

INTERNATIONAL SEABED AUTHORITY WORKSHOP

ON

*MINING OF COBALT-RICH FERROMANGANESE
CRUSTS AND POLYMETALLIC SULPHIDES – TECHNOLOGICAL AND
ECONOMIC CONSIDERATIONS*

BACKGROUND PAPER PREPARED BY THE SECRETARIAT



*KINGSTON, JAMAICA
31 July to 4 August 2006*

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1. The International Seabed Authority will convene a workshop on technical and economic considerations for mining cobalt rich ferromanganese crusts (CRFCs) and polymetallic sulphides (PSDs) resources of the international seabed area (“the Area”) in Kingston, Jamaica, from 31 July to 4 August 2006.

I. ISSUES TO BE ADDRESSED

2. During the fourth session of the International Seabed Authority in August 1998 the delegation of the Russian Federation requested that the Authority adopt regulations for mineral resources other than polymetallic nodules, namely polymetallic sulphides and cobalt crusts. Until 2000 the main focus of the work of the Authority was the completion of regulations for prospecting and exploration for polymetallic nodules in seabed areas beyond the limits of national jurisdiction (the Area).

3. At the tenth session of the Authority, the Legal and Technical Commission submitted “Draft regulations on prospecting and exploration for polymetallic sulphides and cobalt-rich ferromanganese crusts in the Area” to the Council for its consideration at the eleventh session. Document ISBA/10/C/WP.1 comprises 43 regulations and four annexes. Annex 1 is on “Notification of intention to engage in prospecting”, Annex 2 is on “Application for approval of a plan of work for exploration to obtain a contract”, Annex 3 “Contract for exploration”, and Annex 4 contains standard clauses for exploration contracts.

4. At the eleventh session of the Authority (August 2005), following the first reading of “Draft regulations on prospecting and exploration for polymetallic sulphides and cobalt-rich ferromanganese crusts in the Area”, the Council requested the Secretariat to clarify the technical content of some of the regulations.

5. The purpose of the workshop is to examine the prospects for the development of cobalt-rich ferromanganese crusts and polymetallic sulphides deposits in the Area, and to provide the members of the Authority with relevant and up-to- date data and information on, inter alia,

- (a) The process through which occurrences of cobalt-rich ferromanganese crusts and polymetallic sulphides in the Area may be converted to commercially exploitable deposits;

- (b) The geologic characteristics and geographic distribution of potential cobalt-rich ferromanganese crusts deposits/occurrences in the Area;
- (c) The geologic characteristics and geographic distribution of potential polymetallic sulphides deposits/ occurrences in the Area;
- (d) Technological issues associated with commercializing cobalt-rich ferromanganese crusts deposits in the Area;
- (e) Technological issues associated with commercializing polymetallic sulphides deposits/occurrences in the Area;
- (f) Economic and financial issues associated with commercializing cobalt-rich ferromanganese crusts deposits in the Area;
- (g) Economic and financial issues associated with commercializing polymetallic sulphides deposits in the Area;
- (h) The market outlook for the base and precious metals to be found in these two potential ores;
- (i) Financial terms of exploration/production contracts for the relevant base metals in terrestrial mining;
- (j) A comparison of the costs for environmental protection in land-based mining of the relevant base metals and for cobalt-rich ferromanganese crusts and polymetallic sulphides in the Area;
- (k) A hypothetical cobalt-rich ferromanganese mining venture in the Area, and
- (l) A hypothetical polymetallic sulphides mining venture in the Area.

6. As part of the workshop, it is proposed to use the two hypothetical mining ventures as the basis for a practical application of the system of participation by the Authority in either venture, should a contractor select this option.

7. Though these subjects have not all been addressed explicitly in previous workshops by the Authority, a number of presentations and papers at these workshops provide valuable information in this regard. This background paper contains excerpts that are relevant to the various workshop topics, from papers presented at some of the Authority's previous workshops.

**II. RELEVANT INFORMATION FROM THE AUTHORITY'S
PREVIOUS
WORKSHOPS AND ITS CENTRAL DATA REPOSITORY**

8. The Authority's workshop in June 2000, on the subject "**Minerals other than polymetallic nodules of the Area**", was focused on polymetallic sulphides and cobalt-rich ferromanganese crusts (occurrences/deposits), their environments of deposition, associated flora and fauna, measures that could be taken to protect associated flora and fauna from future mining, and issues related to the differences between these two mineral resources and polymetallic nodules, that would impact the application of the common heritage principle in relation to the development of the latter resources. In addition, the workshop was informed of international programmes researching various aspects of polymetallic sulphides and cobalt-rich ferromanganese crusts (occurrences/deposits).¹

9. Some of the papers presented at the 2000 workshop that are of relevance to the current workshop include, inter alia,

- "Metallogenesis of Marine mineral resources" – Dr Peter Rona.

(This paper encompassed a wide-range of topics on the marine minerals industry, and the types of marine mineral resources that have attracted commercial interest from coastlines to the deep ocean basins. In relation to seafloor mineralization, he addressed the discovery, origins, and the distribution of both polymetallic sulphides and cobalt-rich ferromanganese crusts deposits. He also addressed the exploration methods for both types of deposits subdividing exploration into finding and characterizing the deposits).

- "A comparison of possible economic returns from mining deep seabed polymetallic nodules, seafloor massive sulphides(polymetallic sulphides) and cobalt-rich ferromanganese crusts" – Jean-Pierre Lenoble.

(This paper undertook a comparison of the possible economic returns from mining a polymetallic nodule deposit, a polymetallic sulphides deposit and a cobalt-rich ferromanganese deposit. It examined the characteristics of each deposit (nature of the deposits, parameters needed to estimate the tonnage and metal content of each type of deposit and the state of the art of mining and processing technologies), and based on an average of metal prices for the period 1960 to 1999,

¹ Minerals other than Polymetallic Nodules of the International Seabed Area – Proceedings of the International Seabed Authority's workshop held in Kingston, Jamaica 26 – 30 June 2000

compared the value of the three types of deposits based on the value of a tonne of *in situ* ore).

10. At this workshop, papers were presented that dealt exclusively with polymetallic sulphides. In that regard, the following papers are relevant:

Polymetallic Sulphides

- “Seafloor massive sulphides deposits and their resource potential” – Professor Peter Herzig, S. Petersen and Mark D. Hannington.

(This paper addressed the origin, occurrence, metal composition, size, tonnage, resource potential and global distribution of polymetallic sulphides deposits).

- “Hydro thermal sulphide mineralization of the Atlantic – Results of Russian investigations” – G. Cherkashev, A. Ahsadze and A. Glumov.

(This paper informed the workshop about polymetallic sulphides deposits that had been found in the Mid-Atlantic Ridge. The paper highlighted areas showing promise for new hydrothermal fields, provided metal content information for three deposits (Logachev 1 and 2, and the MIR mound) and informed participants of the results of metallurgic tests of samples recovered from the MIR mound).

- “Technical requirements for exploration and mining seafloor massive sulphides deposits and cobalt-rich ferromanganese crusts” – Professor Herzig and S. Petersen.

(This paper described the technical requirements for exploration and mining of polymetallic sulphides and cobalt-rich crusts deposits).

- “Financing exploration for seafloor massive sulphides deposits” – Julian Malnic

(This paper addressed issues involved in raising finance for the exploration of polymetallic sulphides deposits in Papua New Guinea’s marine jurisdiction).

- “Status report on the data and information requirements of Papua New Guinea’s seafloor massive sulphides deposits” – James Wanjik.

(This paper addressed the data and reporting requirements for exploring for polymetallic sulphides deposits under Papua New Guinea’s Mining

Act. It provides information on the terms of an exploration license, including duration, size of exploration areas, and the role of marine scientific research in the development of these resources).

11. Similarly, some of the papers presented at this workshop dealt exclusively with cobalt-rich ferromanganese crusts. In that regard, the following papers are relevant to the current workshop:

Cobalt-rich ferromanganese Crusts

- “Regional and local variability in the spatial distribution of cobalt-bearing ferromanganese crusts in the world’s ocean” – V.M. Yubko and Y.B. Kazmin.

(This paper presents data and information on cobalt-rich ferromanganese crusts provinces in the oceans from a multi-tiered graphical database created from 2217 sampling stations from which parameters on ore abundance from 20 ore provinces and 64 regions where crusts deposits are known to occur. It provides data on a typical crusts ore field, and it also presents critical statistics for the eight main areas of cobalt-rich crusts in the North-West Pacific Ocean).

- “Cobalt-rich ferromanganese crusts: Global distribution, composition. Origin and research activities” - James R. Hein.

(This paper provided information on the origin, composition and distribution of cobalt-rich ferromanganese crusts deposits in the world’s oceans. It provided ranges for the cobalt content of crusts deposits, objectives to met during the initial and later stages of exploration for crusts deposits, twelve criteria that have been developed for the exploration and mining of such deposits and recommendations for future research on the subject).

12. In 2004, the Authority convened a workshop on **the establishment of environmental baselines at deep seafloor cobalt-rich ferromanganese crusts and deep seabed polymetallic sulphides mine sites in the Area, for the purpose of evaluating the likely effects of exploration and exploitation of these resources on the marine environment.**

13. Some of the papers of the 2004 workshop of relevance to the current workshop include, inter alia,

Polymetallic Sulphides

- Proposed exploration and mining technologies for polymetallic sulphides. *Professor Steven Scott, Scotiabank Marine Geology Research Laboratory, University of Toronto.*

(This paper reviews prospecting and exploration methodologies for polymetallic sulphides deposits, the prospects and economics of polymetallic sulphides mining and possible mining technologies).

- “Exploration for and pre-feasibility of mining polymetallic sulphides – a commercial case study” - Mr. David Heydon, Chief Executive Officer of Nautilus Minerals Ltd.

(This paper presents the steps being taken by Nautilus Minerals Ltd, a company that has an exploration license for polymetallic sulphides deposits in the territorial sea of Papua New Guinea to commercialize sulphides deposits in that area. The company is in a technical alliance with six companies that have expertise in different aspects of the integrated operation. These are: Worley as Project Manager, Perry and Voest-Alpine Bergtechnik providing the required expertise in Remote Operated Vehicles and Miner cutting tool respectively: Siemag is in the alliance for ore hoisting, and Seacore and Williamson Associates bring their expertise in drilling and resource geophysics to the alliance. The paper describes the exploration methods being used (water column testing to locate evidence of active plumes for the purposes of identifying older and mature orebodies along strike or rift), geophysical tools (such as resistivity, self potential, magnetics, induced polarization, gravity and video cameras), and sampling and drilling. The paper also compares sulphides exploration with crusts exploration and identifies the amount of seafloor area required to obtain 2 million tons of ore in each case. The paper provides information on the foreseen mine (annual production, mine life, the characteristics of ore bodies to support the operation and specifications of its ROV miner).

- “Mining on land versus the seafloor – a case study. Antamina Mine comparison” - Mr. David Heydon, Chief Executive Officer of Nautilus Minerals Ltd.

(This paper compares the Nautilus Seafloor project (grades of copper, zinc and gold, and annual production) to the Antamina mine (zinc and copper producer) being undertaken by Teck Cominco, Noranda and BHP-Billiton in Peru. The paper states that the seafloor project compares favourably to the land-based operation).

Cobalt-rich ferromanganese Crusts

- Proposed exploration and mining technologies for cobalt-rich crusts - Dr. Rahul Sharma, National Institute of Oceanography, Dona Paula, Goa, India.

(This paper evaluates mining scenarios for cobalt-rich ferromanganese crusts deposits and associated environmental considerations. Using data contained in the 1987 Hawaii Department of Planning and Economic Development publication on “Mining Development Scenario for cobalt-rich Manganese Crusts in the Exclusive Economic Zones of the Hawaiian Archipelago and Johnston Island”, this paper outlines the possible environmental impact of crusts mining. The paper also provides the estimates of the resource potential of crusts within the EEZ of the Hawaiian archipelago and Johnston Island).

14. At the Authority’s eleventh workshop which was convened in March 2006 on the subject **“Cobalt-rich crusts and the diversity and distributions patterns of seamount fauna”**, Dr.Hein presented a paper on the characteristics of seamounts and cobalt-rich ferromanganese crusts which provided an update of his 2000 paper. This paper also provides information that is of particular relevance to the current workshop.

- Characteristics of Seamounts and cobalt-rich ferromanganese crusts. James R. Hein, Senior Geologist United States Geological Survey, USA.

(This paper provides relevant information on the factors that lead to the formation of cobalt-rich ferromanganese crusts in the oceans, the metals that they contain, and identifies the different regions of the world’s oceans where the metals of commercial interest in cobalt-rich crusts are highest. The paper provides criteria that have to be met by cobalt-rich bearing ferromanganese crusts seamounts to meet the requirements of likely first generation mine-sites, pointing out that seamounts in the Central Pacific Ocean region best meet these criteria. The paper provides data on the surface areas of typical equatorial guyots and conical seamounts and estimates that based on a crust thickness of 26 kilograms per square meter, 77 square kilometres of crusts had to be mined to satisfy a production rate of 2 million tonnes of crust per year. The paper also estimates the area of crusts (with an average crust thickness of two centimetres) that would be required to meet a twenty year mining operation and the number of seamounts (large and average-sized) that would undertake the project).

III. THE AUTHORITY’S CENTRAL DATA REPOSITORY

15. The Authority continues to maintain and upgrade its Central Data Repository (CDR) on marine mineral resources. The CDR presently has mineral data on cobalt-rich ferromanganese crusts occurrences on seamounts from over 1130 locations. The data on polymetallic sulphides occurrences are from around 50 locations (with several additional entries showing detailed sampling in most of the stations). The Authority has used these data sets along with additional data from workshops that it convened, and data available in the public domain (the InterRidge web site for the PMS data) to prepare several maps showing the occurrences of these two types of marine minerals in the world's oceans and in the International Seabed Area. The Authority has used the data in its repository to produce the two maps contained in Annex I on world-wide distribution of cobalt-rich ferromanganese crusts and polymetallic sulphides occurrences/deposits in the Area.

IV. THE DRAFT REGULATIONS ON PROSPECTING AND EXPLORATION FOR POLYMETALLIC SULPHIDES AND COBALT-RICH CRUSTS IN THE AREA (ISBA/10/C/WP.1)

16. The Draft Regulations on prospecting and exploration for *polymetallic sulphides* and *cobalt-rich ferromanganese crusts* in the Area, document ISBA/10/C/WP1, provide definitions for prospecting, exploration and exploitation of these minerals as follows:

- (a) "Prospecting" means the search for deposits of **polymetallic sulphides or cobalt crusts** in the Area, including estimation of the composition, sizes and distributions of deposits of **polymetallic sulphides or cobalt crusts** and their economic values, without any exclusive rights;¹
- (b) "Exploration" means searching for deposits of **polymetallic sulphides or cobalt crusts** in the Area with exclusive rights, the analysis of such deposits, the use and testing of recovery systems and equipment, processing facilities and transportation systems, and the carrying out of studies of the environmental, technical, economic, commercial and other appropriate factors that must be taken into account in exploitation, and
- (c) "Exploitation" means the recovery for commercial purposes of **polymetallic sulphides or cobalt crusts** in the Area and the extraction of minerals there from, including the construction and operation of mining, processing and transportation systems, for the production and marketing of metals;¹

Prospecting

14. In accordance with the Draft Regulations,

- Prospecting shall be conducted in accordance with the Convention and the Regulations and may commence only after the prospector has been informed by the Secretary-General that its notification has been recorded pursuant to regulation 4, paragraph 2.
- Prospecting shall not be undertaken if substantial evidence indicates the risk of serious harm to the marine environment.
- Prospecting shall not be undertaken in an area covered by an approved plan of work for exploration for **polymetallic sulphides or cobalt crusts** or in a reserved area; nor may there be prospecting in an area which the Council has disapproved for exploitation because of the risk of serious harm to the marine environment.
- Prospecting shall not confer on the prospector any rights with respect to resources. A prospector may, however, recover a reasonable quantity of minerals, being the quantity necessary for testing, and not for commercial use.
- There shall be no time limit on prospecting except that prospecting in a particular area shall cease upon written notification to the prospector by the Secretary-General that a plan of work for exploration has been approved with regard to that area, and
- Prospecting may be conducted simultaneously by more than one prospector in the same area or areas.

Exploration

18. With regard to applications for approval of plans of work for exploration in the form of contracts, in addition to meeting requirements with regard to the form of applications, a certificate of sponsorship² and financial and technical capabilities³ the Draft Regulations specify that the total area covered by the application should meet the following conditions:

- The area covered by each application for approval of a plan of work for exploration shall be comprised of not more than 100 blocks.
- For polymetallic sulphides or cobalt crusts the exploration area shall consist of contiguous blocks. For the purposes of this regulation two blocks that touch at any point shall be considered to be contiguous.

² Regulations 10 and 11.

³ Regulation 13.

- Notwithstanding the provisions in paragraph 1 above, where a contractor has elected to contribute a reserved area to carry out activities pursuant to annex III, article 9, of the Convention, in accordance with regulation 17, the total area covered by an application shall not exceed 200 blocks.

19. Where the applicant elects to contribute a reserved area, the area covered by the application shall be sufficiently large and of sufficient estimated commercial value to allow two mining operations. The applicant shall divide the blocks comprising the application into two groups of equal estimated commercial value and composed of contiguous blocks. The area to be allocated to the applicant shall be subject to the provisions of regulation 27.

20. Each such application shall contain sufficient data and information, as prescribed in section III of annex 2 to these Regulations, with respect to the area under application to enable the Council, on the recommendation of the Legal and Technical Commission, to designate a reserved area based on the estimated commercial value of each part. Such data and information shall consist of data available to the applicant with respect to both parts of the area under application, including the data used to determine their commercial value.⁴

21. The Council, on the basis of the data and information submitted by the applicant pursuant to section II of annex 2 to these Regulations, if found satisfactory, and taking into account the recommendation of the Legal and Technical Commission, shall designate the part of the area under application which is to be a reserved area. The area so designated shall become a reserved area as soon as the plan of work for exploration for the non-reserved area is approved and the contract is signed. If the Council determines that additional information, consistent with these Regulations and annex 2, is needed to designate the reserved area, it shall refer the matter back to the Commission for further consideration, specifying the additional information required.⁵

22. Once the plan of work for exploration is approved and a contract has been issued, the data and information transferred to the Authority by the applicant in respect of the reserved area may be disclosed by the Authority.⁴

23. A plan of work for exploration shall be approved for a period of 15 years. Upon expiration of a plan of work for exploration, the contractor shall apply for a plan of work for exploitation unless the contractor has already done so, has obtained an extension for the plan of work for exploration or decides to renounce its rights in the area covered by the plan of work for exploration.

24. Not later than six months before the expiration of a plan of work for exploration, a contractor may apply for extensions for the plan of work for exploration for periods of not

⁴ In accordance with article 14, paragraph 3, of annex III to the Convention.

more than five years each. Such extensions shall be approved by the Council, on the recommendation of the Commission, if the contractor has made efforts in good faith to comply with the requirements of the plan of work but for reasons beyond the contractor's control has been unable to complete the necessary preparatory work for proceeding to the exploitation stage or if the prevailing economic circumstances do not justify proceeding to the exploitation stage.⁵

25. The contractor shall relinquish the blocks allocated to it as follows:

- (a) By the end of the fifth year from the date of the contract, the contractor shall have relinquished:
 - (i) At least 50 per cent of the number of blocks allocated to it; or
 - (ii) If 50 per cent of that number of blocks is a whole number and a fraction, the next higher whole number of the blocks.
- (b) By the end of the tenth year from the date of the contract, the contractor shall have relinquished:
 - (i) At least 75 per cent of the number of blocks allocated to it; or
 - (ii) If 75 per cent of that number of blocks is a whole number and a fraction, the next higher whole number of the blocks.
- (c) At the end of the fifteenth year from the date of the contract, or when the contractor applies for exploitation rights, whichever is the earlier, the contractor shall nominate up to 25 blocks from the remaining number of blocks allocated to it, which shall be retained by the contractor. Relinquished blocks shall revert to the Area.^{6 7}
- (d) The Council may, at the request of the contractor, and on the recommendation of the Commission, in exceptional circumstances, defer the schedule of relinquishment. Such exceptional circumstances shall be determined by the Council and shall

⁵ Regulation 28.

⁶ Regulation 27.

⁷ The Council may, at the request of the contractor, and on the recommendation of the Commission, in exceptional circumstances, defer the schedule of relinquishment. Such exceptional circumstances shall be determined by the Council and shall include, inter alia, consideration of prevailing economic circumstances or other unforeseen exceptional circumstances arising in connection with the operational activities of the Contractor. (Regulation 27, paragraph 6).

include, inter alia, consideration of prevailing economic circumstances or other unforeseen exceptional circumstances arising in connection with the operational activities of the Contractor.

26. Under the regulations, the maximum areas that will be allocated to contractors for exploration for cobalt-rich ferromanganese crusts and polymetallic sulphides deposits in the Area will be 100 blocks or 10,000 square kilometres. The possible mining operations from these exploration areas are expected to occur on 2500 square kilometres of the seafloor.

V. MINING COBALT-RICH FERROMANGANESE CRUSTS AND POLYMETALLIC SULPHIDES IN THE AREA - TECHNOLOGICAL AND ECONOMIC CONSIDERATIONS

27. As noted in section II, some of the papers and presentations made during the Authority's previous workshops provide useful information pertinent to this workshop. This section contains relevant excerpts on the two types of mineral resources from the workshops. The excerpts address some of the topics to be discussed at the workshop, including the geologic characteristics and geographic distribution of potential cobalt-rich ferromanganese and polymetallic sulphides deposits in the Area, technological, economic and financial issues that need to be addressed in their development, the market outlook for the metals of commercial interest in these two types of potential orebodies and hypothetical mining ventures for cobalt-rich ferromanganese crusts and polymetallic sulphides that might impact prospecting, exploration and subsequent mining of these mineral resources. For ease of comprehension, for each mineral resource, the relevant excerpts are presented under the topic to be discussed at the workshop. Part I contains excerpts relevant to cobalt-rich ferromanganese crusts and Part III contains excerpts relevant to polymetallic sulphides.

PART I

EXCERPTS FROM PAPERS PRESENTED AT ISA WORKSHOPS ON COBALT-RICH FERROMANGANESE CRUSTS OCCURRENCES/DEPOSITS

1. Geologic characteristics and geographic distribution

"Metallogenesis of marine minerals" - Peter Rona

28. "Sources of metals that form cobalt-rich ferromanganese crusts of the deep ocean are derived from both continental and deep ocean sources and are precipitated from seawater like manganese nodules. The metals in addition iron and manganese includes cobalt, nickel, platinum, and titanium depending on proximity to different sources. These metals precipitate at slow rates over millions of years as crusts up to about 25 cm thick on hard-rock substrates of seamounts and submerged volcanic mountain ranges between ocean depths of 400 and 4000 meters. These crusts are most widespread in the Pacific Ocean because of the large number of seamounts present."

"Cobalt-rich ferromanganese crusts: Global distribution, composition, origin and research activities" - James Hein

29. "Cobalt-rich ferromanganese crusts occur throughout the global ocean on seamounts, ridges, and plateaus where currents have kept the rocks swept clean of sediments for millions of years. Crusts precipitate out of cold ambient seawater

onto hard-rock substrates forming pavements up to 250 mm thick. Crusts are important as a potential resource for primarily cobalt, but also for titanium, cerium, nickel, platinum, manganese, thallium, tellurium, and others. Crusts form at water depths of about 400-4000 m, with the thickest and most cobalt-rich crusts occurring at depths of about 800-2500 m, which may vary on a regional scale.”

“Fe-Mn crusts have been recovered from seamounts and ridges as far north as the Aleutian Trench in the Pacific and Iceland in the Atlantic and as far south as the Circum-Antarctic Ridge in the Pacific, Atlantic, and Indian Oceans. However, the most detailed studies have concerned seamounts in the equatorial Pacific, mostly from the EEZ (200 nautical miles) of island nations including the Federated States of Micronesia, Marshall Islands, Kiribati, as well as in the EEZ of the USA (Hawaii, Johnston Island), but also from international waters in the Mid-Pacific Mountains.”

“Compared to the estimated 50,000 or so seamounts that occur in the Pacific, the Atlantic and Indian oceans contain fewer seamounts and most Fe-Mn crusts are associated with the spreading ridges. Crusts associated with those spreading ridges usually have a hydrothermal component that may be large near active venting, but which is regionally generally a small (<30%) component of the crusts formed along most of the ridges. Those types of hydrogenetic-hydrothermal crusts are also common along the active volcanic arcs in the west Pacific, the spreading ridges in back-arc basins of the west and southwest Pacific, spreading centres in the south and east Pacific, and active hotspots in the central (Hawaii) and south (Pitcairn) Pacific. Very few (<15) of the approximate 50,000 seamounts in the Pacific have been mapped and sampled in detail, and none of the larger ones have been so studied, some of which are comparable in size to continental mountain ranges.”

“The distribution of crusts on individual seamounts and ridges is poorly known. Seamounts generally have either a rugged summit with moderately thick to no sediment cover (0-150 m) or a flat summit (guyot) with thick to no sediment cover (0-500 m). The outer summit margin and the flanks may be terraced with shallowly dipping terraces headed by steep slopes meters to tens of meters high.”

“The thickest crusts occur on summit outer-rim terraces and on broad saddles on the summits. Estimates of sediment cover on various seamounts range from 15% to 75%, and likely average about 50%. Crusts are commonly covered by a thin blanket of sediments in the summit region and on flank terraces. In the Pacific, the thickest crusts occur at water depths of 1500-2500 m, which corresponds to the depths of the outer summit area and upper flanks of most Cretaceous seamounts. The water depths of thick high cobalt content crusts vary regionally and are generally shallower in the South Pacific where the OMZ is less well developed; there, the maximum cobalt contents and thickest crusts occur at about 1000-1500 m. Thick crusts are rarely found in the Atlantic and Indian Oceans, with the thickest (up to 125 mm) being

recovered from the New England seamount chain (NW Atlantic), and a 72 mm-thick crust being recovered from a seamount in the Central Indian Basin.”

“The characteristics of crust deposits that would influence mining include factors that are critical for resource estimation, such as the aerial extent (from few sq. m. to few sq. km.), crust thickness (0.1 to 10 cm), composition (Cobalt (Co) +Nickel (Ni) +Manganese (Mn) + Iron (Fe) = 30-40%) and average density (1.5-2.0 g/cm³). The other factors that would determine the mineability of a deposit would include its depth of occurrence (500-5000 m), location (whether on axis or off axis), the slopes on which they occur (0-40°) and micro topographic undulations (1-100 cm).”

“The surface areas of 34 typical equatorial Pacific guyots and conical seamounts were measured. Surface areas were determined using Arc Map’s 3-D analyst and the amount of sediment versus hard-rock areas were calculated from side-scan sonar back-scatter images. The surface areas of 19 guyots and 15 conical seamounts varied from 4,776 to 313 square kilometres. The total area of the 34 seamounts is 62,250 square kilometres, which cover a geographic region of 506,000 square kilometres. The average surface area of the 34 seamounts is 1,850 square kilometres. The amount of surface area above 2500 m water depth, where mining is likely to occur, averages 515 square kilometres (range 0-1,850 square kilometres). Guyots are bigger than conical seamounts because guyots at one time grew large enough to be islands before erosion and subsidence took place. The conical seamounts never grew large enough to breach the sea surface.”

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“Thick crusts are rarely found in the Atlantic and Indian Oceans, with the thickest (up to 125 mm) being recovered from the New England seamount chain (NW Atlantic), and a 72 mm-thick crust being recovered from a seamount in the Central Indian Basin.”

“The thickest crusts occur on summit outer-rim terraces and on broad saddles on the summits. Estimates of sediment cover on various seamounts range from 15% to 75%, and likely average about 50%. Crusts are commonly covered by a thin blanket of sediments in the summit region and on flank terraces. It is not known how much sediment can accumulate before crusts stop growing. Crusts have been recovered from under as much as 2 m of sediment without apparent dissolution. Based on coring results, Yamazaki estimated that there are 2-5 times more Fe-Mn crust deposits on seamounts than estimates based on exposed crust outcrops because

of their coverage by a thin blanket of sediment. Those thinly veiled crusts would be within reach of mining operations.”

“Within the central Pacific, a great many seamounts occur within the Area (international waters), and promising locations for potential mining occur within the Mid-Pacific Mountains, such as between Wake and Minami Torishima (Marcus) Islands, the Magellan Seamounts, seamounts between the EEZs of Johnston Island and the Marshall Islands and Johnston Island and Howland and Baker Islands, Shatsky Rise farther to the north might also be promising. Figure 1 prepared with the assistance of Dr Hein shows this area.

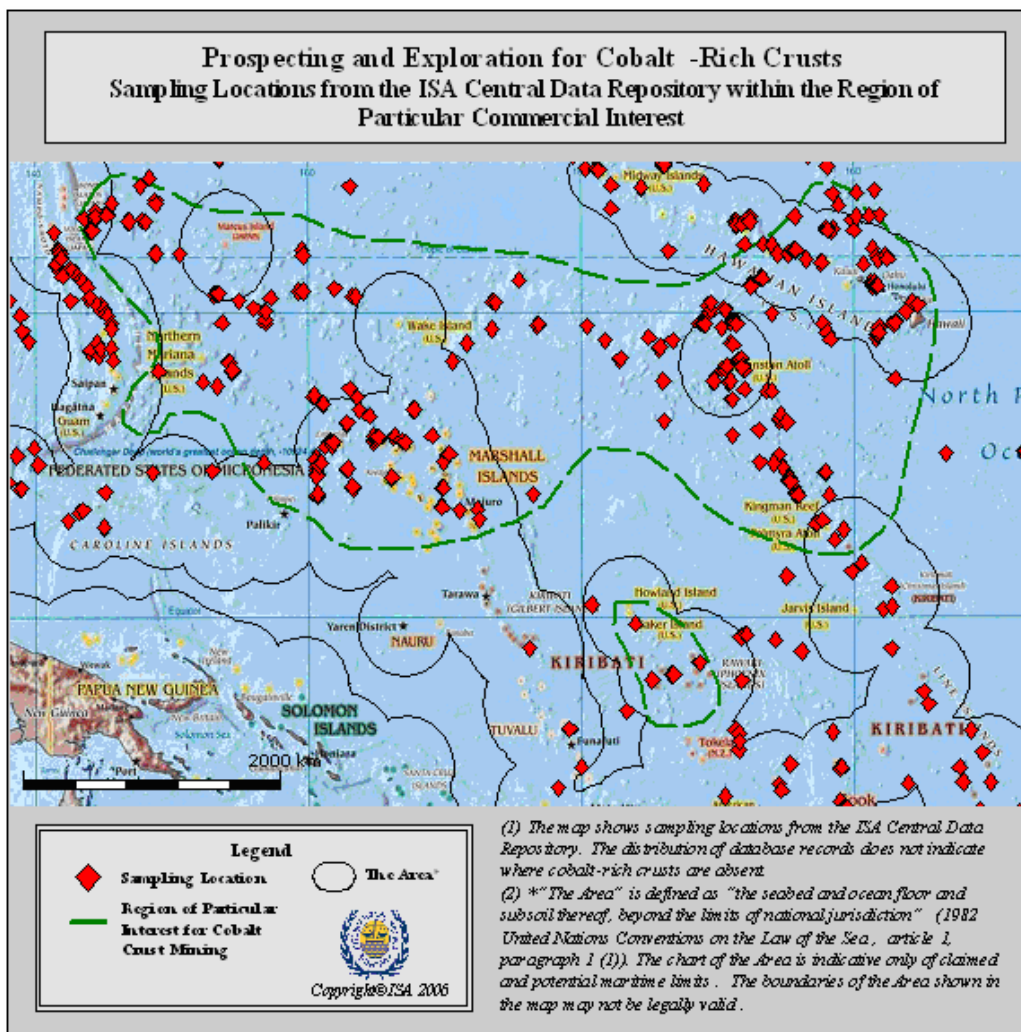


Figure 1: Sampling locations for Cobalt Rich Ferromanganese crusts in Pacific – The green line shows the region of interest for Cobalt Crust Mining.

“A Comparison of the Possible Economic Returns from Mining Deep Seabed Polymetallic Nodules, Seafloor Massive Sulphides and Cobalt-Rich Crusts” - Jean-Pierre Lenoble, Ingenieur Geologue, Legal and Technical Commission (ISA) Chatou, France

30. “Encrustations of ferromanganese hydroxides have been found in many areas of the seafloor, but more particularly, where consolidated sediments and hard rocks outcrop. Most of them were discovered on seamounts or plateaux that constitute elevations of the seafloor in abyssal areas. These summits are frequently linked with volcanic structures and sometimes are sunken atolls.”

“Since the beginning of the nineteen eighties, ferromanganese crusts deposits have attracted the attention of explorers, as potential resources for cobalt. Although several exploration surveys have been carried out in different parts of the world’s oceans, mostly by scientific institutions, the state of knowledge is still limited.”

“Cobalt-bearing crusts are often associated with low-grade nodules. Both these deposits have relatively low manganese to iron ratio (1-2.5) in comparison to polymetallic nodules of economic interest (4-6). Their nickel and copper contents are also lower (0.3-1%). While the cobalt content of crusts can reach 3%, on average it is only 0.6-0.8%, or three to four times greater than the average cobalt content of "good" nodules (0.25%). Other metals occur as trace metals. These include vanadium (0.06%), molybdenum (0.05-0.1%), and platinum (0.14 to 5 ppm).”

“The richest cobalt-crusts deposits appear to be concentrated at water depths of 800-2 000 m. Some scientists have considered a link with the oxygen minimum zone as a possible reason for their formation. However, as in fossil stratigraphy, such crustification is an indication of a lacuna of sedimentation, either by a hiatus (no deposition) or by intermediate erosion. Similar encrustations, associated with nodules, were found in cores made on top of seamounts in the Indian Ocean and later in many DSDP cores. They were proved lacunae of sedimentation. Observations of current activities that prevent sediment deposition have been recorded during several surveys.”

“It seems that there are two kinds of cobalt-rich crusts deposits:

- Flat deposits on top of sunken atolls, where the crust covers old coral reef formations;
- Inclined deposit on the flanks of volcanic seamounts, where the crust covers volcanic breccias and associated sediments.

2. Economic and financial issues associated with commercializing Cobalt-rich ferromanganese crusts in the Area

“Characteristics of Seamounts and Cobalt-Rich Ferromanganese Crusts” - James R. Hein, Senior Geologist, United States Geological Survey, USA

31. “The greatest potential economic value of Fe-Mn crusts has always been their unprecedented high contents of cobalt. However, Fe-Mn crusts contain high concentrations of a great variety of metals that could become important by-products of cobalt recovery. Recently, significant increased demands for metals in the rapidly growing economies of China and India have pushed up the metal prices, notably copper, nickel, and cobalt. This upward trend in prices will fluctuate, but should not be ameliorated anytime soon. Nickel consumption in China has increased five fold in the decade of the 1990s and continues to grow. The projected annual rate of growth of world consumption is expected to range from 4-6% for cobalt, copper, and nickel. Shortages of copper supplies have been projected to occur within the next decade. The price of copper has more than tripled since 2001, and the price of nickel has likewise increased significantly, although with large fluctuations. These increased metal demands may have an impact on the three main deep-seabed mineral-deposit types in that nodules and crusts have high copper, nickel, and cobalt contents, and polymetallic sulphides have high copper contents. Increased metal demand and higher prices make the potentiality for marine mining more likely.”

“The combined cobalt (Co), nickel (Ni), and copper (Cu) contents are highest in the open Pacific Ocean, intermediate in the Indian and Atlantic Oceans, and lowest along the continental margins in the Pacific Ocean. The highest copper contents occur in Indian Ocean crusts because they are generally from deeper water areas and copper contents increase with increasing water depth of crust occurrence. Shatsky Rise Fe-Mn crusts, mid-latitudes of the northwest Pacific, have a surprisingly high mean copper content, as well as the highest copper value yet measured in a bulk crust, 0.4% (4000 ppm). Platinum (Pt) contents are highest in the Atlantic and open South Pacific crusts, intermediate in the open North Pacific and Indian Ocean crusts, and lowest in crusts from continental margins. Cerium (Ce) and the other rare-earth elements are generally highest in Indian and Atlantic Ocean crusts.”

“Cobalt-rich ferromanganese crusts: Global distribution, composition, origin and research activities” – James Hein

32. “Bulk crusts contain cobalt contents up to 1.7%, nickel to 1.1%, and platinum to 1.3 parts per million (ppm), with mean iron/manganese ratios of 0.4 to 1.2. Cobalt, nickel, titanium, and platinum decrease, whereas iron/manganese, silicon, and aluminium increase in continental margin crusts and in crusts with proximity to

west Pacific volcanic arcs. Vernadite- and CFA-related elements decrease, whereas iron, copper, and detrital-related elements increase with increasing water depth of crust occurrence. Cobalt, cerium, thallium, and maybe also titanium, lead, tellurium, and platinum are strongly concentrated in crusts over other metals because they are incorporated by oxidation reactions. Total rare-earth elements (REEs) commonly vary between 0.1% and 0.3% and are derived from seawater along with other hydrogenetic elements, cobalt, manganese, nickel, etc. Platinum-group elements are also derived from seawater, except palladium, which is derived from detrital minerals.”

“Proposed Exploration and Mining Technologies For Cobalt-Rich Crusts”

- Dr. Rahul Sharma, Scientist, National Institute of Oceanography, Dona Paula, India

33. “Although many studies have evaluated their metal contents and geological setting, a study undertaken by the Department of Planning and Economic Development of Hawaii in 1987 entitled “Mining Development Scenario for Cobalt-rich Manganese crusts in the Exclusive Economic Zones of the Hawaiian Archipelago and Johnston Island. Honolulu” addressed several aspects of the deposits, such as mining criteria, techno-economic feasibility and infra-structural requirements. The study area was estimated to have an overall in-place resource potential of 2.6 million tonnes of cobalt, 1.6 million tonnes of nickel, 81 million tonnes of manganese, and 58 million tonnes of iron with an average content of 0.73% Co, 0.45% Ni, 23% Mn and 16.5% Fe. This estimate is based on mean crust coverage of 40%, crust thickness ranging from 0.5-2.5 cm in different areas, and average density of 1.95g/cm³ (wet) or 1.34 g/cm³ (dry).”

3. Technological issues associated with commercializing cobalt-rich ferromanganese crusts in the Area

“Proposed Exploration and Mining Technologies for Cobalt-Rich Crusts”

- Dr. Rahul Sharma, Scientist, National Institute of Oceanography, Dona Paula, India

34. “The characteristics of crust deposits that would influence mining include factors that are critical for resource estimation, such as the aerial extent (from few sq. m. to few sq. km.), crust thickness (0.1 to 10 cm), composition (Cobalt (Co) +Nickel (Ni) +Manganese (Mn) + Iron (Fe) = 30-40%) and average density (1.5-2.0 g/cm³). The other factors that would determine the mineability of a deposit would include its depth of occurrence (500-5000 m), location (whether on axis or off axis), the slopes on which they occur (0-40°) and micro topographic undulations (1-100 cm).”

“The Hawaiian and Johnston islands study reveals that the depth versus axis position relationships of Co, Ni, Mn, and Fe of both on- and off-axis sample locations showed minor variation for similar depth ranges. Also metal concentrations of Co, Ni, and Mn increase with increase in latitude, whereas Fe decreases. Similarly, crusts on sediments have higher concentrations of Aluminium (Al) and Copper (Cu), and lower concentrations of Mn, Co, and Zinc (Zn) than those on basalt substrates.”

“A detailed study on occurrence of these deposits (Yamazaki and Sharma, 2000) has classified zones depending on seabed slopes, such as nodule dominant (0-3°), sediment dominant (3-7°), transitional zone (7-15°) wherein crusts and nodules co-exist at most locations, and crust dominant (>15°). Such a classification of the distribution of crusts deposits on the seafloor would provide critical inputs for designing the mining device and help in optimum utilization of the capability of the mining system. Besides manoeuvrability on different seabed slopes, a mining device would also be required to negotiate the micro topographic undulations associated with different types of crust surfaces, such as step like (100-200 cm), large outcrops (50-100 cm), cobble type (20-50 cm), nodular (10-20 cm) and also nodules (1-10 cm) and sediments (0-5 cm). It has also been suggested if buried crusts are also considered for mining, the resource potential could increase many fold, hence improving the overall efficiency of the mining system (Yamazaki et al., 1994).”

“Besides these, there are several geotechnical properties of crusts that would play a role in mining these deposits. These include their density, hardness, porosity, void ratio, as well as their compressive and tensile strengths that would determine the collection mechanism of the mining device.”

Exploration techniques

35. “There are various parameters that need to be evaluated for resource estimation as well as designing a suitable mining device, for which different techniques would have to be employed. These include the occurrence of rock outcrops, sediment cover, slope distributions, geomorphology, and current patterns. All of these physical properties of the environment affect crust formation. Bottom photographs are useful in determining local distribution of crusts, sediments, and rock outcrops; depth sounding is useful for determining slopes; coring can be useful in interpreting sub-bottom structure including buried crusts. Similarly, deployment of current meters and CTD sensors and collection of water samples at discrete depths would provide critical environment data for operation of mining system as well as environmental impact prediction and assessment. Whereas, the weather recorder would help tracking the meteorological conditions for optimizing mining duration during the year, the position fixing instruments provide the basic location and navigation data.”

Estimation of area to be mined and impacted

36. “It is expected that a number of individual crust deposits will be required to sustain a commercial mining operation over the 15 to 20-yr period. It is estimated that roughly 600 km² area would sustain one commercial mining operation for 15-20 years (Hawaiian study, 1987), which at the mining rate of 1 million tones / year should have a deposit of 15-20 million tones. The Hawaiian study suggested that to estimate the tonnage of in-place crust resources in an area, multiply the appropriate tonnage number times the permissive area. For example, for a seamount having an average crust thickness of 2.5 cm, 40% coverage, and a permissive area of 425 km² the total in-place crust resource is:

$$19,500 * 425 = 8,775,000 \text{ t (wet)}''$$

“Regional and local variability in the spatial distribution of cobalt bearing ferromanganese crusts in the world’s ocean. (Description of the Marcus-Wake underwater rise)” - V.M Yubko and Y.B Kazmin

37. “A typical ore field can be separately located guyots, whose base is 120 to 80 km. The top is at a depth interval between 1300 and 1500m, and the slope brow confined to a depth of 1500m. The configuration of the summit plateau is similar to that of the base and has dimensions of 65 to 35 km at a depth of 3000m. The diameter of the structure at this depth is 15 km. The average dip of the slopes in between 1500 and 3000 m varies from 20 to 30 degrees, whilst the deeper slopes are more gentle, varying between 5 and 10 degrees.”

“Cobalt-rich ferromanganese crusts: Global distribution, composition, origin and research activities” - James Hein

38. “For many guyots and seamounts, the surface area that is likely to be mined is less than the area that exists above 2500 m water depth, because of sediment cover. As a worst-case scenario, about 210 square kilometres (range ~210-410 square kilometres) of the average seamount would have crust exposed (not covered by sediment) that could potentially be mined; and about 530 square kilometres (range ~530-1060 square kilometres) of the largest seamount measured would be available for mining. Those areas would likely be further reduced because of prohibitive small-scale topography, un-mined biological corridors, and other impediments to mining. Consequently, for the largest seamount measured, as little as 130 square kilometres (range ~130-265 square kilometres) might be available for mining; and for the average seamount, as little as 50 square kilometres (range 50-105 square kilometres) might be available for mining. Seamounts and guyots do exist that have little sediment cover and relatively subdued topography and those are the ones that are likely to be mined.”

Implications for Mine Site Characteristics

“Based on the data presented, it is proposed that a future crusts mine site will have the following characteristics.

- (i) Mining operations will take place around the summit region of guyots on flat or shallowly inclined surfaces, such as summit terraces and saddles, which may have either relatively smooth or rough small-scale topography. These are the areas with the thickest and most cobalt-rich crusts; much thinner crusts occur on steep slopes;
- (ii) The summit of the guyots will not be deeper than about 2200 meters, the terraces not deeper than about 2500 meters;
- (iii) Little or no sediment will occur in the summit region, which implies strong and persistent bottom current;
- (iv) The summit region will be large, more than 600 square kilometers (see next section);
- (v) The guyots will be Cretaceous in age;
- (vi) Areas with clusters of large guyots will be favoured;
- (vii) Guyots with thick crusts and high grades (cobalt, nickel, copper) will be chosen;
- (viii) The central Pacific best fulfils all the above criteria.”

“The basic mine-site characteristics listed above can be utilized in the design of mining equipment, and in considering biological and environmental issues. For example, sessile biota and fish may be more important concerns than sediment in fauna. Mining equipment will probably not have to be designed to operate on steep slopes, although that capability would offer greater flexibility.”

Implications for available mine sites

“Based on a conservative estimate of 26 kilograms of crust per square meter of seafloor (range ~25-78 kilograms per square meter based on dry bulk density of 1.3 grams per cubic centimetre and mean range of crust thicknesses of 2-6 centimetres), it would require the mining of 77 square kilometres (range ~26-77) per year to satisfy a rate of production of 2 million metric tons of crust per year. This would translate to 1,540 square kilometres (range ~520-1,540) of crust removal

for a 20 year mining operation. From the data on seamount sizes and likely areas available for mining presented above, it can be concluded that about 3-12 large guyots would be needed for a 20 year mining operation, or about 10-31 average size seamounts based on an average crust thickness of two centimetres. However, it is likely that large areas can be found with twice that average crust thickness.”

“A Comparison of the Possible Economic Returns from Mining Deep Seabed Polymetallic Nodules, Seafloor Massive Sulphides and Cobalt-Rich Crusts” - Jean-Pierre Lenoble Ingenieur Geologue Legal and Technical Commission (ISA) Chatou, France

39. “The dimensions of flat deposits can be 50-200 km² with 70-90% of the area covered by encrustations. Their topography is relatively even, with slopes less than 5%. Cracks form an irregular pattern that cup up the crust and the underlying material to several decimetres deep. The corresponding slabs are one to several square meters wide.”

“Slope deposits are inclined up to 25%, as the flanks of old volcanoes. Crusts cover more or less consolidated sediments as well as hard basaltic rock and breccias. Evidence of sliding along the slope has been recorded.”

“The thickness of the crust can be 2 to 10 cm, sometimes up to 20 cm, but the structure and composition varies from top to bottom. Generally, only the few first millimetres have very high cobalt content (up to 3%). Cobalt grade decreases with depth, as well as manganese and iron, because of mixing with the underlying material. When this material is composed of calcareous phosphorite, there is a corresponding increase of the phosphorus and calcium contents. Therefore, only the first few centimetres (2 to 3) of a deposit have an economic value. Phosphatisation has also been found in slope deposits, probably in relation with up-welling phenomena.”

“The wet specific gravity of crust material is reported to vary from 1.6 to 2.1 g cm⁻³. The crust material, as is the case with polymetallic nodules, is very porous (43-74%). Accordingly, in the Tuamotu area, the average dry specific gravity was 1.4 g cm⁻³.”

“During the surveys made by CNEXO (1970) then IFREMER in this area a submerged old atoll was discovered near Niau Island. The depth of the plateau is 1 000-1 200 m limited by steep flanks of 400 m where the slope is more than 25%. Of the total area of 270 km², at least 80 km² are coated with encrustations, with an apparent coverage ratio of 70%. The surface of the crust is bumpy with smooth decimetric microtopogaphy. Sandy sediments with ripple marks occupy enclosed sectors. One can suspect the existence of buried crust beneath this sediment, as found in other deposits. The large blocks of crust, that have been dredged, showed

a phosphatic-calcareous core, light brown and well consolidated. Fossil foraminifers give an age of 45 Ma (middle Eocene). The outer part is altered with micro fissures impregnated by ferromanganese hydroxides. The crust, dark black and 2 to 5 cm thick, is more continuous and compact at the top part of the blocks. From the surface of this crust, the cobalt content decreases from 2% in the first 3 mm to 1.7% in the next 15 mm and 0.6% in the following 15 mm. A bulk sample taken from the crust had average grades of 0.33% Co, 0.2% Ni, 0.06% Cu, 9.7% Mn, and 7.9% Fe. In 1986, an attempt was made to sample the deposit with a pyrotechnic multicorer with relative success.”

“The representativeness of such sampling versus future mining is questionable, as is the case for many of the surveys conducted elsewhere. An attempt to be more effective was made using a large gravity corer. However, the penetration through the crust and its substrate is limited and consequently does not show a fair picture of the deposit.”

“At Niau, the tonnage of material with economic merit has been estimated to be 1 million dry tonnes with average cobalt content of 1.2%, based on recovering only the first 2 cm of the crusts. Dilution of this layer by the underlying material will certainly occur, but it seems possible to separate the crust by ore processing techniques. Several similar deposits have been discovered in the vicinity that could increase this speculative inferred resource to five Mt, which could then produce 50 000 t of cobalt.”

“Total resources of cobalt from Co-rich crusts in the central Pacific have been estimated to 500 million tonnes (100 deposits similar to Niau).”

“The exploration techniques must be improved considerably in order to provide the necessary parameters for the design of mining and processing methods. A better knowledge of the micro topography can be obtained by using deep-towed multibeam sonar associated with continuous high resolution TV recordings. Sampling methods must be completely retooled. Rotary diamond drilling machines equipped with a multicorer system must be developed to provide a fast and cheap sampling method with better recovery.”

Mining and processing technologies

“Several engineering studies have been carried out to define possible methods of mining and processing cobalt-rich crusts. The studies highlight the current lack of knowledge and the need for better information to be able to design efficient systems.”

“A revised continuous line bucket (CLB) system was proposed by its inventor for crust recovery. Besides the apparent simplicity of the system, strong reservations

must be made about its efficiency. It is doubtful that the buckets will be able to extract large slabs of crust that are firmly attached to their substrate. Buckets could be also severely damaged when they impact the bottom of the deposits. The blocks containing crusts will be low grade, retaining a significant amount of waste material. In slope deposits, blocks of lava and volcanic breccias will also be retrieved, as the buckets cannot be manipulated to discriminate between ore and waste.”

“In 1985, Halkyard proposed a hydraulic lifting system with a self-propelled bottom crawler equipped with cutting devices as suitable technology for mining crusts. The cutting devices would create incisions on the surface layers of the crust, permitting their extraction by suction to the pipe system.”

“In a study conducted during the same year by Gemonod for the Niau deposit, a similar system was envisaged. The proposed cutting device would be a set of hammer drills or a row of rotary cutting drums. A crusher would also be installed on the self-propelled crawling dredge, in order to produce slurry (60% solid) to be pumped to the surface.”

“Chung considered the possibility of using water-jet cutting or fracturing to slice or break the crust top-layers. He also considered adopting a hydraulic lifting system, with a towed or self-propelled bottom collector.”

“Zaiger proposed an innovative system in 1994, known as "solution mining". A large "containment and regulation cover" (CRC: up to 40 000 m²), consisting of an impermeable membrane, is sealed on the bottom by tubes filled with a heavy medium such as barite mud. A leaching solution is introduced between the CRC and the seafloor. After sufficient time, the enriched solution is pumped to the surface platform for metal extraction. The CRC is then moved to another area. Preliminary tests have raised more problems than providing solutions.”

“Research on processing has been limited owing to the lack of information on the composition and physical properties of the possible raw ore. However, some studies have shown possibilities of using ore processing to concentrate the minerals. Magnetic separation, followed by froth flotation, can separate the ferromanganese hydroxides from the calcareous phosphorite or the siliceous volcanic fragments, and form an enriched concentrate. Heavy liquid separation was also proposed to obtain the same result.”

“Minemet Recherche studied this method under a contract from Afernod/Gemonod in 1986. A concentrate grading 1.2% Co, 0.6% Ni, 0.1% Cu and 26% Mn was obtained from the raw ore. The recovery could be better than 70%.”

“Extraction of the metals from the concentrate can be also effected by hydrometallurgy. For polymetallic nodules, both ammoniacal and sulphuric acid leaching were proposed. Japanese institutions studied the dissolution of the valuable metals (Co, Ni, and Cu) in a mixture of ammonium sulphite and ammonium carbonate, or in ammonium thiosulphate. The metals are then extracted from the pregnant solution by selective organic solvents. The refined metals are obtained by final electro winning.”

“Minemet Recherché proposed to use sulphuric leaching in a closed cell under one MPa pressure at 180°C temperature. The introduction of Mn⁺⁺ ions favours cobalt recovery. The process derives from the SRM2 tested for polymetallic nodules by the French CEA. Selective extraction of the different metals (Co, Ni, Cu) is made by organic solvents. Sulphide concentrates are prepared by precipitation for further refining. Cobalt recovery could be 93%. Manganese is confined in a low-grade ferromanganese residue, rich in iron, which could be (doubtfully) used as a manganese ore.”

PART 2

EXCERPTS FROM WORKSHOP PAPERS ON SEAFLOOR POLYMETALLIC SULPHIDES OCCURRENCES/DEPOSITS

I. Geologic characteristics and geographic distribution

“Seafloor Massive Sulphides deposits and their resource potential” – Prof. Herzig and Mr S. Petersen Institute for Mineralogy Brennhaugasse, Germany and Dr Hannington Geological survey of Canada, Ottawa, Canada

40. “The discovery of high-temperature black smokers, massive sulphides, and vent biota at the crest of the East Pacific Rise at 21°N in 1979 confirmed that the formation of new oceanic crust through seafloor spreading is intimately associated with the generation of metallic mineral deposits at the seafloor. It was documented that the 350°C hydrothermal fluids discharging from the black smoker chimneys at this site at a water depth of about 2,600 m continuously precipitate metal sulphides in response to mixing of the high-temperature hydrothermal fluids with ambient seawater. The metal sulphides including pyrite, sphalerite, and chalcopyrite eventually accumulate at and just below the seafloor and have the potential to form a massive sulphide deposit. It has also been documented that circulation of seawater through the oceanic crust is the principal process responsible for the formation of massive sulphide deposits in this environment. Seawater which deeply penetrates into the oceanic crust at seafloor spreading centers is being modified to a hydrothermal fluid with low pH, low Eh, and high temperature during water-rock interaction above a high-level magma chamber. This fluid is than capable of leaching and transporting metals

and other elements which eventually precipitate as massive sulphides at the seafloor or as stockwork and replacement sulphides in the sub-seafloor. The resulting massive sulphide deposits can reach considerable size ranging from several thousand to about 100 million tonnes. High concentrations of base (copper, zinc, lead) and in particular precious metals (gold, silver) in some of these deposits have recently attracted the interest of the international mining Industry.”

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

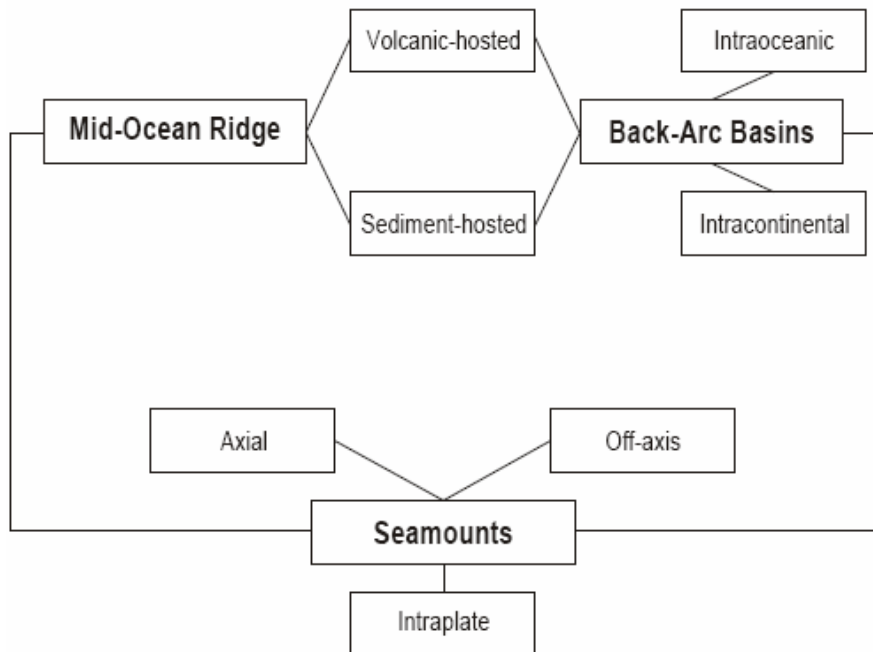


Figure 2. Geological environments for the occurrence of seafloor hydrothermal systems. Polymetallic massive sulphides deposits have been found in all settings except for intraplate seamounts.

“The majority of sites so far have been located at the East Pacific Rise, the Southeast Pacific Rise, and the Northeast Pacific Rise, mainly because the first discovery of an active high-temperature hydrothermal system was made at 21°N at the East Pacific Rise off shore Baja California. Only one site has so far been located at the ridge system of the Indian Ocean, close to the Rodriguez Triple Junction. The scarcity of sulphides deposits on the Mid-Atlantic Ridge and in the Indian Ocean is, at least to

a large extent, a function of restricted exploration activity in these areas. It has been assumed that today only about 5% of the 60,000 km of oceanic ridges worldwide have been surveyed and investigated in some detail.”

“During hydrothermal convection at oceanic spreading centers, seawater penetrates deeply into the newly formed oceanic crust along cracks and fissures, which are a response to thermal contraction and seismic events typical for zones of active seafloor spreading. The seawater circulating through the oceanic crust at seafloor spreading centers is converted into an ore-forming hydrothermal fluid in a reaction zone which is situated close to the top of a sub axial magma chamber (*Fig. 3*). Major physical and chemical changes in the circulating seawater include (i) increasing temperature, (ii) decreasing pH, and (iii) decreasing Eh. The increase in temperature from about 2°C to values >400°C^{31,32} is a result of conductive heating of a small percentage of seawater close to the solidified top of a high level magma chamber. This drives the hydrothermal convection system and gives rise to black smokers at the seafloor.”

“Due to its increased buoyancy at high temperatures, the hydrothermal fluid rises rapidly from the deep-seated reaction zone to the surface along major faults and fractures within the rift valley or close to the flanks of the rift. In particular the intersections of faults running parallel and perpendicular to the ridge axis are the loci of high-velocity discharge black smokers and polymetallic sulphides mounds. The sulphides precipitation within the up flow zone (stockwork) and at the seafloor (massive sulphides) is a consequence of changing physical and chemical conditions during mixing of high temperature (250-400°C), metal-rich hydrothermal fluids with cold (about 2°C), oxygen-bearing seawater (*Fig. 3*).”

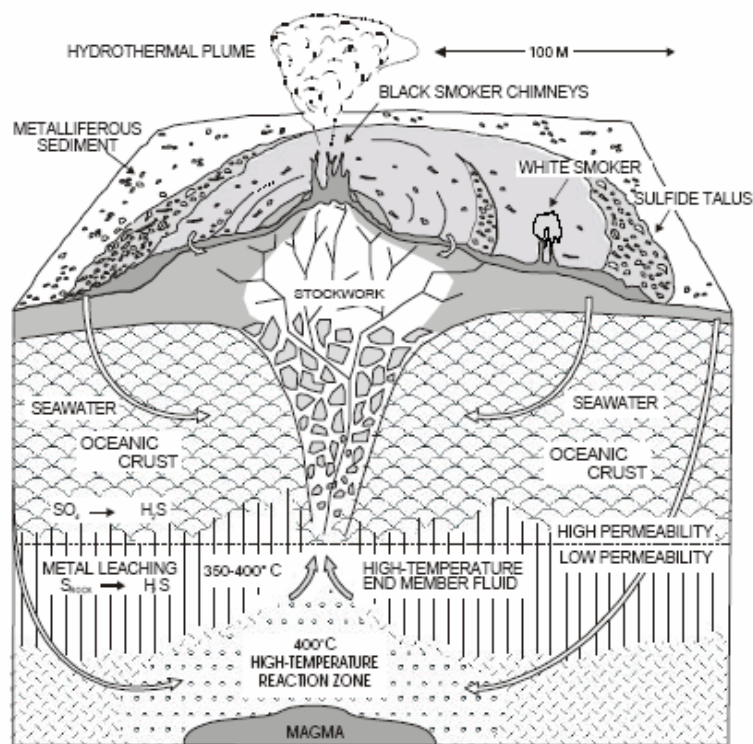


Figure 3: A cross section of a polymetallic sulphides mound showing the principal components of seafloor hydrothermal system.

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

Table 1: Possible Sites for Mining of Seafloor Massive Sulphides Deposits

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

		2,850		
		2,500 – 2,600		
		3,650 – 3,700		

“Preussag has also performed active exploration for massive sulphides deposits in the Galapagos Spreading Center 86°W in the mid 1980s during the GARIMAS project (Galapagos Rift Massive Sulphides), which consisted of three cruises with the German vessel SONNE. At that time it was concluded, that the Galapagos deposits are not sufficiently large and continuous to be economically mined.”

“It is also unlikely that deposits such as the TAG hydrothermal field, which is located in international waters at the Mid-Atlantic Ridge, the 13°N seamount at the East Pacific Rise or the Sonne hydrothermal field at the remote Rodriguez Triple Junction in the Southern Indian Ocean will become mining targets in the near future. This is also true for many of the sulphides deposits along the East, Northeast and Southeast Pacific Rises.”

“Hydrothermal sulphides mineralization of the Atlantic – Results of Russian investigations” – G. Cherkashev, A. Ahsadze and A. Glumov

41. “Some of the investigations that were begun in 1985 in the Mid-Atlantic Ridge are still in progress. Nearly 20 cruises have been organized in this region. Geological and geophysical studies at scales between 1: 1 000 000 and 1: 200 000 were conducted in the course of this period in a 50-100 km band of the axial zone of the Mid-Atlantic Ridge from 12° N to 19° N and from 21° N to 29° N. These studies included bathymetric, magnetic, physical and chemical oceanographic studies, side-scan sonar surveys using frequencies of 30 or 100 kHz, as well as video- and photo-profiling and geological sampling. Ten (10) areas showing promise for new hydrothermal fields that are located at 28°40'– 28°48'N, 27°05'-27°10'N, 25°25'-25°33'N and 16°07'-16°09'N were the most significant discoveries by Russian researchers during this period.”

“Intensive investigations resulted in the discovery of new hydrothermal sulphides fields; the Logachev - 1 and Logachev – 2 fields, the high-cuprous and high gold content sulphides mineralization at 24° 30'N that was photographed and dredged, the MIR hydrothermal mound of the TAG field that was subsequently sampled and studied in detail, as well as the previously known Snake Pit field.”

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

Metallogenesis of marine minerals – Peter Rona

42. “In 1979, on the East Pacific Rise at 21 degrees north latitude off Baja California (Mexico), scientists exploring the ocean floor discovered chimney-like formations of dark rock atop sulphide mounds, spewing hot water and surrounded by animal species different from any previously known. Since then, studies have shown that

these black-smoker complexes are an outgrowth of the formation of new oceanic crust through seafloor spreading as the tectonic plates underlying the earth's surface converge or move apart. This activity is intimately associated with the generation of metallic mineral deposits at the seafloor.”

“At water depths up to 3,700 metres, hydrothermal fluids, having seeped from the ocean into subterranean chambers where they are heated by the molten rock (magma) beneath the crust, are discharged from the black smokers at temperatures up to 400° Celsius. As these fluids mix with the cold surrounding seawater, metal sulphides in the water are precipitated onto the chimneys and nearby seabed. These sulphides, including galena (lead), sphalerite (zinc) and chalcopyrite (copper), accumulate at and just below the seafloor, where they form massive deposits that can range from several thousand to about 100 million tonnes. High concentrations of base metals (copper, zinc, lead) and especially precious metals (gold, silver) in some of these massive sulphide deposits have recently attracted the interest of the international mining industry. Many polymetallic sulphides deposits are also found at sites that are no longer volcanically active.”

“Most sites have been located in mid-ocean at the East Pacific Rise, the Southeast Pacific Rise and the Northeast Pacific Rise. Several deposits are also known at the Mid- Atlantic Ridge but only one has so far been located at the ridge system of the Indian Ocean. The paucity of known sulphide deposits at the Mid-Atlantic Ridge and the Central Indian Ridge is largely explained by the fact that exploration in these areas has been limited. Only some 5 percent of the 60,000 kilometres of oceanic ridges worldwide have been surveyed in any detail.”

“In the mid-1980s, additional sulphides deposits were discovered in the south-western Pacific, at ocean margins where basins and ridges occur on the seafloor between the continent and volcanic island arcs. In these so-called back-arc spreading centres, magma rises close to the surface at convergent plate margins where one tectonic plate slips beneath another in a process called subduction. Further deposits have been discovered from western and south western Pacific (Lau Basin and North Fiji Basin), Okinawa Trough southwest of Japan, Manus Basin, North of New Caledonia, Woodlark basin, Papua New Guinea etc. Today more than 100 sites of hydrothermal mineralization are. Known and around 25 of them are high temperature black smoker venting.”

2. Economic and financial issues in commercializing polymetallic sulphides of the Area

“Seafloor Massive Sulphides deposits and their resource potential” – Prof. Herzig and S. Petersen, Institute for Mineralogy, Freiberg/Sachsen, Germany and Dr Mark Hannington, Geological survey of Canada

43. The Mineralogy of the seafloor sulphides is tabulated below.

Table 2 - Mineralogy of seafloor polymetallic sulphides

	Back-Arc Deposits	Mid-Ocean Ridge Deposits
Fe-sulphides	pyrite, marcasite, pyrrhotite	pyrite, marcasite, pyrrhotite
Zn-sulphides	sphalerite, wurtzite	sphalerite, wurtzite
Cu-sulphides	chalcopyrite, isocubanite	chalcopyrite, isocubanite
silicates	amorphous silica	amorphous silica
sulphates	anhydrite, barite	anhydrite, barite
Pb-sulphides	galena, sulphosalts	
As-sulphides	orpiment, realgar	
Cu-As-Sb-sulphides	tennantite, tetrahedrite	
native metals	gold	

Metal contents:

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

Bulk Chemical composition of seafloor polymetallic sulphides

The bulk composition of some of the known seafloor polymetallic sulphides occurrences is presented in table 3 below.

Table 3 - Bulk chemical composition of seafloor polymetallic sulphides occurrences

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

“Comparison of nearly 1,300 chemical analyses of seafloor sulphides reveals that deposits in different volcanic and tectonic settings have different proportions of metals. Relative to samples from sediment-starved mid-ocean ridges, massive sulphides formed in basaltic to andesitic environments of back-arc spreading centres (573 samples) are characterized by high average concentrations of zinc (17%), lead (0.4%) and barium (13%), but little iron. Polymetallic sulphides at back-arc rifts in continental crust (40 samples) also have low iron content but are commonly rich in zinc (20%) and lead (12%), and have high concentrations of silver (1.1%, or 2,304 grams/t). In general, the bulk composition of seafloor sulphides deposits in various tectonic settings is a consequence of the nature of the volcanic source rocks from which the metals are leached. Recently another dimension is added to the PMS with the report of high concentration of Gold. The Mid oceanic ridges have average 1.2 gm/ton but back arc sulphides the gold concentration can be as high as 28g/ton (Lau Basin) to around 55 gm/ton at Manus Basin. The conical seamount in the EEZ of Papua New guinea has a high 230 gm/ton of gold concentration. Polymetallic sulphides have the advantage in that more than one metal can be mined simultaneously, the extraction of metals from the sulphides is a proven technology and efficient.”

“Financing exploration for seafloor massive sulphides deposits” – Julian Malnic

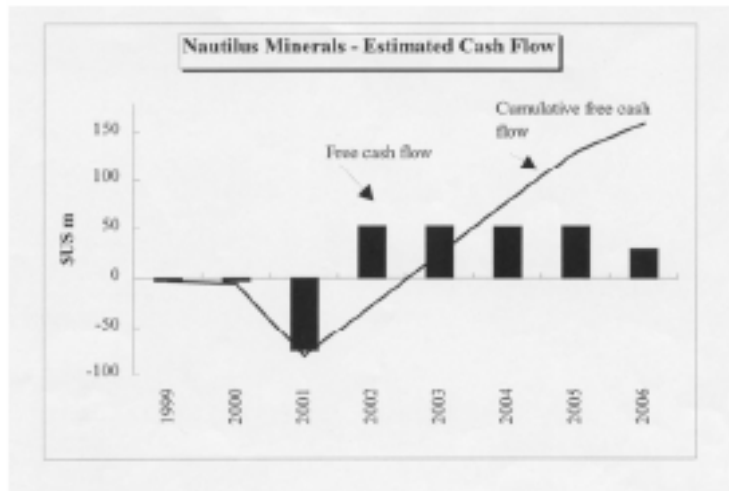
44. “With exploration for Seafloor Massive Sulphides (SMS)* deposits barely half a decade old, there are not statistically sound generalizations that can be drawn from the financing experience so far. Furthermore, because of the normal confidentiality that surrounds corporate activity, knowledge of industry experience does not extend far beyond our own group. However, it is evident that the capital raising process will be similar to either terrestrial mineral exploration, or maybe even to dot.com style, companies.”

“SMS mining offers scope for a highly compressed development cycle. The time between first identifying a plume and tracking down a deposit, and the time of mining the deposit can be very short, a factor that will also carry considerable economic advantage. ‘With the mobility of the production vessel, test mining can be conducted within a matter of weeks of a discovery. On land, the definition drilling required to justify the cost of a test shaft will typically take two years and then test shaft will take additional time. By lowering such development threshold, the feasibility costs are also expected to be significantly lower than for terrestrial mines.”

“Using very basic assumptions and calculations about the most likely system we will use, Nautilus has performed some very useful spreadsheet models for a proposed Manus Basin mining operation. We regard these models as proprietary assets so I do not intend to present them here. But for the sake of illustration, one base case involved an arbitrary mine size of 1.5Mt and at the rate of 1000tpd, the

mine life will be 4.5 years. The following chart shows the summary of net cash flow and cumulative net cash flow for this scenario. Capex costs include the acquisition of a ship for US\$50m.”

Figure 4: Summary of net cash flow for a seafloor polymetallic sulphides mine



3. Technological issues in commercializing polymetallic sulphides in the Area

Metallogenesis of marine minerals – Peter Rona

45. “Exploration for a seafloor mineral deposit involves many variations to achieve two basic objectives: to determine where the mineral deposit is located, and to determine physical, chemical and, in many cases, the biological properties of the deposit and its seafloor setting.
 - (i) **Finding the deposit:** The first objective, determination of where a seafloor mineral deposit is located, involves starting the exploration within the seafloor province where that type of mineral deposit is known to occur, but at unknown distances from deposits that may be present within that province. Then apply complementary exploration methods that will sense diagnostic properties of that type of deposit and its specific setting starting at some distance from a potential deposit and gradually coming closer, that is, closing range to the deposit. The systematic exploration strategy to find a deposit on the seafloor is to progressively close range from far to near according to the sensitivity to detection of physical and chemical properties of the deposit.
 - (ii) Let us consider this approach of closing range 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. This strategy was successfully used to discover the TAG hydrothermal field on the Mid-Atlantic Ridge, the first hot springs and massive sulphide deposits found anywhere in the deep Atlantic Ocean (16). Hot springs associated with an active massive sulphide deposit will discharge certain metals in dissolved and particulate form (iron and manganese) and dissolved gases (helium) that can be carried by deep ocean currents for distances of hundreds of kilometres from a source. These components can be detected in water samples recovered from appropriate depths by standard shipboard water sampling methods. Certain of these metallic mineral particles from black smokers will settle through the water column to the seafloor where the metallic mineral component can be detected in cores of seafloor sediments. The general location of seafloor hot springs can be found by following concentration gradients of these metallic signals in the water column and in seafloor sediments. At ranges of tens to several kilometres (thickness of the water column in the deep ocean), shipboard bathymetric and magnetic methods and near-surface towed side-scan sonar can be employed to determine the seafloor setting and detect a characteristic magnetic signature of either an active or inactive massive sulphide deposit. When within kilometres of the hot springs, various in situ sampling (water, particles, seafloor sediment) and imaging (photos, video, and side-scan sonar) methods can be used on various types of unmanned deep submergence vehicles at altitudes up to tens of meters above the seafloor to locate the massive sulphides deposit. These unmanned deep submergence vehicles comprise Remotely Operated Vehicles (ROV) which are tethered to the ship and controlled through an electrical or electro-fibre optic cable with a real-time video link to the operators, and Autonomous Underwater Vehicles (AUV) which are free-swimming and are programmed to perform imaging, sampling and other measurement procedures. Manned submersibles, also known as Human Occupied Vehicles (HOV), may be used for direct observation, sampling and measurements after the massive sulphide deposit has been targeted.

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

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

*"Hydrothermal sulphides mineralization of the Atlantic
– Results of Russian investigations" – G. Cherkashev, A. Ahsadze and A. Glumov*

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

"Proposed exploration and mining technologies for polymetallic sulphides" -Steven D. Scott, Director Scotiabank Marine Geology Research laboratory, Department of Geology, University of Toronto, Canada

Exploration methodologies

47. "Scientific research cruises have been responsible for the discoveries to date of seafloor polymetallic sulfides and all deposits are prominently exposed and visible on the seafloor. Seemingly, everywhere we looked, we found deposits. Exploration has largely relied on methods such as detailed bathymetric mapping, high resolution sidescan sonar, tracing hydrothermal particulate plumes to their source using transmissometers, dredging, seafloor photography and submersible traverses. All except dredging are passive and inflict no serious environmental damage."

"Close inspection of high-resolution swath bathymetric and sonar maps can usually reveal the most prospective sites in the axial valley, and sometimes off-axis, of mid-

ocean ridges and in the calderas of young, volcanically active seamounts. Tops of magma chambers have been imaged seismically beneath individual segments of ridge axes by recognition of a "bright spot" in multi-channel reflection records. A good example is from 8°50'N to 13°30'N (most notably at 9°30'N) along the East Pacific Rise. Here, the interpreted top of the magma chamber can be traced, with some uncertainty, for tens of kilometres along the ridge axis at depths of 1.2 to 2.4 km beneath the seafloor. Harding et al. (1989) have interpreted the seismic data from 13°N East Pacific Rise to represent a shallow small axial magma at the pinnacle of a much larger zone of hot and only partially molten basalt. Such pinnacles probably occur intermittently along a ridge segment and would be loci for hydrothermal venting, as is presently occurring at 13°N."

"The most successful method for locating actively forming PMS deposits is to find their particulate plume and tracing it to its source. This is typically done using a transmissometer that measures absorption of light by the particles within the water column. Typically, an instrument package measuring conductivity (salinity), temperature (in millidegrees), depth and light absorption with water samplers aboard is towed at slow speed behind a ship and is lowered and raised within the expected depth interval for a particulate plume. Data are recorded real-time and water is sampled within any plume that is encountered. Particles are filtered from this water onboard ship and later analyzed for pathfinder elements such as copper, zinc and barium that might indicate a PMS-forming hydrothermal system. Suspected sources of plumes are dredged, photographed or inspected by submersible."

"Once a sizeable mound has been located, coring of close-spaced and accurately positioned drill holes is required in order to determine with a considerable degree of confidence the deposit's content of metals and its tonnage. As is the case for land deposits, such information is critical for determining whether mining is economically viable and for determining the best methods for metallurgical processing. Near total core recovery is required in holes that may be only a few meters apart. Coring can be accomplished either using a bottom-deployed autonomous drill or a drill operated from a remotely operated vehicle (ROV)."

"Large scale ocean mining for PMS will have high start-up costs, perhaps as much as \$300 million (all values are in current US dollars) phased in over several years through stages of exploration, evaluation and mining. This cost must be seen in the light of discovery and development costs for new land mines that are typically of the same order of magnitude. For example, approximately \$200 million is required to find and develop a PMS deposit in the Abitibi region of western central Quebec and Noranda is spending about \$200 million to develop 30 million metric tons of ore between 2000 and 3000 meters depth in its Kidd Creek mine. The anticipated start-up cost for ocean mining of PMS is favourable relative to the \$650 million spent on the failed attempt to mine manganese nodules."

“Although the technology does not exist for recovering seafloor PMS, some schemes that were developed by Namco for recovering diamonds in the relatively shallow offshore of Namibia and by the Lockheed Corporation for recovering manganese nodules in deep ocean basins, such as robotic bottom mining vehicles and lift systems (Welling, 1981), can probably be adapted to sulfide mining. Small operations, such as that envisaged by Nautilus Minerals, might use television-guided grabs. The Namco vehicle, which has suffered serious mechanical failures, is a bottom crawler with a suction head. The sulfides are at shallower water depth than nodules and are relatively soft so should be easy to break up. The subsurface stockwork mineralization is typically of lower metal content than the massive sulfides and is harder so would require excavation. These are unlikely to be recovered unless by solution mining or bio-leaching. For the softer surface deposits, Scott (1992) envisaged a robotic continuous miner with a cutting blade, much as is used in coal and potash mines, that would extract, grind and pre-concentrate the desired minerals, lift these to surface in a slurry (air lift or pump) and leave the waste minerals on the sea floor.”

“Exploration for and pre-feasibility of mining polymetallic sulphides – a commercial case study” - Mr. David Heydon, Chief Executive Officer of Nautilus Minerals Ltd.

48. “Nautilus Minerals Ltd. is a company which has an exploration license for Polymetallic sulphides in the territorial sea of Papua New Guinea (PNG) to commercialise sulphides deposits in that area. The company is in technical alliance with six other companies that have expertise in different aspects of the integrated operations. The Nautilus has performed major exploration program in PNG. The exploration included water column testing (to locate active plumes or vent smokers). This covered a large prospective regional area. The sea water samples from up to 10 km away can lead to locating the active metal vents. During the geophysical studies methods like Resistivity measurements, self potential, magnetics, induced polarisation, video camera and gravity were employed. This helps in finding the aerial extent of the ore-body to estimate the mass or tonnage of deposit. The geophysical anomalies were ‘ground truthed’ during the sampling phase. The samplers used for the purpose were the dredges and the sophisticated grabs. Unlike the crusts or the polymetallic nodules which lay on the seabed surface, the PMS required drilling to test the vertical or depth extent of mineralization and to test any buried body. Drilling thus assists in determining the average grade of the body and it was carried out by Nautilus using remote operated drill rig lowered to the seafloor. Drilling in deeper waters is not so common and only a couple of ship based operators have the capability to drill in 2000 m water. Even the Ocean Drilling Program (ODP) has not successfully recovered continuous core from the top 20 m. of the seabed where these sulphides may first be mined.”

“The exploration drilling during the first phase should start with about 9 holes at approximately 60 m spacing drilled to 20 m depth with 70 mm core diameter. It may be necessary to include one or two 300 mm (12”) holes reamed for larger sample for first phase metallurgy testing. During the pre-mining phase, for detailed grade and pre mine planning, additional 27 holes (30 m spacing) depending on local variability of geology and grade are consistent. During this phase, larger reamed holes for metallurgical studies may be required.”

Exploration crusts Vs Sulphides

- Crusts are thin average 40mm
- Polymetallic sulphides are relatively thick lenses average 15 – 20 metres
- 2 million tonnes of crust covers a surface area of **16 square KILOMETRES** whereas 2mt of sulphides is **only 200 METRES square**
- To sample a 2mt ore body of crusts therefore requires disturbing a large surface area.
- To sample Polymetallic sulphides disturbs a relatively small surface area as most of the sample is **sub surface drill core** (max 36 x 70mm holes over 200m x 200m area)

“If trial mining of crusts and sulphides is undertaken, it will entail mining 1 million tonnes trailing a 2mtpa mining system. 1 MT of crust covers a surface area of 8 square kilometres whereas 1 million tonnes of PMS to 20 m deep disturbs only 140 square meters of surface area.”

“Nautilus has also done a pre-feasibility engineering study of mining polymetallic sulphides at 2000 m. to mine 2 MT per annum with mine life plus 10 years needs 20 MT of sulphides. 2 MT is 200mX200m@20 m thick. Mine may stay in one spot anchored for a year or more over a field containing several deposits and it will relocate to another area to aggregate 20 mt required.”

“Nautilus has also conceptualised the ROV required for the mining operation. The Remotely Operated Vehicles (ROVs) are already being used for cable and pipe lay

trenching but they are not ‘mining’. Nautilus study is based on 5000 hr operation and 2 million tonnes giving 400 tons per hour. Two mining vehicles per platform powered by electric umbilical each mining 200 ton per hour may be required. As the PMS have the strength of coal, it is proposed to use drum cutters. Drum cutter miner is 5 m wide and cuts a 2 m high ‘face’ with each miner advancing only 7 meters per hour. Siemag, the world leader in hoisting ore from deep underground is associated with Nautilus in helping the lifting of ore. Siemag have proposed a system to hoist at rate of 400 tonnes per hour from 2000 m depth. They propose to hoist 100 ton kibbles at 1.8 m/sec rate. Nautilus has considered both slurry pump and positive displacement pump option which may be assisted by airlift.”

“Technical requirements for exploration and mining seafloor massive sulphides deposits and cobalt-rich ferromanganese crusts” – Professor Herzig and S. Petersen.

49. “Since the discovery of black smokers, massive sulphides and vent biota in 1979, numerous academic and government institutions carry out exploration for seafloor massive sulphides deposits at oceanic spreading centres worldwide. Leading countries in this field are the United States, France, Germany, the United Kingdom, Japan, Canada, Russia, and Australia. In some countries, such as Portugal and Italy, marine exploration programs for massive sulphides have newly been developed over the past few years.”

“Table 4 below shows the major international efforts during the past decade in PMS studies.”

Table 4 - International efforts in PMS studies

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

“For research and resource assessment of polymetallic massive sulphides deposits, technological advances are a critical factor. In the present state of research and commercialization, information on the depth extent and therefore the size of the deposit, and the type of mineralization and alteration are extremely important. Drilling by the Ocean Drilling Program Leg 158 at the active TAG hydrothermal mound at the Mid-Atlantic Ridge⁴ has indicated a total tonnage of 2.7 million tonnes of sulphides above, and 1.2 million tonnes below the seafloor⁵. It was also found that high concentrations of base and precious metals are confined to the upper few meters of the mound. The mound itself consists of breccias with varying proportions of pyrites, silica, and anhydrites that would not be economically recoverable. Initially, it was thought that the entire mound consists of polymetallic massive sulphides. Except for the TAG mound, the Middle Valley site at the Juan de Fuca Ridge and the Atlantis II Deep in the Red Sea, depth information is not available for any of the known seafloor sulphides deposits. Research and resource assessments of these deposits rely on surface samples only. As drilling of hydrothermal systems by the Ocean Drilling Program will be the exception rather than the rule, reliable portable drilling and coring devices are required for research and industry. It has to be demonstrated that these systems are actually capable of supporting drilling and coring several tens of meters of massive sulphides and rock at the seafloor. The available technology is an encouraging start but needs to be further developed in order for drilling at the seafloor to depths of 50-100 m a routine operation by any research vessel, and to reveal reliable information on the depth extent of mound and chimney complexes.”

“After the resource potential of a massive sulphides deposit has been adequately established by grid drilling similar to land-based operations, exploitation and recovery will be the next challenges. Selective mining using large TV-controlled grabs similar to those used for exploration are an option; however, continuous mining appears to be the only economic alternative. It appears that the continuous mining systems used by De Beers Marine, offshore Namibia, for the recovery of diamonds from water depths of about 100-150 m could be converted for massive sulphides mining. These systems consist of large (7 m diameter) rotating cutter heads that are attached to a flexible drill string through which the diamond-bearing sediment is airlifted onto the ship for further processing.”

“Seafloor Massive Sulphides deposits and their resource potential” – Prof. Herzig and S. Petersen, Institute for Mineralogy, Freiberg/Sachsen, Germany and Dr Mark Hannington, Geological survey of Canada

Size and Tonnage:

50. “Considering that estimates of the continuity of sulphide outcrop are difficult, and that the thickness of the deposits is commonly poorly constrained, estimates for

several deposits on the mid-ocean ridges suggest a size of 1-100 million tonnes, although the depth extend of mineralization is difficult to assess. The by far largest deposits are found on failed and heavily sedimented but still hydrothermally active oceanic ridges. Drilling carried out by the Ocean Drilling Program during Legs 139 and 169 at the sediment covered Middle Valley deposit on the northern Juan de Fuca Ridge has indicated about 8-9 million tonnes of sulphide ore.”

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

“Estimates of sizes between 1-100 million tonnes for individual massive sulphide deposits on the seafloor thus are well within the range of typical volcanic-associated massive sulphide deposits on land. However, most occurrences of seafloor sulphides amount to less than a few thousand tonnes, and consist largely of scattered hydrothermal vents and mounds usually topped by a number of chimneys with one or more large accumulations of massive sulphide. More than 60 individual occurrences have been mapped along an 8 km segment of Southern Explorer Ridge, but most of the observed mineralization occurs in two large deposits with dimensions of 250 m x 200 m⁶⁷. The thicknesses of the deposits are difficult to determine unless their interiors have been exposed by local faulting. Typical black smokers are estimated to produce about 250 tonnes of massive sulphide per year. Thus, a local vent field with a few black smokers can easily account for a small size sulphide deposit, pending on the duration of activity.”

“Out of the more than 200 sites of hydrothermal mineralization currently known at the modern seafloor, only about 10 deposits may have sufficient size and grade to be considered for future mining, although information on the thickness of most of those sulphide deposits is not yet available (*Table 5*). These potential mine sites include the Atlantis II Deep in the Red Sea, Middle Valley, Explorer Ridge, Galapagos Rift, and the East Pacific Rise 13°N in the Pacific Ocean, the TAG hydrothermal field in the Atlantic Ocean, as well as the Manus Basin, the Lau Basin, the Okinawa Trough, and the North Fiji Basin in the western and south-western Pacific. All of these sites except two (East Pacific Rise 13°N and TAG hydrothermal field) are located in the Exclusive Economic Zones of coastal states including Saudi Arabia, Canada, Ecuador, Papua New Guinea, Tonga, Japan, and Fiji.”

Table 5: Possible sites for seafloor sulphides mining.

Deposit	Ocean Area	Water Depth	Jurisdiction	Country
Atlantis II Deep	Red Sea	2000-2200 m	EEZ	Saudi Arabia
Middle Valley	Northeast Pacific	2400-2500 m	EEZ	
Explorer Ridge	Northeast Pacific	1750-2600 m	EEZ	Canada
Lau Basin	Southwest Pacific	2700-2000 m	EEZ	Tonga
North Fiji Basin	Southwest Pacific	1900-2000 m	EEZ	Fiji
Eastern Manus Basin	Southwest Pacific	2450-2650 m	EEZ	Papua New Guinea
Central Manus Basin	Southwest Pacific	2450-2600 m	EEZ	Papua New Guinea
Conical seamount	Southwest Pacific	1050-2650 m	EEZ	Papua New Guinea
Okinawa Trough	East Pacific	2600-2850 m	EEZ	Japan
Galapagos Rift East Pacific Rise	East Pacific	2500-2600 m	EEZ	Ecuador
TAG	Mid Atlantic Ridge-	3650-3700 m	-	International

“Located in international waters at the Mid-Atlantic Ridge, the 13°N seamount at the East Pacific Rise or the Sonne hydrothermal field at the remote Rodriguez Triple Junction in the Southern Indian Ocean will become mining targets in the near future. This is also true for many of the sulphide deposits along the East, Northeast and Southeast Pacific Rises. However, in this decade, marine mining appears to be feasible under specific conditions ideally including:

- (1) High gold and base metal grades,
- (2) Site location close to land, i.e., commonly within the territorial waters (200 nm Exclusive Economic Zone or even 12 nm zone) of a coastal state,
- (3) Shallow water depth not significantly exceeding 2,000 m (although the technology exists for mining in deeper water,).”

“Under those circumstances, massive sulphide mining can be economically attractive considering that the entire mining system is portable and can be moved from mine site to mine site. An investment into mining systems and ships is thus not tied to a certain location as is the case on land, where a typical mine

development in a remote area including all infrastructure requires an initial investment of US\$350-500 million.”

“Seafloor massive sulphides mining will likely focus on relatively small areas of the seafloor and largely be restricted to the surface (strip mining) and shallow subsurface (open cast mining) to recover sulphide mounds and chimney fields at and replacement ore bodies just below the seafloor. Environmental impact studies are yet to be carried out and will likely indicate that mining of seafloor massive sulphide deposits has only a relatively small environmental impact.”

“Proposed Exploration and Mining Technologies for Polymetallic Sulphides” -Steven D. Scott, Director Scotiabank Marine Geology Research laboratory, Department of Geology, University of Toronto, Canada

51. There are seafloor deposits of apparent size and grade that, if they were on land, would definitely be targets for further evaluation. Most of these are in territorial waters. An example is the Atlantis II Deep in the Red Sea that contains 94 million metric tons (Mustafa et al., 1984). It rivals the size of analogous “giant” ore bodies on land although at 0.5% copper, 2% zinc, 39 g/t silver and 0.5 g/t gold it is of lower grade than mineable land deposits. Most marine deposits are very much smaller but have an apparent high unit value that makes them attractive (e.g., Sunrise in the Izu-Bonin arc, 9 million metric tons with 44 analyses averaging 5.6% copper, 20.3% zinc, 2.1 % lead, 1197 g/t silver, 18.4 g/t Au; Iizasa et al., 1999). The only known PMS in the Area of sufficient size to be of potential interest is TAG on the Mid-Atlantic Ridge (Rona et al. 1993; Humphries et al., 1995). The main mound (there are several additional “Mir” mounds nearby) and underlying subsurface stockwork mineralization totals about 3.9 million metric tons but, like the Atlantis II Deep, it too appears to have a low a metal content.”

“The *in situ* value of the metals in the Sunrise deposit could be about \$US770 per metric ton at September 3, 2004 metal prices based on the average analysis of 44 samples. Extrapolating this over the 9 million tons that has been estimated for Sunrise gives a potential *in situ* value of \$6.93 billion but these 44 samples are probably not representative of the entire deposit. Regardless, the average metal content (“grade”) of a deposit is only one of the many factors that determine if an accumulation of sulfides is an “ore”. Whether or not Sunrise is an “ore” will depend on its true grade and tonnage but also on how much can actually be recovered, mining costs, metallurgical recoveries and costs and a host of other considerations.”

“A television-guided grab such as that envisaged by Nautilus for lifting chimneys to surface in Manus Basin can never be more than a small operation. Grabs are deployed at 60 meters per minute and the water depth at the main PACMANUS site is about 1800m. Assuming, optimistically, ½ hour for manoeuvring to find a

chimney, each grab would take 90 minutes. Only 36 tons can be recovered per day if the capacity of the grab is 2 tons, 180 tons with a 10-ton capacity, etc. Leaving the 80% rejects on the sea floor instead of lifting them to surface and concentrating them there would reduce recovery costs substantially.”

“Mining on Land vs. the Seafloor- a case study” - Dr David Heydon, CEO, Nautilus Minerals Limited.

51. “The Antamina mine is located at more than 4300 m. above sea level in the Andes Mountains, 385 km north of Lima in Peru, is one of the largest zinc and copper producers in the world. This mine cut about 110mt. of mountain and had the lake drained. The mine generated around 112 mt waste in 2003, 1400 workers worked and has a total of 550 mt tailings slime produced in 20 years. The overview shows the nautilus project has higher copper %- (5.5% compared to 1.23% for Antamina) and Zinc (12% compared to 1.03%). The ocean mine is likely to produce 190 m pounds copper on an average. If you compare the costs, the Antamina had lot of pre-strip expense for 4 years while Nautilus the returns are immediate. The Sea mine can be moved everywhere there is no overburden and can mine around 1,000 tons/hour. No drilling and blasting will be required for ocean mining. The Antamina land mine required 2000 m tunnel to mill, 300 km pipeline and generates lot of waste. Even environmentally the ocean mining is advantageous as there are no waste dumps. Compared to 95 mt slimes/tails for ocean mining, the Antamina has about 550 mt of slimes/tails. The land mine needs around 1400 staff, 100 MW of electricity while the Nautilus project will require less than 500 staff and 40 MW of electricity. In effect the ocean mining needs less capital, has higher grade ores, generates less waste is environmentally friendly and has higher exploration success.”

3. Environmental issues

“Impact of the development of seafloor massive sulphides on deep-sea hydrothermal ecosystems” – Dr S. Kim Juniper, GEOTOP Centre, University of Quebec, Montreal, Canada

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

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

VI. Supply and demand for the metals of economic interest in cobalt-rich ferromanganese crusts and polymetallic sulphides deposits.

51. Based on the documentation available to the ISA, the metals of interest in cobalt-rich ferromanganese crusts are cobalt, nickel, copper and manganese, with cobalt being by far the metal of primary interest. The metals of interest in polymetallic sulphides are copper, zinc, lead and in some cases gold, silver and platinum.

52. In 2002, the ISA commissioned the services of a consultant⁸ to provide it with an outlook for the metals to be found in polymetallic nodules. The metals of interest in these mineral resources are copper, nickel, cobalt and manganese. While cobalt-rich ferromanganese crusts contain the same metals, polymetallic sulphides differ in that they contain zinc, lead and in some cases gold, silver and platinum.

53. Since the submission of the consultant’s report, the metal markets have shown tremendous buoyancy with the prices of all the metals indicated above increasing significantly. The major findings by the consultant at the time with respect to copper, nickel, manganese and cobalt were as follows:

- Estimates of market behavior made in the late 1970’s proved to be overoptimistic (from a producer’s perspective) for both consumption levels and prices. In hindsight, the actual market behavior is understandable but it could not have been predicted at the time of the forecasts. In spite of the difficulty, effective management of the mineral resources of the deep seabed requires the best understanding possible of how markets may behave over the next decade and beyond.
- Looking back to the metals forecasts of the late 1970’s, the markets have shown lower growth and lower prices than anticipated. This is due to several factors:
 - (i) Tight markets and rising prices in the early 1980’s and extreme price variability that led to slow growth in demand beyond unique and essential applications;

⁸ Outlook for metals from polymetallic nodules – Caitlyn L. Antrim, August 2002.

- (ii) Improvements in steelmaking technology that resulted in a 20% reduction in the use of manganese in steel production;
 - (iii) Development of improved processing technologies, expansion of existing mines and development of nickel laterite resources in Australia;
 - (iv) Financial attractiveness of investment in Chile rose sufficiently to significantly increase copper production capacity, more than compensating for reduction of copper production from the Democratic Republic of the Congo due to its political instability;
 - (v) Delays in anticipated growth of developing country economies and reduced growth of demand for metals in industrialized economies as service industries increased their share of the industrial economy;
 - (vi) The 1991 breakup of the former Soviet Union and the subsequent decline of industrial activity in the successor states that resulted in a significant reduction in domestic metal demand and corresponding increase in the availability of Russian nickel to the world market.
- Production capacity developed under the expectations of earlier forecasts resulted in production capacity to force prices for metals gradually downward.
 - Development of improved processing technologies allowed mines and processors to continue to operate even when metals prices measured in constant terms dropped below prices of the late 1970's.

The outlook for the metal markets in the coming decade will be affected by:

- Continued growth of stainless steel and copper consumption in developing countries, undergoing industrialization, particularly in China and India;
- Low cost nickel and cobalt production in Australia and New Caledonia and application of PAL technology to reduce operating costs;
- Development of Voisey Bay's nickel-cobalt deposits in Canada; and,
- Continued low growth of steel demand and further implementation of improved steel-making technology that reduces need for manganese.

54. The conditions that ensured availability of sufficient quantities of low cost nickel, copper, cobalt and manganese will not continue indefinitely. Changing patterns of economic growth, new demands in response to growth of the electronics sector and developments in automotive technology, and long lead times for the development of new mines and processing facilities all contribute to a long term outlook for tighter supplies and rising prices. As if these factors didn't make market forecasting complex enough, there are a number of uncertainties that could have a significant effect on the metals markets, particularly for nickel and cobalt, but whose timing is uncertain. These are:

- Recovery of the economies of the Russian Federation and other former Soviet republics accompanied by significant reduction of exports of metals needed by the domestic industries;
- Return of stability to the Democratic Republic of the Congo and return to production of the copper and cobalt mines;
- Rate of acceptance of hybrid and electric vehicles that require rechargeable batteries, and,
- Competition between nickel and cobalt in the market for rechargeable batteries.

55. Overall, the outlook is good for availability of nickel, copper, cobalt and manganese to support the global economy in quantities and at prices that encourage development and industrialization. It is likely, however, that major events affecting supply and demand will continue to drive the nickel and cobalt markets between periods of over- and under-supply with accompanying cycles of low and high prices. The range of prices, however, should be less pronounced than in the past due to improved production technology that makes it possible to process nickel and cobalt ores at low cost.

56. At this time, the greatest uncertainty appears to lie with the development of electric and hybrid automobiles and the choice of battery technology adopted in support of the vehicles. The size of the market and the division between nickel, cobalt and substitute materials is beyond prediction at this time, and yet it could be a major factor in the nickel market or the dominant use of cobalt within a decade.

**Prospecting and Exploration for Cobalt-Rich Crusts
Sampling Locations from the ISA Central Data Repository**



Notes
 (1) The map shows sampling locations from the ISA Central Data Repository. The distribution of database records does not indicate where cobalt-rich crusts are absent.
 (2) *The Area* (shown between 8° North and 60° South parallel) is defined as "the seabed and ocean floor and subsoil thereof beyond the limits of national jurisdiction" (1982 United Nations Convention on the Law of the Sea article 1, paragraph 1). The chart of the Area is indicative only of claimed and potential maritime limits. The boundaries of the Area shown in the map may not be legally valid.

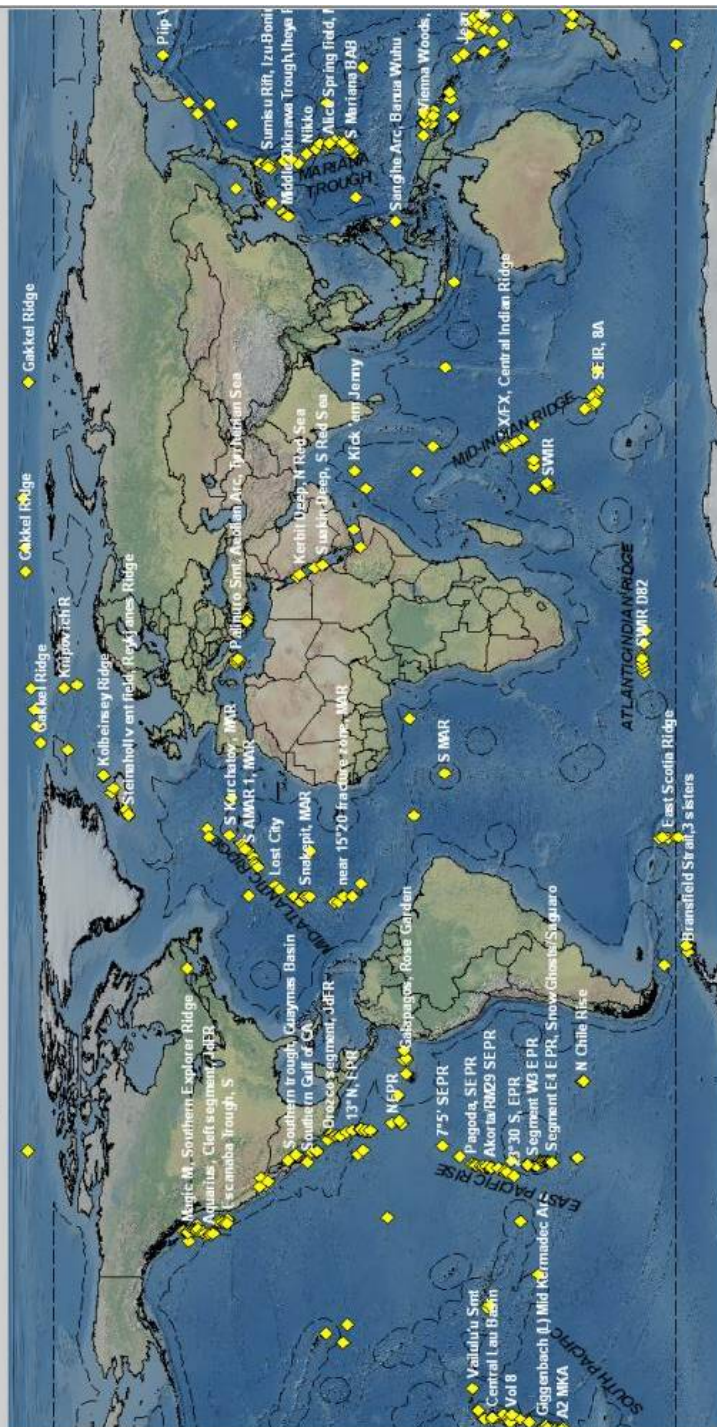
Legend

- ◆ Sampling Location
- ⋯ The Area*



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 Data Source: ISA

Prospecting and Exploration for Polymetallic Sulphides Sampling Locations and Hydrothermal Vents



Legend

- Hydrothermal Vent / Sulphides Sampling Location
- The Area*

Notes

- (1) The map shows hydrothermal vents and sampling locations from the ISA Central Data Repository and the International Hydrothermal Vent Database. The distribution of database records does not indicate where vents and polymetallic sulphide deposits are absent.
- (2) * "The Area" (shown between 85° North and 60° South parallel) is defined as "the seabed and ocean floor and subsoil thereof beyond the limits of national jurisdiction" (1982 United Nations Conventions on the Law of the Sea article 1, paragraph 1 (1)). The chart of the Area is indicative only of claimed and potential maritime limits. The boundaries of the Area shown in the map may not be legally valid.



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