Deep-Sea Mining: Economic, Technical, Technological, and Environmental Considerations for Sustainable Development

Author

Rahul Sharma
Department of Marine Geology, King Abdulaziz University, Jeddah, Saudi Arabia and National Institute of Oceanography, Goa, India

Abstract

Mining of minerals such as polymetallic nodules from the deep-sea floor has been “on-hold” as a result of several factors such as current availability of Cu, Ni, Co and Mn from terrestrial sources and their fluctuating prices. Nonetheless, 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 licenses for exploration and mining of seafloor massive sulfides 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 the sustainable development of deep-sea mining.

A typical area of 75,000 km² with an estimated nodule resource of >200 million tonnes 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 the 20-year 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 deep-sea minerals.

Keywords: deep-sea mining; polymetallic nodules; economic, technical environmental issues

Introduction

Establishment of the potential of deep-sea mineral resources (Mero, 1965) was followed by detailed reports on polymetallic nodule occurrences (Figure 1) from different parts of the Pacific Ocean, such as Northern Peru Basin (Thijsen et al., 1981), South Pacific (Glasby, 1982), Central Pacific (Usui & Iizasa, 1995), North Pacific and the Clarion-Clipperton ore field (Kotlinski, 1996), as well as from Carlsberg Ridge (Glasby, 1972), Central Indian Basin (Siddiquie et al., 1978; Sudhakar, 1989) and other basins of the Indian Ocean (Frazer & Wilson, 1980; Cronan & Moorby, 1981). This initial rush resulted in intense exploration activities followed by seaborne areas being allotted to the erstwhile “Pioneer Investors” (now called the “Contractors”) with exclusive rights over the ferromanganese nodule deposits in different parts of the world oceans (Figure 2) by the International Seabed Authority (ISA, 1998) established under UN Law of the Sea (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 licenses to private companies for exploration of seafloor massive sulfides off Papua New Guinea and New Zealand (Gleason, 2008) reaffirm 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 sulfides (1000–2500 m), to deeper ferromanganese nodules (4000–6000 m).

To facilitate this, the ISA 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 sulfides 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 a 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 nodule mining for a sustained development of the resource.

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 kilometers 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 km²) in the Central Indian Basin and the cutoff value of abundance (5 kg/m²); the total resource available in the area will be 375 million tonnes (wet) or 206.25 million tonnes (dry) with a total metal equal to 54.12 million tonnes (Table 1), for known concentrations of metals (Mn = 24%, Ni = 1.1%, Cu = 1.04%, Co = 0.1%) in the area (Jauhari & Pattan, 2000). Of the 206.25 million tonnes, 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 a duration of 20 years, with a large balance (71-85.5%) to be mined in the future.

### TABLE 1

<table>
<thead>
<tr>
<th>Resource</th>
<th>Potential 1 (million tonnes)</th>
<th>Mean Concentration</th>
<th>Metal Production per Year @ 1.5 million tonnes/year</th>
<th>Metal Production per Year @ 3 million tonnes/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet nodules</td>
<td>375,000,000 (37.5)</td>
<td>55% of wet nodules</td>
<td>208,250,000 (20.825)</td>
<td>312,000,000 (31.2)</td>
</tr>
<tr>
<td>Dry nodules</td>
<td>49,500,000 (4.95)</td>
<td>24% of dry nodules</td>
<td>11,880,000 (1.188)</td>
<td>19,800,000 (1.98)</td>
</tr>
<tr>
<td>Manganese</td>
<td>4,299,750 (4.29975)</td>
<td>1.1% of dry nodules</td>
<td>47,997.5 (0.0479975)</td>
<td>73,245 (0.073245)</td>
</tr>
<tr>
<td>Nickel</td>
<td>1,269,750 (1.26975)</td>
<td>0.1% of dry nodules</td>
<td>12,697.5 (0.0126975)</td>
<td>21,165 (0.021165)</td>
</tr>
<tr>
<td>Copper</td>
<td>1,269,750 (1.26975)</td>
<td>0.1% of dry nodules</td>
<td>12,697.5 (0.0126975)</td>
<td>21,165 (0.021165)</td>
</tr>
<tr>
<td>Cobalt</td>
<td>20,625 (0.20625)</td>
<td>0.1% of dry nodules</td>
<td>2,062.5 (0.0020625)</td>
<td>3,105 (0.003105)</td>
</tr>
<tr>
<td>Total (metals)</td>
<td>54,120,000 (54.12)</td>
<td>26.24%</td>
<td>3936,000 (0.3936)</td>
<td>6,564,000 (0.6564)</td>
</tr>
</tbody>
</table>

**Resource potential and metal production estimates.**

**Gross In-Place Value of Metal $/20 Years**

<table>
<thead>
<tr>
<th>Metal</th>
<th>Gross In-Place Value of Metal @ 1.5 million tonnes/year</th>
<th>Gross In-Place Value of Metal @ 3 million tonnes/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mn</td>
<td>19.008 billion</td>
<td>51.792 billion</td>
</tr>
<tr>
<td>Ni</td>
<td>9.504 billion</td>
<td>25.596 billion</td>
</tr>
<tr>
<td>Cu</td>
<td>7.59 billion</td>
<td>19.008 billion</td>
</tr>
<tr>
<td>Co</td>
<td>15.18 billion</td>
<td>37.25 billion</td>
</tr>
<tr>
<td>Total</td>
<td>104.298 billion</td>
<td>260.556 billion</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Price of Metal ($/kg)</th>
<th>Gross In-Place Value of Metal $/20 Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mn</td>
<td>1.32 million</td>
</tr>
<tr>
<td>Ni</td>
<td>23.00 million</td>
</tr>
<tr>
<td>Cu</td>
<td>8.30 million</td>
</tr>
<tr>
<td>Co</td>
<td>39.20 million</td>
</tr>
<tr>
<td>Total (metals)</td>
<td>104.298 million</td>
</tr>
</tbody>
</table>

**a** Source: Jauhari and Pattan (2000).

**b** At 5 kg/m² for 75,000 km² (7.5 × 10⁹ m²).

**c** Average metal prices for the period from July 2010 to January 2011 (source: www.metalprices.com).
The total annual production of metals would range from 0.39 million tonnes/year (for 1.5 million tonnes/year) to 0.78 million tonnes/year (for 3 million tonnes/year). 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 ∼$20.85 billion in 20 years from a single mine site at 1.5 million tonnes/year 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 million tonnes/year (Table 1). The actual returns could be much higher as the in situ average abundances are normally expected to be higher than the cutoff (5 kg/m²) 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 that have been claimed in the international waters so far, excluding the minerals lying within the Exclusive Economic Zone (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 (UN) 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 three 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 50), 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.

### Technical Considerations

#### 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, 1979, 1981; Holser, 1976; Frazer, 1977), UN Ocean Economics and Technology Branch developed the following criterion for selecting a manganese nodule mine site (UNOET, 1987):

- **Cutoff grade** = 1.8% Cu + Ni
- **Cutoff abundance** = 5 kg/m²
- **Topography** = acceptable
- **Duration (D) = 20 years**
- **Annual recovery (Ar) = 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 mineable area (M) can be estimated as follows:

\[
M = A_t - (A_u + A_g + A_a)
\]

### Table 2

Estimated capital and operating expenditures for polymetallic nodule mining (figures in brackets show the range for different systems).

<table>
<thead>
<tr>
<th>Item</th>
<th>Capital Expenditures</th>
<th>Operating Expenditures</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mining system</td>
<td>$550 million(^a)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>($372–562 million)</td>
<td>$100 million/year(^a)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>× 20 years = $2.0 billion</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$2.55 billion</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ore transfer</td>
<td>$600 million(^a)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>($495–600 million)</td>
<td>$150 million/year(^a) ($93–132 million/year)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>× 20 years = $3.0 billion</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$3.60 billion</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Processing plant</td>
<td>($750 million)</td>
<td>($250 million/year) × 20 years = $5.0 billion</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$5.75 billion</td>
</tr>
<tr>
<td>Total</td>
<td>$1.90 billion</td>
<td>$10.0 billion</td>
<td>$11.90 billion</td>
</tr>
</tbody>
</table>

\(^a\)Rounded off to nearest 50 of the highest value

Values in parentheses are proposed by different contractors (Source: ISA, 2008a).
where \( A_t \) is the total area,
\[ A_u = \text{area unmineable due to the topography}, \]
\[ A_g = \text{area below cutoff grade}, \]
\[ A_a = \text{area below cutoff abundance}. \]

The proportion of unmineable area due to unfavorable 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 \( A_t = 75,000 \text{ km}^2 \) (maximum area allotted to each pioneer investor), the total mineable area (\( M \)) is 37,500 km\(^2\).

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

\[
A_s = \left( \frac{A_r}{A_t} \right) (D) \left( \frac{A_n}{A_t} \right) (E) (M)
\]

\[
= 3 \times 10^9 \times 20 \text{ years} / 5 \text{ kg/m}^2 \times 25\% \times 37,500 \text{ km}^2
\]

\[
= 12,800 \text{ km}^2
\]

where \( A_s = \text{size of mine site (km}^2\),
\( A_r = \text{annual nodule recovery rate (3 million tonnes/year),} \)
\( D = \text{duration of mining operation (20 years),} \)
\( A_n = \text{average nodule abundance in a mineable area (5 kg/m}^2\),
\( E = \text{efficiency of the mining device (25\%) (UNOET, 1987),} \)
\( M = \text{mineable area (37,500 km}^2\). \)

For the mining rate of 1.5 million tonnes/year, \( A_s \) will be 6,400 km\(^2\). The other components being constant, variation in \( A_n \) and \( E \) could alter the size of the mine site (\( A_t \)). It is reasonable to expect a higher value for average nodule abundance (\( A_n \)), for example, 10 kg/m\(^2\) (range 5-15 kg/m\(^2\)) 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 (\( A_t \)) considerably. The smaller 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 million tonnes per year, with an annual operation time of \( \sim 300 \) days/year (UNOET, 1987) and for an average nodule abundance of 5 kg/m\(^2\), the actual area scraped will be 600,000,000 m\(^2\) = 600 km\(^2\)/year, i.e., 2 km\(^2\)/day. If mining is considered at the rate of 1.5 million tonnes/year, as suggested by ISA (2008a), the actual area scraped will be 300 km\(^2\)/year, i.e., 1 km\(^2\)/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 cutoff value considered here, the actual area scraped (or the ‘area of contact’ on the seafloor) will be smaller.

**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 \( \sim 25\% \), is calculated as (UNOET, 1987):

\[
E = e_d \times e_s
\]

where \( e_d = \text{dredge efficiency, which is the ratio of marine minerals effectively gathered by the dredge head, versus the nodules on the seabed before dredging.} \)
\( e_s = \text{sweep efficiency, which is the percentage of the bottom actually swept by the area dredged.} \)

The efficiency of deep-sea mining would also depend on the system for lifting the minerals to the surface (Amann, 1982), such as the airlift, which has two to five 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.

### Technological Issues

#### Mining Systems Development

Mining of either 1.5 or 3 million tonnes in ~300 working days in a year, translates to 5,000 to 10,000 tonnes of ore/day (~210–420 tonnes/h or ~3.5–7 tonnes/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 >5 km 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 (2,000–6,000 km) away from possible landing sites for these ores, involving 5–15 days of travel time (at a 10-knot 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 and cyclones) and hydrographic conditions (high pressure, low temperature, currents and 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 3-D 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 conditions.

### TABLE 3

<table>
<thead>
<tr>
<th>Sr. no.</th>
<th>Contractor</th>
<th>Mining Technology</th>
<th>Processing Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Francea</td>
<td>Model studies on self-propelled miner with hydraulic recovery system</td>
<td>Tested pyro- and hydro-metallurgical processes for Ni, Cu, Co</td>
</tr>
<tr>
<td>2</td>
<td>Japanb</td>
<td>Passive nodule collector tested at ~2200 m depth</td>
<td>Developed a process to recover Cu, Ni, Co</td>
</tr>
<tr>
<td>3</td>
<td>Indiac</td>
<td>(a) Design includes flexible riser and multiple crawlers (b) Crawler tested at ~410 m depth in the sea</td>
<td>(a) Tested three possible routes (b) Pilot plant set up for 500 kg/day for Cu, Ni, Co</td>
</tr>
<tr>
<td>4</td>
<td>Chinac</td>
<td>(a) Includes rigid riser with self-propelled miner (b) Tried different concepts of collector and lifting mechanisms</td>
<td>Developed a process to recover Mn, Ni, Cu, Co, Mo</td>
</tr>
<tr>
<td>5</td>
<td>Koreac</td>
<td>(a) Design includes flexible riser system with self-propelled miner (b) Developed 1/20 scale test miner</td>
<td>(Not known)</td>
</tr>
<tr>
<td>6</td>
<td>Russiac</td>
<td>Collector and mining subsystems in conceptual stage</td>
<td>Recovered Mn, Ni, Cu, Co from nodules</td>
</tr>
<tr>
<td>7</td>
<td>IOMc</td>
<td>Conceptual design includes nodule collector, buffer, vertical lift system.</td>
<td>Economic assessment of different schemes</td>
</tr>
<tr>
<td>8</td>
<td>Germanyf</td>
<td>Considering innovative concepts for mining</td>
<td>Considering different options for processing</td>
</tr>
</tbody>
</table>

*aHerrouin et al. (1991).  
cISA (2008b).*
weather conditions (Hill, 2008) could provide the much required technological support for development of subsea 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.

**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 million tonnes/year capacity plant economically viable’ (ISA, 2008h). It also suggested that a three-metal recovery system needed to operate at higher annual capacities, with 3 million dry tonnes/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 three or four 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 the four metals (Mn, Cu, Ni and Co) being extracted with a total metal content of ~26%, the remaining 74% (i.e., 1.111 million tonnes in case of 1.5 million tonnes/year or 2.222 million tonnes in case of 3 million tonnes/year) of material will have to be disposed of, 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.

**Environmental Issues**

**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 subsystems 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, cost intensive, and always site-specific. Data will have to be

**TABLE 4**

<table>
<thead>
<tr>
<th>Sr. no.</th>
<th>Conditions (Key Parameters)</th>
<th>Influence on Mining System</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Atmospheric (wind, rainfall, cyclone)</td>
<td>Will determine actual fair weather conditions for operating the mining system during different seasons of the year</td>
</tr>
<tr>
<td>2</td>
<td>Hydrographic (waves, currents, temperature, pressure)</td>
<td>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</td>
</tr>
<tr>
<td>3</td>
<td>Topographic (relief, macro- and micro-topography, slope angles)</td>
<td>Will have a bearing on the maneuverability and stability of the mining device on the seafloor</td>
</tr>
<tr>
<td>4</td>
<td>Nodule characteristics (grade, size, abundance, morphology, distribution pattern)</td>
<td>Important for designing the mechanism for collection, crushing as well as screening of nodules at the seafloor from unwanted material before pumping the nodules to the surface</td>
</tr>
<tr>
<td>5</td>
<td>Associated substrates (sediment size, composition, engineering properties; rock outcrops—extent, elevation)</td>
<td>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</td>
</tr>
</tbody>
</table>
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 of 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.

**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), 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 & Nath, 2000; Sharma, 2001; Sharma, 2005; Theil, 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).

**TABLE 5**

Areas likely to be affected by different activities of deep-sea mining.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Seafloor</th>
<th>Water Column</th>
<th>Surface</th>
<th>Land</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collection</td>
<td>#</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Separation</td>
<td>#</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lifting</td>
<td>#</td>
<td>#</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Washing</td>
<td>#</td>
<td>#</td>
<td></td>
<td></td>
</tr>
<tr>
<td>At-sea processing</td>
<td>#</td>
<td>#</td>
<td>#</td>
<td>#</td>
</tr>
<tr>
<td>Transport</td>
<td>#</td>
<td>#</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extraction</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>#</td>
</tr>
<tr>
<td>Tailing discharge</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td></td>
</tr>
</tbody>
</table>

# indicates likely impact. ? indicates impact not known.

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 km² will be

\[ V_s = A_d \times D_p \times C_s / 100 \]

where \( A_d \) = area of disturbance (600 km² or 6 × 10⁸ m²/year)
\( D_p \) = depth of penetration (10 cm or 0.1 m)
\( C_s \) = coverage of sediment (90%).

Hence, \( V_s = 6 \times 10^8 \times 0.1 \times 90/100 = 6 \times 10^5 \times 90 \text{ m}^3/\text{year} \)
\[ = 5400 \times 10,000 \text{ m}^3/\text{year in 300 days} \]
\[ = 180,000 \text{ m}^3/\text{day} \]

If wet density of sediments is 1.15 kg/m³ (Khadge & Valsangkar, 2008), the weight of the sediment to be disturbed would be

\[ \text{Density} \times \text{volume} = \text{weight} \]

i.e., 1.15 kg/m³ × 180,000 m³/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 & Valsangkar, 2008), out of 207 tonnes of wet sediments, the solid particles would weigh about 41.4 tonnes, which will be disturbed for each day of mining. In case of a mining rate of 1.5 million tonnes/year and the area to be mined being 300 km², the volume of sediment disturbed will be half (i.e., 90,000 m³/day) and also the solid particles churned will be half (i.e., 20.7 tonnes/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 resuspended 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 resuspension system in the Pacific and Indian Oceans (Table 6). Considering the duration (18-85 h), 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 km$^2$/year, discharge = 37.5 m$^3$/min) (Yamazaki & 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 the 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

**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 the 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.

**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 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 sulfides 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 nodule 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”.

### Conclusions

Following the recognition of the potential of deep-sea minerals as alternative sources of metals, initial estimates had predicted that deep-sea

---

**TABLE 8**

Applications of key environmental parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mine Site Identification</th>
<th>Design of Mining System</th>
<th>Impact Assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geological</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nodule size, abundance and grade</td>
<td>#</td>
<td>#</td>
<td>–</td>
</tr>
<tr>
<td>Topography</td>
<td>#</td>
<td>#</td>
<td>–</td>
</tr>
<tr>
<td>Rock outcrops</td>
<td>#</td>
<td>#</td>
<td>–</td>
</tr>
<tr>
<td>Sediment thickness</td>
<td>–</td>
<td>#</td>
<td>–</td>
</tr>
<tr>
<td>Geotechnical properties</td>
<td>–</td>
<td>#</td>
<td>#</td>
</tr>
<tr>
<td>Physical</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Meteorological</td>
<td>–</td>
<td>#</td>
<td>#</td>
</tr>
<tr>
<td>Waves, currents</td>
<td>–</td>
<td>#</td>
<td>#</td>
</tr>
<tr>
<td>Temperature, pressure</td>
<td>–</td>
<td>#</td>
<td>#</td>
</tr>
<tr>
<td>Chemical</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oxygen</td>
<td>–</td>
<td>#</td>
<td>#</td>
</tr>
<tr>
<td>Eh, pH</td>
<td>–</td>
<td>#</td>
<td>#</td>
</tr>
<tr>
<td>Nutrients</td>
<td>–</td>
<td>–</td>
<td>#</td>
</tr>
<tr>
<td>Metals</td>
<td>–</td>
<td>–</td>
<td>#</td>
</tr>
<tr>
<td>Biological</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface productivity</td>
<td>–</td>
<td>#</td>
<td>#</td>
</tr>
<tr>
<td>Microbial parameters</td>
<td>–</td>
<td>–</td>
<td>#</td>
</tr>
<tr>
<td>Biochemical parameters</td>
<td>–</td>
<td>–</td>
<td>#</td>
</tr>
<tr>
<td>Biodiversity</td>
<td>–</td>
<td>#</td>
<td>#</td>
</tr>
</tbody>
</table>

# indicates application. – indicates no application.
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 sulfides and the industrialization 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 et al., 2007; Halkyard, 2008; Hill, 2008), it seems that deep-sea mining has the potential of becoming a reality in the future. Estimates show that metal resources from the already identified seabed 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°C temperature, ~500 bars pressure, total darkness, cross cutting currents at different levels in the water column, uneven microtopography, 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 unfavorable areas, in order to save on power consumption and time, and be cost effective.

A considerably small area of each mine site and the actual area of contact are the factors favorable 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 and new exploration on land 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 million tonnes/year 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.

Acknowledgment
This study was carried out under the Environmental Studies for Nodule Mining in Central Indian Ocean program funded by the Ministry of Earth Sciences, Government of India. This is NIO manuscript no. 5045.

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

References


International Seabed Authority. 2005. Recommendations of the workshop on polymetallic sulphides and cobalt crusts: their environment and considerations for the establishment of environmental baselines and an associated monitoring programme for


**International Seabed Authority.** 2008b. Executive Summary of the International Seabed Authority, Jamaica. ISBA/14/LTC/3; pp. 4.


**Thijssen,** T., **Glasy,** G.P., **Schmitz,** W.A., **Friedrich,** G., **Kunzendorf,** H., **Muller,** D., & **Richter,** H. 1981. Reconnaissance survey of manganese nodules from the northern sector of the Peru Basin. Mar Mining. 2:385-428.


**Usui,** A., & **Iizasa,** K. 1995. Deep-sea mineral resources in the Northwest Pacific Ocean:


