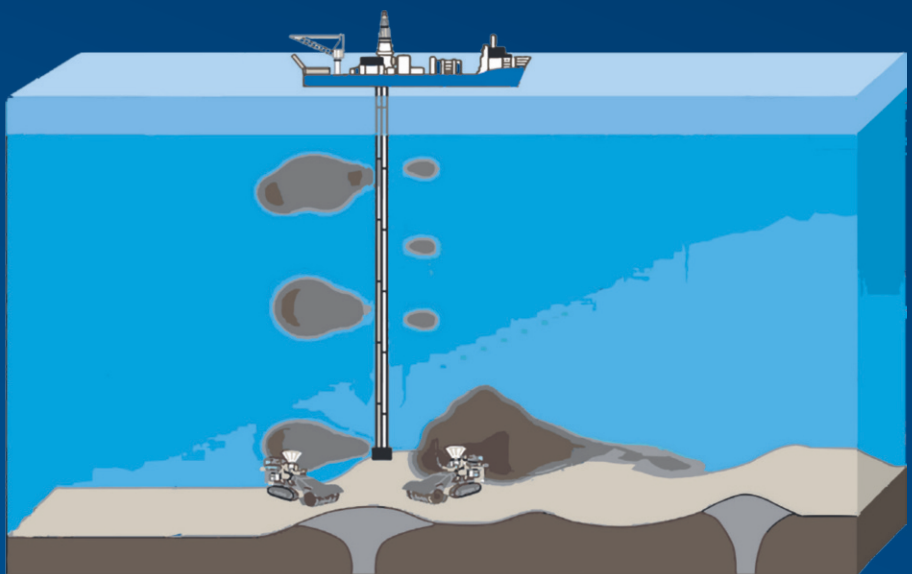
Rahul Sharma *Editor*

Deep-Sea Mining and the Water Column

Advances, Monitoring and Related Issues



Springer

Deep-Sea Mining and the Water Column

Rahul Sharma
Editor

Deep-Sea Mining and the Water Column

Advances, Monitoring and Related Issues

Springer

Editor
Rahul Sharma
Consultant, Deep-sea Mining and Former Chief Scientist
National Institute of Oceanography
Dona Paula, Goa, India

ISBN 978-3-031-59059-7 ISBN 978-3-031-59060-3 (eBook)
https://doi.org/10.1007/978-3-031-59060-3

Cover image: Schematic of Deep-sea mining system and associated impacts on the pelagic and benthic ecosystems (Modified from original diagram from NIWA-IUCN, figure provided by Malcolm Clark).

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Paper in this product is recyclable.

Foreword

I am delighted at receiving the invitation to contribute a foreword for the fourth book by Dr. Rahul Sharma on the topic of deep-sea mining. As with previous volumes, it is a great honour for me to accede to his request.

As the International Seabed Authority progresses its work on the regulatory framework for the inevitable transition from deep-sea mineral exploration to exploitation, the public debate on the topic has become increasingly polarized and frequently misinformed. A few sectors of society have even been calling for a moratorium on all deep-sea mineral activities, notwithstanding that these activities are fully regulated by international law and that deep-sea exploration has in fact provided considerable benefit to humankind through increased scientific knowledge and technological development.

Dr. Sharma's earlier volumes, on the resource potential and technical considerations for deep sea mining (2017), on environmental issues of deep-sea mining (2019), and on sustainability, technology, environmental policy and management (2022), contributed greatly to the scholarly literature on deep-sea mining and brought together the perspectives of experts in the field, including many of the world's leading experts in their subjects.

The present volume addresses the topic from the perspective of the water column, which has a unique significance being the large volume of water mass that will likely be impacted upon and in turn influence decisions related to offshore mining in future. Of particular importance is the fact that, rather than advancing political positions, most of the contributions to the book critically address the way in which the main expected impacts of deep-sea mining can be predicted, measured and mitigated, not least through the rapid maturation of technology that, for the most part, remains under development.

There is no doubt that, as with every other human endeavour, there are pros and cons to deep-sea mining. However, in the short to medium term, it seems likely that a mix of critical minerals from land and sea can more sustainably support the energy transition than relying on terrestrial sources alone. Deep-sea mining thus presents an important opportunity for development. But more technical, impartial and informed discussion is needed, especially on economic, geological and technological aspects, and Dr. Sharma's book makes an important contribution in this respect.

I congratulate Dr. Sharma and all the experts who have contributed to this volume.

Secretary-General
International Seabed Authority,
Kingston, Jamaica
September 2023

Michael W. Lodge

Preface

Deep-sea mining has been a topic of interest in recent years, as after the signing of exploration contracts between the International Seabed Authority (ISA) and several entities for different types of mineral deposits from the deep-sea regions in international areas, the focus is shifting to development and testing of various subsystems for mining and processing of these deep-sea minerals, as well as on the deliberations that are underway at ISA for developing a mining code. Similar efforts are underway for exploration and exploitation of deep-sea minerals within the Exclusive Economic Zones of several countries.

In this series on deep-sea mining, while the earlier three editions have focused on *Deep-sea mining: Resource Potential, Technical and Environmental Considerations*, *Environmental Issues of Deep-Sea Mining: Impacts, Consequences and Policy Perspectives* and *Perspectives on Deep-Sea Mining: Sustainability, Technology, Environmental Policy and Management*, this book deals with *Deep-Sea Mining and the Water Column: Advances, Monitoring and Related Issues*.

It is anticipated that the water column could be the largest volume of water mass that would come in contact with various subsystems as well as the effluents that may be discharged during deep-sea mining operations, leading to impacts on the marine ecosystem. This could lead to various environmental as well as legal issues, since the area impacted in the water column could be larger than the one impacted on the seafloor where mining would take place.

Hence, this book contains sections dealing with general issues of deep-sea mining; engineering concepts; approaches to sea surface and water column monitoring; regional assessment of chemical, physical and biological characteristics of water column; and the legal, policy and economic issues. This book has been possible due to the excellent contributions by researchers from around the world, who have shared their expertise for the benefit of deep-sea community in particular and the humankind in general.

As this book contains articles from authors from diverse backgrounds, readers are requested to note that the views expressed are those of individual authors and do not reflect the view of either the editor or that of the publisher.

The editor is extremely grateful to all the authors for sparing their time and contributing to this book. Mr. Michael Lodge, His Excellency, the Secretary General of ISA, deserves a special mention for his Foreword that sets the tone of the book. A special thanks goes to Dr. Virginie Tilot, Attaché honoraire, Museum National D'Histoire Naturelle, Paris, France, not only for suggesting the theme 'Deep-sea mining and the water column' but also for her constant support during the compilation of the book.

It is expected that this book will serve as an important source of information on different aspects of deep-sea mining with a special focus on the water column, for all stakeholders including the researchers, technologists, contractors, mining companies, regulators and the NGOs involved in deep-sea mining and marine environmental conservation.

Dona Paula, Goa, India Rahul Sharma

Contents

Part I
General Issues and Interdisciplinary Approach to Deep-Sea Mining

Chapter 1
Deep-Sea Mining and the Water Column: An Introduction

Rahul Sharma

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 sources of metals such as Cu, Ni, Co, rare earths and others. These are considered critical for meeting mankind's green energy requirements, among others, especially in view of depleting or low-grade terrestrial resources. This chapter gives an overview of the current status of deep-sea mining, its potential impacts, including on the water column, and the possible mitigation measures and regulations for the same.

Keywords Deep-sea mining · Environmental impacts · Water column · Mitigation · Regulations

1 Introduction

There is a growing need to find alternative sources for metals that are critical not only for meeting the day-to-day demands of mankind that include consumer and biomedical goods, alloys, batteries, pigments and catalysts, as well as heavy machinery and electric transmission, but also to transition from fossil fuel to green energy options including solar and wind farms, electric car batteries and high-capacity energy storage devices (Hein et al., 2020; Cronan, 2022). So far, the metal demand has been met from terrestrial sources, or to some extent from recycling, but the rising demand due to increasing population and economic growth around the world 'will require either expansion of existing mining projects or establishing new ones' (Koschinsky et al., 2018). According to Petersen et al. (2018), issues such as

R. Sharma (✉)
Consultant, Deep-sea Mining and Former Chief Scientist, National Institute of Oceanography, Dona Paula, Goa, India
e-mail: rsharmagoa@gmail.com

R. Sharma (ed.), *Deep-Sea Mining and the Water Column*,
https://doi.org/10.1007/978-3-031-59060-3_1

low-grade deposits, geopolitical concerns and security of metals supply could become the key drivers for deep-sea mining becoming a potential source for the supply of metals in the future.

It is anticipated that the demand for cobalt will be 423%, nickel 136% and lithium 280% of the currently known reserves by 2050 (www.mineralsindepth.org). The European Union has updated its list of critical raw materials (CRMs) to 34, which includes Cu and Ni as strategic metals (https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials_en), and the USGS has listed 50 CRMs (www.usgs.gov) that are essential for sustained growth of the industry. Whereas the major supply (60%) of raw Co, a critical component in lithium-ion batteries, comes from the Democratic Republic of Congo; 80% of refined Co comes from China (Al Barazi et al., 2018). Sourcing these metals from such conflict zones combined with the need to become self-reliant has led to the quest for alternative sources of metals.

Deep-sea minerals such as polymetallic nodules, ferromanganese crusts and hydrothermal sulphides, are emerging as potential sources of metals such as Cu, Ni, Co, Mn, Fe and rare earth elements that can contribute towards the world's growing demands for certain metals critical for sustaining the industrial growth as well as green energy alternatives (Hein et al., 2013; Miller et al., 2018). According to Weaver and Billet (2019), 'Each of these mineral deposits are known to form under specific environmental conditions, associated with discrete seafloor morphology and depth, having different concentrations of metals and found in different parts of the world oceans'. Prospecting of seabed mineral deposits has been underway for several decades, leading to the estimation of their resource potential in millions of tonnes worth billions of dollars, which could meet the global demands in the future (Van Nijen et al., 2018; Hein et al., 2020; Sharma, 2022).

This becomes more critical considering the increasing production rate of different metals (ranging from 1.1% for Au to 8.3% for Co) (Sharma & Smith, 2019) and that the available land reserves of some of these metals will last for just over two decades (e.g. Mn, Cu, Ni, Co), whereas a few others for just about a decade (e.g. Pb and Zn) (Sharma et al., 2019). With the objective of reducing dependency on a few countries that have the monopoly for supply of some of these metals, several entities (called contractors) have embarked upon exploration programmes for deep-sea minerals. Moreover, mining on the seabed area for any one of these mineral deposits can offer several metals as opposed to operating several mines for different minerals on land (Hein et al., 2020).

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 and Y, are higher by 1.15–3.4 times than the entire global resources on land (Hein et al., 2020), underlining the potential of deep-sea minerals as an alternative source for some of these metals. In a typical contract area of 75,000 km^2 for polymetallic nodules with a cut-off abundance of 5 kg/m^2 (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. (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 actually mined at a mining rate of 1.5 million tonnes/year (ISA, 2008a) and three million tonnes/year (UNOET, 1987), respectively, over a 20-year period as the life of a mine-site, with a large balance (78.8–89.4%) that could be mined for more than a century (Sharma, 2017a). Besides these minerals, deep-sea sediments have also been identified as a source for rare earth elements, as found near Minamitorishima island in the 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). A study on cobalt-rich crusts on one of the seamounts in the North-Western Pacific Ocean suggests that '…the area tested around the Takuyo No. 5 Seamount contains enough cobalt to meet Japan's demand for 88 years and enough nickel to meet Japan's demand for 12 years' (www.jogmec.go.jp). An economic feasibility study has also suggested the mining of cobalt-rich crust along with its substrate rich in phosphorus as a by-product to increase the viability of the resource (Yamazaki et al., 2023).

Whereas some of the areas in which deep-sea minerals are located fall within the Exclusive Economic Zone (EEZ) of different countries and their exploration and exploitation are governed by the regulations of the respective state, large deposits of these minerals also occur across thousands of square kilometres in international waters in all the oceans of the world and are regulated by the International Seabed Authority (ISA), Jamaica. Currently, 31 contracts have been signed between different contractors and ISA for these deep-sea minerals (www.isa.org.jm).

Although fluctuating metal prices as well as reduction in demand of metals after the world wars were responsible for deferred technological developments for commercial exploitation, these deposits have always been considered important in the overall metal budget of the earth and expected to 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), as the commercial viability of deep-sea deposits lies in their concentration and magnitude as compared to deposits on land (Lenoble, 2000).

This chapter provides an overview of deep-sea mining, dwells upon the possible environmental impacts, including on the water column, and discusses various approaches towards managing and mitigating the same.

2 Basic Characteristics of Deep-Sea Minerals

The occurrence of deep-sea minerals has been known since the discovery of polymetallic nodules from the deep seabed onboard H.M.S. Challenger expedition, during which the dredge haul of 7 March 1873 was described as 'peculiar black oval bodies about 1 inch long' and 'almost pure manganese oxide' (en.wikipedia.org/wiki/HMSChallenger). Later, Mero (1965) recognised the economic potential of these deposits and predicted that 'deep-sea mining would commence in 20 years' time, which led to a race for developing these resources as an alternative source of metals for the future.

Detailed studies on the distribution, geochemistry and mineralogy of these mineral deposits in different parts of the Pacific Ocean (Hein et al., 1979; Thijssen et al., 1981; Glasby, 1982; Usui & Moritani, 1992) and Indian Ocean (Glasby, 1972; Siddiquie et al., 1978; Frazer & Wilson, 1980; Cronan & Moorby, 1981) gave critical information on this resource. Research also focussed on their formation process, geological factors and their relationship with the sedimentary environment (Cronan, 1980; Frazer & Fisk, 1981; Glasby et al., 1982; Rao & Nath, 1988; Martin-Barajas et al., 1991). Subsequently, studies on other deep-sea minerals, such as hydrothermal sulphides (Rona, 1988; Plueger et al., 1990) and cobalt-rich ferromanganese crusts (Halbach et al., 1989; Hein et al., 1997), also helped in identifying these as potential resources for critical metals, in future.

These are known as deep-sea minerals owing to their occurrence in water depths ranging from 1000 to 6000 m, each having some common and some distinct features in terms of their occurrence, formation process, geochemistry and physical characteristics (Table 1.1). While the polymetallic nodules (or manganese nodules)

Table 1.1 Salient features of deep-sea minerals[a] (Sharma & Smith, 2019)

Type	Description	Area, thickness of the deposit	Metals and their mean concentration[b]	Principal deposits
Poly-metallic 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 upto 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 sulfides (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
Ferro-manganese crusts	Layered manganese and iron oxides with associated metals on hard substrate rock of subsea mountains and ridges	Up to several km^2; generally a 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

[a]Modified from Cuyvers et al. (2018)

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

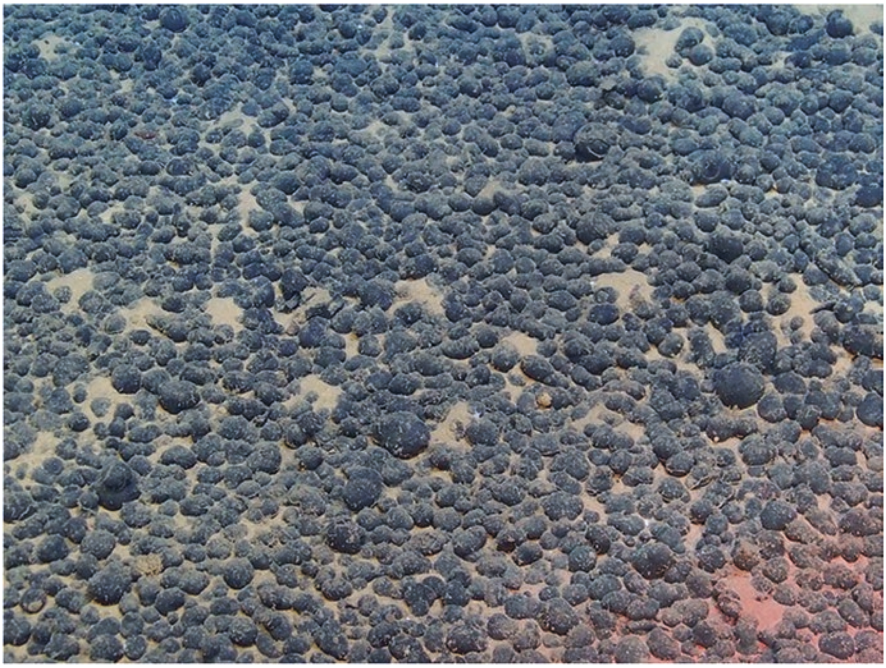


Fig. 1.1 Polymetallic nodules at the pelagic basin near the Takuyo-Daigo seamount, NW Pacific basin (JAMSTEC Cruise KR16–13#704, at 5490 m depth). Width approximately 2.0 m. (Photograph courtesy of Prof. A. Usui, Kochi University, Japan)

are layered concretions of iron and manganese oxides around a nucleus (generally a sediment particle, rock piece, shark tooth or any hard substrate) and occur as loosely lying spherical objects on abyssal plains (Kuhn et al., 2017 and the references therein), the ferromanganese crusts (or cobalt-rich ferromanganese crusts) are layered iron and manganese oxides on hard substrate of a rock (Cherkashov, 2017 and the references therein) and are generally located on underwater mountains or ridges, both containing metals precipitated from the water column and the associated substrates. On the other hand, hydrothermal sulphides (or 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).

Whereas the nodules (Fig. 1.1) are found to be spread over thousands of square kilometres, generally within the top 50 cm of the sediment (sometimes down to a few meters deeper), the crusts (Fig. 1.2) and sulphides (Fig. 1.3) could be spread over several square kilometres, with their thickness ranging from a few centimetres (for crusts) to several metres (for sulphides). Owing to different processes of formation, each of these deep-sea minerals has varying metal concentrations of major, minor and trace elements, of which some (Ni, Cu, Co, REEs and others) are

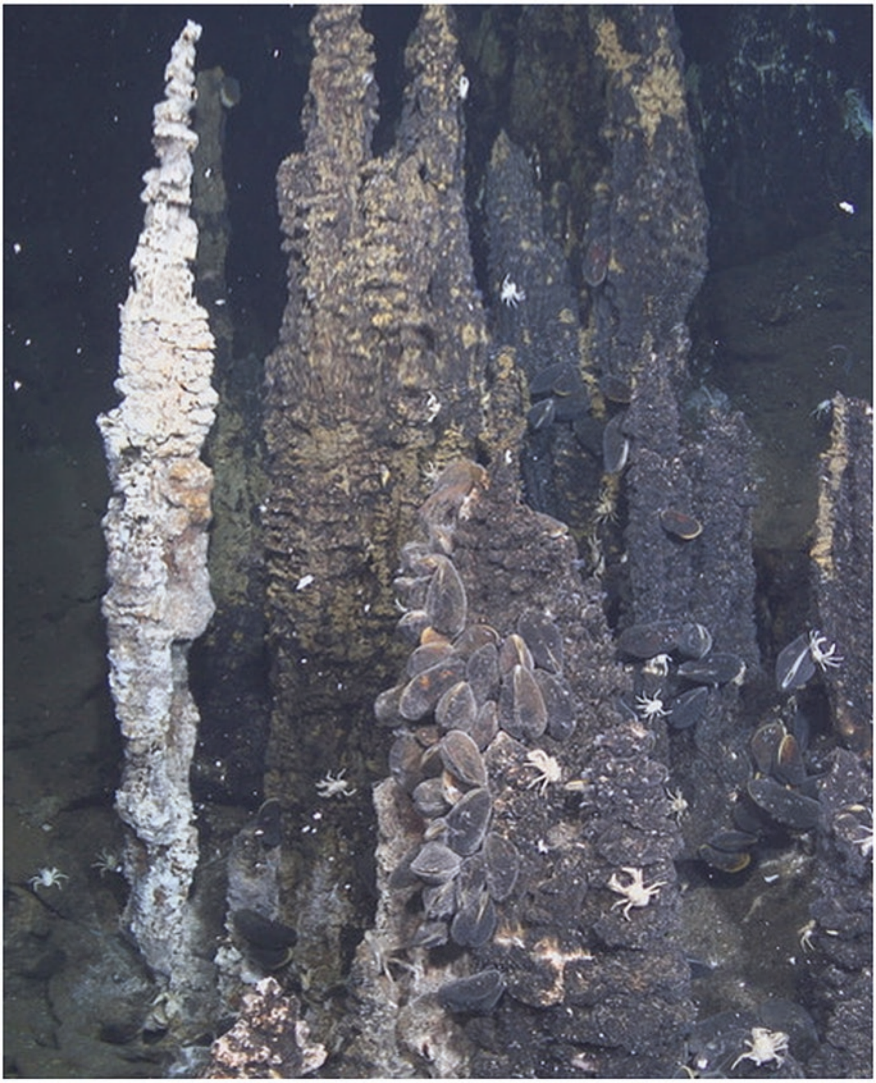


Fig. 1.2 Hydrothermal sulphide chimneys with black smokers, biological communities, and microbial mats, at the Kita-Bayonnaise Caldera, Izu-Bonin Arc (JAMSTEC Cruise NT13–05 #1494 at 1370 m depth). Width approximately 2.0 m. (Photograph courtesy of Prof. A. Usui, Kochi University, Japan)

considered critical for meeting the global demands in future (Van Nijen et al., 2018; Hein et al., 2020).

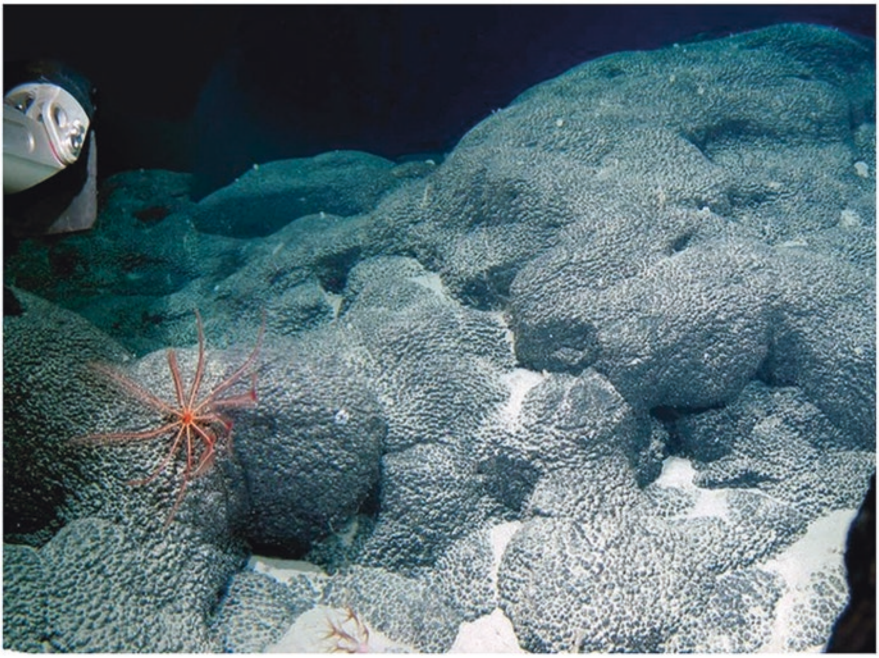


Fig. 1.3 Ferromanganese crusts near the summit of the Takuyo-Daigo seamount, NW Pacific basin (JAMSTEC Cruise KR09–02#955, at 1449 m depth). Width approximately 1.5 m. (Photograph courtesy of Prof. A. Usui, & B. Thornton)

3 Potential Sites for Deep-Sea Mining

Exploration and exploitation of some of these mineral deposits that are found to occur within the jurisdiction of some countries, that is Exclusive Economic Zones (EEZ), are governed by their respective laws. Some examples are the polymetallic nodules found within the national jurisdictions of Japan, Cook Islands and Kiribati (Hein et al., 2005; Hein et al. 2015), as well as Korea and France (Fouquet & Lacroix, 2014). Recently, Cook Islands has issued exploration licenses for mapping, sample collection and environmental studies for polymetallic nodules over an area of 254,654 km^2 within their EEZ (https://www.sbma.gov.ck). Approximately 650,000 km^2 area of the seafloor is covered by exploration contracts within EEZs of different coastal states in the Pacific Ocean (SPC, 2013; Petersen et al., 2018). Similarly, prospecting licenses to investigate hydrothermal sulphide deposits rich in silver and gold that occur along the Kermadec Volcanic Arc and on back-arc seamounts in their EEZ have been issued by the New Zealand government (Boschen-Rose et al., 2022). Recently, rich deposits have been found in the Norwegian Sea and Greenland Sea consisting of 38 million tonnes of copper and 45 million tonnes of zinc in polymetallic sulphides, as well as 24 million tonnes of magnesium, 3.1 million tonnes of cobalt and 1.7 million tonnes of cerium, a rare earth metal used in

Table 1.2 Estimated area under exploration contracts in the Area (as of December 2023)

Mineral type	Area (km^2)/contract	Total contracts[a]	Total area (km^2)
Nodules	75,000	19	1,425,000
Crusts	1000	5	5000
Sulphides	2500	7	17,500
Total		31	1,447,500

[a] www.isa.org.jm

alloys in manganese crusts, which the Norwegian government is considering developing as a future resource (https://www.reuters.com).

On the other hand, the deep-sea minerals that are located in international waters, beyond the national jurisdiction of any country, referred to as the 'Area', are regulated by the International Seabed Authority (ISA) established under Part XI of UN Law of the Sea (UNCLOS, 1982). There has been considerable interest over the last few decades in exploring these deposits, as evident from the fact that whereas only eight contracts were signed during the first decade of the century (2001–2010) by the erstwhile pioneer investors who had claimed deep-sea areas earlier (1980–2000), 23 new contracts were signed in the following decade (2011–2021) (www.isa.org.jm). Currently, there are 19 contracts for polymetallic nodules (each measuring 75,000 km^2), 5 for ferromanganese crusts (each measuring 1000 km^2) and 7 for hydrothermal sulphides (each measuring 2500 km^2) distributed over different parts of Pacific, Indian and Atlantic Oceans, totalling to 1,447,500 km^2 (Table 1.2). Although the total area appears to be large, it is critical to note that it forms just 0.45% of the area of all oceans in the world put together (Sharma, 2022).

The details of all the contracts between ISA and different contractors for each of the mineral types are given in Tables 1.3a, 1.3b and 1.3c and areas shown in Figs. 1.4a, 1.4b, 1.4c, 1.4d and 1.4e.

4 Development of Deep-Sea Mining Systems

In view of the evolving scenario of possible mining of deep-sea minerals in coming decades, several entities, including contractors and private enterprises, have initiated research and development for the design, fabrication and testing of different components as well as integrating them into pre-prototype systems that can be scaled up into full-scale commercial mining systems. Among the contractors, Korea has demonstrated a pilot mining system to collect nodules from 5000 m depth (Hong et al., 2019), India is developing a pre-prototype system for nodule collection that has been tested at 5200 m (Atmanand & Ramadass, 2017; Atmanand et al., this volume), and China has carried out a successful nodule collecting test at 500 m depth in South China Sea (https://chinadialogueocean.net). Japan has operated its prototype system for excavating sulphide ores containing Zn, Au, Cu and Pb from a depth of 1600 m off the coast of Okinawa (Kawano & Furaya, 2022) as well as a

Table 1.3a Contractors for exploration of polymetallic nodules in the Area (as of December 2023)

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 1.3b Contractors for exploration of ferromanganese crusts in the Area (as of December 2023)

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 1.3c Contractors for exploration of hydrothermal sulphides in the Area (as of December 2023)

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
Govt 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 1 December 2023

crust-excavation testing machine and collected 649 kilograms of cobalt and nickel-rich seabed crust (www.jogmec.go.jp).

Several contractors have entered into contracts with private enterprises for exploration and exploitation of seabed mineral resources in their contract areas. These include Nauru Ocean Resources Inc. (NORI, Nauru), Tonga Offshore Mining Limited (TOML, Tonga), Global Sea-mineral Resources NV (GSR, Belgium), UK Seabed Resources Ltd. (taken over by Loke Marine Minerals, Norway), Marawa Research and Exploration Ltd. (MRE, Marawa), Cook Islands Investment Corporation (CIIC, Cook Islands), China Minmetals Corporation (China), Beijing

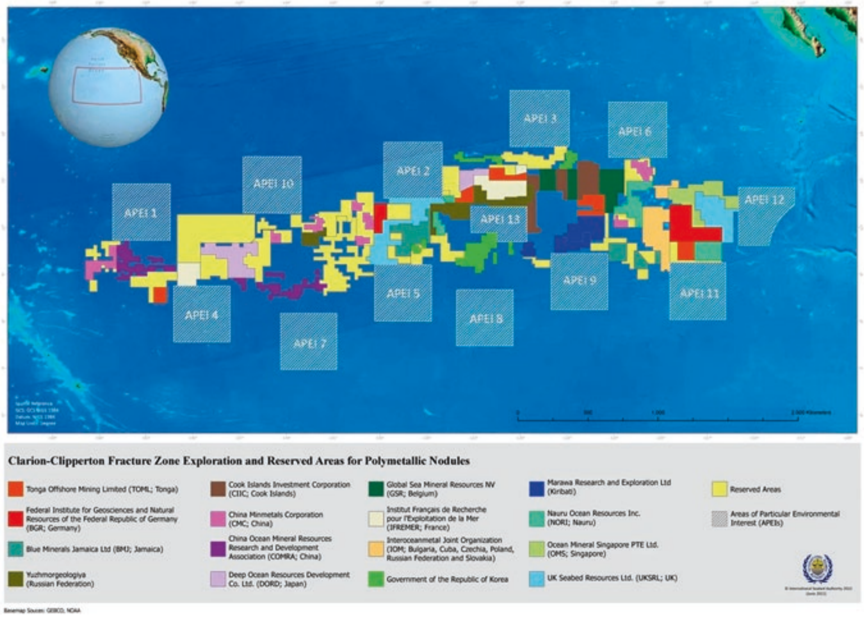


Fig. 1.4a Exploration areas for polymetallic nodules in Clarion-Clipperton Zone. (Courtesy: International Seabed Authority, Jamaica)

Pioneer Hi-Tech Development Corporation (China), Blue Minerals (Jamaica) and Ocean Mineral Singapore Pte Ltd. (OMS, Singapore) (www.isa.org.jm).

Some of the private enterprises have also started to develop and test their pre-prototype mining systems in international waters. Global Sea-mineral Resources NV (GSR) tested a 25-tonne nodule collector in the Belgian and German areas in the Clarion-Clipperton Zone (CCZ) of the Pacific Ocean over a distance of 54.3 km with a throughput of ~2000 tonnes of nodules in April 2021 (Bruyne et al., 2022). Nauru Ocean Resources Inc. (NORI—a subsidiary of The Metals Company) conducted a pilot collector test in September 2022 over 80 km of seafloor in NORI-D area and collected 4500 tonnes of nodules (of which 3000 tonnes were transported to a surface vessel) at a production rate of 86.4 tonnes per hour and plans to scale up from 1.3 to 12.5 Mtpa in future (www.tmc.com). Impossible Metals 'has successfully completed its first trial of selectively harvesting rocks in an underwater environment' in December 2022 and 'plans to have the technology ready for large scale deployment by 2026' (www.impossiblemetals.com).

Similar developments are also seen with respect to developing mineral resources within the EEZ of some countries. For example, Cook Islands Seabed Minerals Authority has signed 5-year contracts with three companies, viz. CIIC Seabed Resources Ltd., CIC Ltd. and Moana Minerals Ltd., for the development of seabed mineral resources (polymetallic nodules) within their EEZ (www.sbma.gov.ck/exploration). Odyssey Marine Exploration, which has experience in deep-sea

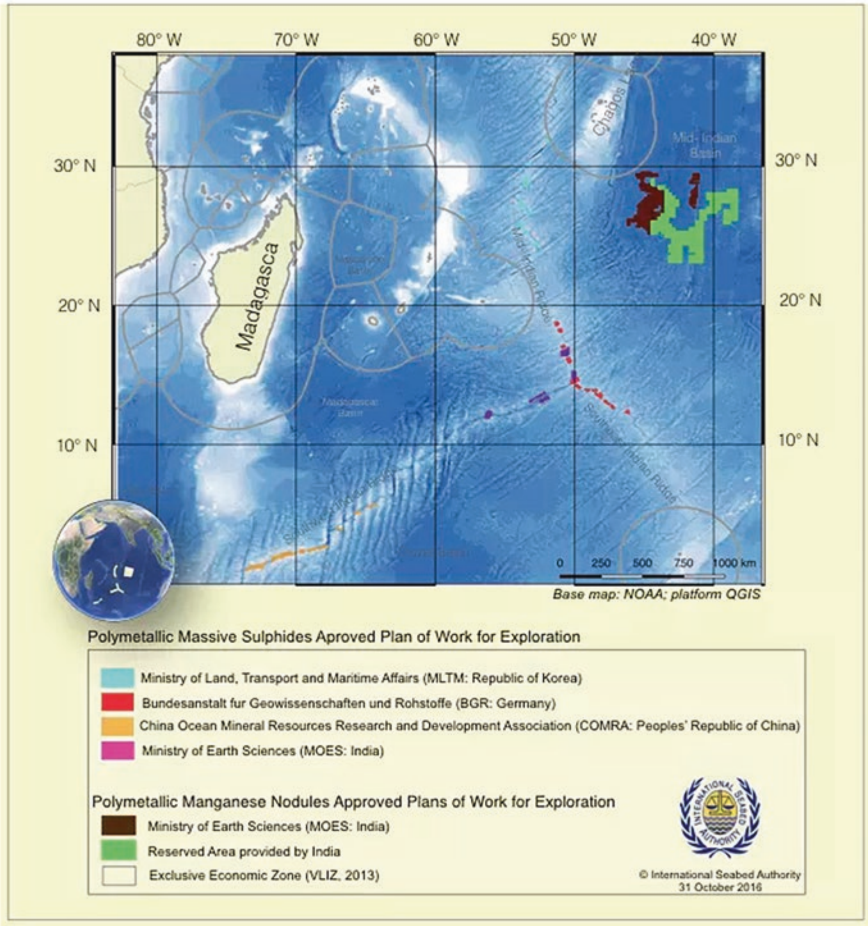


Fig. 1.4b Exploration areas for polymetallic nodules and sulphides in the Indian Ocean. (Courtesy: International Seabed Authority, Jamaica)

mineral exploration, validation and development, is involved with several government agencies interested in identifying mineral resources within their EEZs (https://www.odysseymarine.com/projects). Nautilus Minerals (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).

However, different activities of deep-sea mining are expected to have diverse environmental impacts (Weaver & Billet, 2019), right from the seafloor from where the minerals will be picked up to the water column through which the ores will be lifted to the mining platform, as well as at the surface where pre-processing, transfer to supply vessels and transportation of ores to land will be conducted. Hence, there is a need to evaluate the impacts on the physical, chemical and biological conditions

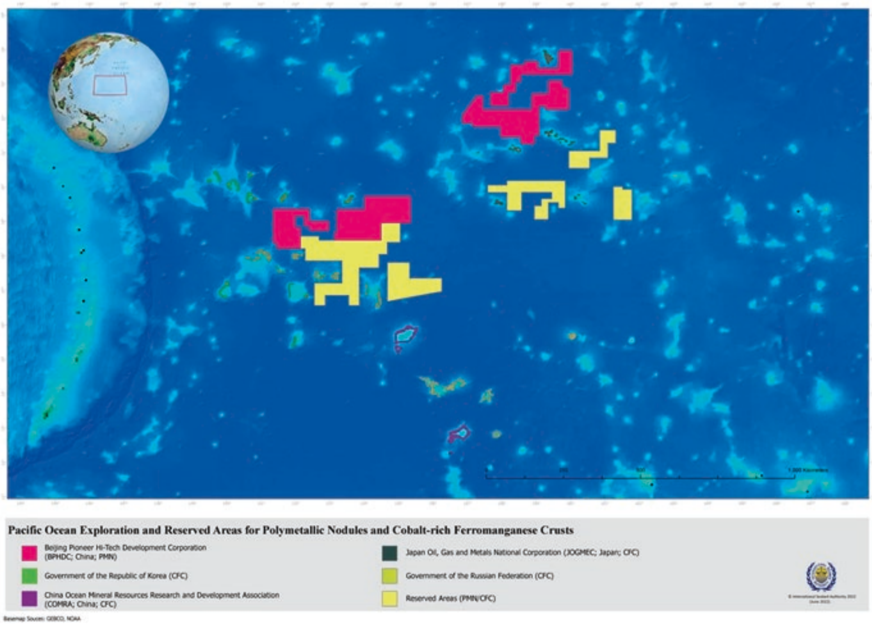


Fig. 1.4c Exploration areas for polymetallic nodules and cobalt-rich ferromanganese crusts in the Pacific Ocean. (Courtesy: International Seabed Authority, Jamaica)

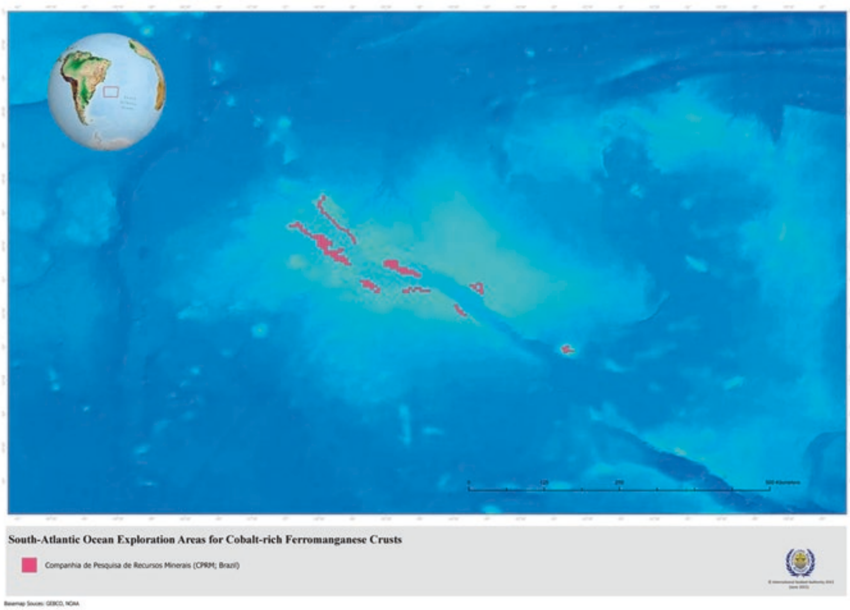


Fig. 1.4d Exploration areas for cobalt-rich ferromanganese crusts on South Atlantic seamounts. (Courtesy: International Seabed Authority, Jamaica)

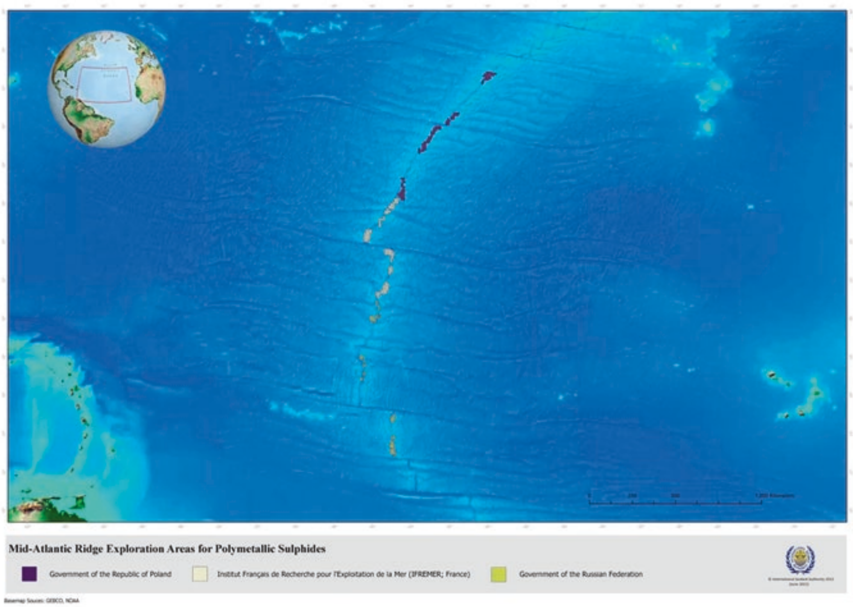


Fig. 1.4e Exploration areas for polymetallic sulphides on the Mid-Atlantic Ridge. (Courtesy: International Seabed Authority, Jamaica)

in the water column (Christiansen et al., 2020; Drazen et al., 2020), as well as the baseline conditions, and the likely impacts on the benthic environment (Sharma et al., 2001; Jones et al., 2017; Tilot, 2019; Radzeijewska et al., 2022, Fukushima et al., 2022).

5 Deep-Sea Mining and Environment

5.1 Impact of Environment on Mining

Environment and any developmental activity always have a two-way relationship. Whereas the issue of the impact of human activity on the environment attracts higher attention, the impact of the environment on the activity itself also has an equal significance. This is true for deep-sea mining as well. Whereas it is anticipated that deep-sea mining could have certain impacts on the marine environment, the environmental conditions at sea would also have different types of impacts on the mining activity in view of the prevailing atmospheric, hydrographic and seafloor topography, as well as sub-seafloor conditions at the mine site, and play a major role in the design and performance of different mining sub-systems (Table 1.4). Hence, evaluation of environmental conditions would not only help in the assessment of

Table 1.4 Influence of environmental conditions on mining system design and operation

Sr. no.	Conditions (key parameters)	Influence on mining system
1	Atmospheric (wind, rainfall, cyclone)	To determine the weather conditions for design as well as operation of the mining system during different seasons of the year, including likely shutdown periods.
2	Hydrographic (waves, currents, temperature, pressure)	Will influence operations on the platform including ore-handling as well as 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 manoeuverability 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 and screening of mineral at the seafloor from un-wanted material before pumping the ore to the surface as well as identifying relatively richer deposits for better output.
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.

Modified from Sharma (2017a)

impacts resulting from mining activity but also play a key role in the design and planning of the operation of the mining system itself (Sharma, 2011).

Long-term data on environmental parameters in the area of operation that need to be evaluated from local, regional or global meteorological perspectives, include seasonal variation of maximum, minimum and average for various atmospheric as well as sea-surface parameters such as sea surface temperature, wind speed, rainfall, frequency; path and intensity of cyclones (depressions, storms, hurricanes/typhoons, severe hurricanes/super typhoons); waves (season-wise frequency, direction, height and wave period); and the water column characteristics (depth wise profile of temperature, salinity) and currents (Sharma, 2019). Similarly, detailed evaluation of seafloor characteristics that will have an influence on the performance of the seabed mining device would include distribution characteristics of mineral deposits (size, coverage, abundance), substrates (sediment thickness, rock outcrops), topography, micro-topography and slopes (Sharma, 2017b, 2019).

5.2 Impact of Mining on Environment

Various activities associated with deep-sea mining are expected to create impacts at various levels in the marine ecosystem (Fig. 1.5). The likely impacts include those related to at-sea processing and transportation on the surface, altering the physico-chemical characteristics of the water column due to particles discharged (accidently or otherwise) during lifting of the ores, as well as on the seafloor, from where the

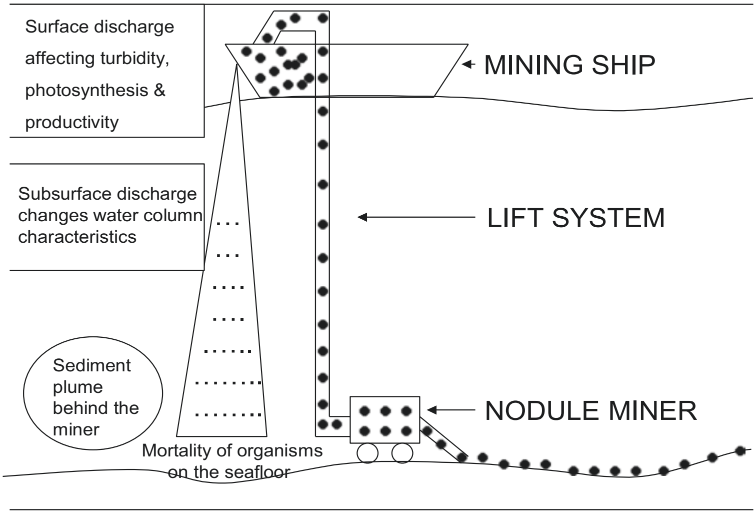


Fig. 1.5 Schematic for environmental impact of deep-sea nodule mining. (Sharma, 2017c)

minerals will be picked up and separated from the associated substrate either by scooping (in case of polymetallic nodules), scraping (in case of ferromanganese nodules) or drilling (in case of hydrothermal sulphides), leading to alteration in environmental conditions due 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, leading to changes in diversity and abundance of benthic organisms (Pearson, 1975; Amos et al., 1977).

Various activities associated with deep-sea mining that could lead to environmental impacts include (Sharma, 2022):

(a) *Offshore activities.*

(i) *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.*
(ii) *Suspension of fine particles of minerals and associated sediment into the water column.*
(iii) *Resettlement of suspended particles and smothering of seafloor.*
(iv) *Impacts due to light and sound during mining operation.*
(v) *Oil spills and leakages from mining platform and transport vessels.*
(vi) *Ballast water discharge from transport vessels.*
(vii) *At-sea processing, dewatering, waste disposal including chemicals, debris.*
(viii) *Sub-system losses such as pipes, chains, tools or any other hardware.*
(ix) *Human waste such as garbage, including plastics, metals, glass and other non-biodegradable items.*

(b) *Onshore activities.*

   (i) *Pollution during loading/unloading, on land transportation of ore from the port to the processing plant.*
   (ii) *Pollution during processing (fumes, discharges) around the processing plant.*
   (iii) *Pollution after processing (dumping of slag or unwanted material) away from the processing plant.*

Impacts that are expected at various levels in the water column and on the seafloor due to deep-sea mining activities are summarised as follows (after ISA, 1999):

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

   (i) *mortality of organisms along the collector track,*
   (ii) *smothering of the benthic fauna away from the mining site where the sediment plume settles,*
   (iii) *clogging of suspension feeders and dilution of deposit-feeders food resources.*

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

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

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

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

It is also critical to note that due to differences in characteristics and environmental settings of each of the deep-sea mineral type, there could be different kinds of impacts for mining of these on the marine ecosystem (Weaver & Billet, 2019).

5.3 Evaluating the Impact of Mining on Environment

In order to develop an understanding of the possible impacts of deep-sea mining, studies have been undertaken during the pilot mining tests under the Deep Ocean Mining Environment Study (DOMES, 1972–81) conducted by Ocean Mining Inc.

Table 1.5 Benthic Impact Experiments (BIEs) (Sharma, 2022)

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 mins	141 km	6951 m^3
JET[c]	1985	Metal mining Agency of Japan	Clarion Clipperton Fracture Zone	19	1227 mins	33 km	2495 m^3
IOM-BIE[d]	1995	InterOceanMetal – consortium of East Europen Countries	Clarion Clipperton Fracture Zone	14	1130 mins	35 km	2693 m^3
INDEX[e]	1997	National Institute of Oceanography, Govt. of India	Central Indian Ocean Basin	26	2534 mins	88 km	6015 m^3

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

(OMI) and Ocean Mining Associates (OMA) in the Pacific Ocean (Ozturgut et al., 1980). Subsequently, experimental mining was conducted using devices such as plough harrow and sediment suspension mechanism in the Pacific and Indian Oceans (Table 1.5) (Foell et al., 1990; Trueblood, 1993; Fukushima, 1995; Tkatchenko et al., 1996; Sharma & Nath, 2000; Theil, 2001; Sharma, 2001; Sharma, 2005). These experiments have revealed that whereas the impacts were severe immediately after the disturbance (Shirayama, 1999), the impacts were masked by natural variability over a period of time (Sharma et al., 2007). Studies have shown that while mobile and small fauna were less negatively impacted and the density and diversity of meio and mobile megafauna recovered within 1 year, some of the faunal groups returned to control conditions after two decades (Jones et al., 2017).

Analysis of the intensity of disturbance shows that the scale of these experiments was significantly small as compared to that expected during commercial mining (Yamazaki & Sharma, 2001), leading to an engineering assessment of 'experimental' deep-sea mining that suggested to 'test benthic disturbance in scale and system large enough to represent the commercial mining scale' (Chung et al., 2001). This has been evidenced in the case of Global Seabed Resources (GSR) testing its prototype nodule collector in the Belgian and German areas in the CCZ in 2021 (Bruyne et al., 2022), wherein the results have shown that the resulting sediment plume from