenth anniversary of the entry into force of the Law of the Sea Convention would appear to be an opportune moment to provide an overview of the global marine mineral situation to the international community--highlighting the legal regime, explaining the scientific advances, and providing certain broad economic perspectives on potential resources of the Area.[1]

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[1] The study focuses on non-fuel marine minerals only, to keep it within the manageable proportions; however, certain scientific aspects apply to both non-fuel and fuel minerals, and are discussed accordingly.

Chapter 2: The Legal Framework for Marine Mineral Resources: An Overview

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1. Jurisdictional Aspects

The Convention establishes a comprehensive legal order for the world's oceans and seas setting forth the rights and duties of States in various ocean zones and covering all ocean-related activities. Under the Convention, a coastal State is entitled to a territorial sea, a contiguous zone, an exclusive economic zone, and a continental shelf over which it has specific rights and jurisdiction. The Convention also specifies certain duties and obligations of coastal States in each of these zones. These zones have to be measured from baselines, which are normally the low water mark along the coast (normal baselines) or straight or archipelagic baselines defined by reference to lists of geographical coordinates of points. Waters on the landward side of the baseline are internal waters of the State or, in the case of archipelagic baselines, archipelagic waters.

Every State has the right to a territorial sea whose breadth may be established up to a limit not exceeding 12 nautical miles from the baseline.[2] With certain exceptions related to navigation, a coastal State exercises sovereignty over its territorial sea, including the resources contained therein, both living and non-living.

Coastal States may establish a contiguous zone not extending beyond 24 nautical miles from the baselines from which the territorial sea is measured. The rights of a coastal State over the contiguous zone extend to (a) prevention of infringement of customs, fiscal, immigration or sanitary laws and regulations within its territory or territorial sea and (b) punishment of infringement of the above laws and regulations committed within its territory or territorial sea.[3]

Beyond the territorial seas, States may establish an exclusive economic zone (EEZ) extending not more than 200 nautical miles from the baselines from which the breadth of the territorial sea is measured.[4] The exclusive economic zone is subject to a

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[2] Article 3 of the Convention.

[3] Article 33 of the Convention.

[4] Article 56 of the Convention.

specific legal regime according to which the coastal State has sovereign rights for the purpose of exploring and exploiting, conserving and managing the natural resources, whether living or non-living, of the superjacent waters, as well as of the seabed and subsoil. In addition, the coastal State has jurisdiction with regard to the establishment and use of artificial islands, installations and structures, marine scientific research and protection and preservation of the marine environment.[5]

The continental shelf of a coastal State comprises the seabed 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 to that distance.[6] The continental margin comprises the submerged prolongation of the landmass of the coastal State. It consists of the seabed and subsoil of the shelf, the slope and the rise,[7] but does not include the deep ocean floor with its oceanic ridges or the subsoil thereof. While the geological continental shelf may extend up to the outer edge of the continental margin, the Convention prescribes certain criteria for the establishment of the outer limits where it extends beyond 200 nautical miles, and constraints it to a limit of either 350 nautical miles from the baselines from which the territorial sea is measured, or to 100 nautical miles from the 2500 meter isobath, which is a line connecting the depth of 2500 meters.[8] Where the continental margin extends up to 200 nautical miles, or less, the outer limits of the continental shelf coincide with those of the exclusive economic zone.

The coastal State exercises over the continental shelf sovereign rights for the purpose of exploring and exploiting its natural resources.[9] The rights of the coastal States in respect of the continental shelf are exclusive if the coastal State does not explore the continental shelf or exploit its natural resources, no one else may undertake these activities without the express consent of the coastal State.[10]

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[5] Article 56 of the Convention.

[6] Article 76 (1) of the Convention.

[7] Article 76 (3) of the Convention.

[8] Article 76 (4) and 76 (5) of the Convention.

[9] Article 77(1) of the Convention. Non-natural objects such as ship-wrecks are not natural resources.

[10] Article 77(2) of the Convention.

2. *Resources of the Continental Shelf*

The resources of the continental shelf consist of mineral and other non-living resources of the seabed and the subsoil along with living organisms belonging to sedentary species, that is to say, organisms which at the harvestable stage either are immobile, or are unable to move, except in constant physical contact with the seabed or the subsoil.[11] The question of what constitutes sedentary organisms assumes importance in areas of continental shelf beyond 200 nautical miles, since the superjacent waters there are high seas and not waters of EEZs. The rights of a coastal State over the continental shelf do not affect the legal status of the superjacent waters or of the airspace above those waters.

An important aspect of the regime of the outer continental shelf jurisdiction is that the coastal State is required to make payments or contributions in kind in respect of the exploitation of mineral resources beyond 200 nautical miles after the first five years of production at a site. Production does not include resources used in connection with exploitation. The Convention provides that for the sixth year, the rate of payment or contribution shall be 1 per cent of the value or volume of production at the site. The rate shall increase by 1 per cent for each subsequent year until the twelfth year and shall remain at 7 per cent thereafter.[12] A developing State, which is a net importer of a mineral resource produced from its continental shelf, is exempt from making such payments or contributions in respect of that mineral resource.[13] The payments or contributions shall be made through the International Seabed Authority, which will distribute them to the States that are parties to the Convention, on the basis of equitable sharing criteria, taking into account the interests and needs of developing States, particularly the least developed and the landlocked among them.[14]

The provisions of the Convention relating to marine scientific research are very relevant for the evolving legal framework for marine mineral resources. The Convention does not define the term marine scientific research. However, according to the Convention, marine scientific research on the continental shelf shall be conducted with the consent of the coastal State. In normal circumstances coastal States shall grant their consent for marine scientific projects by other States or competent international

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[11] Article 77(4) of the Convention.

[12] Article 82 (2) of the Convention.

[13] Article 82 (3) of the Convention.

[14] Article 82(4) of the Convention.

organizations for peaceful purposes and in order to increase scientific knowledge of the marine environment for the benefit of all mankind, and shall establish rules and procedures ensuring that such consent will not be delayed or denied unreasonably.[15] Coastal States may however in their discretion withhold their consent to the conduct of a marine scientific research project of another State or competent international organization, if that project:[16] is of direct significance for the exploration and exploitation of natural resources, whether living or non-living; involves drilling into the continental shelf, the use of explosives or the introduction of harmful substances into the marine environment; involves the construction, operation or use of artificial islands, installations and structures.

The Convention grants States the sovereign right to exploit their natural resources pursuant to their environmental policies and in accordance with their duty to protect and preserve the marine environment.[17] States must adopt laws and regulations to prevent, reduce and control pollution of the marine environment arising from or in connection with seabed activities subject to their jurisdiction and from artificial islands, installations and structures under their jurisdiction which must be no less effective than the international rules, standards and recommended practices and procedures to be established.[18]

3. *Resources of the Area*

The area beyond the legal continental shelf is referred to in the Convention as the "Area". The Area comprises the seabed and ocean floor and subsoil thereof beyond the limits of national jurisdiction. It is governed by Part XI of the Convention and the 1994 Agreement Relating to the Implementation of Part XI of the Convention (Agreement). In accordance with article 2 of the Agreement, the provisions of the Agreement and Part XI of the Convention are to be interpreted and applied together as a single instrument. In the event of any inconsistency between the Agreement and Part XI, the provisions of the Agreement shall prevail.

The Convention provides that the Area and its resources are the common heritage of mankind.[19] States Parties to the Convention agree that there shall be no

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[15] Article 246 (3) of the Convention.

[16] Ibid; paragraph 5.

[17] Article 193 of the Convention.

[18] Article 208 of the Convention.

[19] Article 136 of the Convention.

amendments to the basic principle relating to the common heritage of mankind set forth in article 136 and that they shall not be a party to any agreement in derogation thereof.[20] The Convention defines the term resources as all solid, liquid or gaseous mineral resources *in situ* in the Area at or beneath the seabed, including polymetallic nodules. When recovered from the Area, resources are referred to as "minerals".[21] The Convention also establishes an autonomous international organization, the International Seabed Authority ("the Authority"), through which States Parties shall organize and control activities in the Area in particular with a view to administering its resources of the Area.[22] All rights in the resources of the Area are vested in mankind as a whole, on whose behalf the Authority acts.[23] The Authority is also empowered to engage in seabed mining in its own right, through its commercial arm, the "Enterprise".[24] The Authority came into existence on 16 November 1994, upon the entry into force of the Convention. Its headquarters are in Kingston, Jamaica.

Since the early 1970s considerable investments have been made in research and prospecting for polymetallic nodules in deep-sea areas. As a result of this one of the major issues during the eleventh session of the Third United Nations Conference on the Law of the Sea was the question of protection of preparatory investments in seabed mining, which had already taken place prior to the adoption of the Convention. Resolution II of the Final Act of the Conference (entitled "Governing Preparatory Investment in Pioneer Activities Relating to Polymetallic Nodules") adopted by the Conference provided for registration of certain States and entities as pioneer investors by the Preparatory Commission, upon fulfillment of certain conditions. That resolution named: (a) France, India, Japan and the former Union of Soviet Socialist Republics; (b) four entities which possessed the nationality of or were effectively controlled by one or more of the following States or their nationals: Belgium, Canada, the Federal Republic of Germany, Italy, Japan, the Netherlands, the United Kingdom of Great Britain and Northern Ireland and the United States of America; and (c) any developing State that signed the Convention. All three categories of States or entities were eligible for pioneer investor status provided they expended at least $US 30 million before 1 January 1983.

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[20] Article 311(6) of the Convention.

[21] Article 133 of the Convention.

[22] Articles 156 (1), and 157 (1) of the Convention.

[23] Article 137(2) of the Convention.

[24] Article 170, Annex IV and the Agreement relating to Implementation of Part XI of the Convention.

By the final session of the Preparatory Commission, the General Committee had registered seven pioneer investors.[25] In accordance with paragraph 14 of Resolution II, the resolution ceased to have effect when the Convention entered into force on 16 November 1994. In this regard therefore, the immediate task of the Authority upon its establishment was to begin its work on Regulations for Prospecting and Exploration of Polymetallic Nodules in the Area, based on the earlier work done by Special Commission 3 of the Preparatory Commission, and subsequent developments so as to enable the Authority to enter into contractual arrangements with the registered pioneer investors. The regulations were finally adopted by the Council and approved by the Assembly of the Authority in July 2000.[26] Thereafter the Authority entered into 15-year exploration contracts with all the seven registered pioneer investors, thus bringing to an end the interim regime established by resolution II.[27]

These regulations supplement the provisions of Part XI and Annex III of the Convention in the sense that they clarify the procedural requirements that must be completed in order to enter into a contract with the Authority. The regulations apply only to polymetallic nodules and the phases of prospecting and exploration. They define the terms “prospecting” and “serious harm to the marine environment”, which were not defined in the Convention. The Authority has also adopted recommendations for the guidance of contractors for assessment of possible environmental impacts arising from exploration for polymetallic nodules in the Area, pursuant to regulation 31.

In August 1998, the Authority was requested to adopt rules, regulations and procedures for exploration for polymetallic sulphides and cobalt-rich ferromanganese crusts.[28] At the tenth session of the Authority held in June 2004, the Legal and Technical Commission submitted the draft regulations on prospecting and exploration for

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[25] These were India on 17 August 1987, Institut Français de recherche pour l’exploitation de la mer/l’Association Franc aise pour l’étude et la recherche des nodules (IFREMER/AFERNOD) (France), the Deep Ocean Resources Development Company (Japan), and Yuzhmorgeologiya (Union of Soviet Socialist Republics) [now Russian Federation], all on 17 December 1987, the China Ocean Mineral Resources Research and Development Association (China) on 5 March 1991, Interoceanmetal Joint Organization
(Bulgaria, Cuba, the Czech and Slovak Federal Republic [now the Czech Republic and Slovakia], Poland and the Union of Soviet Socialist Republics [now Russian Federation], on 21 August 1991 and the Republic of Korea on 2 August 1994.

[26] ISBA/6/A/18.

[27] See the report of the Secretary-General of the International Seabed Authority to the Assembly of the Authority at its eighth session, ISBA/8/A/5, paragraph 37.

[28] See the request of the Russian Federation as reported in the statement of the President on the work of the Assembly, ISBA/4/A/18, and paragraph 14.

polymetallic sulphides and cobalt-rich ferromanganese crusts in the Area for consideration by the Council.

As far as possible, the new regulations follow the framework of the regulations for polymetallic nodules and are in conformity with the provisions of the Convention and the Agreement. However, in view of the differences between polymetallic nodules and these two mineral resources, and the differences between the two mineral resources themselves in terms of their location and dimensions on the seabed, certain issues needed to be addressed. These issues relate to the size of the exploration area, relinquishment provisions, and the system of exploration. The new draft regulations also provide that an applicant may either opt for the parallel system[29] as is the case with polymetallic nodules, or choose to offer an equity interest, joint venture or production sharing participation to the Enterprise[30].

4. Biological Diversity

Under the Convention, States have the sovereign right to exploit their natural resources in accordance with their duty to protect and preserve the marine environment. Marine organisms are associated with marine mineral deposits in all regions of the ocean. In activities relating to marine minerals, such as prospecting, exploration and exploitation, the protection and preservation of the marine environment needs to address the protection of marine organisms and the conservation of biological diversity.

With respect to marine organisms and the related issue of biological diversity, the provisions of the Convention on Biological Diversity need to be taken into account. The objectives of the *Convention on Biological Diversity* are the conservation of biological diversity, the sustainable use of its components and the fair and equitable sharing of the benefits arising out of the utilization of genetic resources. This Convention makes two important distinctions with respect to its jurisdictional application: on the one hand, between "components of biological diversity" and "activities and processes" and, on the other, between areas within and those beyond the limits of national jurisdiction. In areas within national jurisdiction, the provisions of the Convention on Biological Diversity apply to components of biological diversity and to activities and processes that may have adverse impacts on biological diversity. In areas beyond the limits of national jurisdiction, the provisions of the Convention only apply to activities and processes carried out under a Party's jurisdiction or control which may have adverse

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[29] As provided for in Article 8, Annex III of the Convention.

[30] ISBA/10/C/WP.1. The Council will consider the draft regulations at its eleventh session in Kingston, 15-26 August 2005.

impact on biological diversity. Because they have no sovereignty or jurisdiction over the resources, Parties have no direct obligation with regard to the conservation and sustainable use of specific components of biological diversity in areas beyond the limits of national jurisdiction; consequently, the Convention on Biodiversity only underscores the need for cooperation amongst Parties for the conservation and sustainable use of biological diversity.

The Convention requires the International Seabed Authority to take necessary measures in respect of activities in the Area to provide effective protection for the marine environment from activities that may have harmful effects, including interference with the ecological balance of the marine environment. Such measures are to be aimed at protecting and conserving the natural resources of the Area, as well as at preventing damage to the flora and fauna of the marine environment. Between the entry into force of the Convention and the approval of the first plan of work for exploitation, the Agreement specifically requires the Authority to concentrate on, inter alia "Promotion and encouragement of the conduct of marine scientific research with respect to activities in the Area and the collection and dissemination of the results of such research and analysis when available, with particular emphasis on research related to the environmental impact of activities in the Area", and " Adoption of rules, regulations and procedures incorporating applicable standards for the protection and preservation of the marine environment.

In the Regulations on Prospecting and Exploration for Polymetallic Nodules, the Legal and Technical Commission did not elaborate detailed regulations on the protection of the marine environment but rather incorporated basic principles and procedures on this matter. Regulation 18 (Data and information to be submitted for approval of a plan of work for exploration) that is found in Part III (Applications for approval of a plan of work for exploration in the form of contracts) requires the applicant to, *inter alia*, submit:

(i) A preliminary assessment of the possible impact of the proposed exploration activities on the marine environment;

(ii) A description of the programme for oceanographic and environmental baseline studies in accordance with these Regulations and any environmental rules, regulations and procedures established by the Authority that would enable an assessment of the potential environmental impact of the proposed exploration activities, taking into account any recommendations issued by the Legal and Technical Commission, and

(iii) A description of proposed measures for the prevention, reduction and control of pollution and other hazards, as well as possible impacts to the marine environment.

Regulation 31 of Part V of the Regulations (Protection and preservation of the marine environment) states that each contract shall require the contractor to gather environmental baseline data and to establish environmental baselines, taking into account any recommendations issued by the Legal and Technical Commission, against which to assess the likely effects of its programme of activities under the plan of work for exploration on the marine environment and a programme to monitor and report on such effects. The recommendations issued by the Commission may, inter alia, list those exploration activities that may be considered to have no harmful effects on the marine environment. The contractor shall cooperate with the Authority and the sponsoring State or States in the establishment and implementation of such monitoring programme. In addition, contractors, sponsoring States and other interested States or entities shall cooperate with the Authority in the establishment and implementation of programmes for monitoring and evaluating the impacts of deep seabed mining on the marine environment. If a contractor applies for exploitation rights, it shall propose areas to be set aside and used exclusively as impact reference zones and preservation reference zones. "Impact reference zones" means areas to be used for assessing the effect of each contractor's activities in the Area on the marine environment and which are representative of the environmental characteristics of the Area. "Preservation reference zones" means areas in which no mining shall occur to ensure representative and stable biota of the seabed in order to assess any changes in the flora and fauna of the marine environment.

To facilitate the work of the Legal and Technical Commission with regard to issuing recommendations to contractors on gathering environmental baseline data, establishing environmental baselines and establishing programmes for monitoring and assessing the likely effects of contractors activities on the marine environment, and in accordance with article 165, paragraph 2(e) of the Convention,[31] the Authority convened its very first workshop in June 1998.[32]

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[31] Paragraph 2 (e) of article 165 states that the Commission shall make recommendations to the Council on the protection of the marine environment, taking into account the views of recognized experts in the field.

[32] Deep seabed polymetallic nodule exploration: Development of environmental guidelines. Proceedings of the International Seabed Authority's workshop held in Sanya, Hainan Island, People's Republic of China 1-5 June 1998. ISA/99/02.

A number of leading scientists in the field, policy-makers and representatives of registered pioneer investors attended this workshop. In addition to proposing draft environmental guidelines for the assessment of the environmental impact of polymetallic nodule mining for consideration by the Legal and Technical Commission[33], the workshop also made a number of recommendations on cooperative research on remaining environmental problems that needed to be addressed for the Authority to be able to manage impacts from future deep seabed mining of polymetallic nodules. These recommendations took into account the dearth of knowledge of the marine environment in deep seabed areas including the fact that information on the natural variability in such ecosystems had not been studied, that methods used to acquire critical data are not standardized, that most animals or organisms found in the deep sea are new to science and that understanding of the specifics of ocean water dynamics was in its infancy. The recommendations distinguish between work to be undertaken by contractors and those efforts whose results would be required by the Authority to fulfil its responsibilities but could not be made a contractor responsibility. Specifically the workshop recommended the study of the latitudinal and longitudinal patterns of biodiversity; systematic and taxonomic studies of deep-sea biota; standardization of environmental data and methods of acquisition; critical analysis of the siting of Preservation Reference Zones; burial rate studies; and studies of the natural variability of deep-sea ecosystems.

The guidelines and recommendations of the workshop were submitted to the Legal and Technical Commission at the fifth session of the Authority.[34] Following its consideration and revision of the document, including the introduction of an explanatory commentary and some required technical adjustments, on 4 July 2001, the Commission adopted the recommendations for the guidance of contractors for the assessment of the possible environmental impacts arising from exploration of polymetallic nodules in the Area[35] and decided to issue them pursuant to regulation 38 of the exploration code for polymetallic nodules.[36] The recommendations for guidance describe the procedures to be followed in the acquisition of baseline data and the monitoring to be performed during and after any activities in the exploration area that have a potential to cause serious harm to the environment.

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[33] The draft guidelines that are to be found in the proceedings of the workshop also contain lists of exploration activities that are not expected to cause serious harm to the marine environment and those with potential for causing environmental harm.

[34] ISBA/5/LTC/1.

[35] The recommendations are contained in document ISBA/7/LTC/1/Rev.1.

[36] The recommendations are contained in document ISBA/7/LTC/1/Rev.1. See also the report.

For the Authority, a clear outcome of this workshop was the need for standardization of environmental data and information on deep seabed polymetallic nodule deposits if future impacts from deep seabed mining were to be properly managed. In the absence of such standardization, it would not be possible to compare the situation under pristine conditions and subsequently when mining occurred. In this regard, an important requirement under the overall standardization strategy was the need for taxonomic standardization of deep seabed fauna associated with these deposits, so that species were described in a systematic manner to ensure that species extinctions did not occur as a result of deep seabed mining. Another outcome of the workshop was the need to determine the impact of natural variability on deep seabed ecosystems. Such information is deemed to be essential to describe the pristine state and to assess the degree of environmental harm that might occur from mining.

To further the scientific understanding of the biological environment of the potential mining areas in the Clarion-Clipperton Fracture zone (CCZ), the Authority is currently collaborating in a research project coordinated through the University of Hawaii to study the biodiversity, species ranges and gene flow in the abyssal Pacific nodule province with a view to predicting and managing the impacts of deep seabed mining. Other institutions participating in the project include the British Natural History Museum, the Southampton Oceanography Center (United Kingdom), Japan Marine Science and Technology Centre (JAMSTEC), and IFREMER (France). The project is referred to as the Kaplan project because of its main funding source, the J.M. Kaplan Fund. The aims of the project derive from the first workshop of the Authority, and the project focuses on:

(i) Determining the number of Polychaetes, nematode and foraminiferal species at a number of stations in the CCZ using modern molecular methods that can facilitate standardization among scientists, prospectors and contractors;

(ii) The use of state-of-the-art molecular and morphological techniques to evaluate levels of species overlap and rates of gene flow for key components of the polychaete, nematode and foraminiferal fauna.

There are concerns that the biological resources of seamounts are potentially threatened by activities for the development of ferromanganese crusts deposits, while biodiversity associated with hydrothermal vents may be damaged by activities for the development of polymetallic sulphides deposits. Consequently, collaborations will be required to undertake marine scientific research to ascertain the biodiversity found around potentially mineable deposits of these resources, and to study species ranges and gene flow as well. Further marine scientific research would facilitate the development of legal regimes for non-living and living resources.

In this regard, the Authority is planning to cooperate in two programmes within the Census of Marine Life that are directly relevant to its work. These are programmes being undertaken by the Chemosynthetic Ecosystem Group (ChEss) and the Seamounts Group (CenSeam).

Chapter 3: Marine Mineral Resources: Scientific Aspects

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1. *Introduction*

A scientific revolution in our understanding of the way the Earth works started in the 1960's that significantly expanded our knowledge of marine minerals while the 1982 United Nations Convention on the Law of the Sea was being formulated and adopted. The scientific revolution entailed a major change in viewing the ocean basins and continents. Before the scientific revolution, the ocean basins were viewed as big bathtubs that passively contained the oceans. The continents and ocean basins were viewed as permanent features that had remained in their present positions through most of Earth's history. The marine mineral provisions of the Convention recognized those non-fuel marine mineral deposits that were derived from erosion of land and carried into the ocean in particulate or dissolved form by rivers. These minerals comprised heavy metal deposits (tin, gold, etc.), gemstones (especially diamonds), sand and gravel (aggregates) deposited in sediments of continental margins, phosphorites deposited on hard rock substrates of continental margins, and polymetallic nodules (nickel, cobalt, iron, and manganese in varying concentrations) precipitated on the floor of the deep ocean from metals dissolved in seawater. Of these minerals, tin, diamonds, and sand and gravel are viable industries, with the largest annual production value attributed to sand and gravel.

The scientific revolution, based on a theory called plate tectonics, changed our view of ocean basins from big bathtubs to dynamic features that open and close on a time scale of tens to hundreds of millions of years with concomitant movement of the land areas known as continental drift. The scientific revolution recognized the ocean basins as sources of types of non-fuel mineral deposits in addition to those previously known derived from erosion of land. These newly recognized types of marine mineral resources include polymetallic massive sulphides containing copper, iron, zinc, silver, gold and other metals in varying amounts. Polymetallic sulphides deposits are concentrated over thousands of years by seafloor hot springs at sites along an active global submerged volcanic mountain range that extends through all the ocean basins of the world, largely in the international seabed Area. Polymetallic sulphides deposits also occur at submarine sites offshore volcanic island chains, such as those along the western boundary of the Pacific Ocean, largely within the 200 nautical mile exclusive economic zones of the coastal States. Another newly recognized type of marine mineral resource is cobalt-rich iron-manganese (ferromanganese) crusts that are precipitated over millions of years on the submerged flanks of inactive underwater volcanoes from metals dissolved in seawater derived from input of metals by both rivers and seafloor hot springs. None of these newly recognized types of marine mineral deposits are renewable resources, as they all require thousands to millions of years to accumulate in economically interesting grades and tonnages. They are resources for the future with no present production. We are still at an early stage in exploration of the oceans with only a few percent of the seafloor known in detail and even less known about what lies beneath the seafloor, so new discoveries will continue to be made.

Life is ubiquitous in the oceans and at least as diverse as on land. Different assemblages of macrofauna (animals visible with the naked eye), microfauna (microbes visible with a microscope), and meiofauna (animals that are intermediate in size between macrofauna and microfauna) are associated with all types of marine mineral deposits. A particularly close relation exists between minerals, microbes, meiofauna and macrofauna in the case of polymetallic massive sulphides deposits that are being deposited by metal-rich hot springs associated with volcanic activity at plate boundaries. The hot springs not only concentrate polymetallic massive sulphides deposits and disperse metals into the oceans that contribute to the accumulation of cobalt-rich ferromanganese crusts and polymetallic manganese nodules, but provide chemical energy from the Earth's interior that is used by microbes for their growth. The microbes are at the base of the food chain of an ecosystem of life forms at the hot springs that is largely independent of the light energy that fuels the photosynthesis in plants at the base of the food chain on land. The microbes are proving important as the source of new compounds for industrial and medical applications, and also include primitive forms that may hold the key to the origin of life on Earth and beyond. A present challenge is to incorporate marine mineral resources into the regimes of the Convention and of coastal States in a way that protects the valuable life forms that they host.

This chapter presents a brief survey of major types of non fuel marine mineral resources before and after the advent of plate tectonics in terms of their seafloor settings, characteristics, processes of concentration, global distribution, and environmental considerations.

2. The Science of Marine Minerals

2.1 The Science of Marine Minerals: Before the Theory of Plate Tectonics

Prior to the advent of the theory of plate tectonics in the 1960s, the ocean basins were regarded as passive containers like big bathtubs that simply held the oceans and served as a repository for the rock material washed in from the continents. The ocean basins and continents were then considered to be permanent features that had remained in their present positions and retained their present shapes through much of the Earth's 4.6 billion year history.

This pre-plate tectonic view of the Earth correctly recognized those marine minerals that are derived by two processes of erosion of rocks on land and their transport into the ocean primarily by rivers. The first erosional process involves the mechanical breakdown of rocks exposed on land and transport of this material as sediment into the ocean where it is sorted into deposits by moving water (*see Table 1*).

Principal minerals concentrated by this process constitute sand and gravel (aggregates), which occur as beach deposits, and metallic minerals and gemstones mechanically concentrated by virtue of their high density into what are termed “placer” deposits (the word “placer” is derived from the Spanish word “placel” meaning sandbank). The metallic minerals include those that contain useful metals (*Table 2*) including barium, chromium, gold, iron, rare earth elements, tin, titanium, thorium, tungsten and zirconium.

Table 1. Marine mineral resources (modified from Rona, 1983; Cruickshank, 1998)

REGION	ORIGIN	MODE OF OCCURRENCE			
		Unconsolidated (mineral)	Consolidated	Fluid	Heat
Continental Margin (shelf, slope and rise)	Terrigenous (derived by erosion and weathering of rocks on land)	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	

REGION	ORIGIN	MODE OF OCCURRENCE			
		Unconsolidated (mineral)	Consolidated	Fluid	Heat
				Boric acid Calcium Fluorite Potassium Strontium Sulphate Thorium	
	Biogenic (derived from 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 & gas)	
	Authigenic (precipitated from seawater)	Lime (calcite, 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)		

REGION	ORIGIN	MODE OF OCCURRENCE			
		Unconsolidated (mineral)	Consolidated	Fluid	Heat
			Sulpher (pure and as Sulphate)		
	Diagenetic (produced by alteration of existing material)	Placer deposit: Phosphorite (apatite, fluorapatite, etc.)	Solid layered deposit: Phosphorite		
	Volcanogenic (derved from volcanoes)		Lode and vein deposits (all elements) Massive sulphides deposits (copper, iron, zinc, silver, gold)	Freshwater	Geothermal energy
Ocean Basin	Meteoric (derived from the atmospherie)			Fresh water (desalination of seawater)	
	Biogenic		Methane hydrate	Petroleum (oil & 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		

REGION	ORIGIN	MODE OF OCCURRENCE			
		Unconsolidated (mineral)	Consolidated	Fluid	Heat
			Chromium (chromite)		
			Sulpher (pure and as Sulphate and sulphides)		
				Hydrothemal fluids (heat and metals)	
					Geothermal energy

Table 2. Materials in marine minerals

Material	*Type of Deposit*	*Use*
Non-metals		
Solutes including chloride, sodium, Sulphate, magnesium, calcium, potassium, bicarbonate, bromide, boric acid, strontium, and fluorite	Seawater	Various elements and compounds with diverse properties and applications including table salt (sodium chloride)
Freshwater as liquid or ice	Seawater	Freshwater extracted from seawater by desalination or freezing processes; essential for life and a wide range of agricultural, industrial, and domestic applications
Sand and gravel	Beach	Building material (cement), landfill and beach replenishment.
Lime (mud or sand composed of calcium carbonate)	Beach	Used for production of metals, paper, plastics, paint, disinfectant, water treatment, and building compounds (cement and plaster)
Silica (silicon dioxide)	Beach	Used in metal alloys, plastics, lubricants, glass making, as a conductor in integrated circuits and other electrical components, and insulator, and in enamels, pottery, lasers and solar cells; silica sand is also used in building materials and for restoration of beaches and shore protection
Diamond (as mineral diamond)	Placer	Composed of carbon transformed into the hardest of all minerals used for jewelry and industrial cutting applications
Phosphorus (in Phosphorite rocks made of up apatite, fluorapatite and other phosphate minerals)	Placer	Used in fertilizers, insecticides, fireworks, baking powder, chinaware, glass, water softeners, soft drinks, pharmaceuticals, and metal treatments
Calcium carbonate	Coral	Jewelry and decorative material

Sulpher (as native Sulpher and in minerals including anhydrite and gypsum)	Consolidated	One of the most important and intensively used chemical elements; major use is in agriculture; 90 percent is used as Sulpheric acid; used also in industrial processes (e.g., paper making) and pharmaceuticals.
Antimony (in mineral stibnite)	Polymetallic massive sulphides deposits	Used as an alloying agent in lead-accumulator plates, semi-conductors, type metal, bearing alloys, solders, and pewter; antimony compounds are used in flame-proofing paints, ceramics, enamels, glass pottery, rubber technology, and dye-stuffs
Arsenic (main source is in sulphides ores and minerals orpiment and realgar)	Polymetallic massive sulphides deposits	A grey metal is most common form; arsenic and its compounds are used in insecticides, as a doping agent in solid-state devices (semi-conductors, transistors, lasers) and in alloys including lead-based paints to promote hardening; arsenic compounds are accumulative poisons.
Barium (in minerals barite and witherite)	Placer and in consolidated form associated with polymetallic massive sulphides	A soft silvery-white heavy metal used for drilling fluids in oil wells, paints, fireworks, glass and rubber making, and as an x-ray tracer in medical applications.
Cerium	Cobalt-rich ferromanganese crusts	Metal used in heat resistant alloys, especially gas lantern mantles, as a component in glass and ceramics, in carbon arc lamps, and as a catalyst in self-cleaning ovens, and in certain nuclear applications.
Chromium (in mineral chromite)	Placer and consolidated rocks of the Earth's mantle	A lustrous, hard, bluish-gray metal used to make stainless steel; can be polished to a mirror-like finish and used as a decorative and protective plating; hardens steel and may be used in alloys; also used as a yellow coloring agent in the textile industy, and in tanning leather.
Cobalt	Manganese nodules and cobalt-iron manganese crusts	Shiny, brittle, bluish- gray metal used in jet and gas turbine engines, in steel alloys, in paints and dyes, and as a blue coloration in glass, enamels and pottery; mixed with iron and nickel it creates an alloy with strong magnetic properties; also medical applications
Copper (in minerals chalcopyrite, chalcocite and others)	Manganese nodules and massive sulphides deposits	A malleable, ductile, reddish metal that is an excellent conductor of electricity; primary use is in electrical wiring; also used in coins, ornamentation and building materials (plumbing and roofing).
Gold (as microscopic grains in various minerals and rocks)	Placer and massive sulphides	A soft, shiny, malleable, ductile, non-corrosive metal used for currency, jewelry, dental work, electrical/electronic components, photography, heat shields, and pharmaceuticals

Indium	Polymetallic massive sulphides	A soft, shiny, silvery-white metal used in making low melting point alloys for safety devices and solders; some indium compounds are used in transistors, photo-conductors, photocells and thermostats.
Iridium (in mineral osmiridium and as a native platinum alloy)	Polymetallic manganese nodules	One of the platinum group of metals with a high melting point and good mechanical properties; main uses are electrochemical (25per cent), catalysts (8per cent), crucibles (11per cent), and to encapsulate radioactive fuels in space.
Iron (in minerals hematite, pyrite, magnetite, and siderite)	Manganese nodules and polymetallic massive sulphides and cobalt-rich ferromanganese crusts	Used in tool making and building material as the chief constituent of steel
Manganese (in minerals todorokite and birnessite)	Manganese nodules, cobalt-rich ferromanganese crusts, hydrothermal crusts	A grey brittle metal; the major use is in steel (95per cent); also used in alloys; manganese compounds are used in dyes, paints, batteries, chemical processes, fertilizers, herbicides, and fungicides.
Molybdenum (in mineral molybdenite)	Cobalt-rich ferromanganese crusts	A silvery hard metal; used as alloy in steel, particularly cutting steel for high temperature use; also used as a filament material, a solid lubricant and molybdenum compounds are used in pigments.
Nickel (in minerals garnierite and pentlandite)	Manganese nodules and consolidated rocks of the Earth's mantle	A shiny, silvery-white, malleable metal used in alloys with steel (stainless steel), in catalysts, as a plating to protect other metals, and in nickel-cadmium batteries.
Platinum group elements (platinum, palladium, ruthenium, osmium, rhodium and iridium found together as native alloys and in the mineral sperrylite)	Cobalt-iron-manganese crusts and consolidated rocks of Earth's mantle	Lustrous, hard, silvery white metals used in jewelry (platinum), to create alloys with various properties (hardness, high melting point, corrosion-resistant) with electrical, catalytic and coating applications.
Rare earth elements (REE) (in mineral monazite and rock-type basanite)	Placer	A series of 15 metallic elements variously used for heat resistant alloys, and Cd disks and alloys for powerful magnets and lasers; a coloring component in glass and ceramics, in carbon arc lamps, in certain nuclear applications, and color TV tubes.
Silver (in minerals argentite, cerargyrite, prousite, and pyrargyrite)	Massive sulphides	A soft, malleable metal with the highest electrical and thermal conductivity of all elements, used in electric wires and connections; also used in jewelry, mirrors, silverware, currency, dental work, batteries and photography.

Strontium (as minerals strontianite and Celestine)	Cobalt-rich ferromanganese crusts	A soft yellowish metal used in certain alloys, in pyrotechnics and flares, in glasses and ceramics, and in iron for permanent magnets; the isotope strontium-90 is present in radioactive fallout (half-life 28 years) and can be metabolized with calcium so that it collects in bone.
Thorium (in mineral monazite)	Placer	An abundantly radioactive metal used in high-temperature applications, such as incandescent gas mantles, tungsten filament castings, laboratory equipment, as well as in certain camera lenses and other optical instruments; it can be used as a nuclear fuel for breeder reactors
Tin (in mineral cassiterite from continental granite)	Placer	A soft, silvery-white metal used in food storage containers, coating on other metals and as an alloy in solder, pewter and bronze (with copper); in polymer additives for dyeing and marine anti-fouling paints.
Titanium (in minerals ilmenite and rutile)	Placer	Corrosive resistant metal used in chemical production and anywhere light strong alloys are needed; also used in some white paints and as a pigment for coating paper and plastic, as a food additive, in sunscreen lotions, and in fireworks.
Tungsten (from minerals scheelite and wolferamite)	Placer	Metal with the highest melting point of any element, used in alloys that resist great amounts of heat, such as light-bulb filaments, in television tubes, paints, lubricants, tanning leather, and fluorescent lighting; also used in high strength applications, such as furnaces, missiles, dental drills, and other cutting tools
Uranium (in minerals pitchblende, uraninite and certain others)	Polymetallic manganese nodules	A white radioactive metallic element; uranium-235, one of three forms (isotopes) of uranium in nature, is used as fuel in nuclear reactors and nuclear weapons; uranium is also used as an additive in steels; uranium carbide is a catalyst in the formation of ammonia.
Zinc (in mineral sphalerite)	Polymetallic massive sulphides	A lustrous bluish-white metal used to plate iron and protect it from corrosion, in brass (alloyed with copper) and solder, batteries, tires, cement, paint, rubber, cosmetics, plastics, printing inks, soap, textiles, TV screens, medicines, and coins.
Zirconium (in mineral zircon)	Placer	A hard, lustrous, gray-white metal resistant to water, most acids and bases; used as a shield against corrosive compounds in the chemical industry, for steel alloys, bricks, ceramics and abrasives, flashbulbs, explosive primers, lamp filaments, and artificial gemstones.
Material	Type of Deposit	Use
Energy Minerals		
Coal	Consolidated layers	A carbon-based fossil fuel.

Hot rocks	Consolidated	Geothermal energy source at volcanic island arcs and submerged volcanic mountain ranges.
Hydrothermal fluids containing heat and metals	Seafloor hot springs	Contain heat for geothermal applications, metals in dissolved and particulate phases that are precipitated to form mineral deposits and dispersed in the ocean; and gases (hydrogen, hydrogen sulphides, methane, carbon dioxide) that are used as an energy source for chemosynthesis by bacteria at the base of the food chain in hydrothermal ecosystems.

A variety of gemstones may occur seaward of land occurrences with diamonds as the most economically important at this time.

The second type of erosion involves dissolution in water of materials from rocks on land, particularly calcium, manganese and phosphorus. The dissolved materials are transported by rivers into the ocean where they contribute to the chemical precipitation of lime and phosphorite at sites on continental margins, and as polymetallic manganese nodules and cobalt-rich ferromanganese crusts on the deep-sea floor (*see Table 1 and Figure 1*).

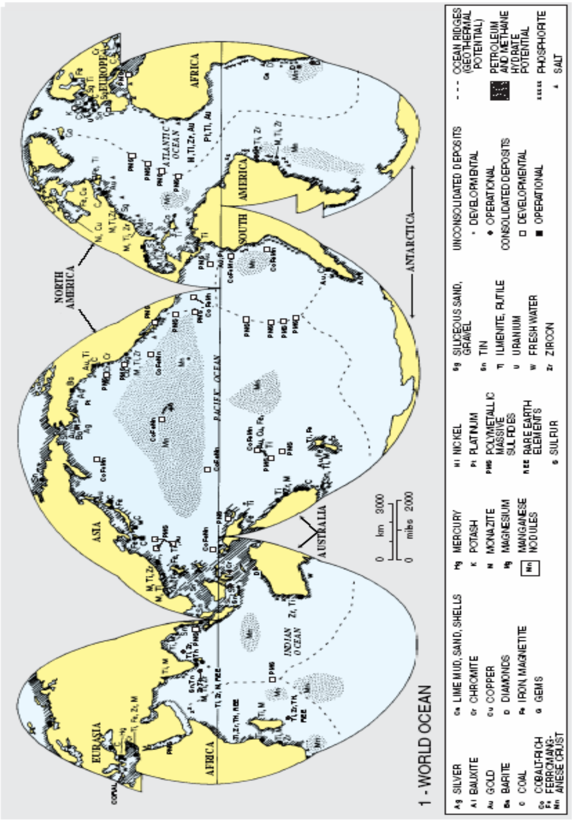

Figure 1. Global distribution of marine mineral resources (Cronan, 1980; Rona, 1981, 2003; Lenoble, 1995; Cruickshank, 1998; Ghosh and Mukhopadhyay, 2000; Andreev et al., 2000)

2.2 *The Science of Marine Minerals: After the Theory of Plate Tectonics*

The theory of plate tectonics changed our view of the ocean basins from big bathtubs that contain materials washed off the land by rivers, to active sources of materials that form types of mineral deposits different from those derived from the erosion of land. A new view of a dynamic Earth according to plate tectonics has replaced the old view of a static Earth with permanent immobile continents and ocean basins.

According to this new view the outermost shell of the Earth is formed by a rigid layer about 100 kilometres (about 62 miles) thick called the "lithosphere". The lithosphere effectively floats on a more plastic underlying layer called the "asthenosphere". The lithosphere is fragmented into some twelve major plates and numerous minor plates separated by three different types of boundaries (*see Figures 2 and 3*).

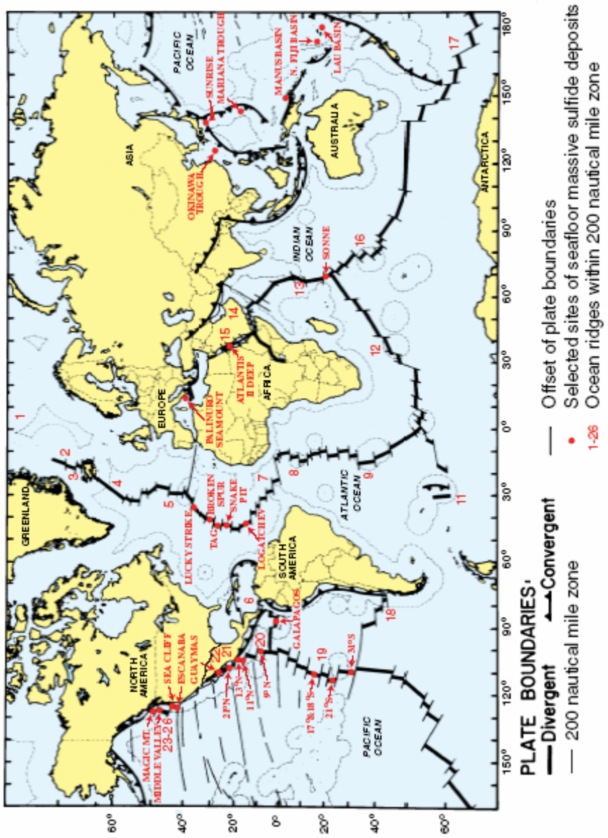

Figure 2. World map showing plate boundaries, the 200 nautical mile (370 km) exclusive economic zone (dashed line around land; Office of the Geographer, 1978; McBryde, 1982), and sites at plate boundaries where some of the larger massive sulfide deposits have been found (Rona and Scott, 1993). Only a few percent of prospective areas of the deep seafloor has been explored in sufficient detail to find such deposits. Numbers indicate locations where the submerged volcanic mountain range at divergent plate boundaries (ocean ridges) lie within the 200 nautical mile zone of a coastal state, as listed in Table 7

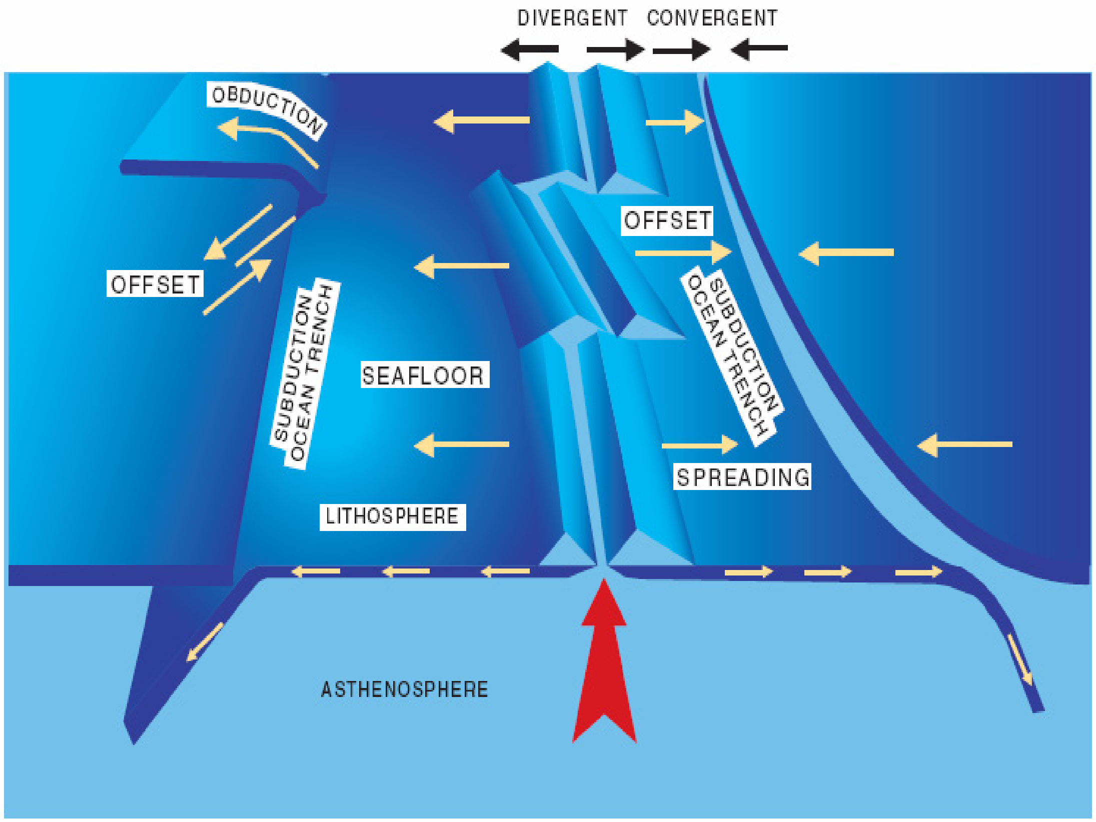

Figure 3. Types of plate boundaries

The first type of boundary between lithospheric plates is called a "divergent" boundary. Molten rock (magma) upwells beneath divergent plate boundaries, cools, solidifies, and forms new lithosphere, which moves apart to either side of the boundary like two diverging conveyor belts at an average rate of centimetres or inches per year in the process of seafloor spreading (see Figure 3). Divergent plate boundaries form a submerged volcanic mountain range that extends through all the major ocean basins of the world as the largest geographic feature on Earth (see Figure 2). Seafloor spreading at divergent plate boundaries causes ocean basins to open and continents to move apart in the motion of continental drift. For example, the continents around the Atlantic Ocean have been moving apart in tandem with opening of the Atlantic ocean basin for nearly two hundred million years, as a consequence of creation of lithosphere by seafloor spreading to either side of the Mid-Atlantic Ridge. The Mid-Atlantic Ridge is a divergent plate boundary expressed as a submerged volcanic mountain range that extends north-south along the centre of the North Atlantic and the South Atlantic ocean basins.

The second type of plate boundary is called a "convergent" plate boundary because two lithospheric plates come together. One plate generally moves down beneath the other at an ocean trench. The downgoing plate descends and melts back into the Earth's interior in the process of subduction (see Figure 3). Volcanic island chains like Japan, the Marianas, the Philippines, and New Guinea that lie along the western margin of the Pacific Ocean, and volcanic mountain chains like the Andes of South America and the Cascades of North America, are formed by volcanic activity generated by melting of the lithosphere as it descends at convergent plate boundaries. The "Ring of Fire" around the Pacific Ocean is produced by volcanism at convergent plate boundaries that surround the Pacific.

Divergent plate boundaries at the globe-encircling submerged volcanic mountain range and convergent plate boundaries at volcanic island chains are delineated by earthquakes, which are produced by the grinding of the plates against each other as they intermittently move at the boundaries. The overall size (volume and diameter) of the Earth remains constant as a consequence of the balance of creation and destruction of lithosphere at divergent and convergent plate boundaries.

A third type of plate boundary, expressed as an offset along the length of a divergent or a convergent plate, serves to accommodate the linear boundaries to the curvature of the spherical Earth.

Plate boundaries are part of a global system of transfer of heat and chemicals between the Earth's hot interior and the oceans. The heat drives processes of mineralization and the chemicals are the source of the materials that are concentrated as mineral deposits at and away from plate boundaries (Rona, 1973; Mitchell and Garson, 1981; Sawkins, 1984). These mineral deposits include polymetallic massive sulphides deposits at sites along plate boundaries and emissions of metals that combine with those dissolved from continents to form polymetallic nodules and cobalt-rich ferromanganese crusts (*Table 3*)

Table 3. Association of potential mineral and energy resources with types of plate boundaries

Type of plate boundary	Potential mineral resources	Potential energy resources	References
Divergent: Ocean ridges	Metalliferous sediments (copper, iron, manganese, lead, zinc, barium, cobalt, silver, gold; e.g., Atlantis II Deep of Red Sea)	Geothermal	(Rona and Scott, 1993)
	Stratiform manganese and iron oxides and hydroxides and iron silicates (e.g., sites of Mid-Atlantic Ridge and Galapagos Spreading Centre)	Hydrocarbons at early stage of rifting and opening of ocean basin (e.g., Red Sea; Atlantic continental margins; marginal seas of western Pacific region)	
	Polymetallic massive sulphides deposits (copper, iron, zinc, silver, gold; e.g., sites on East Pacific Rise, Galapagos Spreading Center, Mid-Atlantic Ridge, Central Indian Ridge and marginal seas behind volcanic island chains of western Pacific)		
	Polymetallic stockwork sulphides(copper, iron, zinc, silver, gold; e.g., sites on Mid-Atlantic Ridge, Carlsberg Ridge, Galapagos Spreading Centre)		
	Other polymetallic sulphides in disseminated or segregated form (copper, nickel, platinum group metals)		
	Asbestos		
	Chromite		
Convergent: Offshore	Sections of oceanic crust containing types of mineral resources formed at divergent plate boundaries uplifted onto land (e.g., sites at volcanic island chains of western Pacific)	Geothermal Hydrocarbons	(Mitchell and Garson, 1981; Sawkins, 1984)

	Tin, uranium, porphyry copper and possible gold mineralization in granitic rocks		
Convergent: Onshore	Porphyry deposits (large relatively low-grade deposits of copper, iron, molybdenum, tin, zinc, silver, gold; e.g., deposits at sites in the Andes volcanic mountain chain)	Geothermal	(Mitchell and Garson, 1981; Sawkins, 1984)
	Polymetallic massive sulphides (copper, iron, lead, zinc, silver, gold, barium; e.g., Kuroko deposits of Japan)		
Offset: Offshore	Mineral deposits similar to those formed at divergent plate boundaries (ocean ridges) may occur at offshore transform plate boundaries; (e.g., sites on Mid-Atlantic Ridge in Atlantic Ocean and Carlsberg Ridge in Indian Ocean)		(Bonatti, 1981)

3. *Seafloor Settings of Marine Mineral Deposits*

The survey of marine minerals in this chapter begins by considering the seafloor settings of both fuel and non-fuel marine minerals.

The seafloor forms two broad divisions and numerous subdivisions. The two broad divisions are the margins of continents and the ocean basins. Continental margins are subdivided into passive and active types with important implications for the occurrence of non-fuel and fuel minerals (oil and gas).

Passive Continental Margins

Passive continental margins are the edges of continents, which have been broken apart by initiation of an intervening divergent plate boundary and separated while an ocean basin has widened between the continental fragments as a consequence of the process of seafloor spreading (*see Figure 3*). A typical passive margin is formed of a continental shelf, slope, and rise. The continental shelf is a seaward continuation of the continent that inclines seaward at a low inclination from a horizontal surface (about 1 degree seaward) and varying widths up to hundreds of miles or kilometres from the beach to a sharp increase in slope, which generally occurs at a water depth of about 100 metres (about 330 feet).[37] The continental slope extends from the edge of the continental shelf to the continental rise. The slope exhibits a relatively steep average seaward inclination (5 to 15 degrees from the horizontal) and is generally cut by seaward-sloping canyons, which act as conduits for transport of sediment from the continent to the deep ocean basin. The average inclination of the seafloor abruptly decreases from the base of the continental slope to the continental rise (about 1 degree from the horizontal), which extends to the deep ocean basin (average water depth 3.8 kilometres or 2.4 miles). Examples are the passive continental margins that surround the Atlantic Ocean and those that occur along the western margin of the Indian Ocean.

These margins are termed "passive" because they passively subside after breaking apart and are generally buried by layers of sediment up to tens of kilometres thick eroded from the adjacent landmass and deposited on the original rifted edges of the continents. Therefore, passive continental margins have potential for placer-type mineral deposits of metals and gemstones eroded from the adjacent landmass and for lime and phosphorite deposits precipitated directly from seawater and/or indirectly by marine organisms.

The thick accumulations of sediment generally contain organic matter primarily from the remains of tiny marine plants and animals that settle out of the overlying water. The combination of pressure and heat as the organic matter is buried by sediment gradually converts it into hydrocarbons that form oil, gas and gas hydrates. The hydrocarbons form prospective accumulations when concentrated by the coincidence of a large volume of porous and permeable sediment as a reservoir and one of a variety of structures capped by an impermeable layer as a trap.

In the case of gas hydrates, methane gas generated primarily by the decay of organic matter is incorporated into ice that forms under the high-pressure, low-temperature conditions that exist within portions of the sedimentary layers underlying passive continental margins. In contrast to oil and gas, which is concentrated in natural reservoirs within the sedimentary layers, methane is disseminated in large volumes of sediment underlying large areas of continental margins. The challenge remains how to tap methane from the gas hydrates as a potential energy resource. The estimates of the extent of energy resources in methane gas trapped within and beneath the ice layers in sediments primarily of continental margins vary widely, with a range of estimates from greater than 100 percent (Kvenvolden, 1998) to less than ten percent (Milkov, 2003) of known reserves of fossil fuels (oil, gas, and coal).

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[37] It should be noted that the geological concept of the continental shelf may differ from the legal concept as defined in article 76 of the Convention.

Active Continental Margins

Active continental margins occur at convergent plate boundaries where plates come together and the lithosphere is destroyed by descending back into the Earth's interior in the process of subduction (*see Figure 3*). Examples are the continental margins that surround the Pacific Ocean and the eastern margin of the Indian Ocean. These margins are termed "active" because they are associated with earthquakes and volcanically active island chains like Japan, the Ryukus, the Philippines, New Guinea, and the Kermadec and Tonga islands north of New Zealand.

The generation of molten rocks or magma beneath the seafloor as one plate descends beneath another accompanied by volcanic eruptions create conditions for concentration of seafloor polymetallic massive sulphides and related metallic mineral deposits (see Table 3). Sedimentary basins on the seaward and landward sides of the volcanic island chains have the potential for the occurrence of placer deposits and of oil, gas, and gas hydrates (*see Figure 4).*

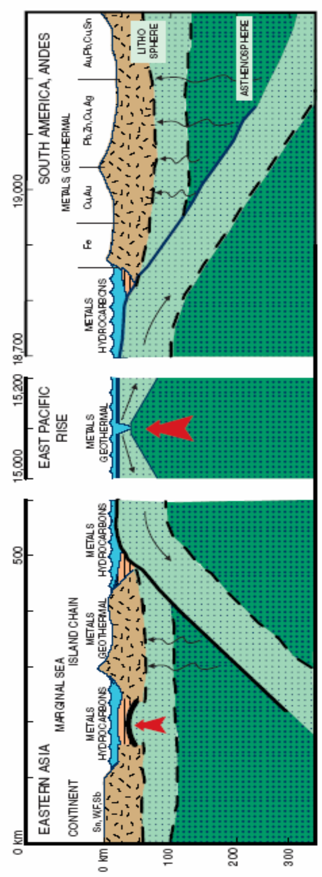

Figure 4. A diagrammatic east-west cross-section of the Pacific Ocean between South America and eastern Asia shows the relation of potential mineral and energy resources to submerged divergent (East Pacific Rise) and convergent (Pacific margins), as discussed in the text (Rona, 1983). Metal deposits including polymetallic massive sulfides may occur in ocean crust represented by the black layer at the top of the lithosphere

4. *Sources of Marine Minerals*

Non-fuel marine minerals are considered in this chapter in the following order related to their sources of origin:

(a) Mineral deposits derived from land sources known prior to the advent of the theory of plate tectonics. These constitute beach deposits and placer mineral deposits, as well as certain deposits precipitated from seawater (lime and phosphorite).
(b) Mineral deposits derived from sources in ocean basins discovered at and after the advent of the theory of plate tectonics. These comprise metalliferous sediments, polymetallic massive sulphides, and related deposits.
(c) Mineral deposits derived from a combination of land and ocean basin sources. These comprise polymetallic manganese nodules and cobalt-rich ferromanganese crusts.

4.1 Marine Mineral Deposits from Land Sources

Marine mineral deposits from land sources comprise placer deposits, deposits of lime, phosphorite, and salt as well as beach deposits of continental margins.

(i) Placer Deposits

As noted, placers are those deposits of metallic minerals and gemstones that are eroded from source rocks on land and transported into the ocean by rivers where they are sorted and concentrated by water motions (waves, tides, currents) by virtue of the high density of the minerals relative to surrounding sediments. Principal metals in minerals of placer deposits are barium, chromium, gold, iron, rare earth elements, tin, titanium, thorium, tungsten, and zirconium. The principal gemstone is diamond.

The potential for the occurrence of placer deposits on and within the sedimentary accumulations of entire continental margins (continental shelf, slope and rise) associated with land sources of minerals is great. However, current knowledge of the occurrence is limited by the extent of exploration carried out up to the present time, which has only located the most accessible deposits on or near the seafloor of small areas of inner portions of the continental shelves that have been systematically explored. The sediment column of the entire continental margin has potential for the occurrence of such deposits, but the deposits most accessible for exploration and exploitation under current conditions lie on the seafloor in shallow water.

(ii) Lime, Phosphorite and Salt Deposits

As noted, lime, phosphorite and salt deposits of continental margins are derived by chemical weathering of continental rocks and transported by rivers in a dissolved state into the ocean where they are precipitated on continental margins under the right conditions.

Lime (calcium carbonate) may be precipitated in shallow water in subtropical and tropical climate zones or extracted from seawater by microscopic plants and animals and deposited as their remains (shells and other forms).

Phosphorite is deposited in the form of nodules and layers where phosphate-rich deep seawater upwells at continental margins. The upwelling occurs to replace near-surface water pushed offshore by the trade winds blowing from east to west in belts between 30 degrees of latitude north and south of the equator. The upwelling zone places these offshore phosphorite deposits adjacent to agricultural regions of Africa and India. However, the supply of phosphorite deposited on land at former higher stands of sea level is adequate for present use as an agricultural fertilizer.

Salt occurs as layers up to kilometres thick and as dome-shaped masses deeply buried within the sediments that cover passive continental margins. Layers of salt were deposited at an early stage of opening of an ocean basin by rifting of continental margins represented by the present Red Sea and subsequently buried beneath thick layers of sediment represented by the continental margins of the two sides of the Atlantic (Rona, 1982). The presence of salt buried within the sedimentary layers that accumulate on passive continental margins has significance for the occurrence of hydrocarbons. Organic matter usually accumulates with salt when salt is precipitated from seawater. If and when the organic matter matures into oil and gas under the heat and pressure of burial through geologic time, the salt may act as both a cap and a trap favouring the accumulation of these hydrocarbons or hydrocarbons derived from organic matter preserved in regional sediments.

Global Distribution of Placer, Lime, Phosphorite and Salt Deposits

Present knowledge of the distribution of placer, lime, phosphorite and salt deposits on and beneath the seafloor of continental margins is shown on a global series of maps comprising an index map (*Figure 5*) and deposit distribution maps for the different regions of the world (*Figures 6-11*). The distribution of placer deposits shown on the maps is based largely on the MARMIN database (Lenoble et al., 1995).

The known distribution of placer, lime, phosphorite and salt deposits are shown on the regional maps (*see Figure 5; Table 4*), as follows:

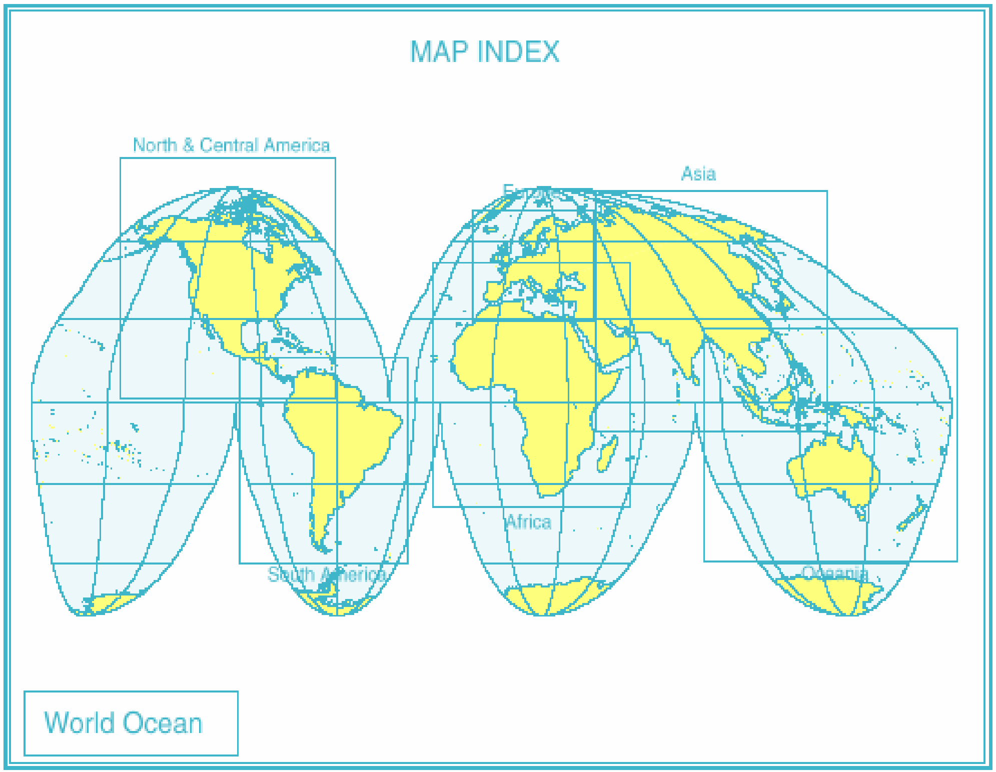

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Figure 5. Index of maps (Figures 6-11) showing placer and phosporite deposits on continental margins, salt deposits underlying continental margins, and polymetallic massive sulfide deposits, and polymetallic manganese deposits of the adjacent ocean basin. Note that more deposits remain

Table 4. Operational marine mineral deposits

Name	Commodity	Type of Deposit	Water Depth (m)	Location (Latitude, Longitude)
Non-metals				
Coastal Zone	Sand and gravel	Beach	0	Multiple sites worldwide
Coastal Zone	Water/Ice	Fluid and Solid	0	Multiple sites worldwide
Groen River	Diamond	Unconsolidated Placer	25	South Africa, 30.5° S, 17.6° E
Chameis Bay	Diamond	Placer	0-25	Namibia, 28.0° S, 15.7° E
Broadacres	Diamond	Placer	0.5	South Africa, 31.6 S, 18.2 E
Casuarinas Prospect (inactive)	Diamond	Placer	30	Australia, 14.4° S, 127.8 °E
Hayward San Leandro	Lime (shell fragments)	Beach	0	San Francisco Bay, USA, 37.7° N, 122.1° W
Laucala Bay	Lime (coral sand)	Beach	0	Fiji, 18.2° S, 178.5° E
Faxa Bay	Lime (shells)	Beach	35	Iceland, 65.5° N, 22.5° W
Vembanad	Lime (shells)	Beach	0	India, 9.6° N, 76.3° E
Bahia Coast	Lime (algae and shells)	Beach	0	Brazil, 13.0° S, 38.5° W
Cape Breton Islands	Coal	Consolidated Layers		Canada, 46.2 N, 60.9° W
Sunderland	Coal	Consolidated Layers		England, 54.9° N, 1.4° W
Torre de Geco	Coral	Unconsolidated	5-300	Naples Bay, Italy 40.8° N, 14.5° E
Metals				
Thai Muang	Tin	Placer	10	Thailand, 8.5° N, 98.2° E
Tongkah Harbour	Tin	Placer	20	Thailand, 7.9° N, 98.5° E
Takua Pa	Tin	Placer	0-18	Thailand, 9.0° N, 98.3' W
Copat Kelabat Bay	Tin	Placer	0-1	Indonesia, 1.6° S, 105.7° E
Laut Tempilang	Tin	Placer	10	Indonesia, 2.2° S, 105.7° E

Belitung (Billiton)	Tin	Placer	10-20	Indonesia, 3.0° S, 108.2° E
Heinze Basin	Tin, Tungsten	Placer	16-30	Myanmar, 14.7° N, 97.8° E
Nome (Presently inactive)	Gold	Placer	18-20	Alaska, USA, 64.5° N, 165.4° W
Bluff Soloman (Presently inactive)	Gold	Placer	0-10	Alaska, USA, 64.6° N, 164.4° W
Gillespie’s Beach	Gold	Placer	0-15	New Zealand, 43.4° S, 169.8° W
Richard's Bay	Titanium, Zirconium	Placer	0-30	South Africa, 28.8° S, 32.0° E
Name	Commodity	Type of Deposit	Water Depth (m)	Location (Latitude, Longitude)
Fort Dauphin	Titanium, Thorium, Rare Earths, Zirconium	Placer	0	Madagascar, 25.0°S, 47.0° E
Kanniyaknmari Manavalakurichi	Titanium, Zirconium, Thorium	Placer	0	India, 8.2° N, 78.5° E
Chatrapur	Titanium, Zirconium, Thorium	Placer	0	India, 19.4° N, 85.0° E
Castle Island	Barium	Consolidated Layered Material	0-5	Alaska, USA, 56.8° N, 133.0 W
Sulawesi	Chromite	Placer	0	Indonesia, 2.0° S, 121.5° E

Modified from Lenoble et al., 1995

Africa (*see Figure 6; Table 4*): Salt layers up to several kilometres in thickness lie buried beneath and intrude as salt domes beneath the Atlantic continental margin of Africa. The salt that forms these domes was deposited at an early stage of opening over 100 million years ago when the Atlantic was a sea in which evaporation exceeded inflow causing the precipitation of salt and the preservation of organic matter (Rona, 1982). The salt is associated with the production of petroleum offshore West Africa, including Angola and Gabon. The distribution of salt suggests that potential for petroleum may extend northward along the western continental margin of Africa (Rona, 1982; Meyers et al., 1996).

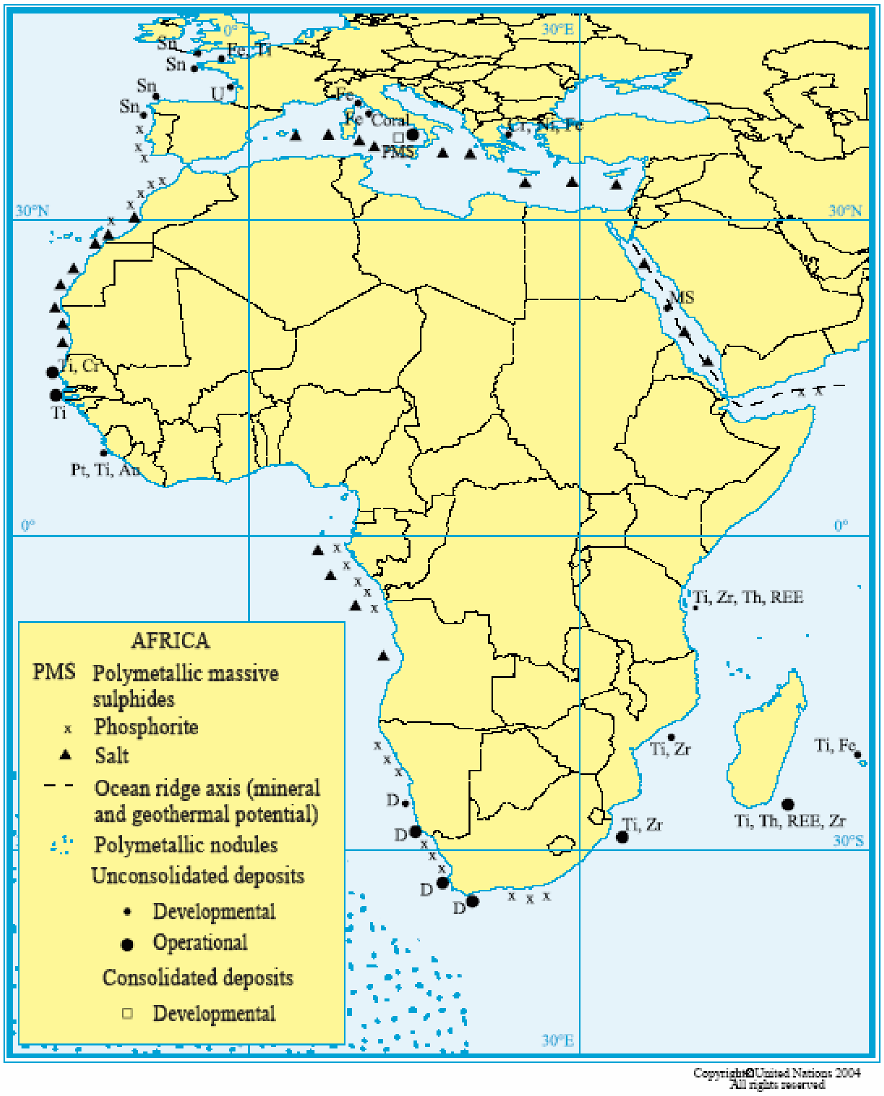

Figure 6. Offshore mineral map of Africa

Phosphorite is being deposited on the continental shelf of northwest Africa by upwelling of phosphate-rich deep water in the easterly trade wind belt.

Diamonds are being mined from the shore to offshore distances of 100 kilometres and to water depths of 200 metres on the continental shelf and upper slope off the southwest coast of Africa in concessions of the countries of Namibia and South Africa (Garnett, 2000a). The diamonds were transported hundreds of kilometres westward from their source rocks in South Africa and Botswana to the ocean by the ancestral Orange River system and concentrated along with gravel by water motions into pockets on the irregular surface of bedrock on and beneath the seafloor. Recovery of some 514,000 carats (1 carat=0.2 gram=0.006 ounce) of high-quality diamonds using seafloor mining machines and drills by the contractor (De Beers Marine) was reported for 1999 by the principal producer (Namdeb) with estimated annual production value of about US$ 250 million (Garnett, 2000a). Exploration for diamonds has also been conducted offshore West Africa, Australia, and Indonesia, but without economic success (Garnett, 2000a).

Placer deposits containing titanium, thorium, rare earth elements, and zirconium have been mined at a location on the southeast coast of Madagascar (*Figure 6*).

North and Central America (*see Figure 7; Table 4*): Gold is intermittently mined offshore Alaska dependent on market price (currently inactive) where it was concentrated as marine placer deposits from glacial and stream sediments (Garnett, 2000b). Alaska is the only place in the world where such economic marine placer gold deposits have been found to date. Other placer metal and nonmetal deposits that occur offshore North America are undeveloped. Extensive phosphorite deposits lie in shallow water of the Pacific continental shelf of Baja California. The Bahama Banks off Florida are built up of layers of limestone thousands of metres thick and continue to grow as lime is precipitated over shallow water areas of the Banks. Lime is dredged from some of these areas. An underground coal mine extends offshore in the Cape Breton Islands of Canada. The continental margins of Central America are virtually unexplored for mineral deposits.

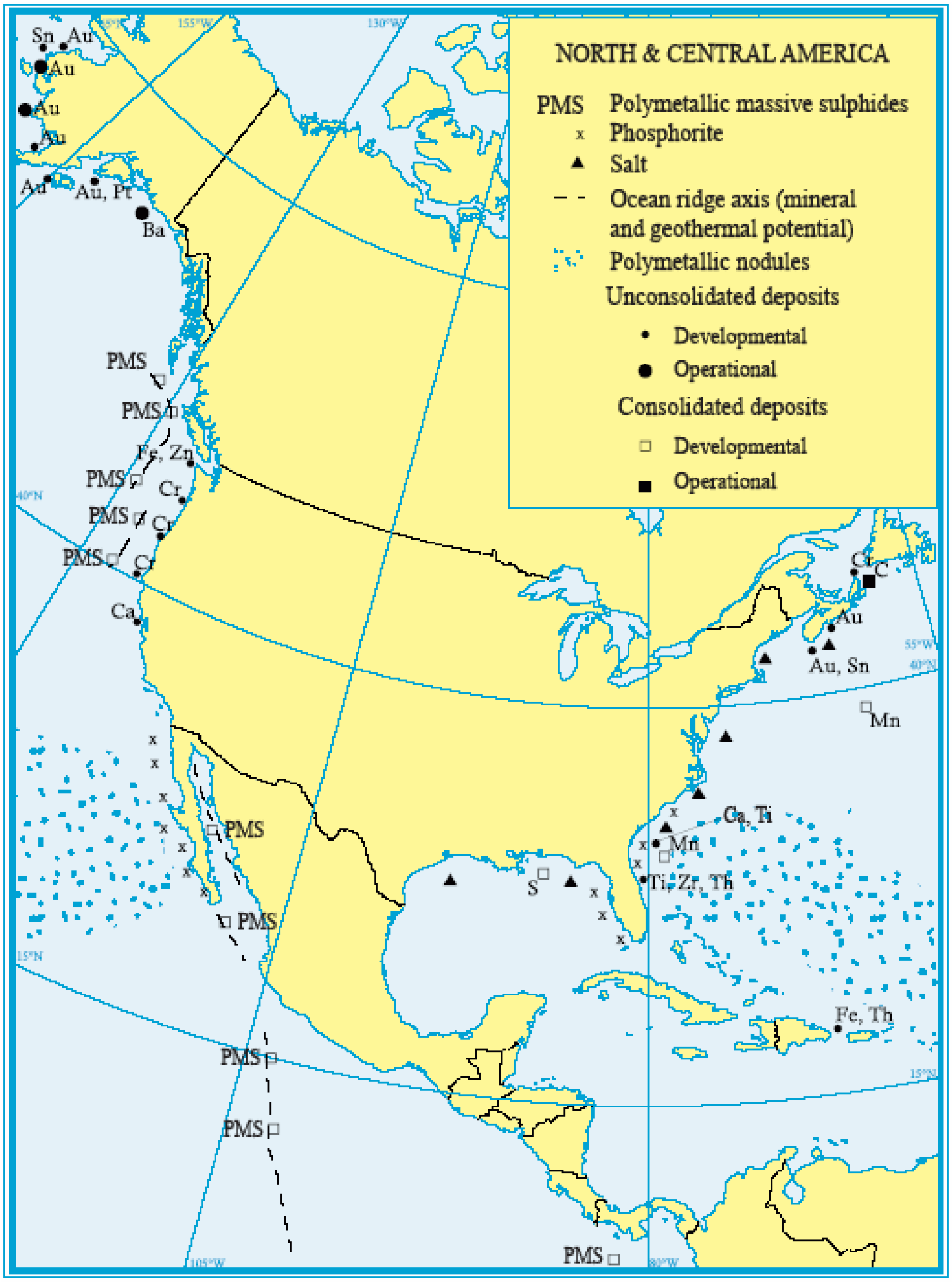

Figure 7. Offshore mineral map of North and Central America

South America (*see Figure 8*): South America is a continent noted for its metallic mineral deposits (sites along the west coast in the Andes mountains and elsewhere) and gemstones (Brazil, Colombia, and elsewhere). The primary marine minerals shown on the map are phosphorite deposits in areas of upwelling off Peru and Brazil; buried salt layers offshore Brazil deposited at an early stage of separation and drift of South America from Africa (associated with present petroleum production); and lime precipitated by marine plants and recovered at a site offshore Brazil. The continental margins of South America, especially the western margin, have great potential for metallic and nonmetallic placer deposits that remain to be discovered.

Figure 8. Offshore mineral map of South America

Europe (*see Figure 9; Table 4*): Layers of rock salt hundreds of metres thick were deposited on the floor of the Mediterranean under conditions of restricted ocean circulation some 10 million years ago and are deeply buried beneath the subsequent accumulation of sediment. Undeveloped phosphorite deposits lie off the Atlantic coasts of Morocco and Spain. An underground land coal mine extends seaward on the east coast of England. None of the many metallic marine placer deposits have been developed. Coral recovery is an industry in the Bay of Naples.

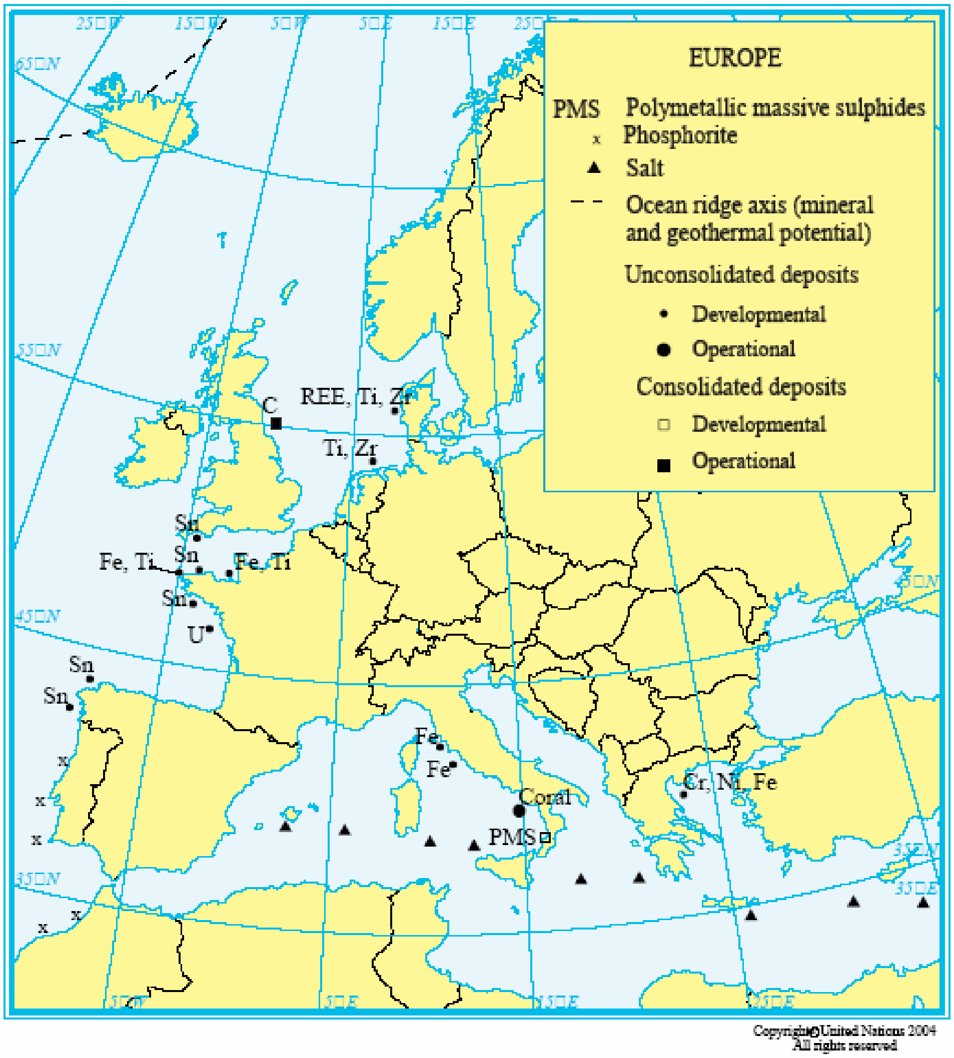

Figure 9. Offshore mineral map of Europe

Asia (*see Figure 10; Table 4*): A diverse suite of metallic placer deposits exists on the continental margins of Asia.

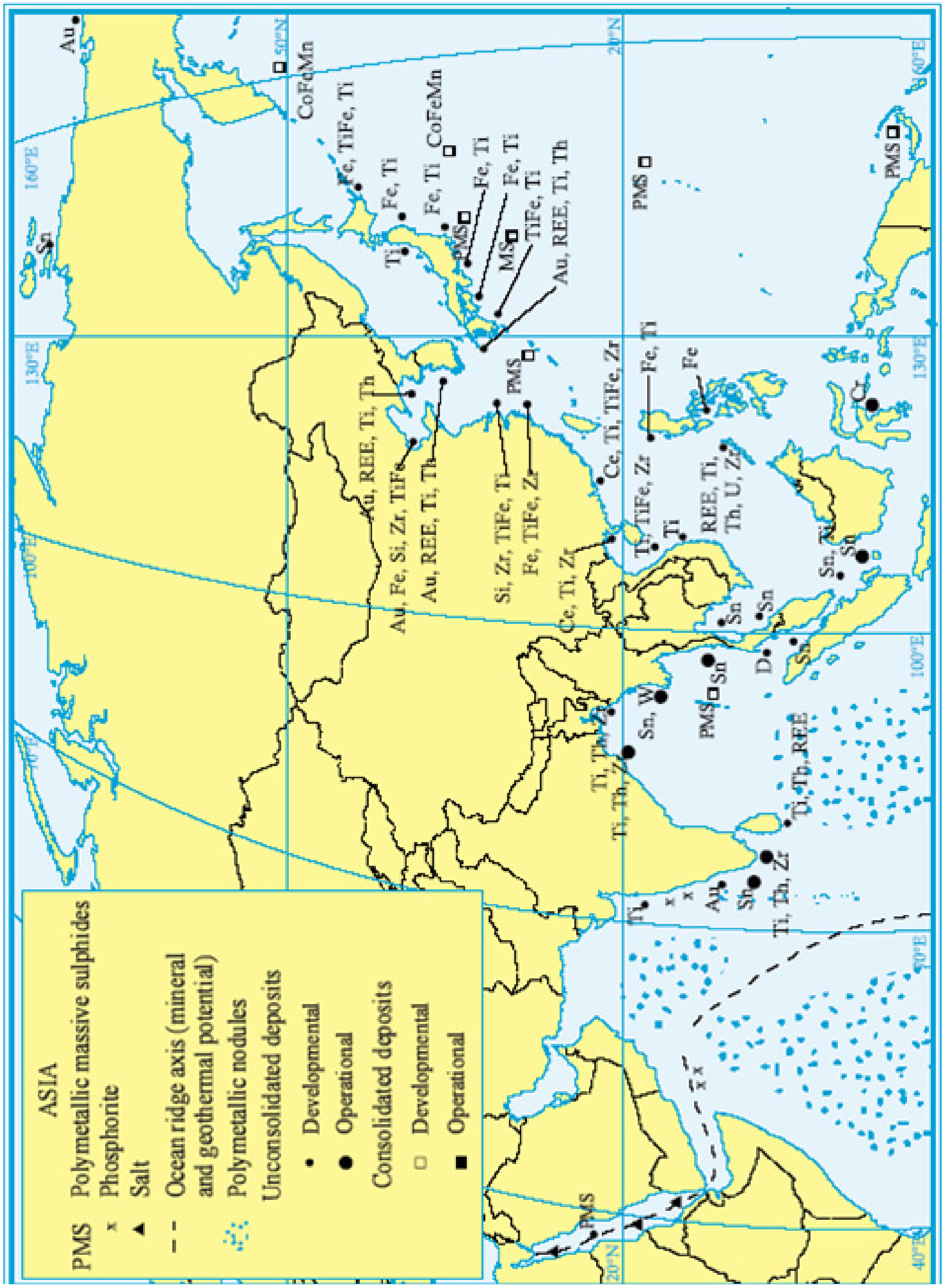

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Figure 10. Offshore mineral map of Asia

Tin is the major placer deposit that is mined. Tin-bearing gravel is dredged from water depths up to 50 metres (about 164 feet) on the continental shelf at sites off Myanmar, Thailand, and Indonesia. It is estimated that offshore production of tin in these areas accounts for some 10 percent of world production with an annual value approaching US$100 million (Cruickshank et al., 1968; Yim, 2000). Extensive placer deposits of metallic minerals occur along the coast of southern India (Rajamanickam, 2000), with mining operations for titanium, thorium, and zirconium, reported at three locations (*Table 4*). A diverse suite of large metallic placer deposits has been mapped on the section of the southeastern continental shelf of the People's Republic of China verging on the South China Sea (Tan et al., 1996; Institute of Marine Geology, 1988).

Oceania (*see Figure 11; Table 4*): Mining of placer tin deposits off Myanmar, Thailand and Indonesia has been described above. Placer chromite (chromium) has been produced from a site on the east coast of the Indonesian island of Sulawesi. Extensive metallic placer deposits (titanium, zirconium) have been found along the east coast of Australia, while the other coasts are relatively unexplored for such deposits. A gold placer deposit has been intermittently active off New Zealand (*Table 4*). Undeveloped phosphate deposits occur at sites along the east coast of New Zealand, including an extensive fossil deposit on the Chatham Rise some hundreds of kilometres to the east (Cullen, 1986; von Rad and Kudrass, 1984; Cronan, 1992).

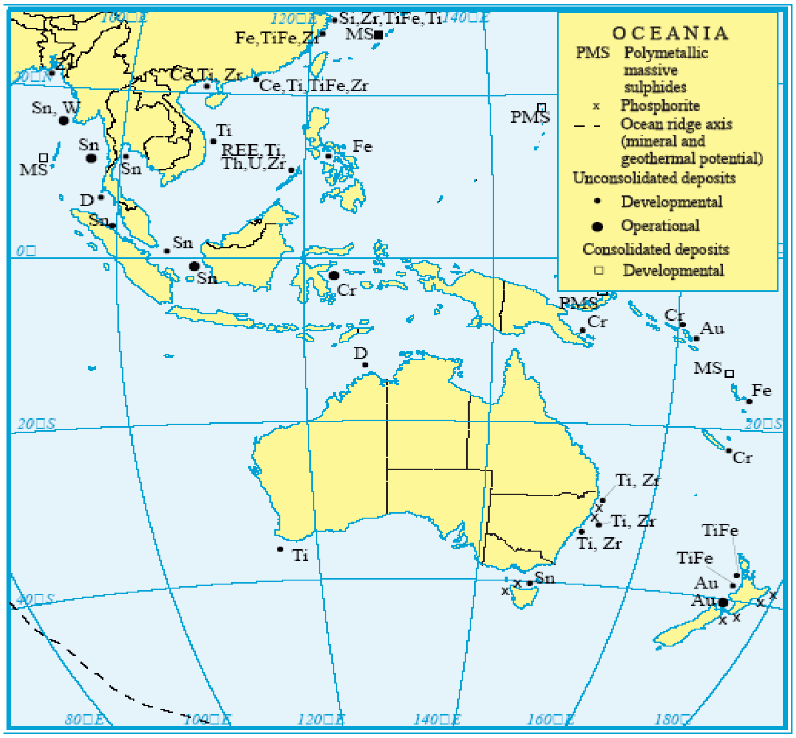

Figure 11. Offshore mineral map of Oceania

(iii) Beach Deposits of Continental Margins

Beach deposits of continental margins constitute the sediments that form beaches and related accumulations at a shoreline. These deposits may lie at, above, or below the present shoreline because height of sea level has changed as much as 150 metres (about 490 feet) over the past 18,000 years. The sediments that form beach deposits generally contain silt-, sand- and gravel-sized particles (also termed "aggregates" when used for construction material) with either siliceous (quartz) composition derived by erosion of continental rocks, or lime (calcium carbonate) composition derived from broken shells or direct precipitation from seawater. Beach deposits constituting sand and gravel are the most extensively mined and utilized of marine minerals at numerous sites around the world (*see Table 4*). They are dredged either directly from a beach or from offshore sand bars in shallow water close to the beach. These materials are used to make construction materials (cement) or, in the case of offshore bars, to protect property by replenishing beach material that is lost to erosion by ocean waves and longshore currents. The annual production value of beach sand and gravel is estimated at $US 3,000 million (based on production in metric tons and value of $US 15 per metric ton; D.J Harrison, British Geological Survey, personal communication with Professor Peter Rona), and is growing as an increasing fraction of the world's population inhabits the coastal zone.

(iv) Seawater at Continental Margins

A number of materials are extracted from seawater at some 300 coastal operations in 60 countries including rock salt (sodium chloride), magnesium metal, magnesium compounds, and bromine. Of these materials freshwater is the most important as a mineral resource. Water is scientifically defined as a mineral with a definite chemical composition and a crystal form (ice).

4.2 Marine Mineral Deposits from Sources in Ocean Basins

(i) Hydrothermal Deposits: Metalliferous Sediments

The metalliferous sediments of the Atlantis II Deep in the northern Red Sea constitute the first hydrothermal deposit (a mineral deposit concentrated by hot, metal-rich aqueous solutions) found at a divergent plate boundary in the ocean (Degens and Ross, 1969), and remain the most efficient ore-forming system and the largest such deposit found to date. The Atlantis II Deep is a basin roughly 10 kilometres (6.2 miles) in diameter at a water depth of 2 kilometres (1.2 miles) that lies on the divergent plate boundary that rifted Africa from the Arabian peninsula about 10 million years ago and generated lithosphere at a slow full-spreading rate (2 centimetres or 0.8 inches per year) to account for the present width of the northern Red Sea (200 kilometres or 124 miles).

The ore-forming system entails: downwelling of seawater through permeable ocean crust; an order of magnitude increase in salinity over normal seawater salinity (35 parts per thousand) by flow in proximity to marginal salt deposits (primarily sodium chloride) up to several kilometres in thickness that precipitated at an early stage in opening of the Red Sea when evaporation exceeded inflow through narrow shallow straits; heating by flow in proximity to axial magmatic intrusions; upwelling of the thermally expanded highly saline solutions; dissolution and transport of metals from the volcanic rocks and magmatic solutions as complexes linked to the chloride in the dissolved salt; accumulation of the heavy solutions by density stratification in the axial trough; and precipitation of metallic sulphides, oxides and hydroxides that settle to form layers of unconsolidated metalliferous sediments with the consistency of jelly up to 30 metres (100 feet) thick (*see Figure 12; Table 5*). The Atlantis II Deep is the largest of a number of such troughs subsequently found along the axis of the northern Red Sea.

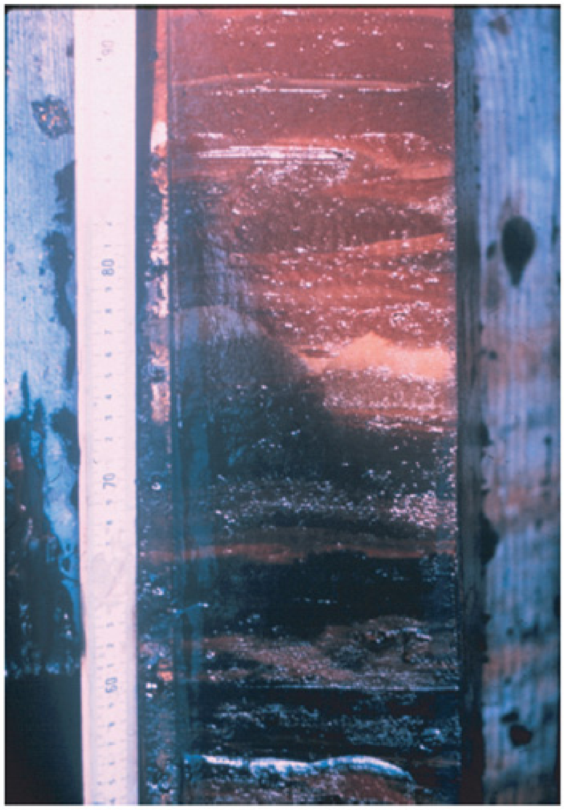

Figure 12. Metalliferous sediment core from Atlantis II Deep.

Table 5. Resource potential of metalliferous sediments of the Atlantis II Deep, Red Sea (Nawab, 2000)

Metal	Grade (weight percent; dry salt-free basis)	Weight (metric tons; dry salt-free basis)
Metalliferous sediments		89,500,000
Zn	2.06	1,838,000
Cu	0.45	402,000
Ag	38 grams/metric ton	3,432

As seafloor spreading continues, the Red Sea may widen into an ocean like the Atlantic. Metalliferous hydrothermal deposits may be aligned along flow lines of spreading extending away from the spreading axis, depending on the persistence, periodicity, and position of axial hydrothermal activity (Rona, 1985). Deposits of metalliferous sediments like those forming in the Atlantis II Deep are expected to be present, buried beneath sediments at sites along rifted continental margins of ocean basins that underwent a stage like the Red Sea early in their opening, for example in the Atlantic Ocean.

(ii) Seafloor Polymetallic Massive Sulphides and Related Deposits

The theory of plate tectonics changed our understanding of ocean basins from passive sinks that simply contained the oceans and material washed into the oceans to active sources of materials that form polymetallic massive sulphides and related types of deposits. In fact, the ocean basins are poor containers for seawater because they are leaky (Rona, 1985). The volcanic rocks that underlie the seafloor are permeated by fractures formed by thermal contraction during cooling of submarine lava flows and crustal movements. Over most of the seafloor cold and heavy seawater penetrates several kilometres downward through the fractures and makes a one-way trip back into the Earth's interior where a volume of water comparable to that of the oceans is thought to be assimilated into the rocks (Meade and Jeanloz, 1991).

In certain places the downwelling cold and heavy seawater encounters hot or molten rocks at depths of several kilometres beneath the seafloor. The seawater is then heated, expands thermally, becomes lighter, and rises buoyantly. As the hot seawater rises through fractures in the ocean crust it reacts chemically with the surrounding volcanic rocks and dissolves metals, which are present in small amounts in the rocks. The solutions become enriched in metals as they flow upward through fractures. The metals combine with in the solutions and precipitate under changing chemical conditions beneath and on the seafloor to form polymetallic massive sulphides deposits (*see Figures 13 and 14*).

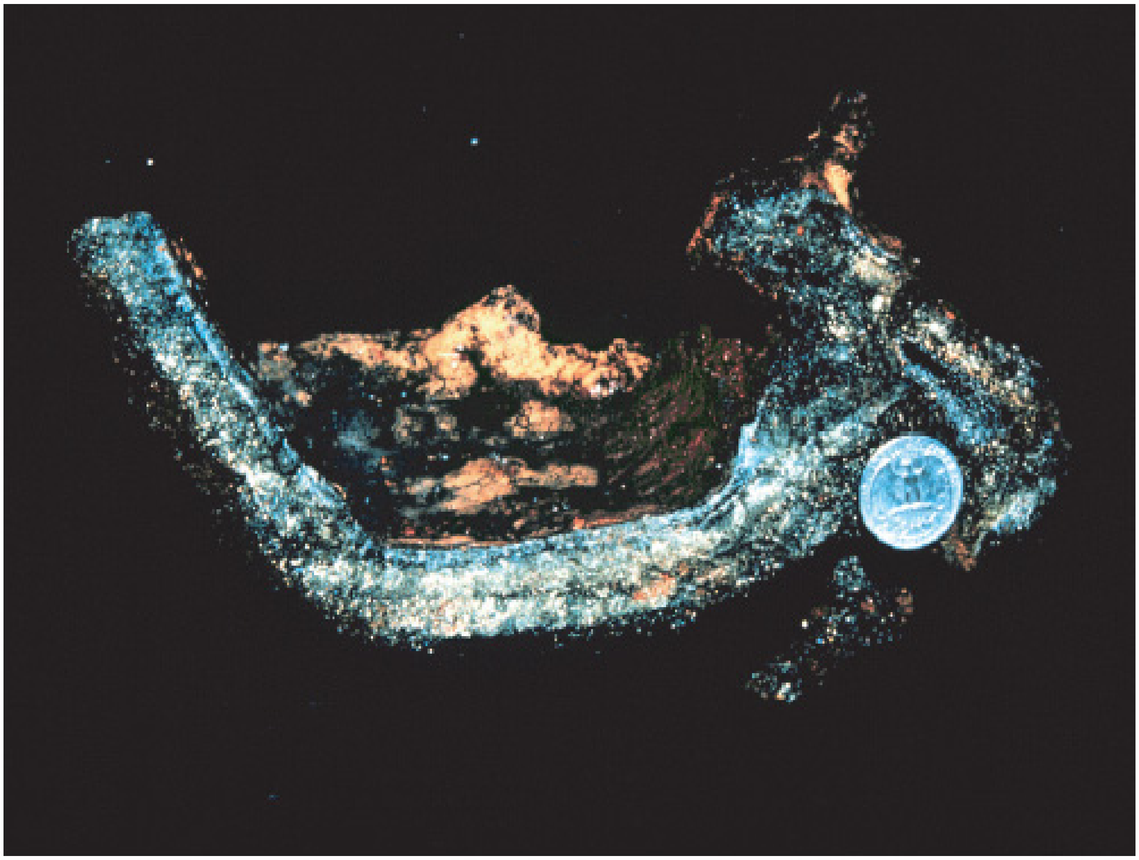

Figure 13. A fragment of polymetallic massive sulfide recovered from the wall of an active black smoker vent (coin is 2.5 cm or 1 inch in diameter; from Rona, 1985)

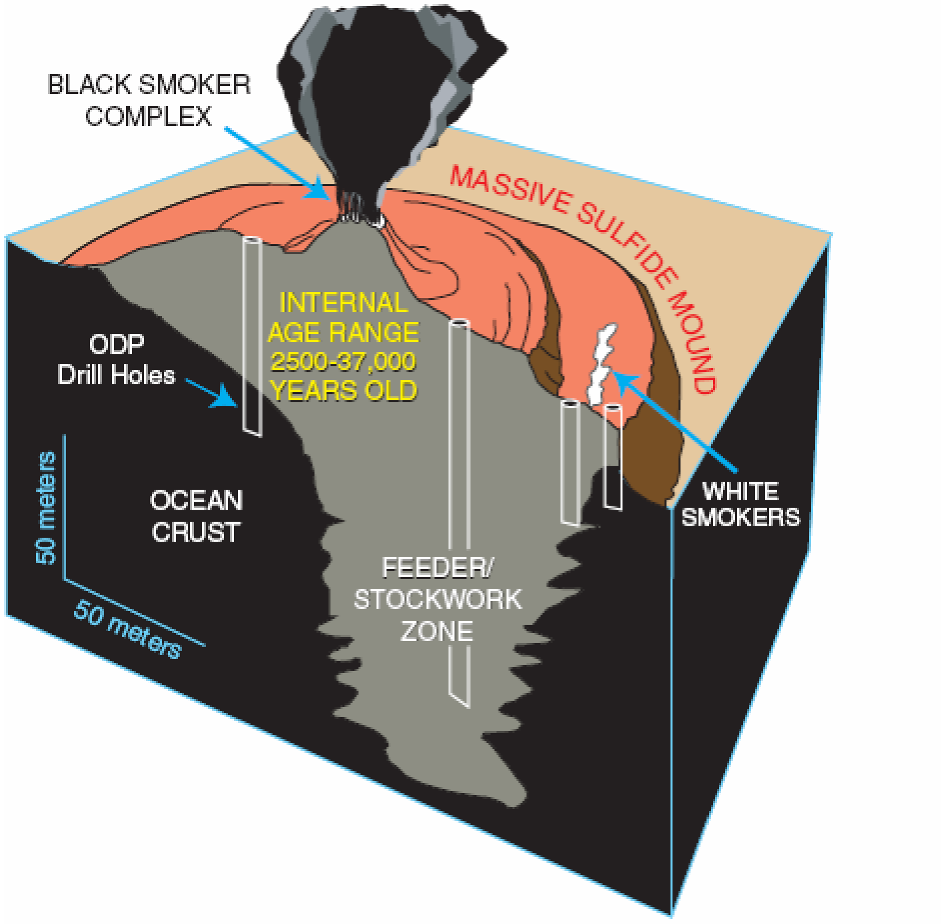

Figure 14. A schematic section through the TAG active massive sulphide on the Mid-Atlantic Ridge (showing characteristic surface and subsurface features of a seafloor polymetallic sulfide deposit based on drilling of the mound by the Ocean Drilling Programme (see Figure 2; Rona, 1992; Humphris et al., 1995).

Polymetallic sulphides with high contents of copper, iron, zinc and silver combined with as sulphides minerals are referred to as “massive” sulphides; the term massive pertains to metal content rather than to size or shape of the deposit. Gold and other metals may also be present in lower concentrations (see Table 6). The metal-rich solutions discharge at high temperatures (up to 400° C= 752° F) from the seafloor into the water column where the remaining metals precipitate as clouds of tiny crystalline sulphides particles. These hot springs were named "black smokers" because the plume of metallic sulphides particles discharging from a chimney-like structure formed by precipitation of metallic minerals from the solutions resembles an active factory smokestack. “White smokers” also exist with lower metal contents and lower temperatures than the black smokers.

Table 6. Composition of seafloor polymetallic massive sulphides deposits (Herzig and Hannington, 1995)

Element	**Mid-Ocean Ridges at Divergent Plate Boundaries**	**Volcanic Island Chains at Convergent Plate Boundaries (range of composition)**
Lead (weight percent)	0.1	0.4 - 11.8
Iron	26.4	6.2 - 13
Zinc	8.5	16.5 - 20.2
Copper	4.8	3.3 - 4.0
Barium	1.8	7.2 - 12.6
Arsenic (parts per million)	235	845 - 17,500
Antimony	46	106 - 6,710
Silver	113	217 - 2,304
Gold	1.2	4.5 - 3.1
Number of samples analyzed	1,259	613

The hot and molten rocks that heat the seawater circulating through the ocean crust to form massive sulphides deposits and hot springs occur at sites along the two types of tectonic plate boundaries, as follows (*see Figure 3; Table 3):*

(a) At divergent plate boundaries where hot molten rocks (magma) upwell to create ocean crust by the process of seafloor spreading at the submerged volcanic mountain range that extends through all the ocean basins of the world;

(b) At convergent plate boundaries where volcanic activity is generated by melting of the ocean crust as it is destroyed when it descends back and is assimilated into the Earth's interior in the process of subduction. The conditions for formation of polymetallic massive sulphides deposits occur at submerged sites associated with the volcanic island chains and with subsidiary sections of the submerged volcanic mountain range that lie in marginal seas behind these islands.

The hot springs and polymetallic massive sulphides deposits do not occur continuously along these plate boundaries, but are extremely localized at sites where the right combination of heat, fluid circulation pathways, metal sources and other factors focus the ore-forming systems. These sites are generally no larger than the size of a sports stadium, which is the reason why it is extremely challenging to find them as exploration targets. Exploration of the oceans is at an early stage when only about 5 percent of the plate boundaries have been investigated in sufficient detail to find such deposits, much less the ocean basin away from plate boundaries and the rocks beneath the seafloor where older, inactive deposits may lie. At the present early stage we know of about 200 sites of active and inactive mineral deposits, mostly small, at plate boundaries in the Pacific, Atlantic, Indian and Arctic Oceans (Rona and Scott, 1993). Major sites at plate boundaries are shown on a global map in *Figure 2*. Once formed at plate boundaries, the deposits are transported away from the boundaries by the process of seafloor spreading (*Figure 3*). Almost nothing is known about these off-axis deposits at this early stage in exploration of the oceans.

The TAG (Trans-Atlantic Geotraverse) hydrothermal field situated on the Mid-Atlantic Ridge, a divergent plate boundary in the North Atlantic (Rona et al. 1986), is one of the largest and best studied of the active deposits. It is the first such field found in the Atlantic Ocean (Rona et al., 1986). The TAG field clearly illustrates general features of seafloor polymetallic sulphides deposits (*see Figures 2 and 14*; Rona et al., 1993). The field occurs at a water depth of nearly 4,000 metres (about 13,000 feet) in the rift valley that lies along the north-south trending axis of seafloor spreading where molten rocks upwell to generate ocean lithosphere at a slow rate (about 1 centimetre or 0.4 inch per year) to each side of the spreading axis. As described, cold, heavy seawater downwells several kilometres along fractures in the ocean crust, is heated by the hot rocks beneath the rift valley, expands, and buoyantly rises as hot metal-rich solutions to build a mound constructed primarily of polymetallic massive sulphides. The mound is the size and shape of the sports stadium in Houston, Texas, of the United States, the Houston Astrodome (*Figure 14*; 200 metres or about 650 feet in diameter and about 40 metres or 130 feet high). A cluster of high-temperature black smokers vigorously discharges from near the centre of the top of the mound and progressively lower temperature solutions discharge out to its margins. An area of exceptionally pure manganese deposits (52 per cent manganese by weight) lies peripheral to the active mound and is inferred to have been deposited from lower temperature solutions.

The Ocean Drilling Programme (ODP), an international consortium of 20 nations that support a scientific programme of drilling with an offshore oil-drilling vessel modified to operate in oceanic depths,[38] drilled a series of holes into the active TAG polymetallic massive sulphides mound to determine its internal composition and structure (Humphris et al., 1995). The drilling revealed that the TAG mound consists of two parts (*Figure 14*):

---

[38] The current successor of the ODP is the Integrated Ocean Drilling Programme (IODP).

(a) A lens-shaped body convex-up at the seafloor and concave-up beneath the seafloor constructed primarily of polymetallic massive sulphides. The most interesting metals (copper, zinc, silver, gold) are concentrated in the upper 10 metres (33 feet) of the mound with mostly iron sulphides (the mineral pyrite or "fool's gold") composing the rest of the mound. Samples of the sulphides were dated and ranged in age up to 50,000 years. Various lines of evidence suggest that, rather than continuous activity over that time interval, the activity was episodic turning on for tens of years and then turning off for several thousand years. Reworking of the massive sulphides by the circulating solutions gradually concentrated the most interesting metals in the upper layer of the lens-shaped body.

(b) An underlying feeder zone consisting of a network of fractures through the volcanic rocks of the ocean crust, which serves as the upwelling pathways for the hot metal-rich solutions. The total estimated weight of lens and feeder zone of the deposit is about 5 million metric tons.

The TAG-type polymetallic massive sulphides mound and its associated manganese deposit found at the Mid-Atlantic Ridge bear similarities and also differences to those deposits at the convergent plate boundaries associated with the volcanic island chains of the western Pacific Ocean. As noted, the volcanic island chains form at convergent plate boundaries where the ocean crust bends down and descends into the Earth's interior where it is destroyed through remelting to counterbalance the creation of ocean crust at divergent plate boundaries (*Figure 4*). The components of ore-forming systems consisting of hot rocks beneath the seafloor as a heat source, seawater as the circulating fluid, and permeable pathways through volcanic rocks that contain metals, are present at local sites on the seaward and landward sides of these volcanic island chains.

The seafloor settings favourable for the formation of polymetallic massive sulphides deposits and associated manganese deposits are the collapsed centres of seafloor volcanoes (calderas) situated primarily on the seaward side, and subsidiary sections of the submerged volcanic mountain range in marginal seas on the landward side of the volcanic island chains (*Figure 4*). Recently discovered examples of polymetallic sulphides deposits in these two settings at the seaward and landward sides of volcanic island chains are, respectively: (a) the Sunrise deposit about 400 metres (1,300 feet) in diameter of unknown thickness in a water depth of about 1,300 metres (4,300 feet) in the caldera of an active seafloor volcano on the seaward side of a volcanic island chain south of Japan (Isu-Ogasawara Arc; Iizasa and others, 1999), and (b) the PACMANUS and an adjacent polymetallic massive sulphides deposit in a water depth of about 1,600 metres (about

5,300 feet) in the Manus basin of the Bismarck Sea within the archipelagic waters of Papua New Guinea (Binns and Scott, 1993). These deposits have been leased from the government of Papua New Guinea by an Australian mining company (Nautilus Minerals) for development and eventual mining contingent on their assessment and market conditions (*see Figure 15*).

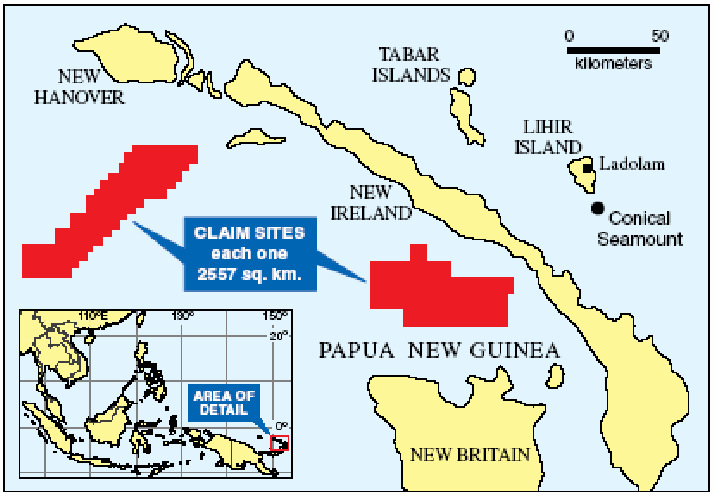

Figure 15. Map showing the location of two areas (water depth 1500 to 2500 m) covered by an exploration license for seafloor massive sulfide deposits from the Papua New Guinea government to an Australian mining company in the Bismarck Sea of the Manus back-arc basin southwest of New Ireland. The crater of a volcanic seamount (Conical Seamount; water depth 1050 m) in the fore-arc region on the northeast side of New Ireland contains hydrothermal minerals with gold content comparable to commercial gold deposits on a neighboring island (Lihir island; Herzig and Hannington, 2000).

Some general observations about seafloor polymetallic massive sulphides deposits may be made based on knowledge gained at the present early stage of exploration.

- **Massive Sulphides at Divergent versus Convergent Plate Boundaries**

Based on the limited sampling methods noted, seafloor massive sulphides deposits associated with volcanic island chains (settings on seaward and landward sides) at convergent plate boundaries are generally enriched in metals of interest, especially precious metals, relative to those at the submerged volcanic mountain range along divergent plate boundaries (*see Table 5*).

- **Distribution**

More than 80 per cent of the approximately 55,000 kilometre (about 34,000 mile) globe-encircling length of the submerged volcanic mountain range at divergent plate boundaries lies in the international seabed Area, while some 26 sections of the submerged volcanic mountain range extend within the 200 nautical mile exclusive economic zones of various coastal States (*Figure 2; Table 7*).

Table 7. Submerged divergent plate boundaries (ocean ridges) within 200 nautical miles (370 km) of land (location identified by number in Fig. 2)

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 Center	Cayman Islands Swan Island	Jamaica Honduras
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 Center	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 Center	Democratic Republic of Yemen	Democratic Republic of Yemen
15	Red Sea	Red Sea Spreading Center	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 Center	Galapagos Islands	Ecuador
21	Pacific Ocean	East Pacific Rise	Mexico	Mexico
22	Pacific Ocean	Gulf of California Spreading Center	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

- Non-Renewable Resource

It has been contended that active seafloor polymetallic massive sulphides deposits are renewable resources that will regenerate by precipitation from hot springs almost as quickly as the material is mined. This may be valid for certain individual active mineralized chimneys, which have been observed to regenerate within days to years after removal. However, as determined by dating of materials that compose the TAG active polymetallic massive sulphides mound using radiometric methods, it takes thousands to tens of thousands of years for the natural processes to operate, that form and concentrate the interesting metals in a massive sulphides deposit as a whole. In order to avoid depletion of resources, one idea that has been suggested is to leave the already accumulated deposits intact and to obtain the metals by capturing directly the hot metal-rich discharges; however, this method, in addition to destroying equipment, will only generate quantities of iron and little else.

- Ancient Analogues

The size, shape, tonnage and composition of the TAG mound and the seafloor settings of the Sunrise and PACMANUS deposits are similar to those of a class of ancient metallic mineral deposits, volcanogenic (origin related to volcanic activity) massive sulphides (VMS) deposits, that have been mined on land for centuries as a source for copper, iron, zinc, silver and gold without an understanding of how these deposits were formed. These and other active seafloor polymetallic massive sulphides deposits enable economic geologists to observe VMS deposits in the process of formation. These observations give the geologists unprecedented insight to guide their exploration for and mining of ancient counterparts, which were formed at submarine plate boundaries in the geological past and subsequently uplifted onto land where the deposits are accessible for exploration and exploitation.

(iii) Chromium, Nickel and Platinum Group Metal Deposits from Sources in Ocean Basins

The polymetallic massive sulphides and manganese deposits precipitated from relatively high- and low-temperature hot springs, respectively, occur primarily in the volcanic rocks of the ocean crust, which is typically the upper 5 kilometres (about 3 miles) of the lithosphere (*see Figure 16*).

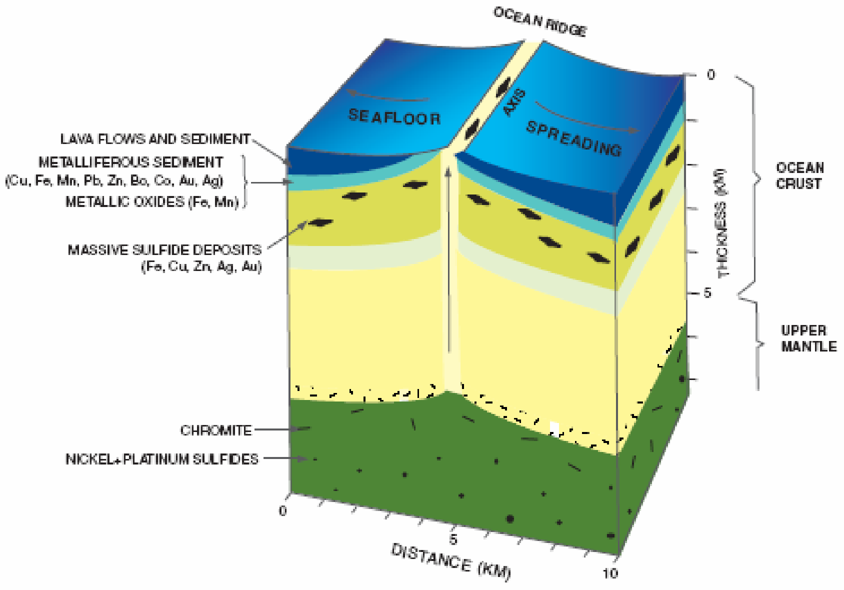

Figure 16. Schematic block diagram showing potential occurrence of metal deposits in ocean crust (shaded) and the underlying upper mantle formed at a divergent plate boundary (modified from Bonatti, 1981 and Rona, 1983).

Metallic mineral resources of the Earth's mantle, which underlies the ocean crust, are poorly known because of limited exposures of these deeper subseafloor rocks. The types of deposits anticipated in the upper mantle comprise chromium in the form of chromite deposits, and nickel- and platinum-rich sulphides mineral phases. These deposit types are potential future sources of chromium and platinum group metals (platinum, palladium, ruthenium, osmium, rhodium, and iridium).

4.3 *Marine Mineral Deposits from Sources on Continents and in Ocean Basins*

(i) Polymetallic Manganese Nodules

Polymetallic manganese nodules were the only mineral resource known in the deep ocean at the time prior to the advent of the theory of plate tectonics. The nodules played a significant role in driving the development of the Convention. A survey of the large quantity of metals (cobalt, copper, iron, lead, manganese, nickel, and zinc) contained in nodules, including estimates of the value of these metals (Mero, 1965), was an important factor behind the development of the legal regime for resources found in the seabed beyond the limits of national jurisdiction.

Polymetallic nodules typically range in size from that of a golf-ball to a tennis-ball. They lie partially buried on the surface of sediments that cover vast plains on the deep seafloor (typical water depth 5 kilometres or 2.5 miles) (*see Figure 17*). These "abyssal" plains are the largest physiographic province on Earth covering some 70 percent of the area of ocean basins and 30 percent of the Earth's surface (*see Figure 1*).

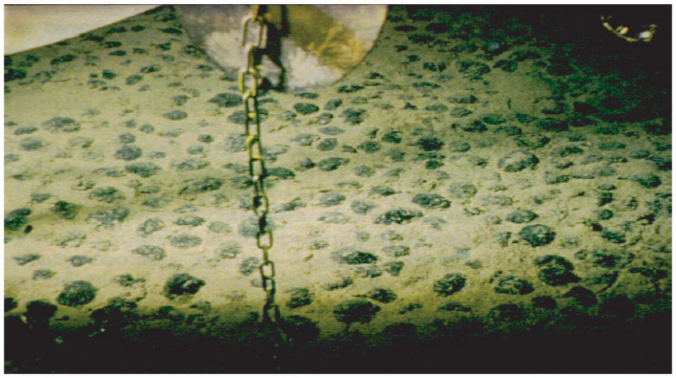

Figure 17. Photo of polymetallic manganese nodules on seafloor which typically range in size from that of a golf ball to a tennis ball

The upper portion of the nodules accumulates metals that are precipitated from seawater (authigenic process in Table 1); the lower portion of the nodules partially buried in sediment accumulates metals from pore-water in the underlying sediments (diagenetic process in *Table 1*; *Figures 17 and 18*).

Figure 18. Photo of an individual polymetallic manganese nodule specimen (about the size of a golf ball)

The metal accumulation rates are so slow that it generally takes millions of years to form a manganese nodule. The metals come from two sources. The primary source is considered to be metals that are dissolved from rocks on land as part of the weathering process and transported to the ocean by rivers. The secondary source is metal-rich solutions that discharge as warm- and hot-springs at ocean ridges. The metal concentration in the nodules varies depending on distance from sources and intermediary processes. The highest values of metals in nodules occur in equatorial regions of oceans where the remains of tiny plants and animals that concentrate the metals from seawater sink to the seafloor, dissolve, and release the metals into the pore water of seafloor sediments, where the metals are assimilated by the nodules as they grow (see *Table 8*). Areas of commercial interest in the eastern equatorial Pacific (Clarion-Clipperton zone) and in the central equatorial Indian Ocean cover millions of square kilometers (*see Figures 19 and 20)*

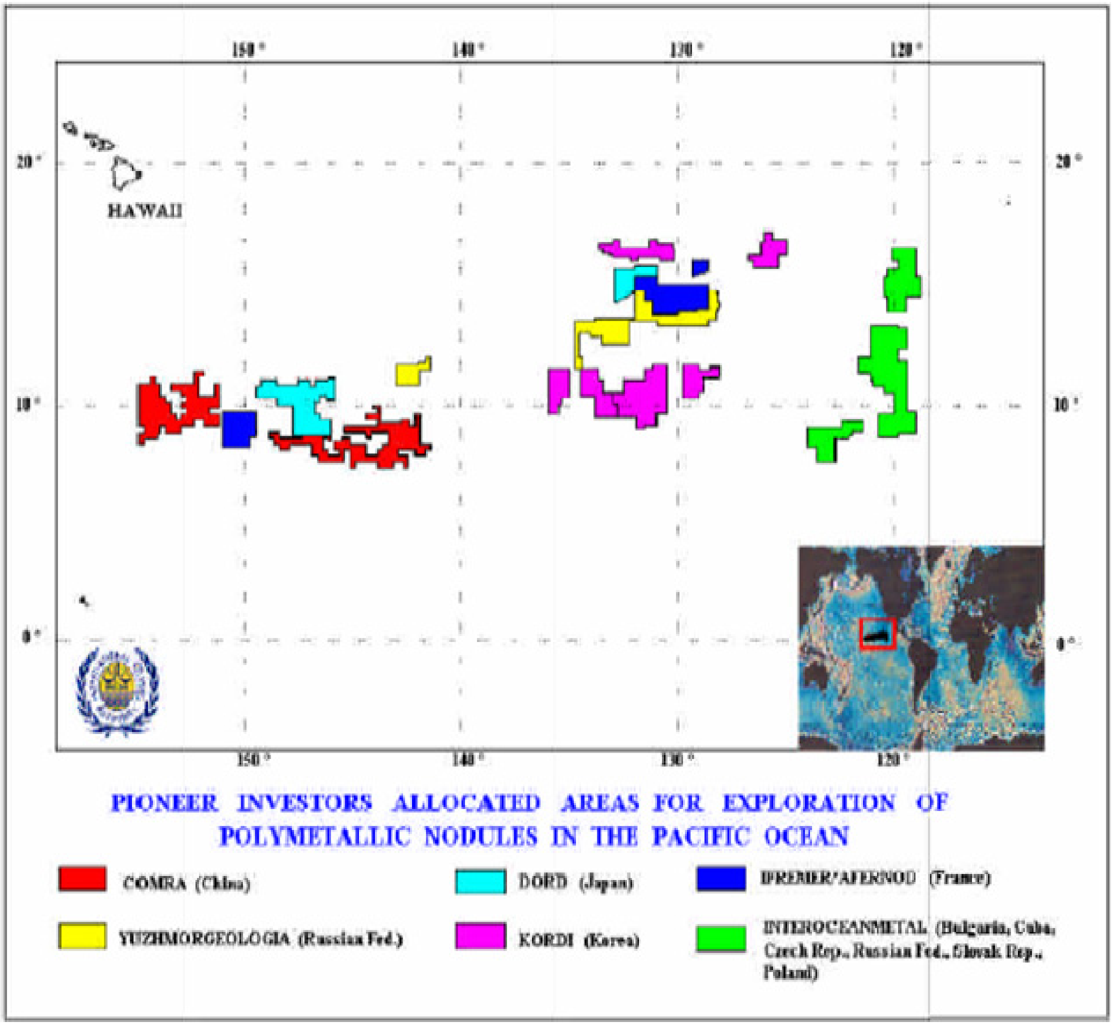

Figure 19. Map of polymetallic manganese nodule contact areas in the Clarion-Clipperton zone in the northeastern equatorial Pacific ocean (courtesy International Seabed Authority)

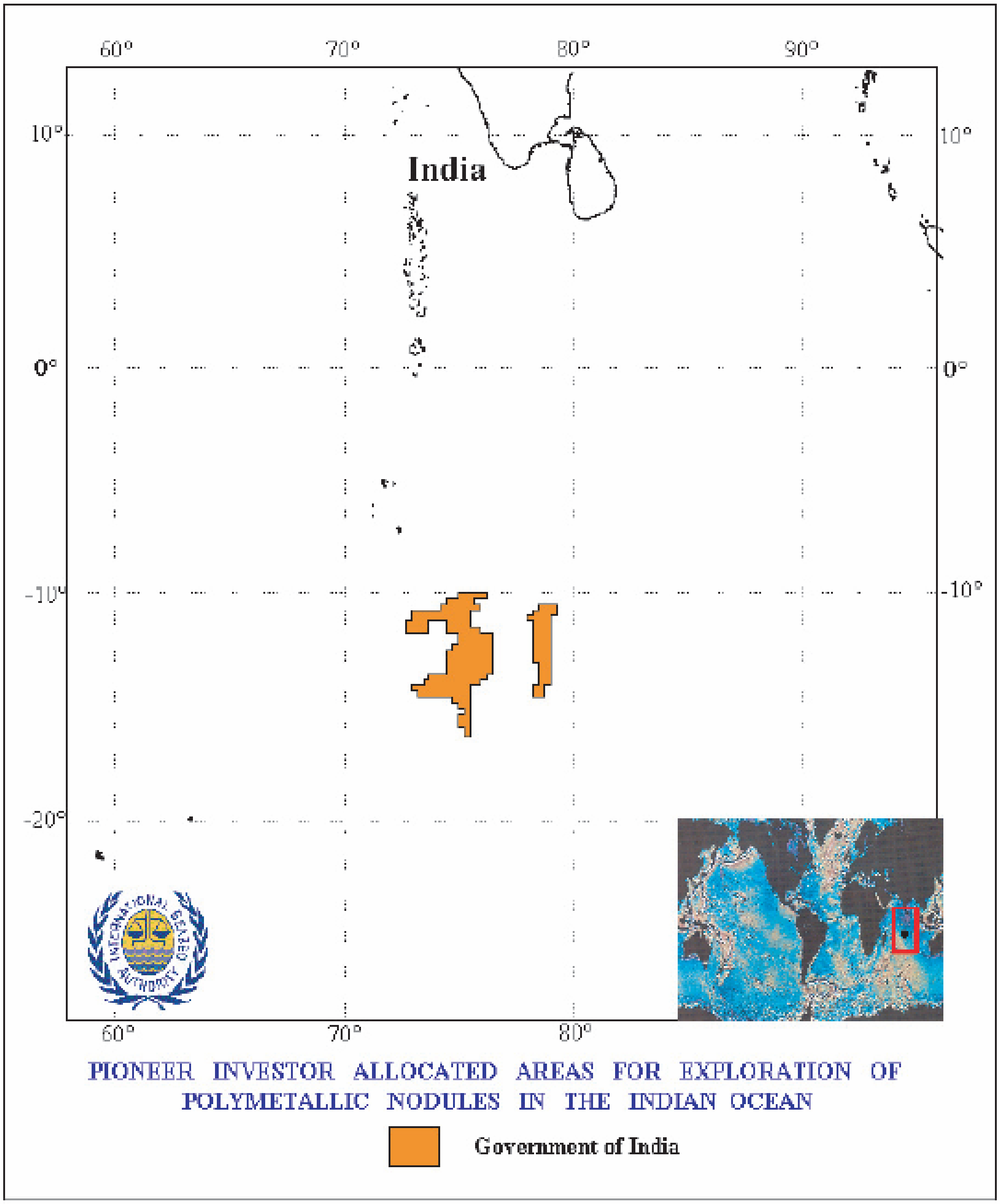

Figure 20. Map of polymetallic manganese nodule contract areas: Indian Ocean (courtesy International Seabed Authority).

Table 8. Average concentration of metals in manganese nodules from different oceans (Ghosh and Mukhopadhyay, 2000)

Element	Atlantic	Pacific	Indian	World Oceans
Manganese (weight percent)	13.25	20.10	15.25	18.60
Iron	16.97	11.40	14.23	12.40
Nickel	0.32	0.76	0.43	0.66
Copper	0.13	0.54	0.25	0.45
Cobalt	0.27	0.27	0.21	0.27
Zinc	0.12	0.16	0.15	0.12
Lead	0.14	0.08	0.10	0.09
Iridium	9.32	6.64	3.48	-
Uranium	7.4	7.68	6.20	-
Palladium (parts per million	5.11	72	8.76	-
Thorium	55.00	32.06	40.75	-
Gold (parts per billion)	14.82	3.27	3.59	-

(ii) Cobalt-Rich Ferromanganese Crusts

Cobalt-rich ferromanganese crusts exhibit similarities and differences to polymetallic manganese nodules (Hein et al., 2000). Like manganese nodules, the crusts are slowly precipitated from metals that are dissolved in seawater. The metals are derived from a combination of sources comprising dissolution from continental rocks and transport into the ocean by rivers, and discharge of metal-rich hot springs in the deep ocean. Like manganese nodules the crusts contain a suite of metals (iron, manganese, cobalt, nickel, platinum, and other metals), (*see Table 9*), that varies depending on proximity to different sources. Instead of accumulating as nodules on the sediment surface of abyssal plains in the deep ocean, cobalt-rich-ferromanganese crusts accumulate as extensive layers directly on volcanic rock that forms submerged volcanic seamounts and volcanic mountain ranges.

Table 9. Range of mean concentration of metals in cobalt-rich ferromanganese crusts from the Pacific, Atlantic and Indian Oceans (Hein, 2000)

Iron (weight percent)	15.1 - 22.9
Manganese	13.5 - 26.3
Nickel (parts per million)	3,255 - 5,716
Copper	713 - 1,075
Cobalt	3,006 - 7,888
Zinc	512 - 864
Barium	1,494 - 4,085
Molybdenum	334 - 569
Strontium	1,066 -1,848
Cerium	696 - 1,684

Chemical conditions including low oxygen content in the seawater favour accumulation of the crusts between water depths of 400 and 4,000 metres (1,300 and 13,000 feet; *see Figures 21 and 22*).

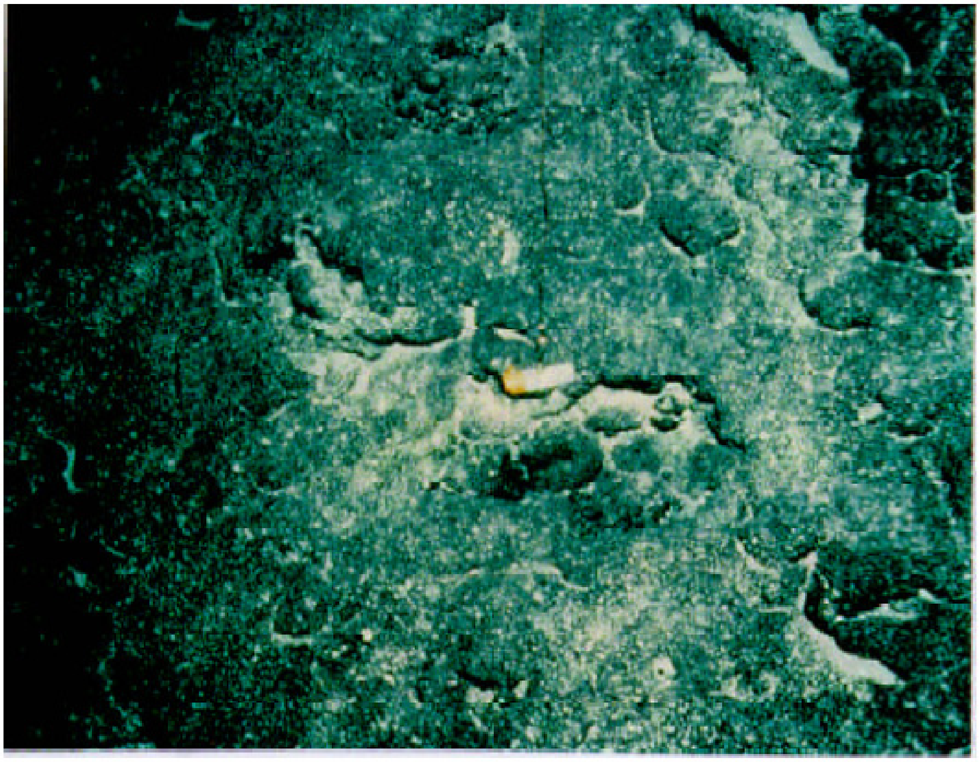

Figure 21. Photo of cobalt-rich ferromanganese crust on the seafloor (area about one square meter, about 11 square feet, which accumulates on volcanic rocks of seamounts and typically attain thickness up to 25 centimeters/10 inches)

Figure 22. Photo of hand specimen of cobalt-rich ferromanganese crust

The crusts accumulate slowly over millions of years and attain a thickness up to 25 centimetres (10 inches). The large number of seamounts in the Pacific Ocean is particularly favourable settings for the occurrence of cobalt-rich ferromanganese crusts. The seamounts occur within and beyond the 200 nautical mile exclusive economic zones of the island States of the western Pacific Ocean.

5. Environmental Considerations

The consideration of environmental issues relating to marine mineral resources involves different dimensions in comparison with land-based mineral resources. This is mainly because of the relatively limited knowledge of the marine environment, combined with the limited understanding of the possible impacts of activities, such as prospecting, exploration and exploitation of marine minerals.

In this context, the International Seabed Authority (ISA) has convened a number of workshops and published a number of studies which point to a need for a systematic process of observation and analysis of environmental factors (International Seabed

Authority, 1999, 2000). Although the ISA workshops and studies address deep-sea mining in particular, their conclusions apply to marine mining in general.

The following provides a brief outline of the process:

(a) Marine scientific research activities to address the need for baseline data;

(b) Establishment of environmental baselines;

(c) Development of a programme to monitor and assess effects of prospecting, exploration and exploitation, including cooperative marine scientific research to address major gaps in the knowledge base;

(d) Determination of the nature and extent of effects that could be considered "harmful effects" on the marine environment;

(e) Development of programmes to ensure effective protection for the marine environment from harmful effects which may arise from marine mineral-related activities;

(f) Establishment of clear and common methods to address each of the issues referred to in (a) to (e) above, and standardization in areas of taxonomy;

(g) Additionally, in view of the fact that all of the matters in (a) to (f) above are based on the current scientific knowledge of the marine environment and the technology to be used in marine mineral-related activities and that future advancements in both scientific knowledge and technology can be substantial, periodic review of such matters.

Environmental considerations on marine exploration and mining takes on an additional dimension, because in many cases marine organisms are associated with marine mineral deposits and must be considered with reference to exploration and exploitation activities.

Key observations of biodiversity of these organisms in context of seafloor settings in general, settings associated with deep ocean hot springs, and settings associated with cobalt-rich ferromanganese crusts are, as follows:

5.1 Biodiversity in the Deep Ocean in General

(a) Life is ubiquitous in the ocean including the water column, the seafloor, and beneath the seafloor. By life is meant both macrofauna visible to the naked eye, microfauna comprising microbes too small to be seen by the naked eye, and meiofauna (animals that are intermediate in size between macrofauna and microfauna). A recent study identified over 1.2 million previously unknown genes in microbes sampled from Atlantic surface water offshore Bermuda (Venter et al., 2004). Another investigation found new species in every square metre of seafloor sediment sampled (Grassle and Maciolek, 1992).

(b) An estimated number of species in excess of 10 million (exclusive of microbes) exist in the ocean. The species diversity of microbes is unknown. Marine species diversity in the deep ocean is comparable to that in tropical rainforests (May, 1994).

(c) Marine organisms are associated with all types of marine mineral deposits. The assemblage of organisms differs with different types of marine mineral deposits and their seafloor settings.

(d) Microbes and larger organisms of the deep ocean have significant potential as a source of useful products for emerging industrial and medical applications including pharmaceuticals (Fenecal, 1993, 1996), as well as of value for preserving biodiversity and for understanding the evolution and adaptations of life.

5.2 Biodiversity at Deep Ocean Hot Springs at Polymetallic Massive Sulphides Deposits

(a) In contrast to high species diversity in the deep ocean exclusive of hot springs (hydrothermal vents) at polymetallic sulphides deposits, the species diversity at hot springs (exclusive of microbes) is low (Van Dover, 2000). However, the lower number of species present is represented by a high diversity of major animal groups (taxonomic phyla) and high numbers per unit area (biomass several orders of magnitude higher than that of the deep sea).

(b) The vent fauna is currently known to have at least 442 species, most of which are new to science. The fauna is endemic to the vent ecosystems and taxonomically distinct from that of the normal deep sea (Tunnicliffe, 1991, 1992; Tunnicliffe and Fowler, 1996; Fowler and Tunnicliffe, 1997).

(c) The number of species of vent fauna is growing as new vents are found. Every seafloor hydrothermal field examined to date has some species that are not found in any other field (Tunnicliffe et al., 1998).

(d) Varieties of heat-loving microbes (thermophiles) are associated with the seafloor hot springs. They manufacture carbohydrates (sugars and starches) to nourish themselves using chemical energy in the hot springs. In other words, the same hydrothermal solutions that form the polymetallic massive sulphides and related metal deposits provide the chemical energy used by the microbes to manufacture their food. In turn, these "chemosynthetic" microbes are at the base of the food chain for the entire ecosystem of vent organisms. The microbes actually live in and around the polymetallic massive sulphides deposited by the hot springs and the underlying rocks that host these deposits. These microbes are of great interest to science, to industry, and to medicine (Jannasch, 1995; Rona, 2003). Analysis of their genetic material indicates that certain of these heat-loving (thermophillic) microbes that live in warm to hot hydrothermal solutions exhibit genetic characteristics that place them at the base of the tree of life. The study of these mirobes is throwing light on the relation between volcanic activity and life that may elucidate the origin of life on Earth, and may provide a key to deciphering possible life on Mars and elsewhere in the solar system and beyond. Enzymes extracted from certain of these microbes are already employed in replicating genetic material for forensic and other identification applications (polymerase chain reaction for DNA fingerprinting), household detergents, and food preservation. Heat and pressure resistant chemical compounds produced by certain of these microbes are being adapted to high-temperature industrial processes, such as hydrofracturing to improve the flow and recovery of oil in deep wells. Bioactive compounds produced by other vent microbes are being tested for medical applications including pharmaceutical products applicable to the treatment of cancer and other diseases. Certain of the microbes themselves have potential as bioreactors with roles in concentrating and refining metallic mineral ores. The present utilization of this unanticipated living resource without a legal framework before the anticipated future utilization of deep seabed minerals has been described as "the deepest of ironies" (Glowka, 1996).

(e) Actively venting seafloor hydrothermal fields that contain polymetallic massive sulphides deposits are generally no larger than a sports stadium, so they are vulnerable to disruption by sampling and drilling by the scientific community and by potential mining for minerals or for microbes.

(f) Documentation of rejuvenation of a vent ecosystem three years after it was destroyed by a volcanic lava flow is cited as an example of the resilience of such ecosystems to all manner of disruptions (Lutz and Haymon, 1994). In fact, the volcanic activity that destroyed the vent ecosystem contained the seeds of rejuvenation. The same upwelling molten rock that produced the lava flow contained the heat to regenerate the hot springs which, in turn, contained the chemicals to regenerate the microbes at the base of the food chain for the whole ecosystem. If an ecosystem and the associated hydrothermal circulation system are destroyed, then the ecosystem will lack the basis to regenerate.

(g) Polymetallic massive sulphides deposits exist that are no longer associated with the active hot springs and ecosystems where they formed. These inactive polymetallic sulphides deposits lie where volcanic activity has ceased and where the deposits have been carried away from the volcanically active area by the process of seafloor spreading. Exploration methods are being developed to find these deposits (e.g., Rona, 1978a, 1978b, and 1999-2000).

(h) The deep ocean exclusive of hot springs and the hot springs in the deep ocean both appear to have served through geologic time as sanctuaries that have protected certain species of marine animals from major global episodes of extinction of animals that have occurred in shallow water and on land.

Measures of management to ensure the conservation and sustainability of biodiversity in deep ocean and vent ecosystems (seafloor, sub-seafloor, and water column biosphere), are being developed for the 200 nautical mile exclusive economic zone and the international seabed Area. Examples for the 200 nautical mile exclusive economic zone include the Madang Guidelines produced by the South Pacific Applied Geoscience Commission (SOPAC, 1999); Canada's designation in 2003 of certain seafloor vent ecosystems off its northwest coast as a Marine Protected Area (Dando and Juniper, 2001); and Portugal's consideration of a similar regime for such ecosystems offshore the Azores islands (Santos et. al., 2003). Consideration has been initiated for environmental guidelines for vent ecosystems (polymetallic sulphides; e.g., Mullineaux et al., 1998).

5.3 Biodiversity Associated with Polymetallic Manganese Nodules

The abyssal plains where the polymetallic nodules occur look like vast deserts of the deep sea. The abundance of life at the abyssal seafloor is relatively low, as a consequence of sparse food supply due to the low flux of particles of organic carbon in the form of tiny plant and animal remains that settle from surface layers of the ocean. However, the sediments contain an extraordinarily high diversity of marine invertebrate animals and microbes (Smith, 1999). Macrofauna in the sediment of the nodule areas belong to many different major animal groups (phyla) and the seafloor exhibits a variety of biogenic traces, such as fecal pellets, body tubes, burrow openings, feeding tracks, locomotion trails, and mounds and cones built by worms and other types of marine invertebrates and fish (Jauhari and Pattan, 2000). A cubic sample of the sediment 0.25 metre (1 foot) on each side is likely to recover 30 to 40 different macrofaunal species (mostly tiny worms; Smith, 1999). The nodules themselves support a distinct community of small animals that feed by picking particles from the water column and include microbes (Gardner et al., 1984). Significant biodiversity has been documented on the scale of hundreds of kilometres (miles) of a single polymetallic nodule province like that in the eastern equatorial Pacific (Clarion-Clipperton Zone; Smith, 1999).

5.4 Biodiversity Associated with Cobalt-Rich Ferromanganese Crusts

The summits of seamounts within the zone of light penetration (water depth about 300 metres or 1,000 feet) exhibit extraordinary biodiversity in terms of deep-sea corals, other invertebrates, and fish. Deep-sea corals are also known to occur on seamounts outside the zone of light penetration. Investigation of biodiversity is needed for the deeper flanks of seamounts in the water depth range for the occurrence of cobalt-rich ferromanganese crusts (400 m to 4,000 metres; 1,300 to 13,000 feet).

Chapter 4: Marine Mineral Resources: Economic and Technological Perspectives

Scientific advances in the past few decades have revolutionized the international community's knowledge and ability to search for marine mineral resources. In some cases, applied science has found ways to make some of these resources available to mankind through the development of new technologies or the adaptation of existing technologies for mining the mineral deposits concerned and processing them to recover the valuable products that they contain. For both land-based and marine mineral deposits, an ore body is generally defined as a mineral concentration (a mineral deposit) from which an element or a compound can be economically extracted under the existing legal, political and economic conditions. For marine mineral resources found in the international seabed area (the "Area"), a legal framework has been provided for by the Convention. For polymetallic nodules, this framework and the Agreement relating to its implementation have been used to develop a prospecting and exploration code. For any further development of this code, applied science (engineering) will have to provide a solution to the problem of economically viable mining and processing technologies.

For all mineral resources, a generally accepted classification has been developed to describe the economic concepts of reserves and resources. In this classification system, reserves are defined as known deposits from which minerals can be extracted profitably under present economic conditions and with existing technology. Resources are the total amount of an element, both known and unknown, down to some defined grade that is higher than the crustal abundance of the element in the earth's crust but lower than the present economic grade. In general, the quantity of material currently classifiable as reserves is much less than the total quantity of resources. By implication, the quantity of reserves will become progressively smaller as more and more material is withdrawn through mining operations unless an equal amount of material is transferred from resources into the category of reserves. Such transfers can be accomplished in three ways: by normal development procedures, by technological advances, and by price increases. In fact, the transfer of resources to the reserve category is generally the result of the interplay of these three factors.

1. *Integration of Science and Economics in Marine Mineral Development.*

Once a mineral deposit has been discovered in the ocean, the questions concerning whether there is a use for the mineral (a commodity that can be traded) and whether or not technology exists to recover the valuable products from the deposits have to be addressed. This is the starting point in a sequential process that progressively attempts to determine if the resource constitutes a reserve of the mineral in question. The sequential process starts with large seabed areas that are regionally appraised for the deposits that they contain, in order to select the most promising areas for further investigation. This phase is generally described as the prospecting phase. The next phase, exploration, is conducted with a view to identifying deposits, characterizing the deposits, and determining whether or not technology exists or has to be developed to recover the valuable products from the deposits. Where such technology is readily available and tested, the process quickly lends itself to pilot mining tests to establish the economic prospects of mining these deposits.

For marine minerals on the continental shelf for which there has been a relatively long tradition of mining, the progression from discovery to production is fairly straightforward. Technology development is generally focused on technology adaptation. The development of mineral resources of the international seabed area (the “Area”) however presents a number of challenges. These include the high costs of exploration (time and money), and the fact that none of the minerals for which rules, regulations and procedures are being developed (polymetallic nodules, polymetallic seafloor massive sulphides and cobalt-rich ferromanganese crusts) have ever been mined in the area. Applied science will have to assist in developing lower cost methods for exploration.

For future mining, in particular in the case of polymetallic nodules, science is currently playing a significant role in the work of the International Seabed Authority with respect to the protection and preservation of the marine environment. For example, in the Clarion Clipperton fracture zone, where the Authority has issued exploration contracts to six entities, projects are currently underway to encourage standardization in the collection of environmental data, including the taxonomic classification of fauna, the determination of species ranges, etc. for the zone. The results of these projects are expected to assist the Authority and contractors to manage impacts from nodule mining.

The major challenge however still remains mining technology. In this regard, in the absence of new developments in mining technology to replace the configurations of technology that were proposed in the 1970s and 1980s, discussions of when seabed mining of polymetallic nodules will occur will continue to focus on price increases in the valuable elements that they contain.

(i) Exploration Methods for Marine Mineral Deposits

Exploration methods differ for different types of marine mineral deposits. However, exploration objectives are common to all types of deposits. These objectives are to find the deposit, and to characterize the deposit. Characterizing a deposit means to determine its grade (concentration of the material of interest per unit volume of the rock or sediment that hosts the material), tonnage (how much rock or sediment is present that hosts a concentration of the material of interest being sought), and related information on physical, chemical and biological properties of the deposit and surrounding area. This information is an essential part of assessing the potential value of the deposit and the environmental impact of a potential mining operation.

- ***Locating a Deposit***

Exploration for most types of mineral deposits on the seafloor is time consuming and resource intensive because the deposits are small targets. Even in the case of polymetallic manganese nodules and cobalt-rich ferromanganese crusts, which are two-dimensional deposits extending over large areas, it is time and resource intensive to find the areas of highest grade and tonnage. On the broadest scale, exploration begins in a seafloor region where the particular type of mineral deposit is known to occur. From that point on, the procedure is to systematically employ exploration methods designed to detect various physical, chemical and biological properties of the deposit and seafloor characteristics (structure, composition) that are known to be associated with the type of deposit being sought. This systematic procedure of progressively closing range as a combination of methods is used to sense properties of the deposit and the surrounding seafloor is outlined in *Table 10*.

Table 10. Exploration strategy to find a seafloor mineral deposit (Modified from Rona, 1983, 1999-2000)

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

[1] Distance: 1 kilometre = 1,000 metres = 1.852 nautical miles.

[2] ROV: Remotely Operated Vehicle (tethered to ship with electro-fiber optic cable).

[3] AUV: Autonomous Underwater Vehicle (untethered).

[4] HOV: Human Occupied Vehicle (untethered).

This approach of progressively reducing a large area to a potential mineral deposit, using as an example an actively forming massive sulphides deposit in the seafloor province of a submerged volcanic mountain range at a divergent plate boundary, was successfully implemented to discover the TAG hydrothermal field on the Mid-Atlantic Ridge (Rona et al., 1986). The TAG field contains the first hot springs, polymetallic massive sulphides deposits, and associated ecosystem of vent organisms found anywhere in the deep Atlantic Ocean and remains one of the largest such fields found in the world (Rona et al., 1986). Hot springs associated with an active polymetallic massive sulphides deposits discharge certain metals in dissolved and particulate form (iron and manganese) and dissolved gases (helium) that can be transported by deep ocean currents for distances of hundreds of kilometres (hundreds of miles) from an active source. These components can be detected in water samples recovered from appropriate depths by standard shipboard water sampling methods. The metallic mineral particles discharged from black smoker-type vents 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 be found by following concentration gradients of these metallic signals in the water column and in seafloor sediments.

The sequence of progressively closing range from far to near the deposit (*Table 10*) employed in finding the large polymetallic massive sulphides deposits of the TAG field is, as follows:

- Distance tens to several kilometres (thickness of the water column in the deep ocean) from the deposit: Mapping the depth and shape of the seafloor with bathymetric methods and side-scan sonar and measurement of the magnetic field to detect a diagnostic magnetic signature (Rona, 1978a, 1978b, 1999-2000; Tivey et al., 1993).

- Distance several kilometres from a deposit to the deposit itself: Various methods for *in situ* sampling (water, particles, seafloor sediment) and imaging (photos, video, and side-scan sonar) can be used, mounted on various types of unmanned deep submerged vehicles operated at altitudes up to tens of metres above the seafloor to locate the mineral deposit. These unmanned deep submerged vehicles comprise remotely operated vehicles (ROVs), which are tethered to the ship and controlled through an electro-fiber optic cable with a real-time video link to the operators, and autonomous underwater vehicles (AUVs), which are free-swimming and are programmed to perform imaging, sampling and other measurement procedures in a pattern on the seafloor.

- The deposit itself: Manned submersibles, also known as human occupied vehicles (HOVs), may be used for direct observation, sampling and measurements after the mineral deposit has been targeted (Rona, 1999-2000). ROVs can also be used at this state.

- ***Assessing a Deposit***

When the deposit has been found, the next procedure is to characterize it. A so-called "nested survey" may be used to characterize the deposit (Fornari et al., 1997), which employs complementary methods to provide detailed information about the deposit.

Using the polymetallic massive sulphides deposit in TAG field as an example, the exploration procedures employed to find the deposit provided information primarily on that portion of the deposit exposed on the seafloor. As discussed, the surface expression of the polymetallic massive sulphides body is only the "tip of the iceberg", because most of the body extends beneath the seafloor as an overall lens-shape (*Figure 14*). Drilling to recover a suite of samples from the interior of the polymetallic massive sulphides body is needed to determine the overall shape, grade and tonnage of the deposit. Metals are not evenly distributed in a deposit and drilling is also needed to determine the actual distribution of metals to guide a potential mining operation to the zones in the deposit most highly enriched in the metals of interest. In the case of polymetallic massive sulphides bodies on land, literally hundreds of cores are recovered by drilling holes at spacings of metres. Drilling is technically more difficult in deep water at sea than on land. The Ocean Drilling Programme (ODP) in its Leg 158 spent two months at sea in 1994 and with formidable technical difficulty drilled 17 holes up to 125 metres into the seafloor with overall core recovery of 12 percent (Humphris et al., 1995). Drilling methods for massive sulphides deposits and associated volcanic rocks in the deep ocean are being improved, but will fall far short of land standards for the foreseeable future.

2. Mineral Resources of the Continental Shelf

Mineral resources of maritime areas under the national jurisdiction of coastal States including the continental shelf, can be divided into two groups: (a) placers; and (b) phosphorites.

2.1 Placers

As noted in Chapter 3, placers are heavy minerals resulting from a process of erosion of rocks on land involving the mechanical breakdown of rocks and transport of material into the ocean where it is sorted into deposits of the material by moving water. Table 11 presents the main characteristics of placers found on the continental shelf.

Table 11. Main characteristics of placers on the Continental Shelf

Type	Element	Mineral	Composition	Density
Native	gold	gold	Au	19
	platinum	platinum	Pt	21.5
	carbon	diamond	C	2.3
Oxides	tin	cassiterite	SnO_2	6.7
	titanium	rutile	TiO_2	4
		ilmenite	$(Fe,Mg)TiO_3$	4.8
		titanomagnetite	Fe_2TiO_4, Fe_3O_4	
	iron	magnetite	Fe_3O_4	5
	chromium	chromite	$(Fe, Mg)(Cr, Al, Fe)_2O_4$	5
	aluminum	corundum	Al_2O_3	4
		rubis	$(Cr,Al)_2O_3$	4
	iron	magnetite	Fe_3O_4	5
	rare earths	columbo-tantalite	$(Fe, Mn)(Ta, Nb)_2O_6$	8
Phosphates	thorium rare earths	monazite	$(Ce, La,Y,Nd,Th)PO_4$	5
Tungstates	wolfram	wolframite	$(Fe, Mn)WO_4$	7.2
		scheelite	$Ca WO_4$	4.7
Silicates	gemstone	garnets	$(Fe, Al, Mg, Ca, Mn)Si_3O_{12}$	4
	zirconium	zircon	$ZrSiO_4$	4.6

Phosphorite, consisting of varieties of the heavy mineral apatite, is authigenically formed in sediments of upwelling areas. Phosphorite is used mainly in the phosphate fertilizer industry.

For the economics-related data on placers and phosphorite, this study relies on a global database developed and operated by the Institut Francais de recherche pour l'exploitation de la mer (IFREMER), called MARMIN (Lenoble et, al., 1995). MARMIN is a computerized database that has been operational since 1993.

MARMIN provides descriptive summary records and distinguishes among three types of mineral assemblages. These are occurrences, deposits and ore deposits. An "occurrence" is defined as a presence of minerals, quoted in the literature, in a specified location with insufficient information to designate it as a deposit. A "deposit" is a well-documented occurrence that can be considered as a future target of mining. An "ore deposit” is a well-known deposit that can be mined under current economic and technological conditions. Given the limitations of data on marine minerals, this database is found to be among the most comprehensive, using a consistent and uniform methodology.

(i) Placers of Cassiterite (Tin, Sn)

Primary cassiterite is found in high-temperature hydrothermal veins and pegmatites (a course type of granite) associated with intrusive granites and rhyolites (a fine-grained type of granite). This kind of deposit is still mined in some countries (Australia, Bolivia, Portugal, and Russia) even if the production costs are high. After weathering and erosion the mineral can be trapped in eluvial or alluvial deposits, which constitute the main sources of tin currently mined in different regions of the world; China, Peru, Indonesia, Brazil, Australia, Malaysia, Vietnam, Russia and Thailand.

In South East Asia, tin placers were found in the submerged estuaries of the largest rivers. As most valleys in the area have prolongation under sea level, paleochannels bearing tin minerals were found offshore.

During the late 1970s, more than 12 percent of the world supply of tin was mined from the sea, mainly in Malaysia, Burma (currently Myanmar), Thailand and Indonesia. At the beginning of the 1980s, most of the tin produced in Indonesia came from the sea. The major tin producer in Indonesia at that time ordered the largest ever built dredge (Bima) from the Netherlands. However, due to large volumes of tin produced from South American mines, the tin price collapsed in 1985 after the dissolution of the International Tin Council[39] and Bima was not delivered to Indonesia. Offshore mining stopped in Malaysia and Thailand shortly afterwards while it continued in Indonesia. Currently PT Timah, the main Indonesian tin company, gets half of its production from offshore deposits. It extracts approximately 42 million cubic metres each year for an output of 20,000 metric ton of tin, which implies 476 gram of tin per metric ton of ore.

Currently, the lower grade ores mined on land, contain more than 0.4 per cent tin in the ore (e.g., placers in Russia and tailings in Tasmania), i.e. 4,000 gram per metric ton (g/t).

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[39] The International Tin Council was created in 1956 to regularize the market price. It was unable to avoid the consequence of speculation after 1974, and was largely ineffective since then.

The MARMIN database contains records of 41 offshore occurrences of tin, some of them having been mined thirty years ago (Lenoble et al., 1995). *Table 12* presents the 17 that contain information on ore grade.

Table 12. Offshore tin placers (Active in 1990)

Country.	Area	Deposit	Sn g/t	Mined
Indonesia	Bangka	Tempilang	206	
		Laut Tempilang	206	*
	Belitung	Belitung	2000	*
	Karimun	Karimun E	188	
		Karimun E A1	88	
		Karimun E A2	85	
		Karimun E A3	68	
	Kundur	Paya Kundur	147	
		Kobil Valley	118	
		Timun valley	135	
Thailand	Phan Nga	Area A Blk 1	64	
		Thai Muang	262	*
		Takua Pa	560	*
	Phuket	TongKah Harbor	235	*
United Kingdom	Cornwall	Par	1000	
		St Ives	2000	
		St Agnes	1176	

Many of these occurrences cannot constitute potential deposits at the present time. These deposits were mined in Indonesia and Thailand at the time of the development of the MARMIN database. They were providing marginal profit, with paid-off equipment, low wages and high metal price.

(ii) Placers of Diamond

Diamonds were discovered on the shores of Namibia and South Africa around 1928. They were picked up from the desert of the Namib deflation basin formed by the reworking of beach sand by strong winds from the south (Corbett, 2003 and 2004). The origin of the diamonds is the mouth of the Orange river from their original kimberlite pipes, as well as from intermediate sedimentary formations, some of them being of Archaean age.

At a later time, the beaches were prospected and the presence of diamonds was revealed in gullies and potholes sculpted by previous erosion in the Paleozoic bedrock. From the land, the miners went to sea, using gravel suction pumps operated by divers. During the 1970s, exploration was undertaken to determine the possibility of discovering offshore deposits in paleobeaches and paleochannels. Exploration revealed the presence of offshore deposits that extend to the south in Namaqualand (South Africa).

After a prolonged period of testing, mining started in 1990 with a production of 29,000 carats (ct). In 1998, offshore production was close to 1 million ct. It decreased to 650,000-800,000 ct during subsequent years due to mechanical breakdowns of the mining equipment and the cessation of activity of one company (Namco).

The ore is mined either by large diameter drills or by seabed crawlers operated by large vessels. The sediment is airlifted or pumped and processed in dense media to obtain gravel concentrate. Diamond sorting is by hand or by automatic X-ray equipment.

The diamond content of the deposits varies from 0.15 carat per square metre (ct/m^2) to 2.45 ct/m^2 for corresponding sediment thicknesses of 1 to 6 metres (Diamond Fields International, 1999; MBendi, 2004; Namdeb, 2000). Corresponding grades by weight are approximately 0.07 to 0.28 carat per metric ton (ct/t). Richer deposits have been reported with 1.00 ct/t. The diamonds are of 95 per cent gem quality, with the stones weighing 0.3 to 0.7 ct on average, with a value of $150 to $400 per carat.

(iii) Placers of Gold and Platinum

In 1992, the MARMIN database contained records of 21 occurrences of offshore gold in Alaska (USA), Nova Scotia (Canada), Chile, China, India, Korea, Fiji, Philippines, Russia, Sierra Leone, Solomon Islands and Southern New Zealand.

The only offshore mining operation for gold occurred in Nome (Alaska) from 1987 to 1990. The total production was 3,672.6 kg of gold recovered from 4,460,000 cubic metres of sediment (0.82 g/t). The deposit was identified as an ancient moraine reworked by waves and tides.

The MARMIN database also contains records of two occurrences of platinum, one in Alaska and the other in Sierra Leone. In the mid-1980s, gold prospecting in Good News Bay in Alaska revealed sand with a platinum grade of 1 gram per cubic metre (equivalent to 0.6 g/t).

Considering the price evolution and the Nome venture, a potential gold deposit would have to contain at least 2 g/t under current prices. A similar grade would be necessary to develop a platinum deposit.

(iv) Placers of Ilmenite, Rutile and Zircon

Ilmenite, rutile and zircon are generally associated with one another in the same titanium-bearing ore, and are commonly referred to as "heavy minerals", in the mining literature. They are derived from the alteration of igneous and metamorphic rocks of which they are accessory minerals. Being very resistant to chemical alteration, abrasion and shocks, they travel down the fluvial system and arrive intact at the sea. The main source of these minerals is consequently beach placer deposits. Most mined deposits are onland, corresponding to ancient (fossil) beaches, but mining recent beaches on the shore has also been attempted.

The MARMIN database contains records of 88 occurrences of titanium-bearing placers, of which 26 are located offshore as submerged paleobeaches. In the detailed records of MARMIN 25 placers are stated to be on the foreshore or the backshore.

The global land-based reserves of ilmenite are about 470 million metric tons (Mt) of titanium dioxide with 48 Mt of TiO_2 in rutile (Gambogi, 1996, 2000-2004). Annual world production is 4.7 Mt of contained TiO2. Associated zircon reserves exceed 38 Mt. These reserves are relatively easy to mine at low cost and consequently there is no pressure to develop offshore deposits.

In the currently mined deposits, the content of heavy minerals varies from 2.0 to 16.8 per cent (MBendi, 2004). Ilmenite is generally more abundant, comprising more than 75 per cent of the total, but some deposits are richer in rutile (42 per cent). Zircon grades are very low, about 0.2 per cent.

Ilmenite prices are very stable (*Figure 23*). Rutile prices have been declining since its peak in 1980, which was caused by increasing demand from the aircraft industry. The end of the cold war and the reduction of military needs explain the low prices of 1992-1994. Zircon showed some variability in prices resulting from changes to military and nuclear programmes, but is expected to now remain stable.

The first offshore deposit that would be developed must be sufficiently rich to support the capital cost of a large dredge capable of working in rough seas near the shore.

One can make the following assumptions for this potential deposit: 15 per cent heavy minerals with 11.5 per cent ilmenite, 3.5 per cent rutile and 0.5 per cent zircon.

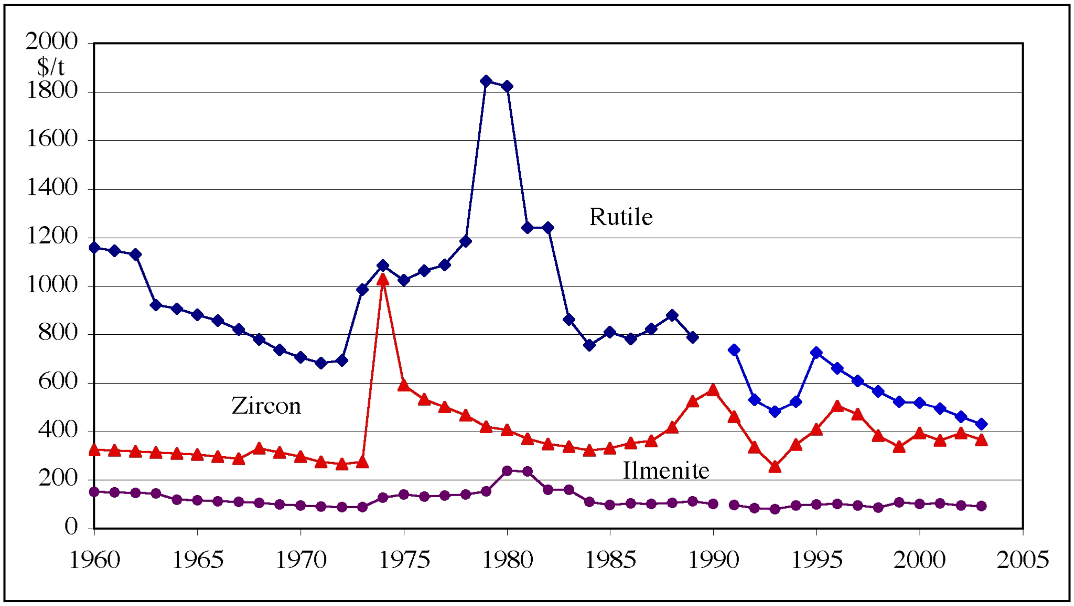

Figure 23. Prices of rutile, ilmenite and zircon in 2003 in US dollars. (Ilmenite and rutile prices are "simulated" from the titanium sponge prices).

(v) Placers of Chromite (Chromium, Cr)

Chromite results from mineral segregation during the cooling of magma of mantelic origin. It is found in basic and ultrabasic igneous rocks. The Bushveld complex in South Africa possesses 80 per cent of the global reserves of chromite, in stratiform bodies. Additional resources are contained in the Great Dyke, where chromite is concentrated in pockets inside the dunites (podiform).

As chromite is a relatively stable and shatterproof mineral, it can travel through the fluvial system to the sea. There, as with other heavy minerals, it will be concentrated by gravity separation at the bottom of channels and on beaches. However the closer the rock source, the more abundant are the chromite grains in the sediment. Consequently the richer paleochannels and paleobeaches are found in the proximity of ultramafic massifs. Chromite is also associated with magnetite and ilmenite in heavy mineral sands.

The MARMIN database contains records of 13 occurrences of chromite. Half of them are located offshore in the Western Pacific belt of islands where mantelic material was trapped during the subduction of the Pacific plate (Fiji, New Caledonia, Solomon Islands, Papua New Guinea). The others are close to ultrabasic outcrops (Sulawesi, Indonesia, Oregon and Alaska (USA), and Newfoundland (Canada)). Among the six occurrences that were investigated, the richest deposit contained 4 per cent chromite (Ploum, New Caledonia). To be profitable under current conditions, a potential offshore deposit may have to contain 5 times more chromite (20 per cent). With the decreasing trend in chromium prices and the large on-land reserves (12 Gt), it is unlikely that any offshore deposit would be developed in the near future. The recent shock in the market resulting from unusual demand from China would not change the price for long because global production capacity is sufficiently flexible.

2.2. Phosphorite

The MARMIN database contains records of 56 occurrences of offshore phosphate deposits. They can be categorized in three groups: (i) clastic deposits; (ii) coral deposits; and (iii) upwelling deposits.

(i) Clastic Deposits

Clastic deposits are detritic sands resulting from the erosion of on-land phosphate deposits. They can be concentrated in paleobeaches or paleochannels owing to the high density of the grains: 4 compared with the 2.7 for quartz and carbonate.

Clastic deposits of phosphorite have been found offshore Morocco, Congo, Namibia, South Africa, USA (Florida, North Carolina) and Mexico (Baja California) at depths varying from 5 to 200 metres. The phosphate pentoxide (P_2O_5) content of the grains is 30 per cent and the grade of the sand is approximately 10 per cent P_2O_5 containing grains.

(ii) Coral Deposits

Coral deposits were formed by the phosphatisation of coral limestones associated with volcanic seamounts. Several deposits of the same origin have been mined in the islands of Nauru (Pacific) and Ocean (Indian Ocean). The ore contained up to 45 per cent soluble calcium phosphate. Mining at Ocean Island stopped in 1979 and at Nauru around 2000.

Several atolls have been speculated to contain underwater deposits of phosphate. Mataiva Atoll was the object of intensive exploration during the 1980s by French, American and Australian companies. The deposit was estimated to contain 23.5 million metric tons of phosphate with 37.5 per cent P_2O_5. Its development however was hampered by strong environmental limitations and the cost of transportation to consuming countries.

(iii) Upwelling Deposits

The MARMIN database includes records of 33 occurrences of phosphate-bearing sediment apparently linked with upwelling of deep ocean water along steep margins. It must be noted that phosphatisation of coral limestone is hypothesized to have the same origin. Deep ocean waters are known to hold a high content of dissolved phosphate anions. Upon reaching the ocean surface, the effect of depressurization, warming and oxidation results in the precipitation of calcium phosphate in interaction with carbonate sediment. Another explanation is related to the abundance of organic matter issued from the decaying of microscopic organisms in areas where cold and warm waters are admixed.

Small concretions of phosphate are formed. Their size varies from tenths of a millimeter to several millimeters with a spherical shape that resulted in their being named oöliths. Oölithic sands can contain 15 per cent oöliths. Larger nodule concretions can reach several decimeters, with an average of 5 centimetres. Some of those nodules contain up to 29 per cent P_2O_5.

Such deposits are found offshore California at depths varying from 30 to 500 metres, where they are estimated to contain more than 60 million metric tons of ore with 27 per cent P_2O_5. However, the nodules and the oölithic sands are dispersed on only 1 to 10 per cent of the bottom surface. Consequently mining them would have to take this factor into account.

Phosphatic nodules are also reported on the floor of the Chatham Rise and Campbell Plateau near New Zealand, as well as on the Blake Plateau, offshore Florida (USA).

None of the upwelling occurrences seems to constitute a potential deposit at this time.

2.3 Freshwater

Freshwater is produced from seawater or icebergs extensively, most notably in Algeria, Bahrain, Egypt, Iran, Israel, Kuwait, Libya, Malta, Mexico, Netherlands, Oman, Qatar, Russia, Saudi Arabia, United Arab Emirates, and several countries in the Caribbean. Freshwater is obtained from submarine springs offshore of a number of countries.

Maintaining an adequate supply of freshwater for drinking, agriculture, and industrial processes is a leading environmental challenge of our age. As land supplies of water are depleted and polluted, desalination of seawater offers a viable alternative source. The desalination process is energy intensive so its use is limited at this time to those coastal States that need and can afford it, such as coastal States of the Persian Gulf region. Freshwater from seawater is expected to become a major marine mineral product as the need for freshwater grows and alternative energy sources for the desalination process are developed.

3. Mineral Resources in the Deep Sea

As described in Chapter 3, mineral resources in the deep sea may be derived from sources in ocean basins or a combination of land and ocean basin sources. These include metalliferous sediments, seafloor polymetallic massive sulphides, polymetallic manganese nodules, and cobalt-rich ferromanganese crusts.

An important aspect of these mineral resources is that they can occur both in maritime areas under the jurisdiction of coastal States or in the international seabed Area beyond the limits of national jurisdiction.

None of these minerals are commercially mined as yet, but a considerable amount of commercial interest has been shown in some of the deposits. What is essential before commercial exploitation of these minerals could commence is that the profitability of a mining operation is established. The profitability, in turn, depends on a number of interrelated factors, including characteristics of the mineral deposit, suitable technology to mine it, technology for processing the ore obtained from the deposit to extract the products of economic value, market conditions as well as environmental considerations (Lenoble, 2004).

Currently, various stages are underway worldwide in the sequential process described earlier of prospecting and exploration combined with research and development on technology. At this time, it is extremely difficult to ascertain when the requisite degree of geological assurance and of economic feasibility would be achieved to convert these potential resources to reserves, and therefore to start a viable mining operation.

(i) Metalliferous Sediments

As noted in Chapter 3, the metalliferous sediments of the Atlantis II Deep in the northern Red Sea remain the most efficient ore-forming system among hydrothermal deposits found at a divergent plate boundaries in the ocean, and constitute the largest such deposit found to date.

The Saudi-Sudanese Red Sea Commission oversees development of the Atlantis II Deep deposit located within the overlapping 200 nautical mile exclusive economic zones of the two coastal States, Saudi Arabia and Sudan (Mustafa, 1979). The Commission sponsored a pre-pilot mining test in 1979, which demonstrated the feasibility of using hydraulic dredging to recover the metalliferous sediments, and shipboard flotation to separate out zinc, copper and silver. Estimated grades and tonnages based on statistical analysis of the composition of 605 cores are presented in *Table 13* (Nawab, 2001).

Table 13. Resource potential of metalliferous sediments of the Atlantis II Deep, Red Sea (Nawab, 2000)

Metal	Grade (weight percent; dry salt-free basis)	Weight (metric tons; dry salt-free basis)
Metalliferous sediments		89,500,000
Zn	2.06	1,838,000
Cu	0.45	402,000
Ag	38 grams/metric ton	3,432

The fine size of the sediment will require modification of existing refining techniques. The resources are considered adequate to support an operation with average annual production of 60,000 metric tons of zinc, together with 10,000 metric tons of copper, 100 metric tons of silver, and 1 metric ton of gold, for a period of approximately 20 years (Nawab, 2001).

(ii) Seafloor Polymetallic Massive Sulphides

As noted in Chapter 3, discovered as recently as in 1978, polymetallic massive sulphides are associated with extinct or active hydrothermal springs that occur on the sea floor in areas of active volcanism, at spreading ridges, back-arc subduction zones and flanks of intraplate volcanoes at depths of 1,400 -3,500 metres.

They occur in different shapes such as chimneys, mounds, sedimented layers, blocks, breccias, conglomerates, etc. They are made of fine layers or breccias of different metal sulphides such as pyrite or pyrrhotite (Fe), chalcopyrite (Fe-Cu), sphalerite (Zn), galena (Pb), associated with sulphates (barite, anhydrite, gypsum), silica (quartz, opal, chert) and clay minerals.

The determination of the economic feasibility of mining a deposit of polymetallic sulphides depends on a number of characteristics of the deposit itself, primarily the morphology of the structures where polymetallic sulphides occur, their average thickness, the internal structure of the deposit, its diversity, and the variety and content of various metals in the deposit.

Assessment of grade and tonnage of the metals contained in the total volume is essential for economic evaluation of a deposit. Most samples are obtained from the surface of a seafloor deposit by dredging and sampling devices on submersibles. Recovery of cores that penetrate through the body of a deposit is the only method to accurately determine grade and tonnage of the deposit. In the case of polymetallic massive sulphides deposits on land, hundreds of holes are drilled through a prospective massive sulphides body spaced metres apart in order to recover enough cores to estimate grade and tonnage. It is currently a technological challenge to recover a much smaller number of partial cores from a seafloor polymetallic massive sulphides deposit. In any case, the smaller number of partial cores is considered inadequate for making an assessment by land standards.

As a consequence of their generally higher metal contents (*Table 6*), lesser water depths, and proximity to land within the 200 nautical mile zone, polymetallic massive sulphides deposits at convergent plate boundaries associated with the coastal States of the volcanic island chains, especially in the western Pacific, are more likely to be developed before those at sites on the submerged volcanic mountain range associated with divergent plate boundaries in the international seabed area of the oceans (*see Figure 2*).

Based on data currently available, nearly 200 deposits of seafloor polymetallic sulphides are known to exist. Of these, only about 11 may have sufficient size and grade to be considered for mining in the future. Out of these 11 deposits, 9 occur within maritime areas under national jurisdiction, and 2 occur in the international seabed area. The 9 deposits within national jurisdiction are found offshore Canada, Ecuador, Fiji, Japan, Papua New Guinea and Tonga (Herzig et al., 2000). This situation may merely reflect the extent of exploration efforts expended in maritime areas within national jurisdiction and in the international seabed Area, rather than any geological reality. As mentioned in Chapter 3, more than 80 per cent of the approximately 55,000 kilometers globe encircling submerged volcanic mountain range at divergent plate boundaries (one of the favourable geological settings for the occurrence of polymetallic sulphides) lies in the international seabed area.

In addition to government-sponsored activities, recent years have witnessed interest on the part of the private sector in seafloor polymetallic sulphides development. The first ever exploration licence was issued in 1997 to an Australian company, Nautilus Minerals Corporation, by the government of Papua New Guinea. The licence is for two deep-sea areas in the maritime area within the jurisdiction of Papua New Guinea in the Manus basin of the Bismarck Sea. In 2000, another Australian Company, Neptune Resources, obtained an exploration licence from the government of New Zealand. The licence is for an area in the exclusive economic zone of New Zealand, off North Island in the Havre Trough region. In the late 1990s, a U.S. Company, Deep Sea Minerals, in partnership with a major American mining company, began activities worldwide related to polymetallic sulphides development. “There are at least three other “entities” investigating investment and mining opportunities in the deep ocean [related to polymetallic sulphides]” (Scott, 2001).

In a review of the literature and data on polymetallic seafloor sulphides made in 2000 two types of polymetallic sulphides deposits were distinguished "mean" and "rich". The latter type of deposit corresponds to the PACMANUS deposit discovered North-East of Papua-New-Guinea in 1991 (Lenoble, 2004). Since that time, Leg 193 of the Ocean Drilling Programme (ODP) visited the site in November-December 2000. Unfortunately, the boreholes, either by missing the massive sulphides or because of poor core recovery, did not furnish better information on the extent and quality of the deposit. It was suggested that the drilled site "may be the actively forming precursor to a “subhalative” massive sulphides body" (Binns et al., 2002). Drilling did not show vertical extension of the surface massive sulphides, but revealed the deep alteration of the underlying dacite to more than 100 metres below the surface. However, even if the PACMANUS site is suspected to be limited to a surface deposit, it represents a type of ore that can be found elsewhere.

In 2002, Fouquet made a synthesis of the known hydrothermal sulphides deposits classified by their geologic environment: fast and slow spreading ridges, sediment-buried ridges and back-arc basins (Fouquet, 2002). He pointed out that the geochemistry of a deposit depends also on the nature of the underlying rocks, due to their interaction with the percolating seawater.

Most of the data from the literature are now accessible at the Central Data Repository developed by the International Seabed Authority (ISA) with the help of the Geological Survey of Canada. However it is still difficult to evaluate the chemical composition of the deposits without the knowledge of the representativeness of the samples. Samples dredged, grabbed, or even collected from submersibles produce information related only to the surface of the deposit. Drilling the deposit is a necessity. However, the sampling procedures of the ODP cores are guided by scientific objectives that are not necessarily compatible with the requirements of mining evaluation. For instance, when indication of the size and position of the sample is not given in relation to core description, it is difficult to determine the worth of its analytical results. Even when analyses are numerous, averaging them can be misleading. This could explain the discrepancies observed when comparing the information presented in different studies. A scrutiny of the ISA database shows that a more accurate evaluation is not possible.

Tables 14 and 15 show the main characteristics of the deposits for which information are available. On the basis of these data, the PACMANUS type deposit, even if not confirmed by the ODP survey, still appears to be the most attractive deposit because of its high gold content. It is supposed to contain 10.9 per cent copper, 26.9 per cent zinc and 1.7 per cent lead with 15 ppm (parts per million) gold and 230 ppm silver.

Table 14. Major characteristics of the massive sulphides deposits of back-arc basins

Type	Name	Ref	Depth	Cu	Zn	Pb	Au	Ag	T	Rock types
Location			m	per cent	per cent	per cent	ppm	ppm	Mt	
Back-arc basins										
Japan	Myojin-sho	(1,6)		2.10	36.60	6.08	1.6	260	5.7	
	Suiyo	(1)		12.60	28.80	0.80	28.9	203		
Pacmanus	Pacmanus	(5)	1675	10.90	26.90	1.70	15.0	230		dacite
	Susu	(5)		15.00	3.00		21.0	130		
Mariana		(3)		1.15	9.96	7.40	0.8	184		
Okinawa		(3)	1610	1.77	22.00	14.27	4.6	2100		rhyolite / sediment
	Okinawa	(4)		3.10	24.50	12.10	3.3	1160		dacite rhyolite
	Minami-Ensei	(1)	1400	3.70	20.10	9.30	4.8	1900		
	Izena	(1)		4.70	26.40	15.30	4.9	1645		

North Fiji		(3)		7.45	6.64	0.06	1.10	151		basalt
Lau Basin		(3)	1710	4.56	16.10	0.33	1.40	256		andesite
	White Church	(2)		3.32	11.17	0.23	2.00	107		
	Vai Lili	(2)		7.05	26.27	0.17	0.60	143		
	Hine Hina	(2)		3.32	10.87	0.59	1.70	517		

Sources (Ref = References): (1) Kotlinski, 1999 (2) Fouquet, 1991: (3) Fouquet, 2002, (4) Scott, 1983, (5) Kia 1999, (6) Iizasa .1999.

Table 15. Major characteristics of the massive sulphides deposits of ridges and young ocean

Type	Name	Ref	Depth	Cu	Zn	Pb	Au	Ag	T	Rock types
Location			m	per cent	per cent	per cent	ppm	ppm	Mt	
Fast ridges										
NE Pacific	S. Explorer	(3)	1800	3.23	4.85	0.11	0.80	122	3	basalt
	Explorer	(1)	1800	3.60	6.10		1.00	132	3	
	Explorer	(4)		3.20	5.30	0.11	0.63	97		
	Middle valley	(3)	2500	2.55	5.90	0.01			8	basalt / sediment
	Endeavour	(1)	2100	3.00	4.30			188		
	Axial SM	(3)		0.40	18.31	0.35	4.70	175		
	S. Juan de Fuca	(3)	3300	0.16	36.72	0.26	0.10	178	5	basalt / sediment
	Juan de Fuca	(1)	2200	1.40	34.30		0.10	169	4.8	
	Escabana	(1)	3200	1.00	11.90			187		
Californian	Guaymas	(1)	2000	0.20	0.90	0.40		78	23	
Galapagos		(3)	2850	4.48	4.02	0.04	0.30	46		basalt
		(1)	2700	4.10	2.10		0.20	35	10	
East Pacific	EPR 21°N Rivera	(1)	2600	1.30	19.50	0.10	0.10	157		
	EPR 14°N	(1)	2500	2.80	4.70		0.50	48		
	EPR 13°N	(3)	2650	7.83	8.17	0.05	0.30	49	7	basalt
	EPR 11°N	(3)		1.92	28.00	0.07	0.10	38		
	EPR 2°N	(3)		0.58	19.76	0.21	0.10	98		
	EPR 7°S	(11)	2750	11.14	2.13		0.05	23		
	EPR 16°S	(11)	2650	10.19	8.54		0.32	55		
	EPR 17°26S	(3)		1.25	5.55	0.03	0.10	31		
	EPR 21°50S	(3)		2.39	21.74	0.05	0.40	120		
	EPR 17°30S	(3)		2.75	12.49	0.06	0.50	51		
	EPR 18°15S	(3)		8.96	4.56	0.02	0.40	46		
	EPR 18°26S	(3)		1.22	4.94	0.02	0.20	12		
	EPR 20°S	(1)	2750	6.80	11.40		0.50	121		
Slow ridges										

Mid Atlantic	Lucky Strike	(3)	1650	1.13	6.73	0.08		102		basalt
	Rainbow	(3)	2400	10.92	17.74	0.04	4.00	221		mantle rocks
	TAG	(3)	3650	6.21	11.71	0.05	2.20	80	30	mantle rocks
	TAG 957	(7)		3.10	0.14	0.00	0.44	3		
	TAG	(8)		2.70	0.45	0.01	0.49	14		
	TAG	(4)	3600	9.20	7.60	0.05	2.10	72		
	Snake pit	(3)	3465	12.42	7.00	0.07	2.10	111	3	basalt
	id.	(4)	3400	2.00	4.80	0.03	1.50	50	2.4	
	Logatchev	(9)	3000	24.98	2.58	0.04	7.70	27	2.5	Ultra-mafic
		(12)	3000	20.63	1.37	0.04	9.00	64		
Young ocean										
Red Sea	Atlantis 2	(1)		0.50	2.00		0.50	39	90	sediment
	Atlantis 2	(10)	2000	0.54	2.40		0.50	65	92	

Sources (Ref = References): (1) Kotlinski, 1999 (2) Fouquet, 1991, (3) Fouquet, 2002, (4) Scott, 1983, (7) Miller, 1998, (8) Hannigton, 1998, (9) Krasnov, 1995, (10) Oebius, 1997, (12) Mozgova 1999.

(iii) Polymetallic Nodules

Commercial interest in polymetallic nodule development has been demonstrated since the 1960s. Metal market conditions and development of cost-effective mining and processing technologies are major factors determining the commencement of commercial production in the future.

The total amount of polymetallic nodules lying on the seabed has been estimated as 500 billion metric tons (Archer, 1981). Under certain ad hoc assumptions, most notably about metal grade, annual ore production, and duration of mining operations, it has been estimated that a range of 3 to 10 mining operations, with a physical volume of 100 to 600 million metric tons over their life-time, may be possible in the first generation of mining (Lenoble, 2004).

The most likely geographical region for the future recovery of polymetallic nodules based on metal content (combined nickel and copper content of nodules equal to or exceeding 2 percent by weight) lies in the international seabed Area between the Clarion and the Clipperton fracture zones in the north Pacific between Hawaii and Central America (*see Figure 19*). In 2001 the International Seabed Authority granted exclusive 15-year exploration contracts for tracts in this region, where the combined grade for copper, nickel, and cobalt are greater than 2.5 percent by weight and where the abundance of nodules is greater than 10 kilograms (22 pounds) per square metre (11 square feet) to six former registered pioneer investors[40] consisting of private and public entities, for eventual mining. The estimated quantity of the nodule resource in the Clarion-Clipperton zone, where the six exploration contracts have been issued, is 34 billion metric tons of polymetallic manganese nodules containing: manganese, of 7500 million metric tons, nickel 340 million metric tons, copper 265 million metric tons, and cobalt 78 million metric tons (Morgan, 2000). Another prospective region lies in the Central Indian Ocean basin (Jauhari and Pattan, 2000; *see Figure 20*). The seventh contract issued by the International Seabed Authority is in this region to another former registered pioneer investor.[41]

The International Seabed Authority has adopted regulations for prospecting (non-exclusive rights) and exploration (exclusive rights) for polymetallic manganese nodules in the international seabed Area (International Seabed Authority 2000)[43] and also certain recommendations for the guidance of contractors for the assessment of the possible environmental impacts arising from exploration for polymetallic nodules in the Area. (International Seabed Authority, 2001)[44].

Several economic evaluations have reported in the literature for polymetallic nodules (Agarval et al., 1979; Andrew et al., 1983; Hillman et al., 1985; Ingham, 1986 and Padan, 1990). Most of them were academic studies that had very little access to data obtained by the pioneer investors. Only one feasibility study carried out by a pioneer investor has been partially published (Herrouin et al., 1989). It concluded that development of polymetallic nodules would be a low return venture with high technical risk. The study therefore suggested that it would be judicious to wait for higher metal prices and technological innovations. Since that time, only minor reviews of this study were made until the mid-1980s (Lenoble, 1996). New technological innovations may call for completely new studies rather than mere updates of the above-mentioned study. Another factor to be taken into account is the great abundance of nickel deposits discovered on and since these published studies.

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[40] Institut Francais de recherche pour l'exploitation de la mer (IFREMER)/l'Association Française pour l'etude et la recherche des nodules (AFERNOD) (France), the Deep Ocean Resources Development Company (Japan), Yuzhmorgeologiya (Russian Federation), the China Ocean Mineral Resources Research and Development Association (COMRA) (China), Interoceanmetal Joint Organization (Bulgaria, Cuba, the Czech and Slovak Federal Republic [now the Czech Republic and Slovakia], Poland and the Russian Federation) and the Republic of Korea.

[41] Department of Ocean Development (India).

[43] ISBA/6/A/18

[44] ISBA/7/LTC/1/Rev. 1

(iv) Cobalt-Rich Ferromanganese Crusts

A very rough idea about the vastness of crust resources can be obtained from the estimate of *in situ* quantities of materials of economic value, including cobalt in particular, in cobalt-rich ferromanganese crusts in the central Pacific – 500 million metric tons (Commeau et al., 1984). However, it should be borne in mind that such an estimate has been made by multiplying the estimated amount of crust lying on the seabed and subsoil by metal content, without any consideration of mineability, cut-off grade and abundance, mining efficiency, and processing efficiency.

In the case of cobalt-rich ferromanganese crusts, the important characteristics of a mineral deposit in determining the economic feasibility of mining include the thickness and surface area of the crust, the density of the crust, the average metal content of the deposit, and the macro- and micro-topography of the seabed where the deposit occurs.

For exploration and exploitation of cobalt-rich ferromanganese crusts, researchers have developed certain criteria that fall under regional and site-specific criteria (Hein et al., 2000). Regional criteria include favourable characteristics of volcanic structures, areas of strong and persistent bottom currents, and a shallow and well-developed zone of low-oxygen seawater. The site-specific criteria include average cobalt content (minimum 0.8 per cent), average thickness of the crust (minimum 80 millimetres), absence of local volcanism, and favourable topography.

Based on such criteria, it is concluded that "the central-equatorial Pacific region offers the best potential for Fe-Mn [ferromanganese] crusts mining, particularly the EEZ of Johnson Island (USA), the Marshall Islands, and international waters in the mid-Pacific mountains, although the EEZs of the French Polynesia, Kiribati and the Federated States of Micronesia should also be considered" (Hein, 2000a).

Cobalt is the metal of principal economic interest in cobalt-rich ferromanganese crusts. Cobalt is used to make corrosion-resistant light, strong metal alloys, and paint (refer to *Table 2*). Estimates indicate that the production from a single seabed mine on one seamount could meet up to 25 percent of the global demand for cobalt. However, unlike manganese nodules that lie loose on sediment of the deep seafloor, cobalt-rich ferromanganese crusts adhere to the volcanic rock substrate and would pose challenges for mining and refining.

The Marshall Islands has recently leased certain areas in its EEZ for marine mineral exploration, primarily for cobalt-rich ferromanganese crusts. It should be noted that with respect to research and development of mining technologies for crusts, there appear to be very limited activities, outside of Japan.

Several attempts have been made to evaluate the profitability of cobalt-rich crusts. But only one feasibility study, based on scientific data, has been published (Wenzel et al., 1987). The results of a study commissioned by the government of Cook Islands are not currently available.

In 2002, Yamazaki studied the feasibility of cobalt-rich ferromanganese crusts development (Yamazaki et al., 2002). From exploration surveys made in the North Pacific, he considered a deposit, containing 0.64 per cent cobalt, 0.5 per cent nickel, and 0.13 per cent copper, resulting from scraping the first 5 centimetres of the crust as having economic potential.

The same year, Bonneville made a synthesis of the data collected by South Pacific surveys, Nodco (1986), and Zepolyf and Polydrag (1996-1999) (Bonneville et al., 2002). Inside the EEZ of French Polynesia, 25 sites were mapped by a multibeam echo sounder, and samples collected by dredge or core. The areas covered by crust vary between 200 and 4,800 square kilometres with a thickness of 0.2 to 10 centimetres. The average cobalt content of the samples was 1 per cent with 0.5 per cent nickel and 0.1 per cent copper. With an average of 1 ppm, platinum was found up to 4 ppm in one sample; its recovery is questionable.

A definition of a potential deposit was given by one expert, based on exploration surveys made in the South Pacific (Lenoble, 2004). The ore is to contain 1.2 per cent cobalt, 0.6 per cent nickel and 0.1 per cent copper, as expected from the scraping of the top 2 centimeters only.

4. *Value of a Metric Ton of In Situ Ore*

Costs of production of many marine minerals are extremely difficult to estimate, if not impossible. For some deep seabed marine minerals, e.g., seafloor massive sulphides and cobalt-rich ferromanganese crusts, mining and processing technologies are currently at the conceptual stage. It is virtually impossible to forecast how such technologies would perform in terms of production efficiency in real-life operations. For other deep seabed marine minerals, e.g., polymetallic nodules, technologies while test scales data exist, it is uncertain how these technologies will perform when applied to large-scale operations. Thus, research and development efforts are focusing on developing cost-effective technologies. For some minerals already being exploited, for example, offshore diamonds, reliable data on costs of production do no exist in the public domain.

In the absence of plausible and reliable data on costs of production, economic feasibility studies cannot be carried out in any meaningful way. Under these circumstances, experts are trying to determine whether any guidance can be obtained by studying the revenues that could be derived from operations.

One such exercise, in spite of its limitations, was found useful in an international workshop organized by the International Seabed Authority – estimation of the value of a unit of in situ ore of a marine mineral (Lenoble, 2004). Building upon the experience of that exercise, and with a view to providing certain perspectives for marine mineral resource development, the present study carried out estimation exercises for the value of a metric ton of in situ ore of a number of marine minerals, both on the continental shelf of coastal States and in the international seabed area.

In the estimation, the value, V, of a metric ton of in situ ore of a marine mineral, i is defined as follows:

$$Vi = \Sigma j\ (Cij\ X\ Rij\ X\ Pj),$$

where Cij stands for the grade of metal j in the ore of marine mineral i, Rij stands for the recovery ratio for metal j from the ore of marine mineral i, and Pj stands for the price of metal j. With the application of the metal grade, one arrives at the quantity of a particular metal contained in a metric ton of in situ ore of the marine mineral in question. The recovery ratio yields the quantity of that metal that is actually recovered from the ore. The quantity of the metal recovered multiplied by its price gives the revenue to be earned by that metal. Finally, adding such revenues for all the metals recovered from the ore gives the revenue to be earned from a metric ton of in situ ore of the marine mineral in question, or its value.

The data on metal grade were obtained from existing databases or from the literature. Certain judgements have been made about what represents acceptable metal grade for potential commercial operations.

The recovery ratios ultimately depend on the efficiency of mining and processing technologies. For the purpose of the present study, based on the information available in the literature, "educated guesses", of an ad hoc nature, have been made.

The data on metal prices were obtained from published sources. Time series data were collected for the period 1960-2004. Prices were expressed in US dollars. Prices in current US dollars have been adjusted by the Consumer Price Index in the US (US CPI)[45] to arrive at prices in constant US dollars, taking 2003 as the base year.

The limitations of the concept are obvious. It does not take into account any of the production costs (mining, transporting, processing, and marketing). In addition, no conclusions can be drawn about the profitability of a marine mining operation just by looking at the value of the ore in situ. Any profitability comparison between various deposits of the same marine mineral, between various marine minerals, or between marine minerals and similar land-based minerals is also beset with uncertainties, primarily because costs can vary from deposit to deposit, from one marine mineral to another, and between marine and land-based minerals.

However, the limitations themselves provide a fundamental perspective for policy- and decision-makers: **the crux of the matter is that cost effective technologies have to be developed for mining the resources**. A crucial policy and decision parameter then, is the nature and level of research and development efforts and expenses on technologies.

Given the limitations, certain additional perspectives can still be gained. First of all, a clear and systematic identification of the components of the revenues to be earned from a unit of in situ ore of a marine mineral provides guidance to policy- and decision-makers about optimal strategies to be pursued. Metal grades are not given values beyond the control of decision-makers, rather they are <u>outcomes of decisions</u> about effective exploration efforts. Similarly, recovery ratios are obvious outcomes of decisions about research and development technology.

(i) Tin

Three types of deposits with different metal contents of tin are considered: (a) a deposit with 4 kilograms of tin per metric ton of ore – this corresponds to a marginal on-land operation; (b) a deposit with 2 kilograms of tin per metric ton of ore – this corresponds to the Belitung deposit offshore Indonesia (*see Table 12*) which was mined in the 1980s; and (c) a deposit with 476 grams of tin per metric ton of ore – this corresponds to the offshore deposits currently mined by the Indonesian company PT Timah (see above). *Figure 24* presents the value of a metric ton of tin during the period 1960-2004 expressed in 2003 US dollars. The average value is $54.35 for the first type of deposit, $23.54 for the second type, and only $2.80 for the third type.

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[45] US CP1, all urban consumers, city average, all items, available at http: www.bls.gov/cpi/home.htm.

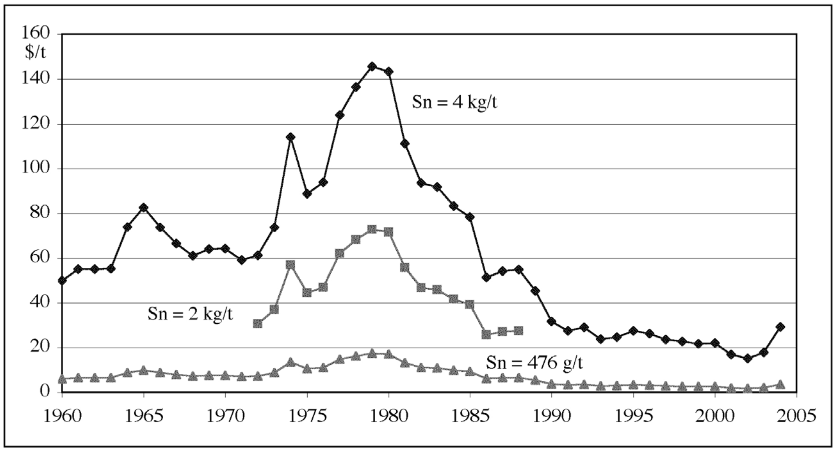

Figure 24. Value of a metric ton of in situ ore containing tin

A number of important facts are evident from the figure. First of all, the considerable variability of the value, resulting from volatility of prices, is noteworthy. Secondly, there are periodical sharp increases and decreases in prices and consequently in the value of the ore, which may pose substantial problems for planning by both consumers and producers. Thirdly, *figure 24* vividly demonstrates the fundamental limitation of the value-of-in-situ-ore approach. PT Timah's offshore deposits have a value per metric ton that is about 1/8th of that of land-based deposits. Its offshore tin operations are still profitable because of a small number of workers achieving higher production tonnage. According to PT Timah, the productivity per worker is 7.2 metric tons. Moreover, ore processing is done on board the mining dredge to produce a high-grade concentrate containing 30 percent tin at a very low cost.

(ii) Gold

Figure 25 presents the value of a metric ton of in situ ore containing gold during the period 1960-2004 expressed in 2003 US dollars. The deposit considered is the Nome deposit, offshore Alaska (USA). The ore has a grade of 0.82 grams of gold per metric ton or ore.

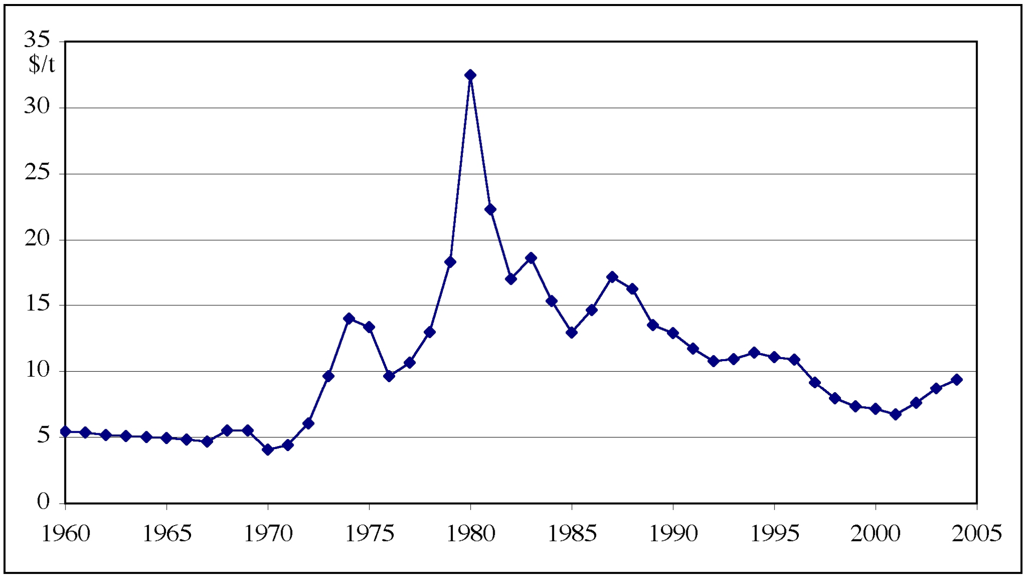

Figure 25. Value of a metric ton of in situ ore containing gold

In addition to demonstrating variability and periodical sharp increases and decreases, *figure 25* depicts the dilemma of planning the development of a marine mineral project. The Nome offshore mining operation was run from 1987 to 1990. During that period, the value of a metric ton of in situ ore averaged $15.00 in 2003 US dollars (Amey, 1999). In the late 1970s, as a result of unusual speculative demand, gold prices increased sharply. Although declining from the peak, gold prices were still high in the mid-1980s when, as the figure shows, the decision to initiate the mineral project was taken. However, price continued to decline, leading to the decision to close the project.

(iii) Polymetallic Massive Sulphides

Two types of deposits have been considered: (a) a deposit corresponding to the PACMANUS type, containing 10.9 per cent copper, 26.9 per cent zinc, 1.7 per cent lead, 15 parts per million (ppm) gold, and 230 ppm silver, and (b) a deposit corresponding to the Myojinsho type, containing 2.1per cent copper, 36.6 per cent zinc, 6.1 per cent lead, 1.6 ppm gold, and 260 ppm silver. These deposits have been described earlier.

Recovery ratios have been assumed as 70 per cent for copper and lead, and 80 per cent for zinc, gold and silver.

Figure 26 presents the value of a metric ton of in situ ore of polymetallic massive sulphides during the period 1960-2004 expressed in terms of 2003 US dollars. *Figure 27* presents the metal prices during the same period as percentages of their average value.

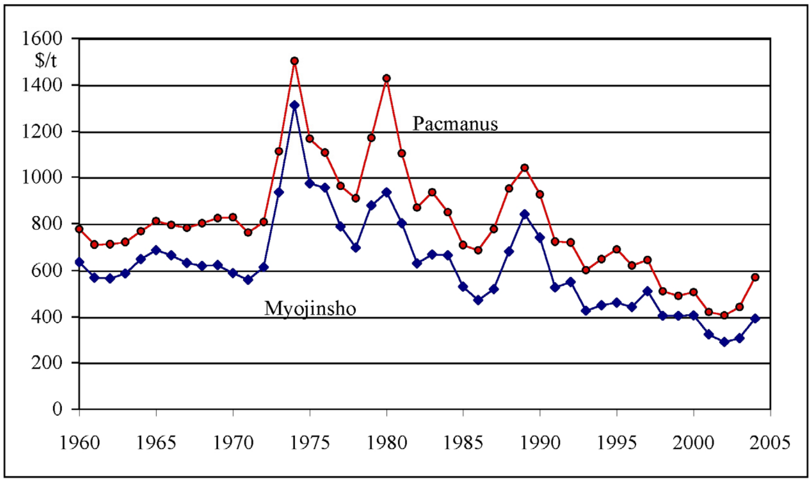

Figure 26. Value of a metric ton of in situ ore of massive sulphides in 2003 US dollars

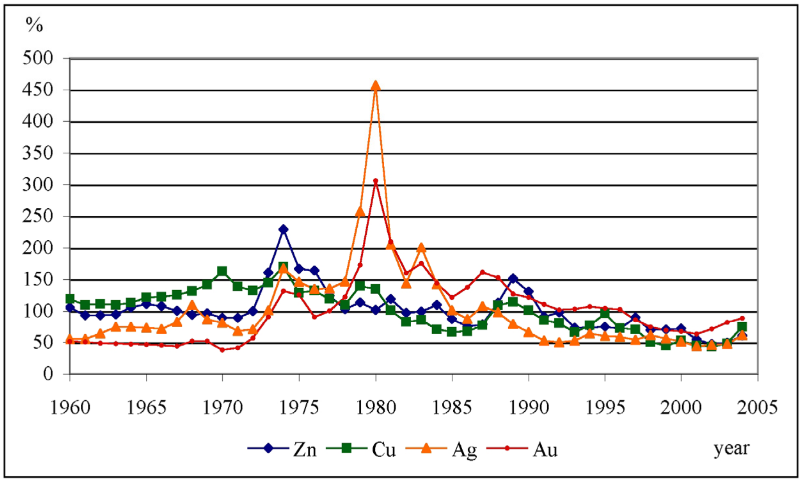

Figure 27. Metal prices, in percentages of their 1960-2004 averages

Year- to- year variations and periodical sharp increases and decreases in the value of ore, resulting from such variations and peaks and valleys in the metal prices, are once again evident from *figures 26 and 27*.

It is interesting to note how planning for both consumers and producers can be extremely difficult because of unanticipated factors and their significant impacts on metal prices. For example, the high values of ore and the high prices of 1974-1975 correspond to the end of the oil crisis and the subsequent increase in industrial activity in the world economy, while the peaks of gold and silver in 1980 are linked to the unexpected speculative activities that provoked a crisis in the precious metals market.

Between 1960 and 2004, the average value of a metric ton of in situ ore of PACMANUS-type polymetallic sulphides could have been $807 in terms of 2003 US dollars, with a minimum of $406 and a maximum of $1,504. The value would have been between $737 and $877 at the 95 per cent statistical confidence level.

During the same period, the average value of a metric ton of in situ ore of the Myojinsho-type polymetallic sulphides could have been $620, with a minimum of $291 and a maximum of $1,312. The value would have been between $571 and $679 at the 95 per cent statistical confidence level.

(iv) Polymetallic Nodules

The deposit considered in the study is from the exploration area allocated to the French contractor. This deposit has been described in the literature (Lenoble, 1996, 2004). The ore is assumed to contain 30 per cent manganese (Mn), 1.37 per cent nickel (Ni), 1.25 per cent copper (Cu) and 0.25 per cent cobalt (Co). According to metallurgic studies, including bench tests and small-scale pilot plant tests, the recovery ratio could be, respectively, 85 per cent (Mn), 96 per cent (Ni), 95 per cent (Cu) and 94 per cent (Co).

Metal prices along with their variations are illustrated in Figure 28. For each metal, the Figure shows the prices in each year as percentages of their 1960-2003 average. For manganese, the price is that of ferro-silico-manganese (Fe Si Mn), an alloy that has been used in the steel industry since 1970. For the 1960-1970 period, the price is that of ferromanganese alloys.

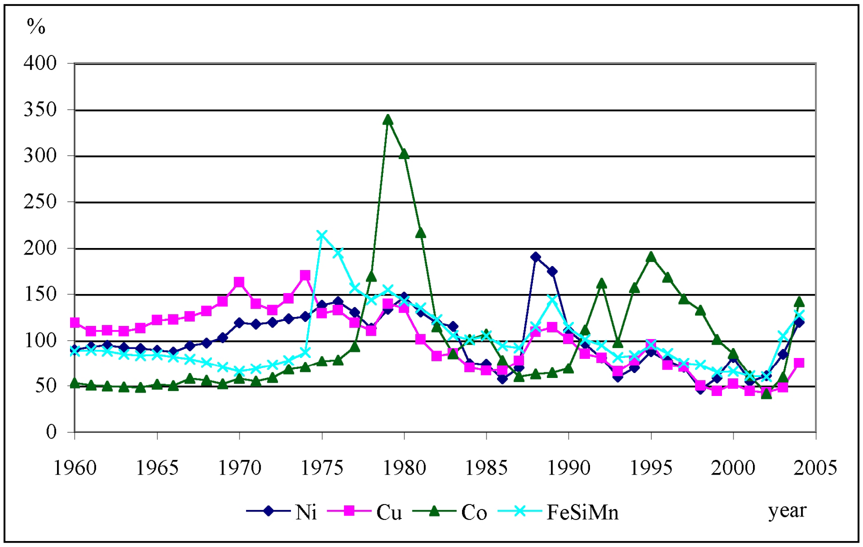

Figure 28. Prices of metals contained in nodules, in percentages of their 1960-2003 average

The corresponding value of a metric ton of in situ ore of polymetallic nodules is shown in *Figure 29*.

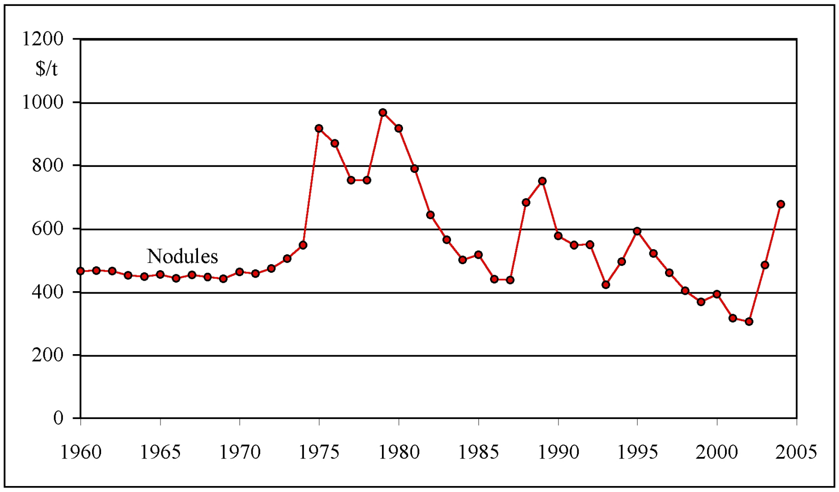

Figure 29. Value of a metric ton of in situ ore of nodules, in 2003 US dollars

Cobalt was the most variable component. Its share, as illustrated in *Figure 30*, was sufficient to maximize the value of a metric ton of nodule in 1979 and again in 1995, when it accounted for 30 per cent of the value, compared to 15 per cent, which occurs in a normal year.

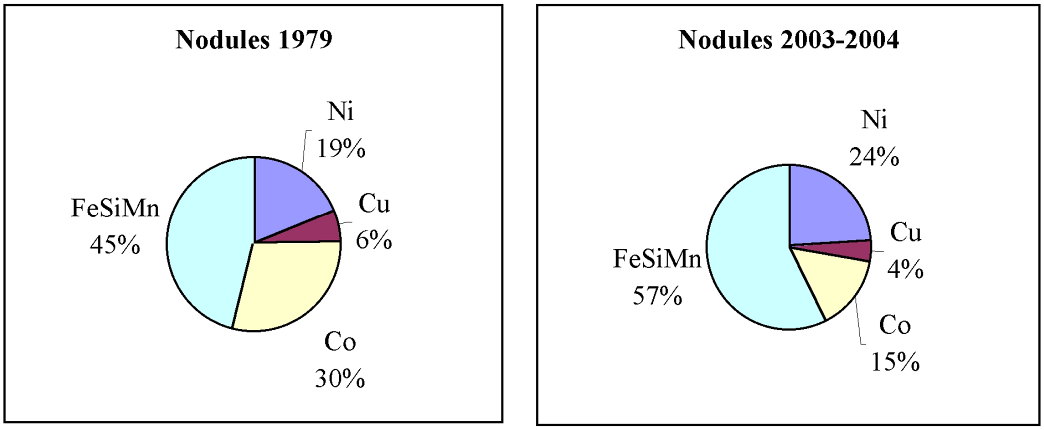

Figure 30. Shares of the four metals in the value of a metric ton of nodules

The high values for the 1975-1983 period explain the interest of industrial companies at that time. It is understandable that, after 1983, the decline of metal prices and consequently of the value of a metric ton of nodules resulted in waning interest by investors.

Between 1960 and 2004, the average value of a metric ton of in situ nodules was \$547 expressed in terms of 2003 US dollars with a minimum of \$307 and maximum of \$ 968. At the 95 per cent statistical confidence level the value was between \$500 and \$594.

It is interesting to note that in 1988, the French group AFERNOD estimated the cost of production in an operation with an annual production of 1.5 million metric tons as 350 2003 US dollars per metric ton, with a 10-year amortization of capital costs (Lenoble, 1992).

(v) Cobalt-Rich Ferromanganese Crusts

A deposit was considered that contains 1.2 per cent cobalt, 0.6 per cent nickel, and 0.1 per cent copper, as described above. Recovery ratio was assumed as 70 per cent for each of the three metals.

Figure 31 presents the value of a metric ton of in situ ore of crusts during 1960-2004, expressed in terms of 2003 US dollars. Obviously, the figure shows the same peaks as in the case of polymetallic nodules, resulting from the high prices of cobalt – in 1980, 1992, 1995 and 2004.

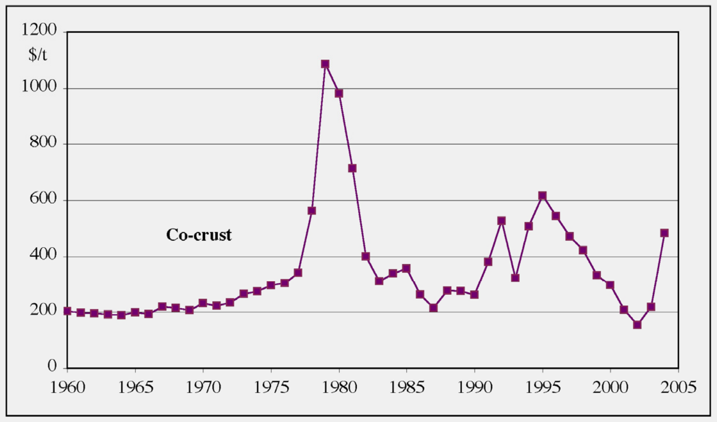

Figure 31. Value of a metric ton of in situ ore of cobalt-rich crust, in 2003 US dollars

Between 1960 and 2004, the average value of a metric ton of in situ ore of cobalt-rich crusts was $349, expressed in terms of 2003 US dollars with a minimum of $199 and a maximum of $1,086. At the 95 per cent statistical confidence level, the average would fall between $291 and $407.

Chapter 5: Concluding Observations

The discussion on marine mineral resources in this study, especially concerning the scientific advances of recent decades may be summarized in the following concluding observations.

(1) Knowledge of marine minerals and associated biological resources is expanding rapidly driven by advances in basic scientific research on Earth and ocean processes and recognition of the increasing need for the materials that they contain.

(2) Processes of erosion, river transport, and motions of the ocean concentrate minerals derived from continental rocks in sediments of continental margins; while internal processes predominate in concentrating minerals in the deep ocean. The deep ocean processes involve transfer of heat and material from the Earth's interior to the lithosphere and the ocean at submerged plate boundaries (*see Figures 2 and* 3; *Table 3*).

(3) Continental margins (continental shelf, slope and rise) have great potential for the exploitation of many metallic and non-metallic mineral deposits (*Figures 1, 5-11; Table 1*) containing a variety of useful materials (*Table 2*). However, actual mining to date has been limited to a small number of placer metal deposits (tin, gold, titanium, chromium, barium, zirconium, and rare earth elements) and non-metal deposits (diamond, thorium, lime, sand and gravel, and water; see *Table 4*).

(4) Placer deposits: Mining tin offshore southeast Asia and diamonds offshore southwest Africa is only a small fraction of the potential that exists for heavy metals and gemstones mining in sediments of global continental margins.

(5) Phosphorites: Extensive deposits on the continental shelves in past and present areas of oceanic upwelling in low latitudes constitute an untapped resource most accessible to developing countries. This resource can be used as fertilizer for agricultural crops as land deposits dwindle.

(6) Sand and gravel: Sand and gravel are the most widely utilized and accessible of non-fuel marine mineral resources with the highest annual production value. Increasing demands for construction materials (aggregates), shore protection, and beach replenishment should lead to further growth in this industry.

(7) Water: The need for a reliable and adequate sources, of freshwater for consumption, agricultural and industrial uses in light of pressures from population growth, industrialization, and climate change is considered to be the most pressing environmental problem for mankind (Revenga et al., 2000). Although the ocean is by far the largest reservoir of water on Earth, extraction of fresh water is contingent on development of cost-effective desalination processes.

(8) Metalliferous sediments: The Atlantis II Deep zinc-silver-copper metalliferous sediment deposit of the Red Sea is the only seafloor hydrothermal deposit in which grade and tonnage are anywhere near to mining standards on land (*Table 5*). Legally its recovery rests with the bordering coastal States (Saudi Arabia and Sudan), with overlapping exclusive economic zones. A pilot mining test has been proposed that should address the issue of refining the fine-grained material. The commencement of commercial mining is subject to market forces. The metallifeous sediments of the Atlantis II Deep represent a type of deposit that should be present at sites buried under sediments of the Atlantic and other rifted passive continental margins.

(9) Nonrenewable mineral resources: Polymetallic massive sulphides require thousands to tens of thousands of years to concentrate from hot metal-rich solutions into large deposits. Polymetallic 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 the bare rock outcrops of seamounts and submerged volcanic mountain ranges, take millions of years to accumulate slowly 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 in economically interesting grades and tonnages.

(10) Polymetallic massive sulphides: The immediate significance of massive sulphides (copper, iron, zinc, silver, gold, and other metals) concentrated by high-temperature hydrothermal systems at plate boundaries is as analogues to guide economic geologists in the search for and mining of ancient volcanogenic massive sulphides (VMS) deposits that formed at similar seafloor settings in the geologic past and have subsequently been uplifted onto land. A surge of discovery of these VMS deposits on land in China (Rona and Hou, 1999) and other places is attributable to insights gained from submarine ore-forming systems.

(11) Mining seafloor polymetallic massive sulphides deposits is more likely to begin at fore- and back-arc settings of volcanic island arcs within the 200 mile exclusive economic zone of coastal States of the western Pacific, rather than on ocean ridges in the international seabed Area (see *Figures 1, 3 and 4*). Present technical limitations on

drilling to adequately determine grade and tonnage will have to be overcome and favourable market conditions relative to land sources must evolve. While individual mineralized chimneys have been observed to grow quickly (days to years), seafloor polymetallic massive sulphides deposits as a whole are not renewable resources because they require thousands of years to accumulate.

(12) Polymetallic manganese nodules: Seven contractors are registered with the International Seabed Authority in the richest international zone (nickel and copper content >2.5 percent by weight) in the northeastern equatorial Pacific Ocean and the Central Indian Ocean (*see Figures 17-20; Table 8*). A strategic need, favourable market conditions and/or technological innovations, relative to currently adequate land sources of these metals, are conditions necessary to drive the considerable investment required to support production.

(13) Cobalt-rich ferromanganese crusts: Cobalt is considered to be the potential driver (*see Figures 21 and 22; Table 9*), but the prospect of recovery and refining from a hard-rock substrate adds an extra challenge.

(14) The International Seabed Authority (ISA) is developing a regime for exploration for polymetallic massive sulphides and cobalt rich ferromanganese crusts (Nandan et al., 2002), and potential mining of these resources is a subject of ongoing evaluation (e.g., Pasho, 1979, 1985; Scott, 2001; Glasby, 2002).

(15) Exploration: Exploration for marine mineral resources is time and cost intensive (*Table 10*), so that only a small percentage of the surface area of the seafloor, and even less of the subsurface volume, has been explored in sufficient detail to find existing mineral deposits.

(16) Microbes and other marine organisms: 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 as a source of useful products. In particular, certain heat and pressure tolerant microbes are hosted in polymetallic massive sulphides deposits and energized by the same solutions that concentrate the deposits. The present harvesting and utilization of certain of these microbes before utilization of the mineral deposits themselves, is described as the “deepest of ironies” (Glowka, 1996).This situation raises pressing issues for development and implementation of management codes for marine exploration and mining that will conserve and sustain the integrated living and non-living resource systems. One possibility could be to focus mining on inactive

deposits that no longer host living ecosystems containing numerous and widely diverse organisms although they may still host certain endemic organisms.

(17) The most common and widespread materials (*Tables 1 and 2*) comprising sand and gravel (construction and beach replenishment), seawater for desalination into freshwater (domestic, agricultural, and industrial water supply), and phosphorite (fertilizer) hold particular potential for future growth because shelter, food, and water are essential for survival. This reinforces the importance of maintaining clean oceans and of developing reasonable energy sources for desalination.

(18) A need exists for a system for making timely estimates of resources, reserves, and to track annual marine mineral production, in order to support the development of national and international management regimes. This information is currently unavailable.

(19) A principal lesson learned from past investigations of polymetallic manganese nodules that applies to all marine mineral deposits is that mineral resources on the seabed must go through a process of geological and economic analysis before they can be considered to be of potential economic value.

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Massive sulphides

http://www.em.csiro.au/ Commonwealth Scientific & Research Organisation
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Other minerals

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