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Deep-sea mining: economic, technical, technological and environmental considerations for sustainable development

Rahul Sharma*
Department of Marine Geology, Faculty of Marine Sciences
King Abdulaziz University, PO Box 80207, Jeddah 21589, Saudi Arabia

Abstract

Mining of minerals such as polymetallic nodules from the deep-sea floor has been 'on-hold' due to several factors such as current availability of Cu, Ni, Co, Mn from terrestrial sources and their fluctuating prices. None-the-less, exploration for new resources from deep-sea areas and development of technologies for deep-sea mining have been progressing consistently. These coupled with recent projections of deep-sea minerals as the alternative source for metals and granting of licences for exploration and mining of seafloor massive sulphides to private entrepreneurs, indicate the continuing interest and support the perception that such deposits may serve as sources of metals in the 21st century. However, there are several considerations for a sustainable development of deep-sea mining venture.

A typical area of 75,000 sq km with an estimated nodule resource of >200 mi t., is expected to yield about 54 million tonnes of metals (Mn+Ni+Cu+Co) and the gross in-place value of the metals is estimated to be ~$ 21-42 billion (depending upon the annual rate of mining) in 20 years life span of a mine-site. The decision on the timing to resume mining of these deposits will be based on the prevalent metal prices and rate of returns on the estimated investment of $ 1.95 billion as capital expenditure and $ 9 billion as operating expenditure for a single deep-sea mining venture.

In view of high investment, technological challenges and economic considerations, private-public cooperation could be an effective means to make deep-sea mining a success. This paper analyzes the current status and discusses the economic, technical, technological and environmental issues that need to be addressed for sustainable development of this deep-sea mineral.

Keywords: Deep-sea mining, polymetallic nodules, economic, technical, environmental issues.

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*Permanent address: National Institute of Oceanography (Council of Scientific and Industrial Research), Dona Paula, Goa - 403004, India (email: rsharma@nio.org, rsharmagoa@gmail.com)

1. Introduction

Establishment of the potential of deep-sea mineral resources (Mero, 1965) was followed by detailed reports on polymetallic nodule occurrences (Fig.1) from different parts of the Pacific Ocean, such as Northern Peru Basin (Thijseen et al., 1981), South Pacific (Glasby, 1982), Central Pacific (Usui and Izasa, 1995), North Pacific and the Clarion-Clipperton ore field (Kotlinski, 1996); as well as from Carlsberg Ridge (Glasby, 1972), Central Indian Basin (Siddique et al., 1978; Sudhakar, 1989) and other basins of the Indian Ocean (Frazer and Wilson, 1980; Cronan and Moorby, 1981). This initial rush resulted in intense exploration activities followed by seabed areas being allotted to the erstwhile 'Pioneer Investors' (now called the 'Contractors') with exclusive rights over the ferro-manganese nodule deposits in different parts of the world oceans (Fig. 2) by the International Seabed Authority (ISA, 1998) established under UNLOS for the purpose.

Recent reports of Fe-Mn deposits from the Christmas island region and Afanasiy-Nikitin seamounts of the Indian Ocean (Exon et al., 2002; Banakar et al., 2007) as well as the Marshall island area of the Pacific Ocean (Usui et al, 2003); and the granting of licences to private companies for exploration of seafloor massive sulphides off Papua New Guinea and New Zealand (Gleason, 2008) reaffirms the continuing interest of scientists and mining companies in exploring and exploiting the deep sea mineral deposits. There appears to be a systematic plan of graduating from relatively shallower deposits, such as the crusts and sulphides (1000-2500 m) to deeper ferro-manganese nodules (4000-6000 m).

To facilitate this, the International Seabed Authority has established regulations on prospecting and exploration for polymetallic nodules in the Area (ISA, 2000), followed by the recommendations for assessment of possible environmental impacts from exploration of nodules (ISA, 2001) and establishment of environmental baselines and associated monitoring program for exploration of polymetallic sulphides and cobalt crusts (ISA, 2005). The decision to commence mining of polymetallic nodules will depend on the availability of metals from terrestrial sources and their prices in the world market, as well as the techno-economic considerations based on capital and operating costs of the deep-sea mining system.

The success of deep-sea mining venture requires the implementation of several components. 'Exploration' invariably forms the first step towards the mining venture, followed by 'Technology development' for mining and metallurgical processing. The 'Environmental' component closely follows these so as to develop protocol for baseline data, impact assessment and monitoring as well as development of environmental management plans. In order to finally execute the project, a 'Techno-economic assessment' as well as 'Legal' framework would guide the decisions and actions for implementation on the basis of inputs received from the earlier components. Activities under each of these components could initially be independent of each other; but a close networking among these will be required to execute the project.

This paper takes a look at various issues and challenges related to different components of polymetallic nodules mining for a sustained development of the resource.

2. Economic considerations

Increasing awareness of the distribution and potential of deep-sea minerals such as the ferro-manganese nodules and crusts (Cronan, 2000; Rona, 2003) has kept the world's interest in these deposits alive, even leading to the preparation of a geological model of polymetallic nodules in the Clarion-Clipperton Fracture Zone of the Pacific Ocean (ISA, 2009). However, the fluctuating metal prices besides factors such as recycling, new onshore deposits and technological developments have delayed the commercial exploitation of these deposits, which are still considered important in the overall metal budget of the earth and constitute a substantial resource that would cover the 21st century demand for metals such as Mn, Fe, NI, Co, Cu, Mo and many others including Rare Earth Elements (Kotlinski, 2001). The commercial viability of the deep-sea deposits lies in their concentration compared to the currently mined deposits on land and also in their estimated magnitude (Lenoble, 2000). Considering the present trends of mining ores with low metal grades, it is estimated that in about 2020, mean metal contents in deep-sea manganese oxide ores will be higher than those in the terrestrial deposits by factors between 1.1 for Ni and >5 for Co (Glumov et al., 2000).

With each of the 'Contractors' being allotted areas averaging several tens of thousands of square kilometres in international waters (ISA, 1998), the mineable resources are expected to be of the order of several million tonnes. For example, considering the resource potential in a typical area (i.e. 75,000 sq. km) in the Central Indian Basin, and the cut off value of abundance (5 kg / sq. m.); the total resource available in the area will be 375 mi. t. (wet) or 206.25 mi. t. (dry) with a total metal equal to 54.12 mi. t. (Table 1), for known concentrations of metals (Mn=24%, Ni=1.1%, Cu=1.04%, Co=0.1%) in the area (Jauhari and Pattan, 2000). Out of the 206.25 mi. t., only 14.5-29 % (i.e. 30-60 million tonnes) of the resource will be used at the proposed mining rate of either 1.5 million tonnes/year (ISA, 2008a) or 3 million tonnes / year (UNOET, 1987) over duration of 20 years, with a large balance (71-85.5 %) to be mined in future.

The total annual production of metals would range from 0.39 mi. t./year (for 1.5 mi. t/y) to 0.78 mi. t/y (for 3 mi. t/y). Considering average metal prices for the second half of 2010 (www.metalprices.com), the value of total metals produced annually will be $ 1.04 billion, with a total yield of about $ 20.85 billion in 20 years from a single mine-site at 1.5 mi. t/y mining rate. The same would be double (i.e. $ 2.08 billion / year, or ~$ 41.7 billion in 20 years) for a mining rate of 3 mi. t/y (Table 1). The actual returns could be much higher as the in-situ average abundances are normally expected to be higher than the cut off (5 kg/sq. m.) and also if the concentrations of metals are higher in the potential mine-site than that considered here as have been reported in the Pacific Ocean (Herrouin et al., 1991).

The estimates of the total resources available in the world oceans are from the areas which have been claimed in the international waters so far, excluding the minerals lying within the EEZ of certain countries such as Papua New Guinea and New Zealand (Gleason, 2008); and so the actual available deep-sea mineral resources would be much more than what is known so far. However, according to the United Nations Ocean Economic and Technology Branch, the nodule deposits can only be termed ‘resources’ (and not ‘reserves’) as ‘they cannot be recovered under prevailing economic conditions, but may be exploitable in the foreseeable future’. Such resources can become economic when prices and market conditions or new technology increase the profit margin to acceptable levels (UNOET, 1987).

The cost estimates for different types of collectors, power generation and risers proposed by different Contractors currently involved in technology development for mining of 1.5 of nodules annually, show a capital expenditure of ~$ 372-562 million and an operating cost of ~$ 69-96 million / year. Similarly, capital expenditure for purchasing 3 vessels for ore transfer is estimated at ~$ 495-600 million with an annual operating cost of $ 93-132 million and a capital expenditure of $750 million for the processing plant with an annual operating expenditure of $ 250 million (ISA, 2008a). Considering the highest values (rounded to the nearest fifty), the total estimated cost of a single deep-sea mining venture works out to $ 11.90 billion (Table 2). These do not take into consideration any unforeseen risks or failures that may escalate the costs. All these factors will have to be weighed against the availability of ores on land as well as the metal prices, in order to ‘fix’ the timing for commencement of deep-sea mining.

3. Technical considerations

3.1 Delineation of mine-site and estimation of area for mining

Consequent to several studies that adopted different criteria for estimating the number of mine-sites (Archer, 1976; Archer, 1979; Archer, 1981; Holser, 1976; Frazer, 1977), UN Ocean Economics and Technology Branch developed the following criterion for selecting a manganese nodule mine-site (UNOET, 1987):

- Cut off grade = 1.8% Cu+Ni

- Cut off abundance = 5 kg / sq. m.
- Topography = acceptable
- Duration (D) = 20 years
- Annual recovery (A_r) = 3 million dry tonnes

A “mine site” is defined as an ocean bottom area where under specific geological, technical and economic conditions, a single mining operation can be carried out for a period of time (UNOET, 1987), and the total mine-able area (M) can be estimated as follows:

$$M = A_t - (A_u + A_g + A_a) \qquad -(1)$$

where, A_t = is the total area,

A_u = area un-mineable due to the topography,

A_g = area below cut-off grade;

A_a = area below cut-off abundance.

The proportion of un-mineable area due to unfavourable topographical factors (A_u), with respect to the total area (A_t) can be calculated as: A_u/A_t, which is generally considered as 20% (UNOET, 1987). Considering A_g as 15%, A_a as 15% along with A_u = 20% and subtracting the corresponding areas from A_t = 75,000 sq km (maximum area allotted to each Pioneer Investor); the total mine-able area *(M)* = 37,500 sq km.

Furthermore, the size of mine site (A_s) can be calculated as:

$$A_s = (A_r)(D) \;/\; (A_n)(E)(M) \qquad -(2)$$

$$= 3 \text{ x } 10^9 \text{ x } 20 \text{ yrs} / 5 \text{ kg/m}^2 \text{ x } 25\% \text{ x } 37{,}500 \text{ sq km}$$

$$= 12800 \text{ sq km}$$

where, A_s = size of mine-site (km^2),

A_r = annual nodule recovery rate (3 million t/year),

D = duration of mining operation (20 years),

A_n = average nodule abundance in a mineable area (5 kg / m^2),

E = efficiency of the mining device (25%) (UNOET, 1987),

M = mineable area (37,500 sq km).

For the mining rate of 1.5 mi. t/y, A_s will be 6400 sq. km. The other components being constant, variation in A_n and E could alter the size of the mine-site (A_s). It is reasonable to expect higher value for average nodule abundance (A_n), for example 10 kg/sq. m (range 5-15 kg/sq. m) in the potential first generation mine-sites and a higher efficiency (E) of the mining system due to advancement in technology that would further reduce the size of the mine-site (As) considerably. Smaller the proportion of the size of the mine-site with respect to the allotted area augers well with the concept of restricting the mining activities to a small area, especially from the point of environmental impacts.

For nodule mining at the rate of 3 mi. t. per year, with an annual operation time of ~300 days/year (UNOET, 1987) and for an average nodule abundance of 5 kg/sq m, the actual area scraped will be 600,000,000 m^2 = 600 sq.km. / year, that is 2 sq km / day. If mining is considered at the rate of 1.5 mi. t/year, as suggested by ISA (2008a), the actual area scraped will be 300 sq. km. / year, i.e. 1 sq. km. / day, which in effect is miniscule with respect to the area of the oceans on the surface of the earth. Once again, if the average nodule abundance is more than the cut-off value considered here, the actual area scraped (or the 'area of contact' on the seafloor) will be smaller.

3.2 Efficiency of mining system

The overall efficiency (E) of a mining system would depend upon the collection efficiency of the dredge head that would sweep the seafloor to collect the nodules. This, estimated from various studies to be ~25 %, is calculated as (UNOET, 1987):

$$E = e_d \times e_s, \qquad - (3)$$

where, e_d = dredge efficiency, which is the ratio of marine minerals effectively gathered by the dredge head, versus the nodules on the seabed before dredging,

e_s = sweep efficiency, which is the percentage of the bottom actually swept by the area dredged.

The efficiency of deep-sea mining would also depend on the system for lifting the minerals to the surface (Amann, 1982); such as, the air-lift, which has 2-5 times higher energy consumption, but is easier to maintain as the compressors are above the water surface. On the other hand, the hydraulic lift, requires less power, allows higher transport densities (50 %) and hence needs smaller pipes for lifting the nodules, but is difficult to maintain due to under water pump system (Amann, 1982). In view of the high investment – high risk nature of the operations, a number of autonomous nodule collectors launched from the mining platform could provide better operational and maintenance options, also from environmental impact consideration due to limited area of contact of these devices with the water column and the seafloor; and also in evacuating procedures in case of emergency situations, as the mining platform and collecting devices would be independent of one another.

4. Technological issues

4.1 Mining systems development

Mining of either 1.5 mi. t. or 3 mi. t. in ~300 working days in a year, translates to 5000 to 10,000 t of ore / day (~ 210-420 t/hr or ~ 3.5-7 t/min) that the mining system will not only be collecting from the seafloor, but will also require lift mechanism to bring them to the surface through > 5km of water column, as well as handling equipment on the mining platform. Also for these operations, continuous power supply and adequate storage space for nodules will be required on the platform, as the mining sites lie several thousand kilometers (2000-6000 km) away from possible landing sites for these ores, involving 5-15 days of travel time (at 10 knots speed) for the transport vessels besides loading / unloading time (for ores, spares, fuel, manpower and provisions) during each visit to the mining platform.

Although, development of mining technology is in different stages, with a number of crawlers and lifting mechanisms being tested by the Contractors (Table 3), the real challenge lies in up scaling and integrating different subsystems and making them work on a sustained basis continuously for 300 days / year under extreme conditions, such as meteorological factors (rainfall, winds, cyclones), hydrographic conditions (high pressure, low temperature, currents, lack of natural light); coupled with seafloor environment (undulating topography, variable sediment thickness and compactness, and heterogeneous distribution of deposits).

To overcome these, application of new technology to nodule mining, such as 3D sensing, autonomous navigation, robotic manipulators and vehicles for the extreme environment of space missions (Jasiobedzki et al., 2007) could provide some of the solutions. Similarly, advances in floating oil platforms, availability of riser hardware for deep-water and harsh environments, sub-sea power systems and pumps required for mining (Halkyard, 2008); as well as the advantages of flexible risers in connecting pumps and power cables, reduced top tension for surface vessel, ability to retrieve and reinstall, and easy handling in severe weather conditions (Hill, 2008) could provide the much required technological support for development of sub-sea mining systems.

Whereas considerable research and analyses have been carried out on the collector and riser systems (Chung, 2003), very few studies have been conducted on the mining platform and ore handling / transfer at sea. These studies (Amann, 1982; Ford et al., 1987; Herrouin et al., 1991) have proposed possible designs, dimensions, weight, production capacity, and power generation required on the platform to support a deep-sea mining activity. This sector (mining platform and ore transfer) will have to depend on existing infrastructure available for offshore oil and gas production and bulk carriers to be modified into mining platforms and transport vessels.

4.2 Processing technology and waste management

Different contractors are pursuing different approaches or processing routes, mainly depending on the number of metals to be extracted (Table 3). It has been suggested that 'the incremental capital requirement of manganese recovery (in addition to Cu, Ni, Co) in a 4 metal route over a 3 metal route was small enough to make a 1.5 mi ton / year capacity plant economically viable' (ISA, 2008b). It also suggested that a three metal recovery system needed to operate at higher annual capacities, with 3 mi. dry tons per year; whereas, four metal systems with additional costs and revenues from manganese production, can operate at half the capacity. However, the final decision of extracting 3 or 4 metals will lie with each contractor, depending on the available technology, investment potential and the returns expected from such investments.

In terms of processing of polymetallic nodules, probably the least attention has been given to the disposal of material that will remain after processing and extraction of metals. Considering 4 metals (Mn, Cu, Ni, Co) being extracted with a total metal content of ~26%, the remaining 74% (i.e. 1.111 mi. t in case of 1.5 mi. t/y or 2.222 mi. t in case of 3 mi. t/y) of material will have to be disposed off, which may not be in its original form after processing. The possible environmental hazard of disposing such tailings or using them for any 'constructive' purpose needs to be evaluated thoroughly. Wiltshire et al. (2001) have shown that mineral rich tailings from manganese nodule processing plants mixed with soil for agriculture stimulated most of the 17 plant species, in one case achieving double growth rate in comparison with the controls.

5. Environmental issues

5.1 Impact of environment on mining

The component of 'environment' has a two-way implication on deep-sea mining. Whereas, the mining activity is likely to have an impact on environment; the reverse i.e. impact of environment on mining activity is equally important because the prevailing environmental conditions at the mine-site would play a major role in the design and performance of different sub-systems of the mining system. The major parameters contributing to this will be the atmospheric conditions, hydrographic conditions, seafloor topography, nodule characteristics and associated substrates (Table 4).

The collection of data on these environmental conditions can be time consuming and cost intensive, and always site-specific. Data will have to be collected independently at every site for a minimum period of 5-10 years for atmospheric conditions (which can also be sourced from various weather atlases), at least 1-2 years data for hydrographic conditions using long term instrumented moorings, detailed mapping for seafloor features, extensive sampling for nodule and sediment characteristics, and seafloor photography for rock outcrops and associated environmental conditions in the area.

5.2 Impact of mining on environment

The areas likely to be affected by deep-sea mining would range from the seafloor (due to the sediment cloud created by the movement of the miner while collecting the nodules), to the water column (due to discharge of the unwanted debris and spillage during lifting), to the surface (due to at-sea processing and transportation) and the land (due to metal extraction and tailing disposal). Whereas, the likely areas to be affected by different activities can be predicted (Table 5), there is still an uncertainty about the means and location for discharge of tailings after the nodules have been processed. However, the most affected site is expected to be the seafloor, where the mineral will be separated from the associated sediment leading to a sediment cloud and compaction of sediment along the path of the collector device (Foell et al., 1990; Trueblood, 1993; Fukushima, 1995; Tkatchenko et al., 1996; Sharma and Nath, 2000; Sharma, 2001; Sharma, 2005; Thiel, 2001). This is further compounded by the resettlement of particles discharged (accidentally or otherwise) during lifting, at-sea processing, transportation and tailing disposal (Pearson, 1975).

On an average, the ratio of nodule to sediment on the seafloor is 1:9 (computed from Sharma et al., 2010), implying that when nodules are picked up, sediments comprising up to 90% of the total material will also be disturbed. Assuming a minimum penetration of nodule collector in the sediment to be 10 cm, the total volume of sediment disturbed from the earlier calculated area of 600 sq. km, will be

$$Vs = A_d \times D_p \times C_s / 100 \qquad \text{- (4)}$$

where, A_d = area of disturbance (600 sq km or 6×10^8 m^2 / year)

D_p = depth of penetration (10 cm or 0.1 m)

C_s = coverage of sediment (90%).

Hence, $V_s = 6 \times 10^8 \times 0.1 \times 90 / 100 = 6 \times 10^5 \times 90$ m^3 / year

$= 5400 \times 10000$ m^3 / year in 300 days

$= 180{,}000$ m^3 /day

If wet density of sediments is 1.15 kg / m^3 (Khadge and Valsangkar, 2008), the weight of the sediment to be disturbed would be:

Density x volume = weight - (5)

i.e. 1.15 kg / m^3 x 180000 m^3 / day = 207,000 kg / day = 207 tonnes / day or 62,100 tonnes / year for 300 days of mining.

As ~80% of the total weight of wet sediment is water (Khadge and Valsangkar, 2008), out of 207 t of wet sediments, the solid particles would weigh about 41.4 t, that will be disturbed for each day of mining. In case of mining rate of 1.5 mi. t/y and the area to be mined being 300 sq/km, the volume of sediment disturbed will be half (i.e. 90,000 m^3/day) and also the solid particles churned will be half (i.e. 20.7 t/day). However, nodule to sediment ratio considered here includes locations without any nodule coverage and low nodule coverage areas, but as the first generation mine sites are expected be in areas of dense nodule populations, the associated sediments would be proportionately less, leading to lesser re-suspended particles.

It is churning of this sediment that would lead to the environmental impact in the benthic ecosystem. Several experiments have been conducted for assessing the potential impacts using devices such as the plough-harrow as well as a hydraulic sediment re-suspension system in the Pacific and Indian Oceans (Table 6). Considering the duration (18-85 hours), distance covered (33-141 km) and the sediments discharged (0.77-1.4 m^3 / min.); the scale of these experiments (Table 7) was significantly smaller than that expected during commercial mining (duration = 300 days/ year, area = 300 sq. km/ year, discharge = 37.5 m^3 / min) (Yamazaki and Sharma, 2001). Syntheses of the results of these experiments have revealed the need for several improvements for conducting similar experiments (Morgan et al., 1999). In view of the scale and methodology expected to be followed in a large-scale mining venture, it would be pertinent to take into consideration the following for assessing the impacts on marine ecosystem in future:

Quantity of sediment	- higher
Altitude of discharge	- variable
Impact in water column	- at various levels
Pattern of disturbance	- irregular
Impact assessment	- in real time
Monitoring of restoration	- long-term and continuous

5.3 Applications of environmental data

Acquisition and evaluation of environmental data will have several applications for deep-sea mining (Table 8). Whereas, most of the geological parameters (topography, sediment thickness and size, geotechnical properties and nodule characteristics) will have a bearing on mine-site identification and design of nodule collector; physical, chemical and biological parameters would be applicable for design of different sub-systems and impact assessment.

In view of the emerging technologies for mining, any ‘experimental’ impact assessment in future should be conducted with a pilot mining system, so as to provide more realistic information about the expected environmental consequences of deep seabed mining (Markussen, 1994). While carrying out an engineering and environmental assessment of the available data on deep-sea mining, it has also been suggested to ‘test benthic disturbance in scale and system large enough to represent the commercial mining scale’ (Chung et al., 2001). Innovations in technology by the time actual mining commences will make this essential for a better evaluation of the potential impacts and to devise measures for mitigation.

6. International policies and cooperation

Deep-sea mining has been in an advantageous position due to the substantial lead time available to the regulatory agencies to put in place the policies required for exploration and exploitation of the seabed resources. As many of the deposits occur in the international waters, any commercial activity could have global consequences. It was as early as 1990, when the Preparatory Commission for the International Seabed Authority (ISA) initiated the ‘Draft regulations on prospecting, exploration and exploitation of polymetallic nodules in the Area (UN, 1990). With the research and developmental activities initiated by different groups on deep-sea mining and the increasing awareness for the need to regulate such activities in the international waters, it was also suggested that the ‘UN and ISA should draw up a concrete plan for keeping abreast of scientific progress and at regular intervals assess the need for revising regulations’ (Markussen, 1994).

Since the formation of the ISA in 1994 (by article 156 of 1982 United Nations Convention on Law of the Sea), it has served as the regulating agency for all activities related to the resources in the Area (i.e. defined as the seabed and subsoil beyond the limits of national jurisdiction). It has notified the plan of work for exploration of the Pioneer Investors and the area allotted to them (ISA, 1998) followed by the establishment of a comprehensive set of rules, regulations and procedures for prospecting and exploration for polymetallic nodules in the international seabed Area (ISA, 2000).

Subsequently through a series of workshops with international experts, ISA has also issued the recommendations for assessment of possible environmental impacts from exploration of nodules (ISA, 2001) and for establishment of environmental baselines and associated monitoring program for exploration of polymetallic sulphides and cobalt crusts (ISA, 2005). The code for environmental management for marine mining adopted by the International Marine Minerals Society provides a framework for development and implementation of an environmental program for a marine exploration or extraction site by marine mining companies and for other stakeholders in evaluating such programs (www.immsoc.org/ IMMS_code.htm).

The participation of representatives of private enterprise as well as researchers, legal experts and the Contractors at the workshop on polymetallic nodules mining technology, during which the cost models for deep-seabed mining and processing venture were worked out (ISA, 2008a); indicates the continued interest of the world community in deep-sea mining. There have also been suggestions for working out collaborative programs by interested research groups to cooperate and share resources, manpower and costs for simulation of deep-sea mining in order to provide a guideline for mining system design and developing a long-term environmental monitoring program for commercial mining (Chung et al., 2001) that would be useful for all the potential ‘Contractors’ as well as mining system ‘Developers’.

7. Conclusions

Following the recognition of the potential of deep-sea minerals as alternative sources of metals, initial estimates had predicted that deep-sea mining would begin by 1990 (Mero, 1977), whereas a detailed analysis of profit potential conducted by Herrouin et al. (1991) had indicated that industrial mining could begin in 10-20 years. However, more recent studies on deep-sea minerals with respect to global economy suggest that in the 21st century, deep-sea polymetallic resources will be increasingly important in meeting the deficit of metals such as Mn, Ni, Cu, Co, and others (Kotlinski, 2001). In financial terms, nickel being the most important component, deep-sea mining can best be compared with nickel mining on land (Dick, 1985). It has also been pointed out that as there are no known large deposits of nickel sulphides and the industrialisation of large developing countries will increase the demand, the oxide ores such as polymetallic nodules are the future source of nickel (ISA, 2008a).

Due to the continuing efforts of the state funded Contractors (ISA, 1998), the growing interest of private entrepreneurs (Gleason, 2008) and development of new technologies (Chung, 2003; Jasiobedzki, 2007; Halkyard, 2008; Hill, 2008), it seems that deep-sea mining has the potential of becoming a reality in future. Estimates show that metal resources from the already identified areas could last for several decades and exploration of new areas could provide resources that would last for centuries. Also, a single mine-site would yield metals worth billions of dollars, the returns of which could be much higher due to enhanced metal prices at the time of mining.

However, the major challenge for the mining technology development would be up-scaling and integration of the subsystems so as to make them operational for ~300 days / year under extreme environmental conditions such as 1-2^o C temperature, ~500 bars pressure, total darkness, cross cutting currents at different levels in the water column, uneven micro-topography, variable seafloor characteristics and heterogeneous nodule distribution. The miner should be a self propelled active device, with acoustic sensors to be able to detect 'promising areas' and to avoid unfavourable areas, in order to save on power consumption and time, and be cost effective.

Considerably small area of each mine-site and the actual area of contact are the factors favourable for deep-sea mining, especially for limiting the ensuing environmental impacts. From the environmental point of view, the mining plan must consider separation of nodules from the associated sediment near the seafloor, lifting of minimum possible sediment to the surface, discharge of debris after initial at-sea processing below the oxygen minimum zone and 'constructive' use of unwanted material after extraction of metals from the ores, to ensure minimum impact of nodule mining on marine as well as terrestrial ecosystems. Also, establishment of baseline conditions, real-time monitoring of mining operations, alteration in mining methods for reducing the impacts, formulation of suitable guidelines and their enforcement are required to ensure safe development of this marine resource (Pearson, 1975).

The decision of the timing for mining depends on the techno-economic feasibility of such a venture. Whereas on one hand, the rising demand of metals and depletion of minerals on land enhances the possibility of deep-sea mining to meet the industrial needs; on the other hand, recycling, new exploration as well as other technological developments offset the same. Considering the investment costs ($ 12 billion) and the gross-in-place value of metals ($ 21 billion) for mining at the rate of 1.5 mi. t/y at current estimates, the net returns may be relatively low indicating the need to aim for higher mine production and/or lowering operating costs for the processing plant that accounts for almost 50% of the total estimated expenditure. In order to make deep-sea mining cost effective, the 'contractors' (who own the sites) and 'developers' (who might have the required expertise and / or technology) may also work out collaborative initiatives so as to pool their resources (funds, expertise, technology and infrastructure) and reap the benefits for sustainable development of this common heritage of mankind.

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Table 1: Resource potential and metal production estimates

Nodule / Metal	Mean concentr -ation[a]	Resource potential t (mi.t)[b]	Metal production per year t (mi.t)		Price of metal ($/Kg)[c]	Gross in-place value of metal $/year		Gross in-place value of metal $/20 years	
			@1.5 mi.t/y	@ 3 mi. t/y		@ 1.5 mi. t/y	@ 3 mi. t/y	@1.5 mi. t/y	@ 3 mi. t/y
Wet nodules	-	375,000,000 (375)	-	-	-	-	-	-	-
Dry nodules	55% of wet nodules	206,250,000 (206.25)	-	-	-	-	-	-	-
Manganese	24% of dry nodules	49,500,000 (49.5)	360,000 (0.36)	720,000 (0.72)	1.32	475,200,000 (475.2 million)	950,400,000 (950.4 million)	9.504 billion	19.008 billion
Nickel	1.1% of dry nodules	2,268,750 (2.26875)	16,500 (0.0165)	33,000 (0.033)	23.00	379,500,000 (379.5 million)	759,000,000 (759 million)	7.59 billion	15.18 billion
Copper	1.04% of dry nodules	2,145,000 (2.145)	15,600 (0.0156)	31,200 (0.0312)	8.30	129,480,000 (129.48 million)	258,960,000 (258.96 million)	2.5896 billion	5.1792 billion
Cobalt	0.1% of dry nodules	206,250 (0.20625)	1,500 (0.0015)	3,000 (0.03)	39.20	58,800,000 (58.8 million)	117,600,000 (117.6 million)	1.176 billion	2.352 billion
Total (metals)	26.24%	54,120,000 (54.12)	393,600 (0.3936)	787,200 (0.7872)	-	1042,980,000 (1042.98 million)	2085,960,000 (2085.96 million)	20.8596 billion	41.7192 billion

[a] Source: Jauhari and Pattan, 2000

[b] @5 kg/sqm for 75,000 sq km (75x10^9 sqm)

[c] Average metal prices for the period from July 2010 to January 2011 (source: www.metalprices.com)

Table 2: Estimated capital and operating expenditures for polymetallic nodules mining (figures in brackets show the range for different systems)

Item	Capital expenditures	Operating expenditures	Total
Mining system	$ 550 mi.* ($ 372-562 mi.)	$ 100 mi/y* ($ 69-96 mi.) x 20 years = $ 2.0 billion	$ 2.55 billion
Ore transfer	$ 600 mi.* ($ 495-600 mi.)	$ 150 mi/y* ($ 93-132 mi/yr) x 20 years = $ 3.0 billion	$ 3.60 billion
Processing plant	($ 750 mi.)	($250 mi/y) x 20 years = $5.0 billion	$ 5.75 billion
Total	$ 1.90 billion	$ 10.0 billion	$ 11.90 billion

* Rounded off to nearest fifty of the highest value
( ) Values proposed by different Contractors (Source: ISA, 2008a)

Table 3: Status of mining and processing technologies for deep-sea polymetallic nodules

Sr. no.	Contractor	Mining technology	Processing technology
1	France[a]	Model studies on self- propelled miner with hydraulic recovery system	Tested pyro and hydro-metallurgical processes for Ni, Cu, Co.
2	Japan[b]	Passive nodule collector tested At~2200 m depth	Developed a process to recover Cu, Ni, Co.
3	India[c]	(a) Design includes flexible riser and multiple crawlers (b) Crawler tested at ~410 m depth in the sea	(a) Tested 3 possible routes (b) Pilot plant set up for 500 kg / day for Cu, Ni, Co.
4	China[c]	(a) Includes rigid riser with self propelled miner (b) Tried different concepts of collector and lifting mechanisms	Developed a process to recover Mn, Ni, Cu, Co, and Mo.
5	Korea[c]	(a) Design includes flexible riser system with self propelled miner (b) Developed 1/20 scale test miner	(Not known)
6	Russia[c]	Collector and mining subsystems in conceptual stage	Recovered Mn, Ni, Cu, Co from nodules
7	IOM[c]	Conceptual design includes nodule collector, buffer, vertical lift system.	Economic assessment of different schemes
8	Germany[c]	Considering innovative concepts for mining	Considering different options for processing

Source: [a] Herrouin et al., 1991; [b] Yamada and Yamazaki, 1998 (for mining technology); [c] ISA, 2008b

Table 4: Influence of environmental conditions on mining system design and operation

Sr. no.	Conditions (Key parameters)	Influence on mining system
1	Atmospheric (wind, rainfall, cyclone)	Will determine actual fair weather conditions for operating the mining system during different seasons of the year.
2	Hydrographic (waves, currents, temperature, pressure)	Will influence operations on the platform including ore-handling and mining system deployment at the surface; and stability of riser system in the water column.
3	Topographic (relief, macro and micro-topography, slope angles)	Will have a bearing on the manoeuvrability and stability of the mining device on the seafloor.
4	Nodule characteristics (grade, size, abundance, morphology, distribution pattern)	Important for designing the mechanism for collection, crushing as well as screening of nodules at the seafloor from un-wanted material before pumping the nodules to the surface.
5	Associated substrates (sediment-size, composition, engineering properties; rock outcrops – extent, elevation)	Will affect the mobility and efficiency of the collector device to be able to operate without sinking (or getting stuck) in the sediment and be able to avoid the rock outcrops for its safety.

Table 5: Areas likely to be affected by different activities of deep-sea mining

Activity	Seafloor	Water column	Surface	Land
Collection	#			
Separation	#			
Lifting	#	#		
Washing	#	#	#	
At-sea processing	#	#	#	
Transport	#	#	#	#
Extraction	?	?	?	#
Tailing discharge	?	?	?	#

# indicates likely impact**,** ? indicates impact not known

Table 6: Basic data of Benthic Impact Experiments (BIEs) for assessing potential environmental impact of nodule mining

Experiment	Tows	Duration	Area/Distance	Discharge [f]
DISCOL (Germany) [a]	78	~12 days	10.8 sq km	--
NOAA (USA) [b]	49	5290 mins	141 km	6951 cu m
JET (Japan) [c]	19	1227 mins	33 km	2495 cu m
IOM (E. Euro. Countries) [d]	14	1130 mins	35 km	2693 cu m
INDEX (India) [e]	26	2534 mins	88 km	6015 cu m

Source:
[a] Foell et al., 1990
[b] Trueblood, 1993
[c] Fukushima, 1995
[d] Tkatchenko et al., 1996
[e] Sharma and Nath, 2000
[f] Yamazaki and Sharma, 2001

Table 7: Scale of Benthic Impact Experiments vis-à-vis commercial mining

Parameter	BIEs data	Commercial Mining data
Duration	18-88 hours	300 days/year
Distance/area	33-141 km	300-600 sqkm/yr
Recovery	0.77-1.4 cu.m/min	37.5 cu.m/min

Source:Yamazaki and Sharma, 2001.

Table 8: Applications of key environmental parameters

Parameter	Mine-site identification	Design of mining system	Impact assessment
Geological			
Nodule size, abundance and grade	#	#	-
Topography	#	#	-
Rock outcrops	#	#	-
Sediment thickness	-	#	-
Geotechnical properties	-	#	#
Physical			
Meteorological	-	#	#
Waves, currents	-	#	#
Temperature, pressure	-	#	#
Chemical			
Oxygen	-	#	#
Eh, pH	-	#	#
Nutrients	-	-	#
Metals	-	-	#
Biological			
Surface productivity	-	#	#
Microbial parameters	-	-	#
Biochemical parameters	-	-	#
Biodiversity	-	#	#

# indicates application, - indicates no application

Figure captions

Fig. 1: Photograph with polymetallic nodules and associated sediment on the seafloor (CIB: 9-1-2-ii/20740a)

Fig. 2: Areas allotted to Pioneer Investors in the Pacific Ocean (above) and Indian Ocean (below) (modified from: www.isa.org.jm)

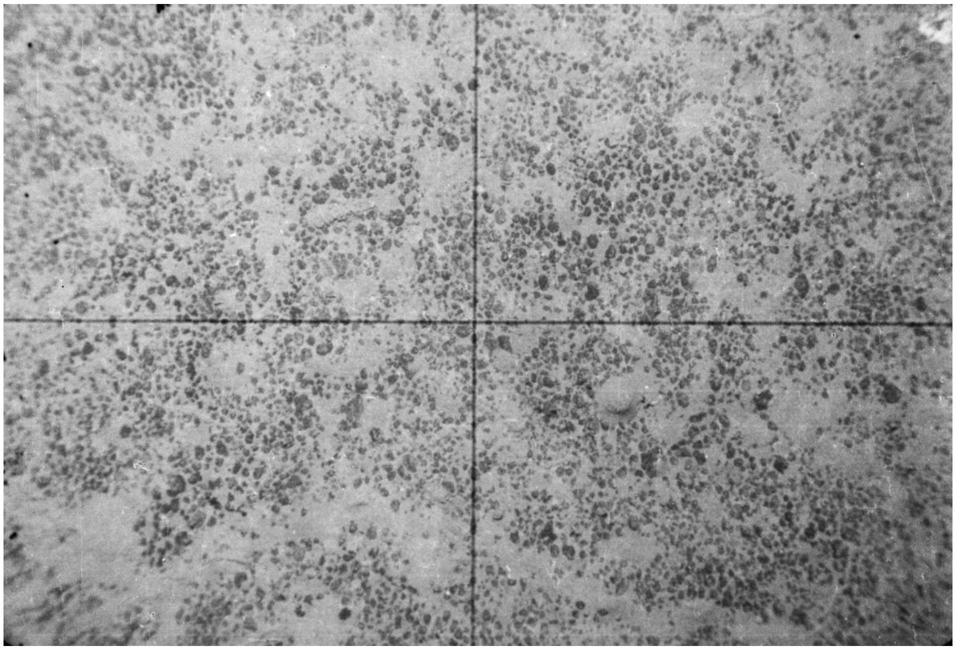
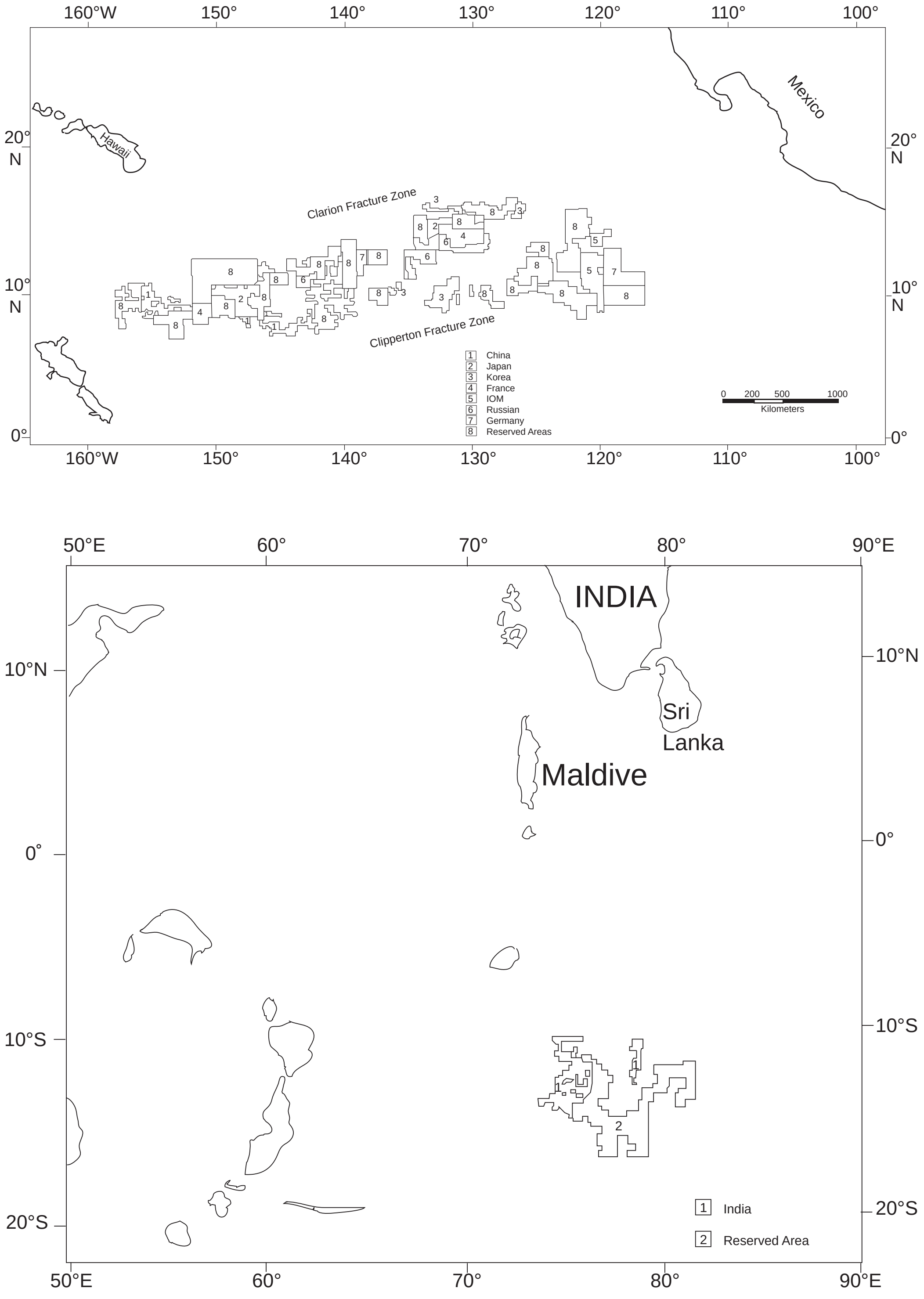


Fig. 1: Photograph with polymetallic nodules and associated sediment on the seafloor (CIB: 9.1/20740a)



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