Chapter 1
Deep-Sea Mining: Current Status and Future Considerations

Rahul Sharma

Abstract Deep-sea minerals such as polymetallic nodule, hydrothermal sulphides, and ferro-manganese crusts have for long attracted attention as an alternative source of metals to terrestrial deposits. The occurrence of many of these deposits in the international waters has necessitated its regulation under the UN Convention on the Law of the Sea through the establishment of International Seabed Authority.

A sudden spurt in the number of 'Contractors' interested in claiming large tracts of seafloor with exclusive rights for exploration from just eight in the first four decades (1970–2010) to 25 in the next 4 years (2011–2015) as well as consistent research and development of technology for prospecting, mining, and processing of these resources, coupled with issuing of licences to private entrepreneurs for deposits within the EEZ of some countries, calls for a re-look at the current status and future prospects of deep-sea mining.

1.1 Historical Perspective

Although the first known discovery of deep-sea minerals (Fig. 1.1) was made during the expedition of H.M.S. Challenger (21 December 1872–24 May 1876) when the expedition leader C.W. Thomson described the dredge haul of polymetallic nodules on 7 March 1873 as 'peculiar black oval bodies about 1 inch long' and the chemist J.Y. Buchanan revealed that they were 'almost pure manganese oxide' (en.wikipedi.org/wiki/HMSChallenger), it was Mero (1965) who unravelled the economic potential of these deposits and predicted that deep-sea mining would commence in 20 years time that steered the world attention towards developing these resources as an alternative source of metals for the future.

A global effort during the conference on 'Ferro-manganese deposits on the ocean floor' at Lamont Doherty Geological Observatory in January 1972 to collate existing data on nodules was followed by studies dealing with distribution, geochemistry, and mineralogy of the deposits in different parts of the Pacific Ocean (Hein et al. 1979; Thijssen et al. 1981; Glasby 1982; Usui and Moritani 1992), as well as Indian

---

R. Sharma (✉)
CSIR-National Institute of Oceanography, Council of Scientific and Industrial Research, Dona Paula, Goa 403004, India
e-mail: rsharma@nio.org; rsharmagoa@gmail.com

R. Sharma (ed.), *Deep-Sea Mining*, DOI 10.1007/978-3-319-52557-0_1

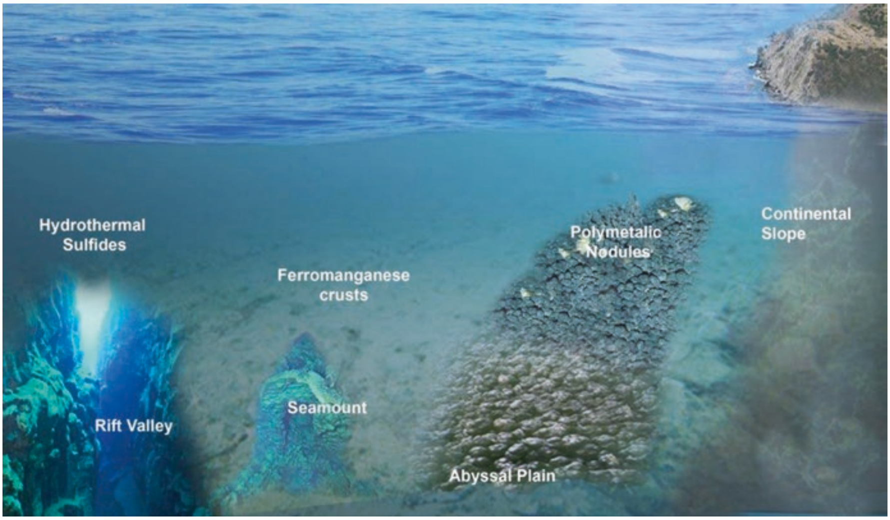


Fig. 1.1 Artist's impression of association of deep-sea minerals with seafloor features

Ocean (Glasby 1972; Siddiquie et al. 1978; Frazer and Wilson 1980; Cronan and Moorby 1981). Many of the studies also deciphered the formation process, geological factors as well as their relationship with sedimentary environment (Cronan 1980; Frazer and Fisk 1981; Glasby et al. 1982; Rao and Nath 1988; Martin-Barajas et al. 1991). Simultaneously, hydrothermal sulphides (Rona 1988; Plueger et al. 1990) and cobalt-rich ferromanganese crusts (Halbach et al. 1989; Hein et al. 1997) were also identified as potential resources.

Following the initial studies, extensive exploration programs ensued leading to several entities laying claims over large tracts of seafloor with potential resources in the international waters for gaining exclusive rights under the United Nations Convention on Law of the Sea, which led to the establishment of International Seabed Authority with its headquarters in Jamaica in 1994 for regulating the activities in the 'Area', i.e. in the international waters beyond the national jurisdiction of any country. Whereas until 2010, there were eight Registered Pioneer Investors subsequently called the 'Contractors' (France, Russia, Japan, China, Korea, Germany and InterOceanMetal Joint Orgnisation—a consortium of East European countries—in the Pacific Ocean and India in the Indian Ocean), all of them for polymetallic nodules only; a sudden spurt of applications was witnessed raising the number to 25 by 2015 for nodules, crusts, and sulfides (Table 1.1, Fig. 1.2a–d) (www.isa.org.jm (2016)).

Persistent interest in exploring these mineral resources, coupled with continued research and development for new technologies for prospecting as well as mining and extracting the metals from these ores, has led to numerous publications in several journals, symposia proceedings, and reports. The objective of this book is to synthesize all the information and make it available in a concise form so as to make it available for future generations. This chapter provides an overview of the

Table 1.1 Contractors for exploration for (a) polymetallic nodules, (b) ferromanganese crusts, (c) hydrothermal sulphides

Contractor	Sponsoring state	General location of the exploration area under contract
Contractors for exploration for polymetallic nodules		
InterOceanMetal Joint Organization	Bulgaria, Cuba, Czech, Poland, Russia, Slovakia	Clarion-Clipperton Fracture Zone (CCFZ), Pacific Ocean
Yuzhmorgeologiya	Russia	CCFZ, Pacific Ocean
Government of the Republic of Korea	Korea	CCFZ, Pacific Ocean
China Ocean Mineral Resources Research and Development Association	China	CCFZ, Pacific Ocean
Deep Ocean Resources Development Co.	Japan	CCFZ, Pacific Ocean
Institut français de recherche pour l'exploitation de lamer	France	CCFZ, Pacific Ocean
Bundesanstalt fur Geowissen Schaften und Rohstoffe	Germany	CCFZ, Pacific Ocean
Nauru Ocean Resources Inc.	Nauru	CCFZ, Pacific Ocean
Tonga Offshore Mining Limited	Tonga	CCFZ, Pacific Ocean
UK Seabed Resources Ltd.—I	UK	CCFZ, Pacific Ocean
G-TEC Mineral Resources NV	Belgium	CCFZ, Pacific Ocean
Marawa Research and Exploration Ltd.	Kiribati	CCFZ, Pacific Ocean
Ocean Mineral Singapore Pte Ltd	Singapore	CCFZ, Pacific Ocean
Cook Islands Investment Corporation	Cook Islands	CCFZ, Pacific Ocean
UK Seabed Resources Ltd.—II	UK	CCFZ, Pacific Ocean
Government of India	India	Indian Ocean
Contractors for exploration for ferromanganese crusts		
Government of the Russia	Russia	Pacific Ocean
China Ocean Mineral Resources Research and Development Association	China	Pacific Ocean
Japan oil, Gas and Metals National Corporation	Japan	Pacific Ocean
Contractors for exploration for hydrothermal sulphides		
Institut français de recherche pour l'exploitation de la mer	France	Mid-Atlantic Ridge
Government of the Russia	Russia	Mid-Atlantic Ridge
Government of the Republic of Korea	Korea	Central Indian Ridge
China Ocean Mineral Resources Research and Development Association	China	Southwest Indian Ridge
Govt of India	India	Southwest Indian Ridge
Bundesanstalt fur Geowissen Schaften und Rohstoffe	Germany	Southeast and Central Indian Ridge

hypothetical estimation of potential of one of the mineral resources in a typical area and introduces economic, technical, environmental, and policy issues related to deep-sea mining. The subsequent chapters deal with each of these issues in detail on the basis of actual experimentation and analysis.

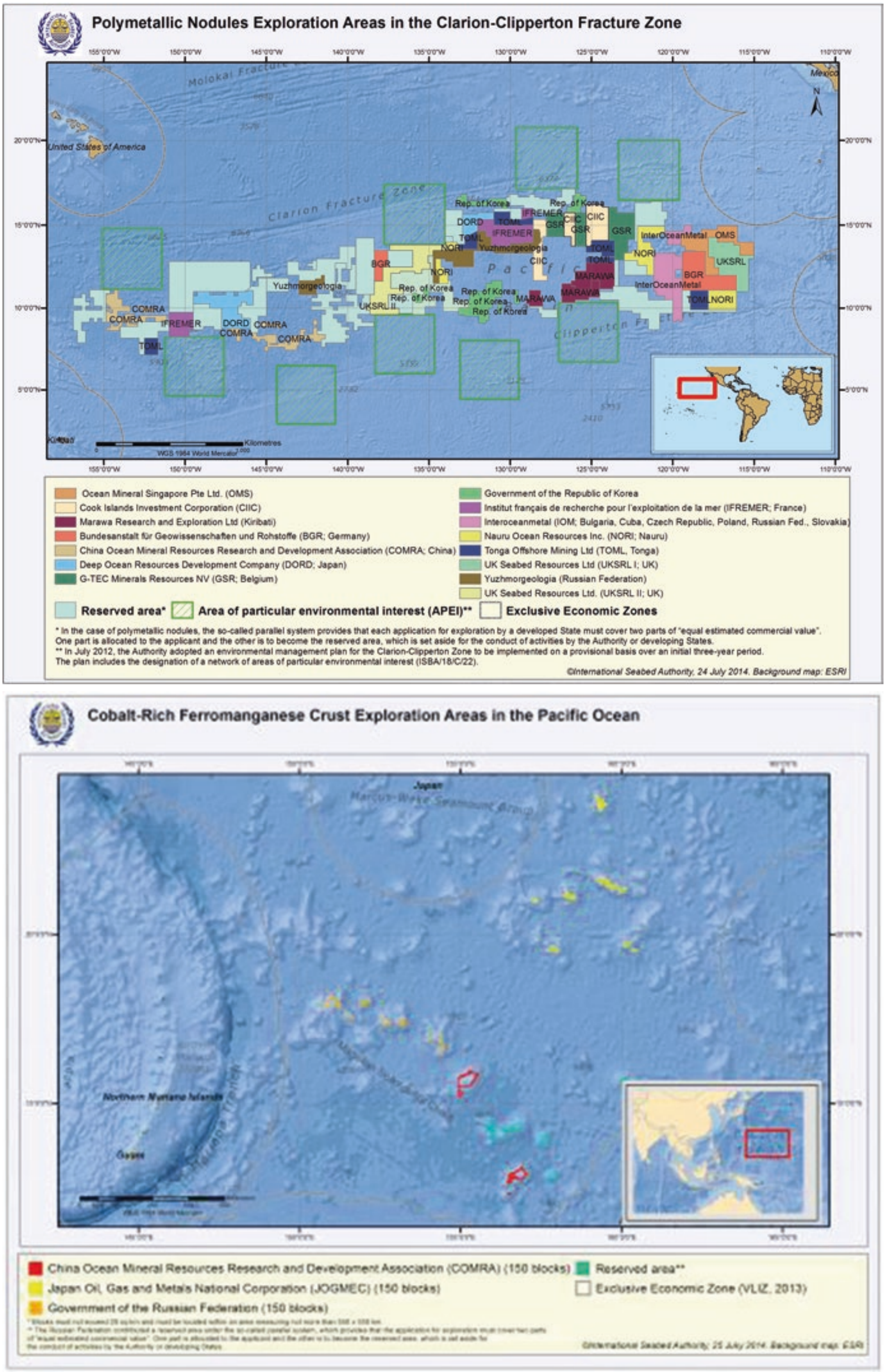


Fig. 1.2 (**a**) Map of exploration areas for polymetallic nodules in Pacific Ocean (www.isa.org.jm). (**b**) Map of exploration areas for ferromanganese crusts in Pacific Ocean (www.isa.org.jm). (**c**) Map of exploration areas for hydrothermal sulphides in Atlantic Ocean (www.isa.org.jm). (**d**) Map of exploration areas for polymetallic nodules and hydrothermal sulphides in Indian Ocean (www.isa.org.jm)

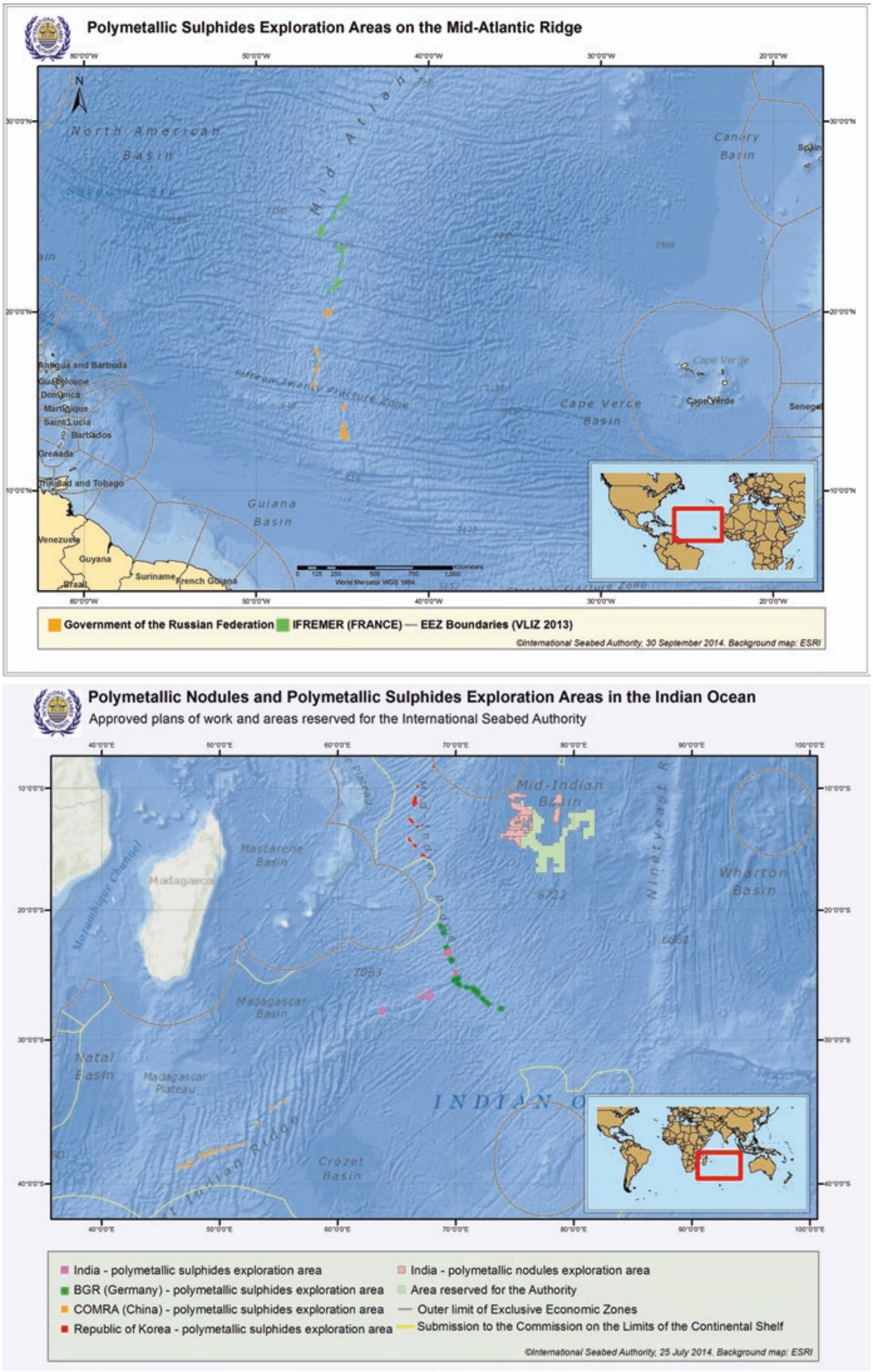


Fig. 1.2 (continued)

1.2 Economic Issues

Periodical evaluation of information on distribution and potential of deep-sea minerals as well as techniques for resource estimation and mining (Pearson 1975; Glasby 1977; Cronan 1980, 2000; UNOET 1982, 1987; Dick 1985; Kunzendorf 1986; Rona 2003) has kept the world's interest in these deposits alive, even leading to the preparation of a geological model for polymetallic nodules in the Clarion-Clipperton Fracture Zone of the Pacific Ocean (ISA 2009). 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 entrepreneurs for exploration of seafloor massive sulphides off Papua New Guinea and New Zealand (Gleason 2008) reaffirm the continuing interest of researchers and mining companies in exploring and exploiting the deep sea mineral deposits, indicating the possibility of gradually developing technologies for mining of marine minerals from relatively shallower deposits such as the crusts and sulphides (1000–2500 m) towards the deeper ferro-manganese nodules (4000–6000 m).

Fluctuating metal prices as well as factors such as recycling, new onshore deposits, and technological developments have stalled the commercial exploitation of these deposits, although these are considered important in the overall metal budget of the earth and constitute a substantial resource that would cover the twenty-first century demand for metals such as Mn, Fe, NI, Co, Cu, Mo, and many others including Rare Earth Elements (Kotlinski 2001). According to Lenoble (2000), the commercial viability of deep-sea deposits lies in their concentration compared to the currently mined deposits on land and also in their estimated magnitude. As per one estimate (Glumov et al. 2000), considering the present trends of mining ores with low metal grades, 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 in about 2020.

The decision to commence mining of any deep-sea mineral will depend on the availability of metals from terrestrial sources and their price in the world market, as well as the techno-economic analysis based on capital and operating costs of the deep-sea mining system. With each of the Contractors being allotted areas averaging several thousand square kilometers in international waters (ISA 1998), considering the resource potential in a typical area of 75,000 km^2. for polymetallic nodules and their cut off abundance (5 kg/m^2) as specified by UNOET (1987), the total resource available in the area could be 375 Mt (wet) or 281.25 Mt (dry) with a total metal equal to 67.081 Mt (Table 1.2), at a conservative value of concentration of metals (Mn = 22%, Ni = 1.0%, Cu = 0.78%, Co = 0.1%). Out of the 281.25 Mt, only 10.6–21.2% (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 (78.8–89.4%) to be mined in future.

The total annual production of metals would range from 0.358 Mt/year (for 1.5 Mt/year) to 0.716 Mt/year (for 3 Mt/year). Considering average metal prices

Table 1.2 Resource potential and metal production estimates—a hypothetical case study

Nodule/ metal	Mean concentr-ation[a]	Resource potential t (Mt)[b]	Metal production per year t (Mt) @ 1.5 Mt/year @ 3 Mt/year		Price of metal ($/Kg)[c]	Gross in-place value of metal $/year @ 1.5 Mt/year @ 3 Mt/year		Gross in-place value of metal $/20 years @ 1.5 Mt/year @ 3 Mt/year	
Wet nodules	–	375,000,000 (375)	–	–	–	–	–	–	–
Dry nodules	25% of wet nodules[d]	281,250,000 (281.25)	–	–	–	–	–	–	–
Manganese	22/24% of dry nodules	61,800,000 (61.8)	330,000 (0.33)	660,000 (0.66)	1.32	435,600,000 (435.6 million)	871,200,000 (871.2 million)	8.712 billion	17.424 billion
Nickel	1.0/1.1% of dry nodules	2,810,750 (2.81)	15,000 (0.015)	30,000 (0.030)	23.00	345,000,000 (345.0 million)	690,000,000 (690 million)	6.90 billion	13.80 billion
Copper	0.78/1.04% of dry nodules	2,190,000 (2.19)	11,700 (0.0117)	23,400 (0.0234)	8.30	97,110,000 (97.11 million)	194,220,000 (194.22 million)	1.9422 billion	3.8844 billion
Cobalt	0.23/0.1% of dry nodules	281,250 (0.281)	1500 (0.0015)	3000 (0.003)	39.20	58,800,000 (58.8 million)	117,600,000 (117.6 million)	1.176 billion	2.352 billion
Total (metals)	24.01/26.24%	67,081,000 (67.081)	358,200 (0.3582)	716,400 (0.7164)	–	936,510,000 (936.51 million)	187,302,000 (1873.02 million)	18.7302 billion	37.460 billion

[a] Source: Morgan (2000) for Clarion-Clipperton Zone in Pacific Ocean/Jauhari and Pattan (2000) for Central Indian Ocean

[b] @5 kg/m^2 for 75,000 km^2 (75×10^9 m^2) considering the lower value of concentration of metals between Pacific and Indian Ocean (in col. 2)

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

[d] Mero (1977)

for a given period (www.metalprices.com (2011)), the value of total metals produced annually will be \$936.5 million, with a total yield of about \$18.73 billion in 20 years from a single mine-site at 1.5 Mt/year mining rate. The same would be double (i.e. \$1873 million/year, or ~\$37.46 billion in 20 years) for a mining rate of 3 Mt/year (Table 1.2). Here it must be noted that these estimates are based on minimum value of metals and also lowest value of abundance and so the actual returns could be much higher as the in-situ average abundances are normally expected to be higher than the cut off (i.e. 5 kg/m^2) and also the concentrations of metals could be higher in the potential mine-sites than that considered here as have been reported in the Pacific Ocean (Herrouin et al. 1991).

In spite of such a potential, most of the deep-sea mineral deposits can only be termed as 'resources' (and not 'reserves') as they cannot be economically recovered under prevailing economic conditions, but may be exploitable in the foreseeable future and such resources could become economic when price and market conditions or new technologies increase the profit margin to acceptable levels (UNOET 1987). According to estimates, the cost of different types of collectors, power generation, and risers, as proposed by different Contractors that are involved in developing technology for mining at 1.5 Mt of nodules annually, shows a capital expenditure of \$372–562 million and an operating cost of \$69–96 million/year. Added to this would be the capital expenditure for purchasing three vessels for ore transfer 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 cost of \$250 million (ISA 2008a). Even if we consider 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 1.3), which when compared with the total yield of metals worth \$18.73 billion (Table 1.2) may seem promising.

However, in order to 'fix' the timing for commencement of deep-sea mining, a detailed economic study looking at the CAPEX and OPEX with respect to production rates and metal values is required to arrive at an optimum mining rate. Most of the earlier studies conducted in 1970s and 1980s based on conditions existing at that time suggested that processing of 3 Mt/year could be less costly per tonne of nodules (UNOET 1987). Calculations had also shown that mining of 3 Mt/year using a single ship was not viable, except in case of higher nodule abundances, higher ship speed, or larger dredge head (Glasby 1983). Earlier estimates for a 2 Mt/year operation,

Table 1.3 Estimated capital and operating expenditures for polymetallic nodules mining [figures in brackets show the range for different systems as proposed by different Contractors (ISA 2008a)]

Item	Capital expenditures	Operating expenditures	Total
Mining system	\$550 mi[a] (\$372–562 mi)	\$100 mi/year[a] (\$69–96 mi) × 20 years = \$2.0 billion	\$2.55 billion
Ore transfer	\$600 mi[a] (\$495–600 mi)	\$150 mi/year[a] (\$93–132 mi/year) × 20 years = \$3.0 billion	\$3.60 billion
Processing plant	(\$750 mi)	(\$250 mi/year) × 20 years = \$5.0 billion	\$5.75 billion
Total	\$1.90 billion	\$10.0 billion	\$11.90 billion

[a] Rounded off to nearest 50 of the highest value

Source: Sharma (2011)

when the capital investment was estimated at $250 m and metal prices were significantly lower than considered here, showed the expected rate of return at 13% per year (Mero 1977). Alternative scenarios of mining operations from 1.2 to 3 million tonnes per year for a 20 year mine-life produced internal rates of return ranging from 14.9 to 37.8% (ISA 2008a). This scenario could undergo a change taking into consideration the techno-economic feasibility as well as metal markets.

1.3 Technical Issues

1.3.1 Delineation of Mine-Site and Estimation of Area for Mining

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. For example, the following criteria have been suggested for polymetallic nodules (UNOET 1987):

- Cut off grade = 1.8% Cu + Ni
- Cut off abundance = 5 kg/m^2
- Topography = acceptable
- Duration (D) = 20 years
- Annual recovery (A_r) = 3 million dry tonnes, which has been subsequently proposed as 1.5 million tonnes by ISA (2008a).

Using this information, the total mineable area (M) can be estimated as follows:

$$M = A_t - \left(A_u + A_g + A_a\right) \tag{1.1}$$

where, A_t = 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.

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

$$A_s = \frac{(A_r)(D)}{(A_n)(E)(M)} \tag{1.2}$$

where,

A_s = size of mine-site (km^2),
A_r = annual nodule recovery rate (dry tonnes/year),
D = duration of mining operation (years),
A_n = average nodule abundance in the mineable area,
E = overall efficiency of the mining device (%),
M = proportion of mineable area.

Higher the average abundance, smaller would be the size of the mine-site with respect to the allotted area that augers well with the concept of restricting the mining activities to a smaller area, especially from the point of environmental impacts.

1.3.2 Mining System Development

The overall efficiency (*E*) of a mining system would largely depend upon the collection efficiency of the dredge head that would sweep the seafloor to collect the minerals which is calculated as (UNOET 1987):

$$E = e_{\mathrm{d}} \times e_{\mathrm{s}}, \tag{1.3}$$

where,

e_{d} = dredge efficiency, which is the ratio of minerals effectively gathered by the dredge head, versus the minerals 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, 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 as compared to the hydraulic lift, which requires less power, allows higher transport densities, and hence needs smaller pipes for lifting the minerals, but is difficult to maintain due to under water pump system (Amann 1982). Given the high investment–high risk nature of the operations, future technology could consider deployment of a number of autonomous vehicles operating from the mining platform that would provide better operational and maintenance options, even from environmental point of view due to limited area of contact of these devices with the water column and the seafloor; and also in recovery or abandoning them in case of a mishap, as the mining platform and collection devices would be independent of one another (Sharma 2011).

Information available in public domain suggests that development of mining technology has been in different stages, including model studies and a few at-sea tests of crawlers and lifting mechanisms by the Contractors (Table 1.4). However, once these designs and prototypes are tested, 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 variable conditions, including extreme weather (rainfall, winds, and cyclones), hydrographical conditions (high pressure, low temperature, currents, and lack of natural light), and seafloor environment (undulating topography, sediment thickness, and heterogeneous distribution of deposits).

Application of new technology for exploration as well as mining, such as 3D sensing, autonomous navigation, robotic manipulators, and vehicles for the extreme environment adopted from space missions, could provide some of the solutions (Jasiobedzki et al. 2007). 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

Table 1.4 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	(a) Tested 3 possible routes
		(b) Pilot plant set up for 500 kg/day for Cu, Ni, Co	(b) Crawler tested at ~410 m depth in the sea
4	China[c]	(a) Includes rigid riser with self-propelled miner	Developed a process to recover Mn, Ni, Cu, Co, and Mo
		(b) Tried different concepts of collector and lifting mechanisms	
5	Korea[c]	(a) Design includes flexible riser system with self-propelled miner	(Not known)
		(b) Developed 1/20 scale test miner	
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)

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 could provide the much required technological support for development of sub-sea mining systems (Hill 2008).

Major research efforts have been concentrated on the development of collector and riser systems (Chung 2003), whereas very few studies have been conducted on the mining platform and ore handling or transfer at sea (Amann 1982; Ford et al. 1987; Herrouin et al. 1991) that have proposed possible designs, dimensions, and infrastructure required to support a deep-sea mining activity. This sector (mining platform and ore transfer) may 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.

1.3.3 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 1.4). According to a study 'the incremental capital requirement of manganese recovery (in addition to Cu, Ni, Co) in a four metal route over a three metal route was small enough to make a 1.5 Mt/year capacity plant economically viable' (ISA 2008b). Further, it has also been suggested that 'a three metal recovery system needed to operate at higher annual capacities, with 3 million dry tonnes per year; whereas, four metal systems with additional costs and revenues from manganese production can operate at half the capacity'. Finally, the decision of extracting three or four metals will depend on the metal prices, available technology, investment potential, and the returns expected from such investments. In terms of post-processing scenario, probably the least attention has been given to the disposal of material that will remain after extraction of metals. In case of polymetallic nodules, it amounts to large quantities of material (as high as 76% in case of four metals and 97.5% in case of three metals) for which due consideration is required for either disposing them or using them for any 'constructive' purpose (see Wiltshire 2000; Wiltshire, this issue).

1.4 Environmental Issues

1.4.1 Impact of Environment on Mining

Generally in case of any developmental activity, the issue of the impact of the activity on the environment occupies higher significance not realising that the component of 'environment' has a two-way implication. As in case of deep-sea mining, the activity in most likelihood would have an impact on the marine environment; the reverse, i.e. impact of environment on mining activity, is equally important because the prevailing conditions such as atmospheric, hydrographic, seafloor topography, mineral characteristics, and associated substrates at the mine-site would play a major role in the design and performance of different sub-systems of the mining system (Table 1.5). Hence, collection of environmental data would not only help in impact assessment after mining activity, but also play a key role in designing of the mining system as well as planning of the mining operation (Sharma 2011).

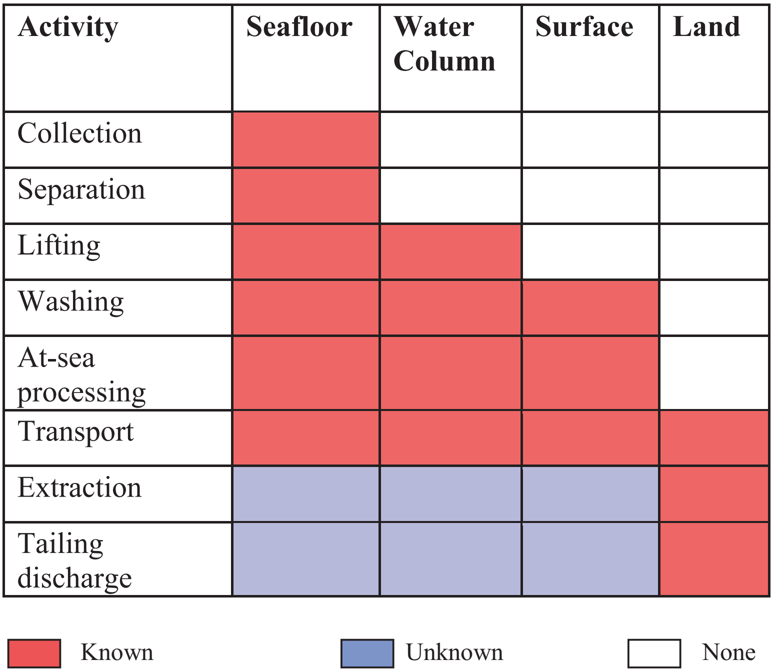
1.4.2 Impact of Mining on Environment

It is known that the areas likely to be affected by deep-sea mining would range from the surface and water column due to particles discharged (accidently or otherwise) during lifting, at-sea processing, and transportation (Pearson 1975; Amos et al. 1977) to the seafloor where the mineral will be separated from the associated substrate either due to scooping or drilling, leading to resuspension and redistribution of debris in the bottom water along the path of the collector device as well as in the vicinity of the mining tracks (Foell et al. 1990; Trueblood 1993; Fukushima 1995; Tkatchenko et al. 1996; Sharma and Nath 2000; Theil 2001; Sharma 2001, 2005) and the land due to metal extraction and tailing disposal (Fig. 1.3).

Table 1.5 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	Mineral characteristics (grade, size, abundance, morphology, distribution pattern)	Important for designing the mechanism for collection, crushing as well as screening of mineral 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

Source: Sharma (2011)



Activity	Seafloor	Water Column	Surface	Land
Collection	🟥	⬜	⬜	⬜
Separation	🟥	⬜	⬜	⬜
Lifting	🟥	🟥	⬜	⬜
Washing	🟥	🟥	🟥	⬜
At-sea processing	🟥	🟥	🟥	⬜
Transport	🟥	🟥	🟥	🟥
Extraction	🟦	🟦	🟦	🟥
Tailing discharge	🟦	🟦	🟦	🟥

🟥 Known 🟦 Unknown ⬜ None

Fig. 1.3 Areas likely to be affected due to different activities of deep-sea mining

The first impact assessment study for deep-sea mining was during two of the pilot mining tests under the Deep Ocean Mining Environment Study (DOMES, 1972–1981) conducted by Ocean mining Inc. (OMI) and Ocean mining Associates (OMA) in the Pacific Ocean (Ozturgut et al. 1980). Subsequently, several experiments have been conducted by Contractors 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 1.6). Their results have shown that the scale of these experiments was significantly smaller than that expected during commercial mining (Yamazaki and Sharma 2001). Syntheses of the results of these experiments have revealed the need for several improvements for conducting similar experiments in future (Morgan et al. 1999). An engineering and environmental assessment of deep-sea mining has suggested to 'test benthic disturbance in scale and system large enough to represent the commercial mining scale' (Chung et al. 2001).

Table 1.6 Basic data of Benthic Impact Experiments (BIEs) for assessing potential environmental impact of nodule mining

Experiment	Conducted by	Area	Tows	Duration	Area/distance	Discharge[a]
DISCOL[b]	Hamburg University, Germany	Peru Basin	78	~12 days	10.8 km^2	–
NOAA-BIE[c]	National Oceanographic & Atmospheric Administration, USA	Clarion Clipperton Fracture Zone	49	5290 min	141 km	6951 m^3
JET[d]	Metal mining Agency of Japan	Clarion Clipperton Fracture Zone	19	1227 min	33 km	2495 m^3
IOM-BIE[e]	Inter Ocean Metal–consortium of East Europen Countries	Clarion Clipperton Fracture Zone	14	1130 min	35 km	2693 m^3
INDEX[f]	National Institute of Oceanography, Govt. Of India	Central Indian Ocean Basin	26	2534 min	88 km	6015 m^3

Source:

[a] Yamazaki and Sharma (2001)

[b] Foell et al. (1990)

[c] Trueblood (1993)

[d] Fukushima (1995)

[e] Tkatchenko et al. (1996)

[f] Sharma and Nath (2000)

1.5 Policy Issues

A deep-sea mining venture requires the implementation of several components starting with ‘Exploration and resource estimation’ followed by ‘Technology development’ for mining and metallurgical processing, and ‘Environmental’ component so as to establish baseline conditions, undertake impact assessment and monitoring, leading to development of environmental management plan. The final execution of the project would depend on a ‘Techno-economic assessment’ as well as ‘Legal’ framework in order to guide the decisions and actions for implementation on the basis of inputs received from other components. Activities under each of these components could initially be independent of each other, but a close networking among these is required to execute the project.

In view of many of the deep-sea mineral deposits occurring in the international waters, any commercial activity related to them could have global implications for which 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 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); beginning with the notification of the plan of work for exploration of the Pioneer Investors and the area allotted to them (ISA 1998) to 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). Through a series of international workshops, 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 International Marine Minerals Society has also prepared a code for environmental management for marine mining, which provides a framework for development and implementation of an environmental program for a marine exploration and extraction site by marine mining companies and for other stakeholders in evaluating such programs (www.immsoc.org/IMMS_code.htm (2011)).

Deep-sea mining is 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 well as the Contractors to adopt such guidelines and gear themselves up for a sustained development of this common heritage of mankind.

Acknowledgments Author gratefully acknowledges the permission given by Secretary General, International Seabed Authority, Jamaica, for reproducing the maps from website.

References

Amann H (1982) Technological trends in ocean mining. Philos Trans R Soc:377–403

Amos AF, Roels OA, Garside C, Malone TC, Paul AZ (1977) Environmental aspects of nodule mining. In: Glasby GP (ed) Marine manganese deposits. Elsevier, Oxford, pp 391–438

Banakar VK, Hein JR, Rajani RP, Chodankar AR (2007) Platinum group elements and gold in ferromanganese crusts from Afanasiy-Nikitin seamount, equatorial Indian Ocean: sources and fractionation. J Earth Sys Sc 116:3–13

Chung JS (2003) Deep-ocean mining technology: learning curve I. In: Proceedings of ISOPE-ocean mining symposium, International Society for Offshore and Polar Engineers, Tsukuba, Japan, pp 1–16

Chung JS, Schriever G, Sharma R, Yamazaki T (2001) Deep seabed mining environment: engineering and environment assessment. In: Proceedings of ISOPE–ocean mining symposium, International Society for Offshore and Polar Engineers, Szcecin, Poland, pp 8–14

Cronan DS (1980) Underwater minerals. Academic Press, London, p 362

Cronan DS (ed) (2000) Marine mineral deposits handbook. CRC Press, Boca Raton, p 406

Cronan DS, Moorby SA (1981) Manganese nodules and other ferromanganese oxide deposits from the Indian Ocean. J Geol Soc Lond 138:527–539

Dick R (1985) Deep-sea mning versus land mining: a cost comparison. In: Donges JB (ed) The economics of deep-sea mining. Springer-Verlag, Berlin, Germany, pp 2–60

Exon NF, Raven MD, De Carlo EH (2002) Ferromanganese nodules and crusts from the Christmas region, Indian Ocean. Mar Georesour Geotechnol 20:275–297

en.wikipedi.org/wiki/HMSChallenger. Information on HMS Challenger expedition 1873–1876.

Frazer JZ, Fisk MB (1981) Geological factors related to characteristics of seafloor manganese nodule deposits. Deep-Sea Res 28A:1533–1551

Frazer JZ, Wilson LL (1980) Nodule resources in the Indian Ocean. Mar Min 2:257–256

Foell EJ, Thiel H, Schriever G (1990) DISCOL: a long-term, large-scale, disturbance-recolonization experiment in the abyssal eastern tropical South Pacific Ocean. In: Proceedings of offshore technology conference, International Society for Offshore and Polar Engineers, Houston, pp 497–503

Ford G, Niblett C, Walker L (1987) The future for ocean technology. Frances, London, 139 pp

Fukushima T (1995) Overview Japan Deep-Sea impact experiment=JET. In: Proceedings of ISOPE ocean mining symposium. International Society for Offshore and Polar Engineers, Tsukuba, Japan, pp 47–53

Glasby GP (1972) Geochemistry of manganese nodules from the Northwest Indian Ocean. In: Horn DR (ed) Ferromanganese deposits on the ocean floor. National Science Foundation, Washington, pp 93–104

Glasby GP (ed) (1977) Marine manganese deposits. Elsevier, Amsterdam, p 523

Glasby GP (1982) Manganese nodules from the South Pacific: an evaluation. Mar Min 3:231–270

Glasby GP, Stoffers P, Sioulas A, Thijssen T, Friedrich G (1982) Manganese nodules formation in the Pacific Ocean: a general theory. Geo-Mar Lett 2:47–53

Glasby GP (1983) The three-million-tons-per-year manganese nodule "Mine Site": an optimistic assumption? Mar Min 4:73–77

Gleason WM (2008) Companies turning to seafloor in advance of next great metals rush. Min Engg April 2008:14–16

Glumov IF, Kuzneicov KM, Prokazova MS (2000) Ocenka znaczzenija mineralych resursov meidunarod nogo rajona morskogo dna w mineralno syriewom potenciale Rossijskoj Federacii (in Russian). In: Proceedings of geological congress, St. Petersburg, pp 27–29

Halbach P, Sattler CD, Teichmann F, Wahsner M (1989) Cobalt rich and platinum bearing manganese crust deposits on seamounts: nature, formation and metal potential. Mar Min 8:23

Halkyard J (2008) Paper presented in Workshop on polymetallic nodule mining technology: current status and challenges ahead, Chennai, India (Sept. 2008). International Seabed Authority, Jamaica

Hein JR, Yeh H-W, Alexander E (1979) Origin of iron-rich montmorillonite from the manganese nodule belt of the north equatorial Pacific. Clay Clay Miner 27:185–194

Hein JR, Kochinsky A, Halbach P, Manheim FT, Bau M, Kang J-K, Lubick N (1997) Iron and manganese oxide mineralisation in the Pacific. In: Nicholon K, Hein JR, Buhn B, Dasgupta S (eds) Manganese mineralisation: geochemistry and mineralogy of terrestrial and marine deposits. Geological Society Special Publication No. 119, London, p 123

Hill T (2008) Paper presented in workshop on polymetallic nodule mining technology: current status and challenges ahead, Chennai, India, Sept 2008. International Seabed Authority, Jamaica

Herrouin G, Lenoble JP, Charles C, Mauviel F, Bernard J, Taine B (1991) French study indicates profit potential for industrial manganese nodule venture. Trans Soc Min Metall Explor 288:1893–1899

International Marine Minerals Society (2011) Code for environmental management of marine mining. www.immsoc.org/IMMS_code.htm

International Seabed Authority (2016) Areas allotted to Contractors and Reserved areas in the Pacific Ocean, Atlantic Ocean and Indian Ocean. www.isa.org.jm

ISA (1998) Plans of work of exploration of Govt. of India, Inst. Francais de Researche pour L'exploration de la mer, Deep Ocean Resources Development Co. Japan, Yuzhmorgeologiya Russia, China Ocean Mineral Resources R & D Association, Interoceanmetal Joint Organisation, and Govt. of Republic of Korea. Report of the Secretary General, International Seabed Authority, Jamaica. ISBA/4/A/1/Rev.2

ISA (2000) Decision of the assembly relating to the regulations on prospecting and exploration for polymetallic nodules in the Area. ISBA/6/A/18, International Seabed Authority, Jamaica, p 48

ISA (2001) Recommendations for guidance of contractors for the assessment of the possible environmental impacts arising from exploration for polymetallic nodules in the Area. International Seabed Authority, Jamaica. ISBA/7/LTC/1 2001; pp 11.

ISA (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 exploration. ISBA/11/LTC/2 2005, International Seabed Authority, Jamaica, p 26

ISA (2008a) Report on the International Seabed Authority's workshop on Polymetallic nodule mining technology: current status and challenges ahead. ISBA/14/LTC/3, International Seabed Authority, Jamaica, p 4

ISA (2008b) Executive summary of the International Seabed Authority's workshop on Polymetallic nodule mining technology: current status and challenges ahead. International Seabed Authority: Chennai, India, p 20

ISA (2009) A geological model for polymetallic nodules in Clarion-Clipperton Fracture Zone. Technical Report No. 6, International Seabed Authority, Jamaica, p 211

Jasiobedzki P, Corcoran R, Jenkin M, Jakola R (2007) From space robotics to deep seabed mining. In: Proceedings of 37th Underwater Mining Institute. International Marine Minerals Society, Tokyo, Japan, pp J1–11

Jauhari PJ, Pattan JN (2000) Ferromanganese nodules from the Central Indian Ocean Basin. In: Cronan DS (ed) Handbook of marine mineral deposits. CRC Press, Boca Raton, pp 171–195

Kotlinski R (2001) Mineral resources of the world's ocean—their importance for global economy in the 21st century. In: Proceedings of 4th ISOPE ocean mining symposium, International Society for Offshore and Polar Engineers, Szczecin, Poland, pp 1–7

Kunzendorf H (1986) Marine mineral exploration. Elsevier Science Publications, Amsterdam, 300 p

Lenoble JP (2000) A comparison of possible economic returns from mining deep-sea polymetallic nodules, polymetallic massive sulphides and cobalt-rich ferromanganese crusts. In: Proceedings of workshop on mineral resources. International Seabed Authority, Jamaica, pp 1–22

Markussen JM (1994) Deep seabed mining and the environment: consequences, perception and regulations. In: Bergesen H, Parmann G (eds) Green Globe Yearbook of international cooperation on environment and development. Oxford University Press, London, pp 31–39

Martin-Barajas A, Lallier-Verges E, Lecraire L (1991) Characteristics of manganese nodules from the Central Indian Basin: relationship with sedimentary environment. Mar Geol 101:249–265

Metals prices for Cu, Ni, Co, Mn for 5 years (July 2011). www.metalprices.com

Mero JL (1965) The mineral resources of the sea. Elsevier, Amsterdam, The Netherlands, 312 pp

Mero JL (1977) Economic aspects of nodule mining. In: Glasby GP (ed) Marine manganese deposits. Elsevier, Amsterdam, The Netherlands, pp 327–355

Morgan C (2000) Resource estimation of the Clarion-clipperton manganese nodule deposits. In: Cronan DS (ed) Handbook of marine mineral deposits. CRC Press, Boca Raton, pp 145–170

Morgan CL, Odunton N, Jones AT (1999) Synthesis of environmental impacts of deep seabed mining. Mar Georesour Geotechnol 17:307–357

Ozturgut E, Lavelle JW, Steffin O, Swift SA (1980) Environmental investigation during manganese nodule mining tests in the north equatorial pacific, in November 1978. NOAA Tech. Memorandum ERL MESA-48, National Oceanic and Atmospheric Administration, p 50

Pearson JS (1975) Ocean floor mining. Noyes Data Corporation, Park Ridge, NJ, 201 pp

Rao VP, Nath BN (1988) Nature, distribution and origin of clay minerals in grain size fractions of sediments from manganese nodule field, Central Indian Ocean Basin. Ind J Mar Sci 17:202–207

Plueger WL, Herzig PM, Becker K-P, Deissmann G, Schops D, Lange J, Jenisch A, Ladage S, Richnow HH, Schultz T, Michaelis W (1990) Dicovery of the hydrothermal fields at the Central Indian Ridge. Mar Min 9:73

Rona PA (1988) Hydrothermal mineralisation at oceanic ridges. Can Mineral 26:431

Rona PA (2003) Resources of the ocean floor. Science 299:673–674

Sharma R (2011) Deep-sea mining: economic, technical, technological and environmental considerations for sustainable mining. Mar Technol Soc J 45:28–41

Sharma R, Nath BN (eds) (2000) Indian BIE: Indian Deep-sea Environment Experiment (INDEX). Mar Georesour Geotechnol 18:177–294

Sharma R (ed) (2001) Indian deep-sea environment experiment (INDEX): a study for environmental impact of deep seabed mining in Central Indian Ocean. Deep-Sea Res II 48:3295–3426

Sharma R (ed) (2005) Indian deep-sea environment experiment (INDEX): monitoring the restoration of marine environment after artificial disturbance to simulate deep-sea mining in Central Indian Basin. Mar Georesour Geotechnol 23:253–427

Siddiquie HN, Das Gupta DR, Sen Gupta NR, Shrivastava PC, Mallik TK (1978) Manganese-Iron nodules from the Indian Ocean. Ind J Mar Sci 7:239–253

Theil H (ed) (2001) Environmental impact study for mining of polymetallic nodules from the deep sea. Deep-Sea Res II 48:3427–3882

Thijssen T, Glasby GP, Schmitz WA, Friedrich G, Kunzendorf H, Muller D, Richter H (1981) Reconnaissance survey of Manganese Nodules from the Northern Sector of the Peru Basin. Mar Min 2:385–428

Tkatchenko GG, Radziejewska T, Stoyanova V, Modlitba I, Parizek A (1996) Benthic Impact experiment in the IOM pioneer area: testing for effects of deep seabed disturbance. In: Proceedings of International Semimar on deep seabed mining technology. China Ocean Minerals R&D Association, Beijing, China, pp C55–C68

Trueblood DD (1993) US cruise report for BIE II cruise. Techical Memorandum No. OCRS 4, National Oceanic and Atmospheric Administration, Washington, p 51.

UN (1990) Draft regulations on prospecting, exploration and exploitation of polymetallic nodules in the Area. Part VIII. Protection and preservation of the marine environment from activities in the Area. Working paper by Secretariat, UNODC. LOC/PCN/SCN3/WP6/add.5

UNOET (1982) Assessment of manganese nodule resources. UN Ocean Economics and Technology Branch and Graham & Trotman Limited London, 79pp

UNOET (1987) Delineation of mine sites and potential in different sea areas. UN Ocean Economics and Technology Branch and Graham & Trotman Limited, London, 79pp

Usui A, Matsumoto K, Sekimoto M, Okamoto N (2003). Geological study of cobalt-rich ferromanganese crusts using a camera-monitored drill machine in the Marshall Islands Area. In: Proceedings of ISOPE-Ocean Mining symposium, International Society for Offshore and Polar Engineers, Tsukuba, pp 12–15

Usui A, Moritani T (1992) Manganese nodule deposits in the Central Pacific Basin: distribution, geochemistry and genesis. In: Keating BH, Bolton BR (eds) Geology and offshore mineral resources of the Central Pacific Basin, Earth Science series, vol 14. Springer, New York, pp 205–223

Wiltshire JC (2000) Innovation in marine ferromanganese oxide tailings disposal. In: Cronan DS (ed) Handbook of marine mineral deposits. CRC Press, Boca Raton, pp 281–308

Yamada H, Yamazaki T (1998) Japan's ocean test of the nodule mining system. In: Proceedings of international offshore and polar engineering conference. International Society for Offshore and Polar Engineers, Montreal, Canada, pp 13–19

Yamazaki T, Sharma R (2001) Estimation of sediment properties during benthic impact experiments. Mar Georesour Geotechnol 19:269–289

Dr. Rahul Sharma (rsharma@nio.org, rsharmagoa@gmail.com) has been working as a Scientist at the CSIR-National Institute of Oceanography in Goa, India and has led a multidisciplinary group on 'Environmental studies for marine mining'. He has a master's degree in Geology and a doctorate in Marine Science. His professional interests include application of exploration and environmental data to deep-sea mining. He has edited three special issues of scientific journals, one symposium proceeding, published 35 scientific papers, 20 articles, and presented 50 papers at international symposia.

His international assignments include Visiting Scientist to Japan, Visiting Professor to Saudi Arabia, member of the UNIDO mission 'to assess the status of deep-sea mining technologies' in Europe, USA and Japan, invited speaker and consultant for the International Seabed Authority, Jamaica, and has contributed to the 'World Ocean Assessment report I' of the United Nations.