Chapter 2
Approach Towards Deep-Sea Mining: Current Status and Future Prospects

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Abstract Deep-sea mineral resources within and beyond the national jurisdictions offer several opportunities for exploration and possible exploitation owing to their potential as alternate source of metals such as Ni, Cu, Co, rare earths and others. These are considered critical for meeting mankind's increasing demands including that of transitioning to green energy in view of depleting or low-grade terrestrial deposits. Currently, several studies are underway for evaluating the economic and potential benefits of mining the deep-seabed minerals as well as developing suitable technologies for their exploitation, on one hand, and also for assessing the ecological risks, suggesting ecosystem-based management approach and developing relevant regulations for deep-sea mining, on the other. This chapter aims to put into perspective the current status and future prospects of deep-sea mining.

Keywords Marine minerals · Deep-sea mining · Techno-economic and environmental considerations · Comparison with land mining

1 Introduction

What probably started as a 'chance' discovery onboard HMS Challenger (21 December 1872 to 24 May 1876), described by the expedition leader C.W. Thompson as 'peculiar black bodies about 1" long' and the onboard chemist J.Y. Buchanan revealing that they were 'almost pure manganese oxide' (en.wikipedia.org./HMS Challenger); eventually got its due recognition when Mero (1965) unravelled the economic potential of deep-sea polymetallic nodules, predicting that given the sudden demand for metals after the world wars, deep-sea mining would commence in 20 years. This led to global efforts by research organisations such as the Lamont Doherty Geological Laboratory in 1972 to collate available data on nodules,

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followed by studies on their distribution characteristics, geochemistry, mineralogy and growth rates in the Pacific Ocean (Hein et al. 1979; Thijssen et al. 1981; Glasby 1982; Usui and Moritani 1992) as well as Indian Ocean (Glasby 1972; Siddiquie et al. 1978; Frazer and Wilson 1980; Cronan and Moorby 1981). Simultaneously, studies were also conducted on nodule formation process, the associated geological factors, and their relation with sedimentary environment (Cronan 1980; Frazer and Fisk 1981; Glasby et al. 1982; Rao and Nath 1988; Martin-Barajas et al. 1991). It was around the same time that researchers also started evaluating other deep-sea minerals such as hydrothermal sulphides (Rona 1988; Plueger et al. 1990) as well as ferromanganese crusts (Halbach et al. 1989; Hein et al. 1997).

Typically, polymetallic nodules, hydrothermal sulphides and ferromanganese crusts are characterised as deep-sea minerals owing to their occurrence in water depths ranging from 1000 to 6000 m each one having some common and some distinct characteristics (Table 2.1). Whereas the polymetallic nodules (also called as

Table 2.1 Salient features of deep-sea minerals (Sharma and Smith 2019)

Type	Description	Area, thickness of the deposit	Metals and their mean concentration[a]	Principal deposits
Polymetallic nodules	Concretions of layered iron and manganese oxides with associated metals from the water column or sediment	Up to thousands of km^{2}., thickness generally up to 50 cm, rarely deeper	Mn (28.4%), Ni (1.3 %), Cu (1.07%), Co (2098 ppm), Mo (590 ppm), Zn (1366 ppm), Zr (307 ppm), Li (131 ppm), Pt (128 ppm), Ti (199 ppm), Y (96 ppm), REEs (813 ppm)	Clarion-Clipperton Zone, Peru Basin, Central Indian Ocean and Penrhyn Basin
Seafloor Massive Sulphides (SMS)	Concentrated deposits of sulphidic minerals (>50–60%) resulting from hydrothermal activity on the seabed	Up to several km^{2}; several metres thick	Cu (0.8–17.9%), Au (0.4–13.2 ppm), Ag (64–1260 ppm), Zn (2.7–17.5%), Pb (0.02–9.7%), Co, As, Al, Si, REEs	Red Sea, back-arc basins, mid-oceanic ridges and other plate boundaries, oceanic hotspots (intra-plate volcanoes)
Ferromanganese crusts	Layered manganese and iron oxides with associated metals on hard substrate rock of subsea mountains and ridges	Up to several km^{2}; generally few cm thick	Mn (21%), Co (6647 ppm), Ni (4326 ppm), Cu (573 ppm), Te (34 ppm), Mo (431 ppm), Zr (423 ppm), Ti (TiO_2, 1.4%), Pt (0.273 ppm), W (68 ppm), REEs (1628 ppm)	Equatorial Pacific Ocean and Central Atlantic Ocean

Modified from Cuyvers et al. (2018)

[a] Concentrations for sulphides from Cherkashov 2017, nodules from Hein et al. 2013, crusts from Halbach et al. (2017)

Fig. 2.1 Polymetallic nodules at the pelagic basin near the Takuyo-Daigo seamount, NW Pacific basin (JAMSTEC Cruise KR16-13#704, at 5490 m depth); width: approximately 2.0 m. (Photograph courtesy of Prof. A. Usui, Kochi University, Japan)

manganese nodules) are layered concretions of iron and manganese oxides around a nucleus (generally a sediment particle, rock piece, shark tooth or any hard substrate) loosely lying as spherical objects on abyssal plains (Kuhn et al. 2017 and the references therein); the ferromanganese crusts (also called as cobalt-rich ferromanganese crusts) are layered iron and manganese oxides on hard substrate of a rock (Cherkashov 2017 and the references therein) located on underwater mountains or ridges, both containing various metals precipitated from the water column or the associated substrates. The hydrothermal sulphides (also called as seafloor massive sulphides) are rich in sulphide minerals deposited from hydrothermal activity on the seafloor along mid-oceanic ridges or subduction zones (Halbach et al. 2017 and the references therein). Nodule deposits (Fig. 2.1) are spread over thousands of square kilometres generally within the top 50 cm of the sediment (sometimes up to a few metres deeper); whereas sulphides (Fig. 2.2) and crusts (Fig. 2.3) have an areal extent up to several square kilometres with their thickness ranging from few centimetres (for crusts) to several meters (for sulphides). Each of these has varying metal concentrations of major, minor and trace elements (Table 2.1); some of which (Ni, Cu, Co, REEs and others) being considered critical for meeting the global demands of these metals in future (Van Nijen et al. 2018; Hein et al. 2020).

Many of these deposits are located in international waters, beyond the national jurisdiction of any country, referred to as the ‘Area’ (UNCLOS 1982). International Seabed Authority (ISA), established under Part XI of UN Law of the Sea to administer seabed resources in the Area, has issued regulations for exploration of all the three types of deep-sea mineral deposits, i.e. polymetallic nodules (ISA 2010a, 2013a), hydrothermal sulphides (ISA 2010b) and ferromanganese crusts (ISA 2012) and is in the process of preparing guidelines for their exploitation in future (ISA 2019a, 2019b).

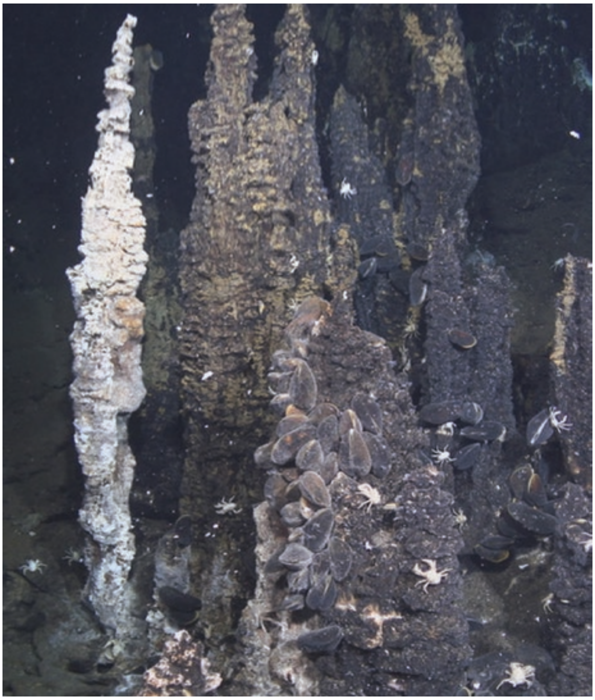


Fig. 2.2 Hydrothermal sulphide chimneys with black smokers, biological communities and microbial mats, at the Kita-Bayonnaise Caldera, Izu-Bonin Arc (JAMSTEC Cruise NT13–05 #1494 at 1370 m depth); width: approximately 2.0 m. (Photograph courtesy of Prof. A. Usui, Kochi University, Japan)

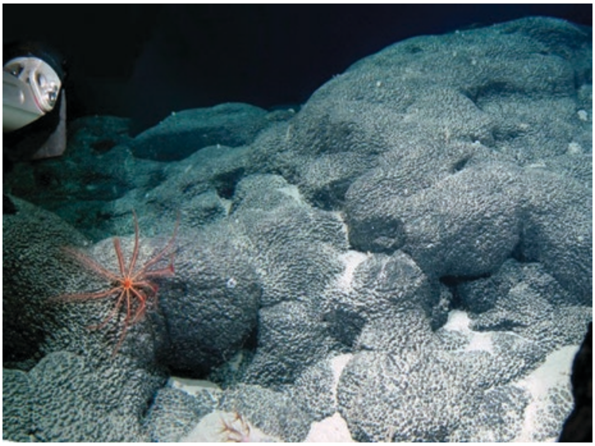


Fig. 2.3 Ferromanganese crusts near the summit of the Takuyo-Daigo seamount, NW Pacific basin (JAMSTEC Cruise KR09-02#955, at 1449 m depth); width: approximately 1.5 m. (Photograph courtesy of Prof. A. Usui, & B. Thornton)

2 Uses and Potential of Deep-Sea Mineral Deposits

The metals found in deep-sea minerals have a variety of applications in mechanical, chemical, metallurgical, electrical as well as electronic industries for products ranging from machines and motors to electric transmission, alloys and electroplating to batteries, pigments and catalysts, as well as biomedical and consumer goods (Table 2.2). During recent years, the increase in the production rate of these metals ranging from 1.1% (for Au) to 8.3% (for Co) and because the reserves of these are depleting in terrestrial deposits, there is a growing need for finding alternative sources for metals such as Ni, Cu, Cd, Li and others. Estimates based on world terrestrial reserves and production rates have shown that the available reserves of some of the metals such as Mn, Cu, Ni and Co would last for just over two decades whereas Pb and Zn would last over one decade (Sharma et al. 2019). Given the significance of these in various industrial applications as well as consumer goods production, the world needs to either find new natural resources or synthetically produce them or else discover new materials that can replace these metals.

Some of these are key metals for manufacturing of batteries required for the world to switch to green energy alternatives (Hein et al. 2020; Cronan 2022, this book). Besides increase in metal demands due to industrial growth and rising living standards, the need to transition the energy, transport and industrial infrastructure from fossil fuel to green and renewable energy options, such as solar and wind farms, electric car batteries and high-capacity energy storage devices, will require millions of tonnes of metals (including Mn, Ni, Cu and Co) that can be derived from deep-seabed minerals (http://deep.green.com). The European Union has identified 27 critical raw materials (CRM), whereas the USGS has updated a list of 35 CRMs that are essential for their economic and sustainable development (Hein et al. 2020). As the supply of many of these CRMs is controlled by selected countries, e.g. 60% of raw Co comes from Democratic Republic of Congo and is a critical component in lithium-ion batteries, whereas 80% of refined Co comes from China (Al Barazi et al. 2018), several countries have embarked upon exploration for deep-sea minerals to become self-reliant.

Estimates of metal resources in nodule deposits in Clarion Clipperton Zone (CCZ) in the Pacific Ocean alone suggest that some of the key metals such as Mn, Ni, Co Y are higher by 1.15 to 3.4 times than the entire global resources on land (Hein et al., 2020), indicating the potential of deep-sea minerals as alternative source for some of these metals. Besides these minerals, deep-sea sediments have also been identified as a source for rare earth elements, as found near Minami-Torishima island in western North Pacific Ocean with an estimated resource of 1.2 Mt. of rare earth oxide that accounts for 62, 47, 32 and 56 years of annual global demand of Y, Eu, Tb and Dy, respectively, that can be exploited as REY resource in future (Takaya et al. 2018).

Table 2.2 Uses and status of key metals found in deep-sea minerals (Sharma and Smith 2019)

Metal	Main uses	World reserves on land in 2018 (https://www.usgs.gov)	Production rate in 2016 (https://www.usgs.gov)	Increase in production rate per year (%)
Mn	Metallurgy, aluminium alloys, reagent in organic chemistry, batteries and coinage (https://en.wikipedia.org)	680 mill t (Manganese content in ore)	15,700 thousand t	4.3
Fe	Metallurgy, industry, alloys, automobiles, machines, trains, ships, buildings and glass (https://en.wikipedia.org)	83,000 mill t (Iron content in ore)	1450 mill t (Iron content of usable ore)	5.1
Cu	Electric energy transmission (26%), electric motors (12%), traction motor (9%), household heating appliances (8%), data transfer/communication (5%), architecture and consumer goods (10%), water supply (13%), mechanical components (6%), electronic contact/heat conduction (3%), car wiring (5%) and other (3%) (Zepf et al. 2014)	790 mill t	20,100 thousand t	3.1
Ni	Stainless/alloy steel (66%), non-ferrous alloys and super alloys (18%), electroplating (8%), other (8%) (Zepf et al. 2014) and increasingly used in energy storage units (e.g. Li-ion batteries).	74 mill t	2,090,000 t	3.7
Co	Batteries (27%), super alloys and magnets (26%), hard metals (14%), pigments (10%), catalysts (9%) and other (14%) (Zepf et al. 2014)	7,100,000 t	111,000 t	8.3
Pb	Lead bullets, protective sheath for underwater cables, construction industry, brass and bronze, lead-acid batteries, oxidising agent in organic chemistry and lead-based semiconductors (https://en.wikipedia.org)	88 mill t	4710 thousand t	2.6
Zn	Galvanising, alloys, anode material for batteries, manufacture of chemicals, daily vitamin and mineral supplement and cosmetics (https://en.wikipedia.org)	230 mill t	12,600 thousand t	2.9
Cd	Rechargeable batteries, photovoltaic cells, pigment in paints, stabilisers in plastics, corrosion-resistant coatings and plating (Zepf et al. 2014)	500,000 t (information of 2014)	23,900 t	1.1

(continued)

Table 2.2 (continued)

Metal	Main uses	World reserves on land in 2018 (https://www.usgs.gov)	Production rate in 2016 (https://www.usgs.gov)	Increase in production rate per year (%)
Mo	Carbon steel (35%), chemicals and catalysts (14%), stainless steel (25%), tool steel (9%), cast iron (6%), molybdenum metal (6%) and other (5%) (Zepf et al. 2014)	17 mill t	279 mill t	4.2
Pt	Autocatalyst (40%), jewellery (35%), investment (6%), medical and biomedical (3%), glass (2%), chemicals (6%), electrical (2%), petroleum (2%) and others (4%) (Zepf et al. 2014)	69,000,000 kg (PGM)	191,000 kg	1.7
Au	Coinage, jewellery, industry (10%), electrical contacts and alloys (https://en.wikipedia.org)	54,000 t	3110 t	1.4
Ag	Jewellery (34%), electronics (24%), photography/mirrors (20%), catalysts (6%) and other (16%) (Zepf et al. 2014)	530,000 t	25,700 t	2.5
REE	Magnets (25%), catalysts (24%), batteries (15%), polishing (11%), glass (6%), steel (9%) and other (10%) (Zepf et al. 2014)	120 mill t	129,000 t	2.9

3 Exploration Contracts for Deep-Sea Minerals

During 1970s and 1980s, eight ‘Pioneer Investors’ were registered under UNCLOS with exclusive rights over large areas containing polymetallic nodules in international waters, who upon entering into contract with ISA in 2001 became Contractors having exploration rights over deep-sea areas for a period of 15 years extendable by 5-year terms. The initial rush for exploring deep-sea minerals slowed down owing to lower demand as well as reduced metal prices during the twentieth century (Cronan 2022, this book), and the number of Contractors remained at eight until 2010, followed by the number of contracts with the ISA for exploration of deep-sea minerals in international waters increasing to 31 between 2011 and 2021 (www.isa.org.jm). Currently out of these, 19 contracts are for polymetallic nodules (each measuring 75,000 km^2), 7 for hydrothermal sulphides (each measuring 2500 km^2) and 5 for ferromanganese crusts (each measuring 1000 km^2) distributed over different parts of Pacific, Indian and Atlantic Oceans (Tables 2.3, 2.4, and 2.5; Fig. 2.4a–e), admeasuring 1,447,500 km^2 in all (Table 2.6).

Table 2.3 Contractors for exploration of polymetallic nodules

Contractor	Sponsoring State	General location of the exploration area under contract	Contract start date
InterOceanMetal Joint Organization	Bulgaria, Cuba, Czech, Poland, Russia, Slovakia	Clarion-Clipperton Fracture Zone (CCFZ), Pacific Ocean	29 March 2001
JSC Yuzhmorgeologiya	Russia	CCFZ, Pacific Ocean	29 March 2001
Government of the Republic of Korea	Republic of Korea	CCFZ, Pacific Ocean	27 April 2001
China Ocean Mineral Resources Research and Development Association	China	CCFZ, Pacific Ocean	22 May 2001
Deep Ocean Resources Development Co.	Japan	CCFZ, Pacific Ocean	20 June 2001
Institut français de recherché pour l'exploitation de lamer	France	CCFZ, Pacific Ocean	20 June 2001
Government of India	India	Indian Ocean	25 March 2002
Federal Institute of Geosciences and natural resources of Germany	Germany	CCFZ, Pacific Ocean	19 July 2006
Nauru Ocean Resources Inc.	Nauru	CCFZ, Pacific Ocean	22 July 2011
Tonga Offshore Mining Limited	Tonga	CCFZ, Pacific Ocean	11 January 2012
Global Sea-mineral Resources NV	Belgium	CCFZ, Pacific Ocean	14 January 2013
UK Seabed Resources Ltd.—I	UK & Northern Ireland	CCFZ, Pacific Ocean	8 February 2013
Marawa Research and Exploration Ltd.	Kiribati	CCFZ, Pacific Ocean	19 January 2015
Ocean Mineral Singapore Pte Ltd	Singapore	CCFZ, Pacific Ocean	22 January 2015
UK Seabed Resources Ltd.—II	UK & Northern Ireland	CCFZ, Pacific Ocean	29 March 2016
Cook Islands Investment Corporation	Cook Islands	CCFZ, Pacific Ocean	15 July 2016
China Minmetals Corporation	China	CCFZ, Pacific Ocean	12 May 2017
Beijing Pioneer Hi-Tech Development Corporation	China	Western Pacific Ocean	18 October 2019
Blue Minerals Jamaica	Jamaica	CCFZ, Pacific Ocean	16 March 2021

Table 2.4 Contractors for exploration of ferromanganese crusts

Contractor	Sponsoring State	General location of the exploration area under contract	Contract start date
Japan oil, Gas and Metals National Corporation	Japan	Pacific Ocean	27 January 2014
China Ocean Mineral Resources Research and Development Association	China	Western Pacific Ocean	29 April 2014
Ministry of natural resources and environment of the Russian Fed.	Russia	Pacific Ocean	10 March 2015
Companhia De Pesquisa de Recursos Minerais	Brazil	South Atlantic Ocean	9 November 2015
Republic of Korea	Republic of Korea	Western Pacific Ocean	27 March 2018

Table 2.5 Contractors for exploration of hydrothermal sulphides

Contractor	Sponsoring State	General location of the exploration area under contract	Contract start date
China Ocean Mineral Resources Research and Development Association	China	Southwest Indian Ridge	18 November 2011
Government of the Russian Federation	Russia	Mid-Atlantic Ridge	29 October 2012
Government of the Republic of Korea	Republic of Korea	Central Indian Ridge	24 June 2014
Institut français de recherche pour l'exploitation de la mer	France	Mid-Atlantic Ridge	18 November 2014
Federal Institute of Geosciences and natural resources of Germany	Germany	Southeast and Central Indian Ridge	6 May 2015
Government of India	India	Central Indian Ocean	26 September 2016
Government of Republic of Poland	Poland	Mid-Atlantic Ridge	12 February 2018

Source: www.isa.org accessed on 29 April 2021

Whereas most of the nodule fields are located in the Areas Beyond National Jurisdiction (ABNJ), some nodule deposits containing large metal resources are also found within the national jurisdictions of Pacific Island countries such as Japan, Cook Islands, Kiribati (Hein et al. 2005, 2015). Countries such as Japan, Korea and France have initiated national exploration programmes within their EEZ for seabed minerals (Fouquet and Lacroix 2014), and approximately 650,000 km^2 area of the seafloor is covered by exploration contracts within EEZs of different coastal states (SPC 2013; Petersen et al. 2018). New Zealand government has also issued prospecting licences to investigate hydrothermal sulphide deposits rich in silver and gold that occur along the Kermadec Volcanic Arc and on back-arc seamounts in its EEZ (Boschen-Rose et al. 2022, this book).

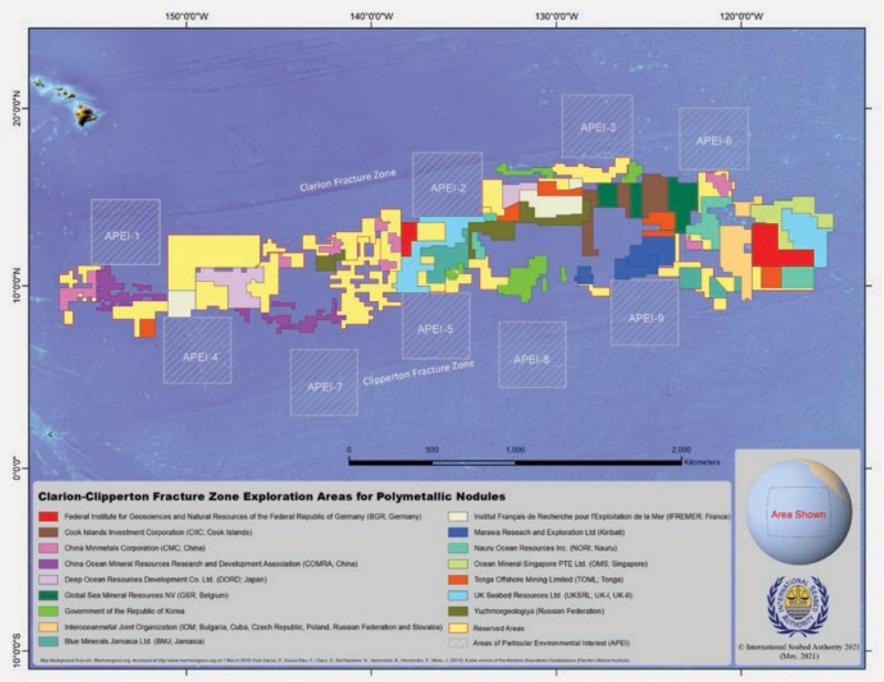
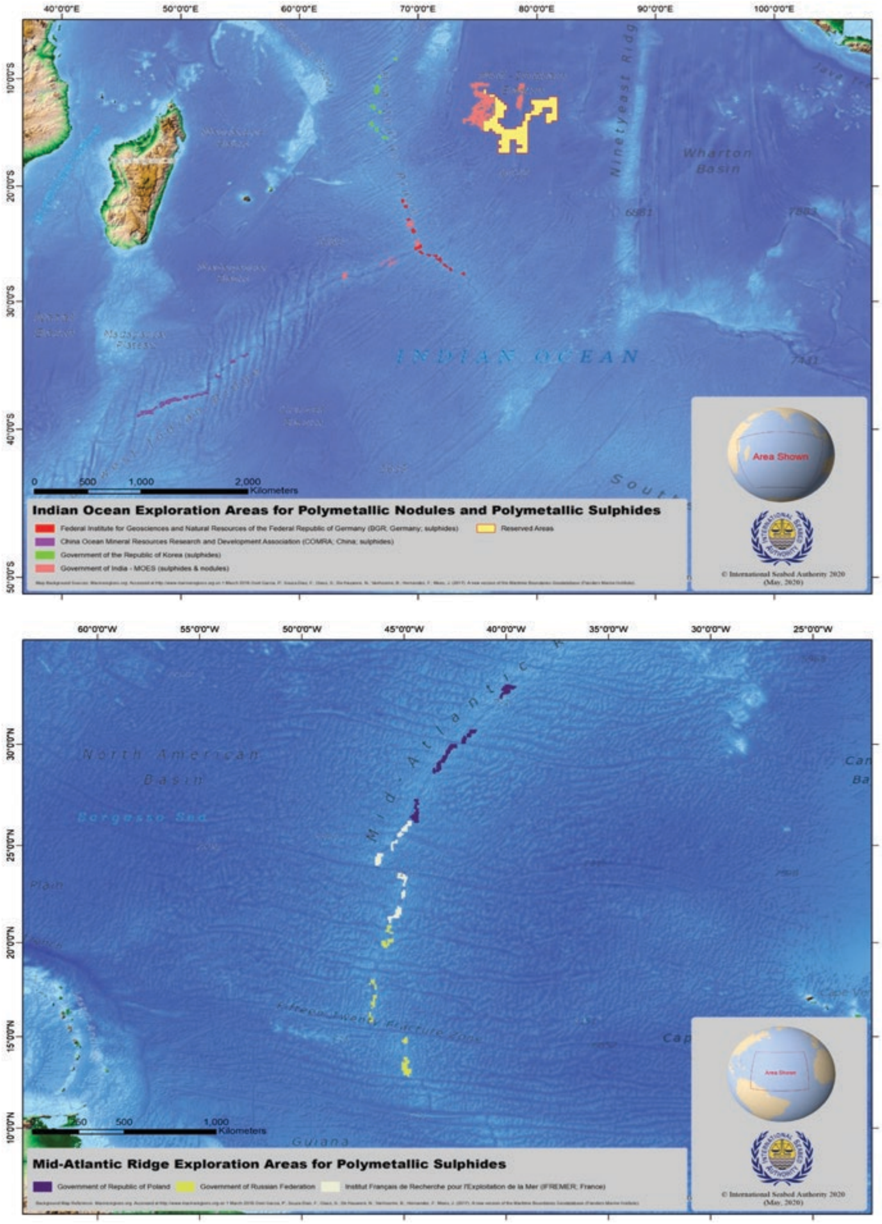


Fig. 2.4 (**a**) Exploration areas for polymetallic nodules in Clarion-Clipperton Zone. (Courtesy: International Seabed Authority, Jamaica). (**b**) Exploration areas for polymetallic nodules and sulphides in Indian Ocean. (Courtesy: International Seabed Authority, Jamaica). (**c**) Exploration areas for polymetallic sulphides on Mid-Atlantic Ridge. (Courtesy: International Seabed Authority, Jamaica). (**d**) Exploration areas for polymetallic nodules and cobalt-rich ferromanganese crusts in Pacific Ocean. (Courtesy: International Seabed Authority, Jamaica). (**e**) Exploration areas for cobalt-rich ferromanganese crusts on South Atlantic seamounts. (Courtesy: International Seabed Authority, Jamaica)



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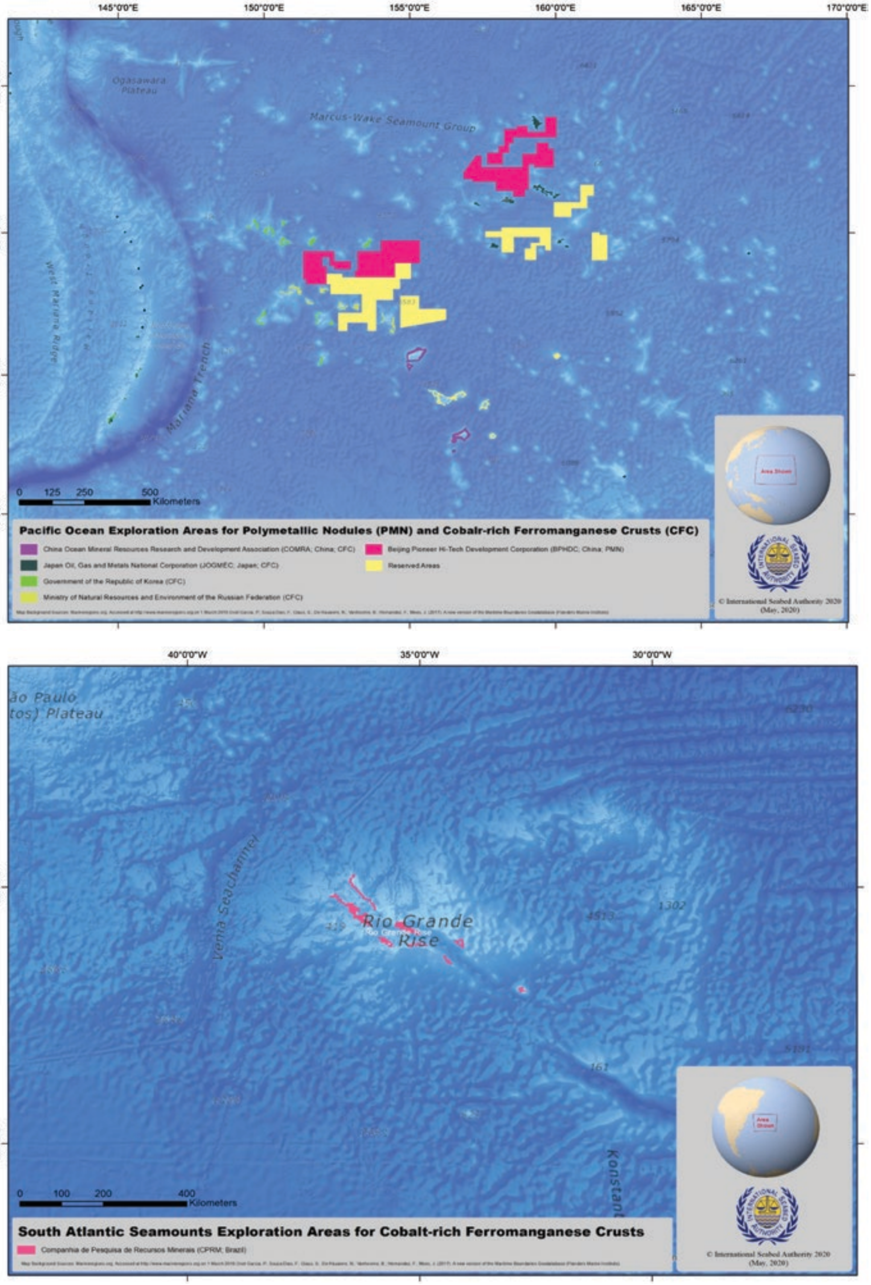

Fig. 2.4 (continued)

Table 2.6 Estimated area under exploration contracts (as of May 2021)

Mineral type	Area (sq km)/contract	Total contracts[a]	Total area (sq km)
Nodules	75,000	19	1,425,000
Sulphides	2500	7	17,500
Crusts	1000	5	5000
		31	1,447,500

[a] www.isa.org.jm

4 Quantitative Estimations of Deep-Sea Mining

Factors such as physical and chemical characteristics of minerals (size, abundance, density, moisture content and metal concentrations), dimension of the ore (2- and 3D), their distribution characteristics (exposed or buried, uniform or patchy), associated substrates (sediments and rocks) as well as topographic setting (micro and macro, slopes) are critical in estimating the mining related variables such as mineable area, size of mine-site, area of contact, volume of sediment that could be disturbed, as well as in design and operation of various components of mining systems (Sharma 2017a).

As per the stipulations of ISA, each contract area for nodules is 75,000 km^2, whereas it is 2500 km^2 for sulphides and 1000 km^2 for crusts (ISA 2019b) and considering that at present there are 19 contracts for nodules, 7 for sulphides and 5 for crusts, the total area of the seafloor currently under contract is 1,447,500 km^2 in the international seabed area (Table 2.6). It is important to note that a single contract area for nodules of 75,000 km^2 is just 0.045% of the total area of the Pacific Ocean (165.2 million km^2), 0.091% of the Atlantic Ocean (82.4 million km^2), 0.10% of the Indian Ocean (73.4 million km^2) and that the entire area currently under contract i.e. 1,447,500 km^2 is 0.45% of the total area of all the oceans (321 million km^2) put together, excluding the adjacent seas around them (www.britanica.com for areas of oceans).

The unlikely that the entire 1.4475 million km^2 would be mined due to heterogeneous mineral distribution and seafloor slope restrictions. Initial studies based on statistical analysis of nodule abundance data have shown that for a typical mining area of 75,000 km^2 allotted to a Contractor for polymetallic nodules, about 10% of the area will be adequate as First Generation Mine-site for supplying three million tonnes of dry nodules annually for a period of 20 years in the Clarion Clipperton Fracture Zone in the Pacific Ocean, whereas the same would be about 20% in the Central Indian Basin (Singh and Sudhakar 2015). Estimates for mining of nodules at different mining rates (1–3 MT/y) show that ores between 3000 and 10,000 tonnes could be mined per day and the area (size) of the mine site would range between 4267 and 12,800 km^2 (Table 2.7) which is 5.68–17.06% of the ‘contract’ area (75,000 km^2) for nodule abundance of 5 kg/m^2 and 25% efficiency of the mining system. Further, the area of contact (i.e. the touchdown area) that would be actually scraped would vary between 200 and 600 km^2 per year for mining rates

Table 2.7 Estimates for mining of polymetallic nodules at different mining rates (from Sharma 2017a)

Estimates for operation of 300 days year^{-1}	Mining rate					Remark/implication
	1.0 Mt. y^{-1}	1.5 Mt. y^{-1}	2.0 Mt. y^{-1}	2.5 Mt. y^{-1}	3.0 Mt. y^{-1}	
Ore production/day	3333.3 t day^{-1}	5000 t day^{-1}	6666.6 t day^{-1}	8333.25 t day^{-1}	10,000 t day^{-1}	Proportionate storage and transport facility required
Area (size) of mine-site[a]	4267 km^2	6400 km^2	8533 km^2	10,667 km^2	12,800 km^2	Negligible (5.68–17.06%) of the contract area
Area of contact per year[a]	200 km^2	300 km^2	400 km^2	500 km^2	600 km^2	i.e. 0.66–2 km^2 day^{-1}
Volume of sediment disturbed at seafloor	60,000 m^3 day^{-1}	90,000 m^3 day^{-1}	120,000 m^3 day^{-1}	150,000 m^3 day^{-1}	180,000 m^3 day^{-1}	Major source of environmental impact
Wt. of disturbed sediment (wet; 1.15 g cm^{-3} density)	69,000 t day^{-1}	103,500 t day^{-1}	138,000 t day^{-1}	172,500 t day^{-1}	207,000 t day^{-1}	In slurry form that can travel with bottom currents to adjacent areas
Wt. of disturbed sediment (dry; 80% water content)	13,800 t day^{-1}	20,700 t day^{-1}	27,600 t day^{-1}	34,500 t day^{-1}	41,400 t day^{-1}	Dominant (50–60%) fine clays may remain suspended for longer periods

[a] For cut-off abundance of 5 kg m^{-2} (minimum required for nodule mining, UNOET 1987), contract (mining) area of 75,000 km^2, mining for 20 years for 300 days of operation per year

between 1.0 and 3.0 million tonnes per year, which is 0.66–2.0 km^2 per day and works out to 5–16% of the contract area that would further reduce with higher nodule abundance expected in the first-generation mine site, proportionately reducing direct environmental impacts as well (Sharma 2017a).

Studies have shown that the average abundance of nodules in the first-generation mine sites (FGMs) as well as the efficiency of the miners will be much higher than those considered here (Hong et al. 2019; Kirchain et al. 2020), and so the actual area that will be mined would be further reduced in order to mine the required quantity. These are also confirmed by a study on planning of nodule mining which suggests that with an overall mining efficiency of 30–40% and for abundances of 13.7 and 16.5 kg/m^2, an area of approximately 114–182 km^2 will be mined per year, or ~ 2300–3600 km^2 in a period of 20 years for production rates of 1.5–2 MT per year (Volkmann and Lehnen 2018), which is between 3 and 5% of the contract area of 75,000 km^2.

The German license area of 75,000 km^2 in CCZ shows that ~80% of the area has ≤3° slope of the seafloor (Ruhlman et al. 2009). Studies by the Blue Mining project in an exemplary mine-site of 255 km^2 within the German area has average nodule abundance of ~16 kg/m^2 and a total tonnage of nodules of 4 Mt. with 113,812 t of Cu + Ni + Co and 1,171,000 t of Mn (Rahn 2016). For the project, the annual production rate is considered as 1.5–2 Mt./y with a collection efficiency of 80% (Volkmann and Lehnen 2018). Volkmann et al. (2018) have further developed a comprehensive approach for techno-economic assessment of nodule mining that could be applied to other similar deposits.

Taking into consideration in case of nodules, an area of 75,000 km^2 with a cut-off abundance of 5 kg/m^2 would contain 375 million tonnes (wet) or 281.25 million tonnes of (dry) nodules (Table 2.8) which can be mined for 187 years at an annual mining rate of 1.5 million tonnes, or for 93.5 years at an annual mining rate of three million tonnes. Moreover, as current exploration contracts are at various stages of development, it is most likely that there would be ~3 to 4 mines operating worldwide in the initial years of commencement of deep-sea mining that could be followed up with more mining ventures depending on the global demand for critical metals.

5 Techno-Economic Assessment of Resource and Exploitation Potential of Deep-Sea Minerals

Assessment of resources and their exploitation potential are critical for investors who would be investing in a project when the revenues expected to accrue from it would be large enough to provide sufficient returns on investment. This would include working out the capital expenses (CAPEX) and the operational expenses (OPEX) for all the offshore as well as onshore installations and processes, such as the exploration costs, mining infrastructure cost (surface and subsurface), transport

Table 2.8 Resource potential and metal production estimates (modified after Sharma 2017b and Sharma 2019c)

Nodule/metal	Mean concentr-ation[a]	Resource potential, *t*[b]	Metal production per year, *t* 1.5 Mt./y 3 Mt/y		Price of metal (\$/t)[c]	Gross in-place value of metal \$/year 1.5 Mt/y 3 Mt/y		Gross in-place value of metal \$/20 years 1.5 Mt/y 3 Mt/y	
Wet nodules	–	375,000,000	–	–	–	–	–	–	–
Dry nodules	75% of wet nodules[d]	281,250,000	–	–	–	–	–	–	–
Manganese	22% of dry nodules	61,875,000	330,000	660,000	1560[c]	514,800,000	1029,600,000	10,296,000,000	20,592,000,000
Nickel	1.0% of dry nodules	2,812,500	15,000	30,000	17975[c]	269,625,000	539,250,000	5,392,500,000	10,785,000,000
Copper	0.78% of dry nodules	2,193,750	11,700	23,400	10028[c]	117,327,600	234,655,200	2,346,552,000	4,693,104,000
Cobalt	0.23% of dry nodules	646,875	3450	6900	45165[c]	155,819,250	311,638,500	3,116,385,000	6,232,770,000
Total (metals)	24.01%	67,528,125	360,150	720,300	-	1057,571,850	2115,143,700	21,151,437,000	42,302,874,000

[a] Source: Morgan (2000) for Clarion-Clipperton Zone in Pacific Ocean

[b] 5 kg/m^2 for 75,000 km^2 (75 × 10^9 m^2)

[c] Average metal prices as of 6 May 2021 (Source: www.lme.com for Ni, Cu, Co; Kirchain et al. 2020 for Mn)

[d] Mero (1977)

Table 2.9 Estimated CAPEX/OPEX for nodule mining (1.5 mi t/year) (modified after Sharma 2017b)

Item	Capital expenditures	Operating expenditures	Total
Mining system	\$550 mi[a] (\$372–562 mi)	\$100 mi/y[a] (\$69–96 mi) × 20 years = \$2.0 billion	\$2.55 billion
Ore transfer	\$600 mi[a] (\$495–600 mi)	\$150 mi/y[a] (\$93–132 mi/y) × 20 years = \$3.0 billion	\$3.60 billion
Processing plant	\$750 mi[a]	\$250 mi/y[a] × 20 years = \$5.0 billion	\$5.75 billion
Total	\$1.90 billion[a] \$2.34 billion[b]	\$10.0 billion[a] \$12.30 billion[b]	\$11.90 billion \$14.64 billion[b]

[a] Figures taken from ISA report (ISA 2008a) and rounded off to nearest 50 of the highest value. Figures in brackets () show the range for different systems

[b] Recalculated cumulative inflation rate at 23% for 2021 (www.usinflationcalculator.com)

vessels (for supplies, ore and manpower), as well as the onshore processing cost. The revenues generated would be calculated from the quantity of metals sold times the unit price for each metal at the time of sale individually and added up cumulatively for each year as well as for the total period of operation (Van Nijen et al. 2018).

As polymetallic nodules are the most studied deep-sea minerals, this section describes a case study for evaluating their potential. As has been shown in a previous publication (Sharma 2017a), if we consider that a typical nodule contract area is 75,000 km^2 and for a cut-off abundance of 5 kg/m^2 (UNOET 1987), the total available resource would be 375 Mt. (wet) or/281.25 MT (dry). This would yield a total metal resource of 67.53 Mt. (Mn = 22%, Ni = 1%, Cu = 0.78%, Co = 0.23%). For 20-year lifetime of mine-site, the resource mined would be 30 Mt at annual mining rate of 1.5 Mt (i.e. 10.6% of the total resource) or 60 Mt at annual mining rate of 3.0 Mt (i.e. 21.2% of the total resource).

At current metal prices, the gross in place value of the four metals would be \$21.15 billion at the mining rate of 1.5 Mt/y and \$42.30 billion at the mining rate of 3.0 Mt/y (Table 2.8). The CAPEX and OPEX estimated from the data provided by different contractors for mining of 1.5 Mt/y for 20 years, including the cost of mining system, ore transfer and processing plant at current prices (corrected with inflation rates) works out to \$14.64 billion (Table 2.9). Hence, at current metal prices and estimated cost of the mining system including offshore infrastructure as well as ore transfer and onshore processing systems, metals worth \$21.15 billion can be extracted for an investment of \$14.64 billion from a single nodule operation at the rate of 1.5 MT per year over a period of 20 years. However, this does not include the taxes, royalties and other payments that may be applicable once the mining licenses are given (Lodge et al. 2017).

A study for nodule mining in CCZ estimates that one mining operation at three million tonnes per year onboard two vessels fitted with independent mining systems and nodule collectors would produce 37.050 × 10^3 tonnes of nickel. About 32.4 × 10^3 tonnes of copper and 6.375 × 10^3 tonnes of cobalt produce annually. For this project, the estimated breakup of cost for pre-feasibility and feasibility phases would be about 9%, whereas construction of the commercial scale mining system would be about 14.4%, surface vessels about 17% and the processing plant about 59.60% of the total capital cost of \$4051 × 10^6, whereas the offshore OPEX are estimated at \$325 × 10^6 annually and onshore processing at \$688.7 × 10^6 annually (Van Nijen et al. 2018). Above studies show that among the capital expenses, the major cost component is for the processing plant (40–60%) and similarly among the operational costs, the expenses on processing plant are the highest (50–70%), which is an onshore component.

Another financial model for nodule mining proposes use of two surface vessels in a mining area having an average nodule abundance of 10.9 kg/m^2 and an average annual collection rate of 3.86 Mt of dry nodules, with the collector efficiency of 70% in the first year, increasing to 85% in second year and 100% thereafter, and a metal recovery of 90% of Mn, Ni, Cu and 80% for Co, with an estimated OPEX of \$840 million and CAPEX of \$2730 million (Kirchain et al. 2020).

While these techno-economic assessments are underway, several entities have started to conduct testing of different components of deep-sea mining systems comprising the shipboard handling systems, the seabed excavation system and the systems for ore transfer and communication between the two. In 2017, Japan Oil, Gas and Metals Corporation (JOGMEC) successfully excavated seabed ores containing Zn, Au, Cu and Pb from a depth of 1600 m off the coast of Okinawa (Kawano and Furaya 2022, this book). In 2017, Nautilus Minerals (recently taken over by Deep Sea Mining Finance Limited, https://dsmf.im) announced successful completion of seafloor production tools with an aim to mine the seafloor massive (sulphide) deposits to produce Cu, Au and Ag from 1600 m depth off Papua New Guinea (http://dsmobserver.com). During April to May, 2021, Global Sea-mineral Resources NV (GSR, Belgium) deployed a 25 tonne deepwater robot on a 5 km long power and two-way communication cable for collecting nodules that is being monitored for its environmental effects by scientists of 29 European institutions with the help of state of the art equipment such as ROVs, AUVs, oxygen profilers as well as hydroacoustic and optical sensors to measure the concentration of resuspended sediment particles (www.deme-group.com/news).

Whereas China Ocean Mineral Resources Research and Development Association (COMRA) has developed deep-sea survey equipment such as a manned submersible capable of diving to more than 7000 metres as well as an unmanned remote-controlled vehicle, they have also carried out a successful nodule collecting test at 500 m depth in South China Sea (https://chinadialogueocean.net). Korea has developed a pilot mining robot designed to operate at 5000 m depth, and a lifting pump and buffer station were tested with a truncated lifting pipe of 500 m (Hong et al., 2019). An integrated mining system is also being developed by India, of which a pre-prototype nodule collector has been tested at around 500 m water depth with an aim to upgrade it for operation at 6000 m (Atmanand and Ramadass 2017). It is in this scenario that private companies are also getting interested in deep-sea mining, e.g. Blue Mining, a European consortium of 19 industry and research organisations from different fields in maritime has been formed with an objective to provide breakthrough solutions for a sustainable deep-sea mining (http://bluemining.eu).

This interest of private enterprise partnering with government and research organisations in exploring and exploiting deep-sea minerals can provide the necessary fillip to deep-sea mining industry in future.

6 Likely Impacts and Environmental Management

6.1 Likely Environmental Impacts of Deep-Sea Mining

The probable causes for environmental impact could be due to the following activities related to deep-sea mining (after Sharma 2017c):

(a) *Offshore activities.*

- Picking up or separation of minerals and the quantity of substrate disturbed on the seafloor due to operation of the miner, crusher and discharge mechanisms
- Suspension of fine particles of minerals and associated sediment into the water column
- Resettlement of suspended particles and smothering of seafloor
- Impacts due to light and sound during mining operation
- Oil spills and leakages from mining platform and transport vessels
- Ballast water discharge from transport vessels
- At-sea processing, dewatering, waste disposal including chemicals and debris
- Sub-system losses such as pipes, chains, tools or any other hardware
- Human waste such as garbage including plastics, metals, glass and other non-biodegradable items

(b) *Onshore activities*

- Pollution during loading/unloading, onland transportation of ore from the port to the processing plant
- Pollution during processing (fumes and discharges) around the processing plant
- Pollution after processing (dumping of slag or unwanted material) away from the processing plant

Probable effects at various levels in the water column as well as on the seafloor due to the offshore activities are summarised as follows (after ISA 1999):

(a) *Potential impacts due to mining activity on the seabed*

- Mortality of organisms along the collector track
- Smothering of the benthic fauna away from the mining site where the sediment plume settles
- Clogging of suspension feeders and dilution of deposit-feeders food resources

(b) *Potential impacts due to discharge of tailings at mid-water depths*

- Mortality of zooplankton species at mid-water depths
- Effects on meso-and bathypelagic fishes and other nekton caused directly by the sediment plume
- Effects on fish behaviour and mortality caused by the sediments or trace metals
- Depletion of oxygen by bacterial growth on suspended particles
- Dissolution of heavy metals and their potential incorporation into the food chain
- Impacts on deep-diving marine mammals

(c) *Potential impacts due to surface discharge and movement of vessels*

- Trace-metal bioaccumulation leading to reduction in primary productivity due to shading on phytoplankton
- Effects on marine mammals due to noise, oil spills and waste disposal

6.2 Studies on Environmental Impact Assessment

Although actual deep-sea mining is yet to start on a commercial scale, several studies to understand the possible impacts of deep-sea mining have been carried out in the Pacific Ocean and Indian Ocean. The earliest was **D**eep **O**cean **M**ining **E**nvironment **S**tudy (DOMES) conducted by National Oceanic and Atmospheric Administration (NOAA) that monitored environmental impacts during two of the pilot scale mining tests conducted by the Ocean Mining Inc. (OMI) and the Ocean Mining Associates (OMA) in 1978 in the Pacific Ocean. During the study, the concentration of particulates was measured in the discharge and the biological impacts in the surface as well as benthic plumes were assessed (Ozturgut et al. 1980). Subsequently, several small-scale experiments were conducted to mimic deep-sea mining in order to evaluate their potential impacts (Table 2.10). These include the **DIS**turbance and Re-**COL**onisation (DISCOL) experiment using a plough harrow (Foell et al. 1990), the NOAA-**B**enthic **I**mpact **E**xperiment (NOAA-BIE) using a Deep-Sea Sediment Resuspension System (DSSRS) (Trueblood 1993), the **J**apan deep-sea impact **E**xperimen**T** (JET) also conducted using DSSRS (Fukushima 1995), the Interoceanmetal **B**enthic **I**mpact **E**xperiment (IOM-BIE) using DSSRS (Tkatchenko et al. 1996) and the **In**dian **D**eep-sea **E**nvironment E**x**periment (INDEX) using DSSRS (Sharma and Nath 1997).

Post disturbance observations as well as studies to monitor the impact and recolonisation after the experiments showed that over a period of time at the DISCOL site, although certain groups of benthic organisms had a quantitative recovery, the faunal composition was not the same as the undisturbed one (Schriever et al. 1997); whereas at the NOAA site, some of the meiobenthos showed a decrease in abundance, the macrobenthos showed an increase in their numbers probably due to

Table 2.10 Benthic Impact Experiments (BIEs) for assessing potential environmental impact of nodule mining (after Sharma 2017b)

Experiment	Year	Conducted by	Area	Tows	Duration	Area/ distance	Discharge[f]
DISCOL[a]	1989	Hamburg University, Germany	Peru Basin	78	~12 days	10.8 km^2	–
NOAA -BIE[b]	1991	National Oceanographic & Atmospheric Administration, USA	Clarion Clipperton Fracture Zone	49	5290 min	141 km	6951 m^3
JET[c]	1985	Metal mining Agency of Japan	Clarion Clipperton Fracture Zone	19	1227 min	33 km	2495 m^3
IOM -BIE[d]	1995	InterOceanMetal—consortium of East European Countries	Clarion Clipperton Fracture Zone	14	1130 min	35 km	2693 m^3
INDEX[e]	1997	National Institute of Oceanography, Govt. Of India	Central Indian Ocean Basin	26	2534 min	88 km	6015 m^3

Sources:
[a] Foell et al. (1990)
[b] Trueblood (1993)
[c] Fukushima (1995)
[d] Tkatchenko et al. (1996)
[e] Sharma and Nath (1997)
[f] Yamazaki and Sharma (2001)

increased food availability (Trueblood et al. 1997). At the JET site, the abundance of meiobenthos decreased in deposition areas immediately after the experiment and returned to original levels but the species composition was not the same and the abundance of certain groups of mega and macro-benthos was still lower than the undisturbed area (Shirayama 1999); whereas at the IOM site, no significant change was observed in meiobenthos abundance and community structure in the re-sedimented area, but alteration in meiobenthos assemblages was observed within the disturbed zone (Radziejewska 1997). At the INDEX site, whereas there was lateral migration and vertical mixing of sediment leading to changes in physico-chemical conditions (Sharma et al. 2001) and reduction in biomass in and around the disturbance area (Ingole et al. 2001), subsequent monitoring over a period of 8 years showed that restoration and recolonisation process had started and that the initial impacts were getting masked by natural variability in the environmental conditions (Sharma et al. 2007). COMRA after conducting a decade of monitoring and scientific analysis in their contract area also found that natural climatic conditions could exert a greater impact on the survival and living environment of marine life than human exploration impact (chinadialogueocean.net).

Whereas most of the experiment sites were monitored for periods ranging from 1 to 5 years, the JET site was revisited after about 17–18 years (Fukushima and Tsune 2019), the IOM site was revisited after 20 years, and DISCOL site was revisited after 26 years (https://miningimpact.geomar.de). A comprehensive analysis of results of all the impact assessment studies (Jones et al. 2017) shows that 'the impacts are severe immediately after the (simulated) mining, with negative changes in density and diversity of most groups' (wherein) 'mobile and small sized fauna experienced less negative impacts over long term'. They further observed that 'almost all studies show some recovery in faunal density and diversity for meiofauna and mobile megafauna within a year', and 'few faunal groups return to baseline after two decades'. Whereas the above studies were conducted in nodule areas, reviews of anthropogenic disturbances at deep-sea hydrothermal vent systems have also described the potential impacts of sulphide mining on marine ecosystems (Boschen et al. 2013; Van Dover 2014).

As most of the previous experiments were small in scale as compared to commercial mining (Yamazaki and Sharma 2001), several contractors are planning to conduct impact assessment studies combined with trials of pre-prototype mining systems. Whereas, the *Mining Impact* project on 'Ecological Aspects of Deep-Sea Mining' investigated experimental and small-scale disturbances of the seafloor, the second phase *Mining Impact 2* proposes to study and monitor in real time the environmental impact of an industrial scale mining of manganese nodules on the seafloor being conducted by the Belgian contractor Global Sea-mineral Resources (GSR) in the Belgian and German license areas in the Clarion-Clipperton-Zone (http:/jpi-oceans.eu/minimgimpact2). Results of these studies could help improve our understanding of the potential impacts either by extrapolation or through modelling, and incorporating the results into mining system design could help minimise the impacts.

6.3 Potential Impacts Associated with Different Deep-Sea Minerals

6.3.1 Likely Impacts Associated with Polymetallic Nodules Mining

Biological communities associated with nodule deposits exhibit diversity but in very small numbers and are generally concentrated in the upper few tens of centimetres of the seabed consisting of meiofauna (<1 mm and >45 μm size) such as nematodes and harpacticoid copepods; macrofauna (>1 mm) that include polychaetes and isopod crustaceans; megafauna (organisms that can be seen in seafloor photographs) that include holothurians, fish and giant protists (Weaver and Billet 2019) as well as fauna that attach to the hard substrate of nodules such as corals, bryozoans, xenophyophores, komokiaceans and sponges (Vanreusel et al. 2016). It is anticipated that nodule mining will scrape the top ~50 cm of the seabed, disaggregate the sediment while picking up nodules and discharge sediment particles behind the collector machine containing much more water and lacking cohesion that could also be devoid of organisms (Weaver and Billet 2019). The clouds of sediment created by the movement of the mining head could not only cause changes in biochemical conditions on the seafloor and reduction in biomass within and around the mining area, but the seabed organisms could also get overwhelmed by the settling particles, and their filter feeding mechanisms could get blocked due to sudden increase in sedimentation rates (Jones et al. 2017; Weaver et al. 2018). The sediment plumes might also travel to distances between a few hundred meters to a few tens of kilometres from the mining site (Sharma et al. 2001; Rolinski et al. 2001) creating unnatural conditions for the biota.

6.3.2 Likely Impacts Associated with Hydrothermal Sulphide Mining

Several biological communities such as bacteria, shrimps, tube worms and other organisms that can sustain in hot and inhospitable environment are associated with hydrothermal sulphides and vent fluids (Fisher et al. 2013). These chemosynthetic organisms have limited distribution because they are confined to the hot springs that are restricted to small areas along the ocean ridges (Weaver and Billet 2019). It is also known that different organisms are associated with different biogeographical zones (Rogers et al. 2012; Chown 2012), whereas certain species could get severely impacted due to their limited extent, others may not be affected due to their widespread occurrence (Weaver and Billet 2019). It is also observed that the active vent fauna can adapt to higher concentrations of heavy metals, but these conditions would probably be toxic for organisms located at inactive sites (Boschen et al. 2013; Van Dover 2011). It is expected that loss of habitat at the seabed due to sulphide mining will be relatively small because these three-dimensional deposits cover an area of a few square kilometres on the seabed. If several hydrothermally active sites are mined together or impacted by mining then these unique ecosystems that occur in relatively few locations could suffer loss of connectivity between populations (Van Dover 2014). On the other hand, mining of sulphides in areas without hydrothermal vent communities (such as inactive ridge systems) may have little impact in terms of loss of habitat because deep-sea taxa associated with them will be more typical of rocky slope fauna, which have wide geographic distributions (Weaver and Billet 2019). Observations have also shown that populations of animals on fast spreading ridges can recover in a few years (Van Dover 2011; Gollner et al. 2017), whereas those on slower spreading ridges may recover more slowly (Boschen et al. 2013).

6.3.3 Likely Impacts Associated with Ferromanganese Crust Mining

Ferromanganese crusts host sessile filter-feeding animals as well as corals and sponges (Nalesso et al. 1995) and suspension feeders such as feather stars and sea pens (Fukushima 2007). Seamounts are also known to be hosts for squids, sea stars, sea cucumbers, crabs and sea squirts as well as foraminiferans including xenophyophores (Mullineaux 1987; Fukushima 2007). It is expected that the mining device that would scrape the top few centimetres consisting of oxide layers on the ferromanganese crusts would remove the organisms living on the crust surface (Roark et al. 2006; Rogers et al. 2007; Carreiro-Silva et al. 2013). It is also known that different communities are associated with different depths along the seamount flanks and the debris or plumes generated by mining could impact these, the extent of which will depend on its volume and composition depending on the mining process and equipment used (Weaver and Billet 2019). The other possible impacts could be clogging of filter feeding mechanisms of organisms that are used to relatively low suspended particles in the water column (Rogers 1999).

6.4 International Regulations for Environmental Protection

As required in Part XI of UNCLOS, ISA either has developed or is in the process of developing guidelines and regulations to ensure effective protection of marine environment from harmful effects that may arise from prospecting, exploration and exploitation activities (www.isa.org.jm), such as:

1. Rationale and recommendations for the establishment of preservation reference areas for nodule mining in the Clarion-Clipperton Zone ISBA/14/LTC/2 (ISA 2008b).
2. Environmental Management Plan for the Clarion-Clipperton Zone ISBA/17/LTC/7 (ISA 2011).
3. Recommendations for the guidance of contractors for the assessment of the possible environmental impacts arising from exploration for marine minerals in the Area ISBA/19/LTC/8 (ISA 2013b) that were subsequently modified (ISA 2019a) and also revised (ISA 2020).
4. Draft regulations on exploitation of mineral resources in the Area ISBA/25/C/WP.1 (ISA 2019b) that include provisions for environmental impact statement as well as format for environmental monitoring and management plan to be furnished by the contactor while applying for mining contract.
5. Draft Guidelines for the establishment of baseline environmental data (ISA 2021a).
6. Draft Standard and Guidelines for environmental impact assessment process (ISA 2021b).
7. Draft Guidelines for the preparation of an environmental impact statement (ISA 2021c).
8. Draft Guidelines for the preparation of environmental management and monitoring plans (ISA 2021d).
9. Draft Guidelines on tools and techniques for hazard identification and risk assessments (ISA 2021e).

As many of the potential mine-sites for deep-sea minerals could be located in international waters, wherein the mining vessels as well as the transport vessels would operate, the following regulatory framework of International Maritime Organisation (IMO) would also apply for all the shipping related activities:

1. Convention on prevention of marine pollution by dumping of wastes and other matter (IMO 1972).
2. International convention of preservation of marine pollution from ships—MARPOL (IMO 1978).
3. Guidelines for reduction of underwater noise from commercial shipping to address adverse impacts on marine life (IMO 2014).
4. The International Convention for the Control and Management of Ships' Ballast Water and Sediments, 2004 (BWM Convention) entered into force on 8 September 2017 (IMO 2019).

6.5 Mitigation of Environmental Impacts of Deep-Sea Mining

As development of deep-sea mining systems is in its nascent stages, various options can be incorporated at the designing and testing stages. Technological innovations would be required to ensure minimum possible disturbance on the seafloor due to the miner movement, negligible transport of sediment associated with minerals by screening them off close to the seafloor and introducing methods of fast resedimentation to avoid lateral transport to adjoining areas (Sharma 2017c). Adopting methods like reducing the height of the plume and increasing the settling velocity by increasing particle aggregation to limit the areal extent of smothering of benthic organisms (Peukert et al. 2018) could help limit the spread of resuspended particles and the ensuing impact.

It is also suggested that adopting strip (or patch) mining thereby leaving alternate strips (or patches) of undisturbed seafloor to allow re-population by organisms from adjoining areas. Further, sediment discharge should be the least at the surface to allow sufficient sunlight to penetrate for photosynthetic activity and preferably any discharge should be at different levels of water column below the oxygen minimum zone where the faunal density is relatively lower. Proper care to be taken during vertical transfer of ore from the collector to the mining platform as well as from the mining platform to the transport vessels to avoid spillage. Oil spills and disposal of any waste from these ships also should be monitored and proper treatment of waste material should be carried out, including use of biodegradable methods, before discharging (Sharma 2017c; Hong et al. 2019). Plume dispersion models (Rolinski et al. 2001), mathematical models (Suzuki and Yoshida 2019) as well as techniques such as ecotoxical bioassay (Yamagashi et al. 2019) could also be used for predicting and monitoring of impacts.

If one goes by the argument that deep-sea environments are food limited, then it needs to be looked into whether deep-sea mining would actually release nutrients trapped in the underlying layers of sediment that might support benthic life to proliferate after the seafloor is mined. Conservation of biodiversity can also be ensured by identifying environmentally sensitive areas as ‘no mining’ zones, similar to areas of particular interest (APIEs) identified in the CCZ (www.isa.org.jm).

6.6 Approaches to Environmental Management

An EIA is a key aspect of planning and environmental management of any industrial project in order to anticipate, assess and reduce risks prior to obtaining regulatory approvals (Durden et al. 2018). In order to ensure effective management practices, a systematic approach for environmental assessment, multidisciplinary baseline data collection, preparation of environmental impact statement (EIS) as well as applying mitigation hierarchy to avoid and minimise the impacts, as well as restore, offset and compensate the ecosystems associated with seabed minerals (Billet et al. 2019) coupled with ecosystem-based approach (Cormier 2019) need to be adopted. This would require a detailed description of the process, components and structures for conducting and reporting an environmental impact assessment as proposed by Clark (2019) as well as an evaluation of the risk associated with mining of nodules, crusts and sulphides, and their habitats (Washburn et al. 2019). Assessment of deep-sea faunal communities associated with nodules (Tilot 2019) and sulphides (Boschen et al. 2013) as well as crusts, as environmental indicators could also be instrumental in developing strategies for management of impacts from deep-sea mining.

One of the concerns is that ‘we do not have enough data’, but given the vastness of the oceans and large variety of ecosystems and biological communities associated with them, it may never be possible to collect all data that are envisaged as required before mining begins. In order to address this, the process of defining the parameters required to do so for the contractors to follow has been put in place in the latest environmental regulations for exploration (ISA 2020) and are under development for exploitation (ISA 2019a). Moreover, it could be pertinent to define thresholds for ‘acceptable’ environmental harm by the regulators and the mechanisms for risk assessment and mitigation measures could be addressed in the environmental management and monitoring plans (EMMP) by the contractors to avoid serious environmental damage (Washburn et al. 2019). Scientific data will be required for decision making to protect and preserve the marine environment from harmful effects of mining on the seafloor as well as in the water column above it (Lodge and Verlaan 2018). Additionally, certain financial safeguards to protect the marine environment that could be adopted include: incentive-based approaches that create strong incentives for contractors to reduce potential environmental damage; environmental taxes—a performance-based approach to create a cost for environmental damage; environmental liability—a performance-based approach to protect the environment; environmental insurance—policy instruments that contactors carry for any residual environmental damage; and environmental bonds—a form of self-insurance (Lodge et al. 2019).

7 Consideration of Deep-Sea Mining with Respect to Land-Based Mining

There is a growing interest in looking at deep-sea mining with respect to terrestrial mining, especially in terms of socio-economic feasibility as well as environmental impacts. With the quantity and quality of ores in terrestrial deposits getting depleted, it could become more expensive to mine on land, for example, terrestrial copper production has decreased by 25% in the last decade, whereas the energy consumption to mine it has increased by 30% (Calvo et al. 2016). In case of deep-sea minerals, it is considered that mining of one mineral deposit would yield at least 3 or 4 metals with a lower carbon foot print than mining at 3 or 4 separate mines on land for one metal each (Hein et al. 2020). Since, new mineral resources may be required to meet the global demands for metals in future and recycling is not a viable option as yet for such quantities of metals, the contribution of large expanses of deep-sea minerals could become the alternative source for critical metals unless such materials are found that could be used as substitutes for the metals of interest (Hein et al. 2020).

There are comparisons being made of the ensuing environmental impacts in deep-sea mining with respect to the impacts of mining on land. Whereas, it is argued that land mining completely devastates the ecosystem that can never be restored to its original state (Sonter et al. 2017); it is possible that due to the dynamic nature of deep-sea environment, it could restore itself over a period of time. On the other hand, whereas on land restoration can be done through human intervention; this would not be possible at sea. Moreover, in deep-sea mining, no human communities are displaced or infrastructure such as roads, electric and water lines need not be built, hence minimising social impacts (Hein et al. 2020). This cannot be avoided in land mining and has been seen to be a contentious issue between the mining companies, local authorities as well as the communities living in the area.

Looking at the likely areas that will be impacted by the two, in case of deep-sea mining the impact is expected to be distributed and hence probably diluted as different activities would impact different regions, with the seafloor being the most affected, followed by the water column and the least at the surface, and to varying degrees; whereas in case of land mining, all the impacts are concentrated on land (Fig. 2.5).

The apprehensions regarding the environmental impact of deep-sea mining are based on our experience of large-scale destruction on land due to deforestation and lack of effective implementation of reforestation programmes. This implies that deep-sea mining would require robust environmental monitoring programmes to ensure compliance, data sharing and accountability on part of the contractors.

Whereas in case of deep-sea mining, the area of impact could be large (tens to hundreds of km^2) as compared to land mining (several km^2), the depth of excavation in deep-sea mining is limited (few centimetres to metres) with no removal of overburden as compared to land mining (tens to hundreds of metres) as in case of open cast or underground mines. Similarly, the intensity of activity in deep-sea mining is

Impact areas	Seafloor	Water Column	Surface	Land	
Activity	**Deep-sea mining**				**Land based mining**
Collection / Excavation	🟥				🟥
Separation	🟥				🟥
Lifting	🟥	🟥			🟥
Washing	🟥	🟥	🟥		🟥
Pre-processing	🟥	🟥	🟥		🟥
Transport	🟥	🟥	🟥	🟥	🟥
Extraction				🟥	🟥
Tailing discharge				🟥	🟥

Fig. 2.5 Environmental impacts of mining activities on different areas (indicated in pink). (Modified from Sharma 2017c)

low (scraping strips or patches that are few metres in width) as compared to mining activity on land (swaths of several tens or hundreds of metres). In terms of impact, whereas deep-sea mining would have impact on marine life, land mining impacts human life as well as terrestrial and aquatic life that directly affects the livelihood of human beings. Moreover, as there is no or limited at-sea processing expected in case of deep-sea mining, the corresponding impacts are expected to be very small as compared to land mining (Table 2.11).

It is important to understand that neither the geologists (who ‘find’ these minerals) nor the mining engineers (who would eventually ‘mine’ them) have any interest in going for deep-sea mining at the cost of intentional environmental destruction but only to ensure a steady supply of metals for the humankind. Alternatively, if mankind could either find other solutions to meet the requirements of these metals or desist from using those equipment or gadgets that require such metals, the mining companies can then concentrate on some other sector, instead of investing in deep-sea mining and risking their equipment and personnel in adverse marine conditions at locations thousands of kilometres from civilisation.

Table 2.11 Comparison of deep-sea mining versus land mining impacts

Factors	Deep-sea mining	Terrestrial mining
Area of impact	Widespread (tens/hundreds of km^2)	Limited (few km^2)
Intensity of activity per m^2	Low	Intense
Expected Impact	Marine life mainly	Humans, terrestrial + marine life
Terrestrial impact	Only processing on land	All activities on land
Processing impact	No beneficiation in nodules and crusts (sulphides)	On land beneficiation is key pollutant
Tailing discharge	Within mine-site at sea (except 15–20% slag on land)	In and around mine-site (on land, air and water)
Natural restoration	Could be faster (due to dynamic environment)	Could be slower (due to static environment)
Artificial restoration	Difficult	Possible to a limited extent
Social impact	Very little	Total

8 Future Prospects

Although the interest in deep-sea mining is growing and several research groups are working on developing techniques to understand and exploit the minerals as well conserve the environment, considerable efforts are required to make it sustainable. While deep-sea minerals seem to hold a promise for the benefit of mankind in future (Mizell et al. 2022, this book; Usui and Suzuki 2022, this book) and new technologies are being developed for analysing, mining as well as processing them (Morishita et al. 2022, this book, De Bruyne et al. 2022, this book; Kawano and Furaya 2022, this book; Duhayon and Boel 2022, this book), it is critical to incorporate measures such as use of renewable resources and a zero-waste approach while recovering the metals (Sen 2022, this book; Mittal and Anand 2022, this book). At the same time, improving our understanding of natural variability versus anthropogenic impacts (Radzeijewska et al. 2022, this book), as well as better understanding of potential environmental impacts on pelagic, meso-pelagic and benthic ecosystems (Fukushima et al. 2022, this book), coupled with integration of adaptive management and integrated management approaches (Clarke et al. 2022, this book; Boschen-Rose et al. 2022, this book), are critical for conservation of marine ecosystems.

Evaluation of techno-economic models of different mining systems as well as 3-dimensional modelling of deep-ocean floor (Yamazaki 2022, this book; Ellefmo 2022, this book) could provide the basis for selection of appropriate systems and planning the mining operations. On the other hand, detailed risk assessment along with implementation of suitable payment regimes (Doorn et al. 2022, this book; Wilde 2022, this book, Lodge and Bourrel-McKinnon 2022, this book) would help devising proper mitigation measures as well as evaluating the economic feasibility of deep-sea mining. Finally, development of seabed mining regulations with due considerations to its scientific and legal issues, operational aspects, socio-cultural dimensions and safeguarding the interests of developing nations (Verlaan 2022, this book; Cormier and Minkiewicz 2022, this book; Tilot et al. 2022, this book; Willaert 2022, this book) would pave the way for a successful deep-sea mining.

9 Conclusions

Deep-sea minerals are considered as an alternative source for supply of critical metals for industrial as well as domestic applications, unless new land resources are found or recycling of metals becomes more efficient, or alternative materials are discovered or synthetically produced, which can replace the metals that are gradually getting exhausted on land. Large quantities of minerals exist on the ocean floor in the form of polymetallic nodules, hydrothermal sulphides and ferromanganese crusts that contain critical metals that could be extracted in future. CCZ nodules alone contain a greater tonnage of Ni, Co, Tl, Te and Y than global terrestrial reserve base for these metals (Hein et al. 2020). Many of the metals found in these deposits are used for making stainless steel, super alloys, wind turbines, electromagnets, photoresistors, infrared optics, televisions, solar cells as well as batteries that can help us transit to green energy alternatives. A very small part of the large tonnage of polymetallic nodules itself can be extracted for decades to meet world's demand for certain metals. Moreover, the entire area encompassed in all the 31 contracts signed so far accounts for just 0.45% of the total area covered by all the oceans in the world, excluding the seas adjacent to them and there is no likelihood of mining taking place in all of these at the same time due to technical and economic reasons.

Deep-sea mining may have several advantages as compared to land-based deposits because the seafloor deposits have higher grades of certain metals than those being mined on land, one seafloor mine could contain a number of metals that can potentially replace the need to develop several mines on land, and they are expected to create much less carbon footprint than their land-based counterparts. As technologies are evolving, deep-sea mining has the advantage of not only learning from experiences but also employing best available technologies (Van Nijen et al. 2018). Moreover, in case of deep-sea mining, no roads, buildings or infrastructure are required to be built, there are no human communities in and around most deep seafloor deposits and so no relocation of human communities and land-use conflicts are expected as compared to land mining.

Increasing collaboration between research organisations and industry partners to address issues from resource assessment to developing technologies for mining as well as legal and regulatory framework is an indication of growing interest in deep-sea mining. Several regulations are being put in place by the International Seabed Authority to safeguard the marine environment from the likely impacts of deep-sea mining and adoption of good management practices as well as strict compliance and monitoring by the contractors could ensure bringing about a balance between mining deep-sea resources to meet the requirements of mankind and environmental conservation (Lodge et al. 2017).

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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. He has contributed to the ‘World Ocean Assessment report I’ of the United Nations and has also been invited to contribute a chapter on ‘Potential impacts of deep-sea mining on marine ecosystem’ for the Oxford Encyclopedia for environmental science. In addition to his research career, he has been involved with several activities relating to science communication and outreach, as well as training programs for international participants, professionals and students .