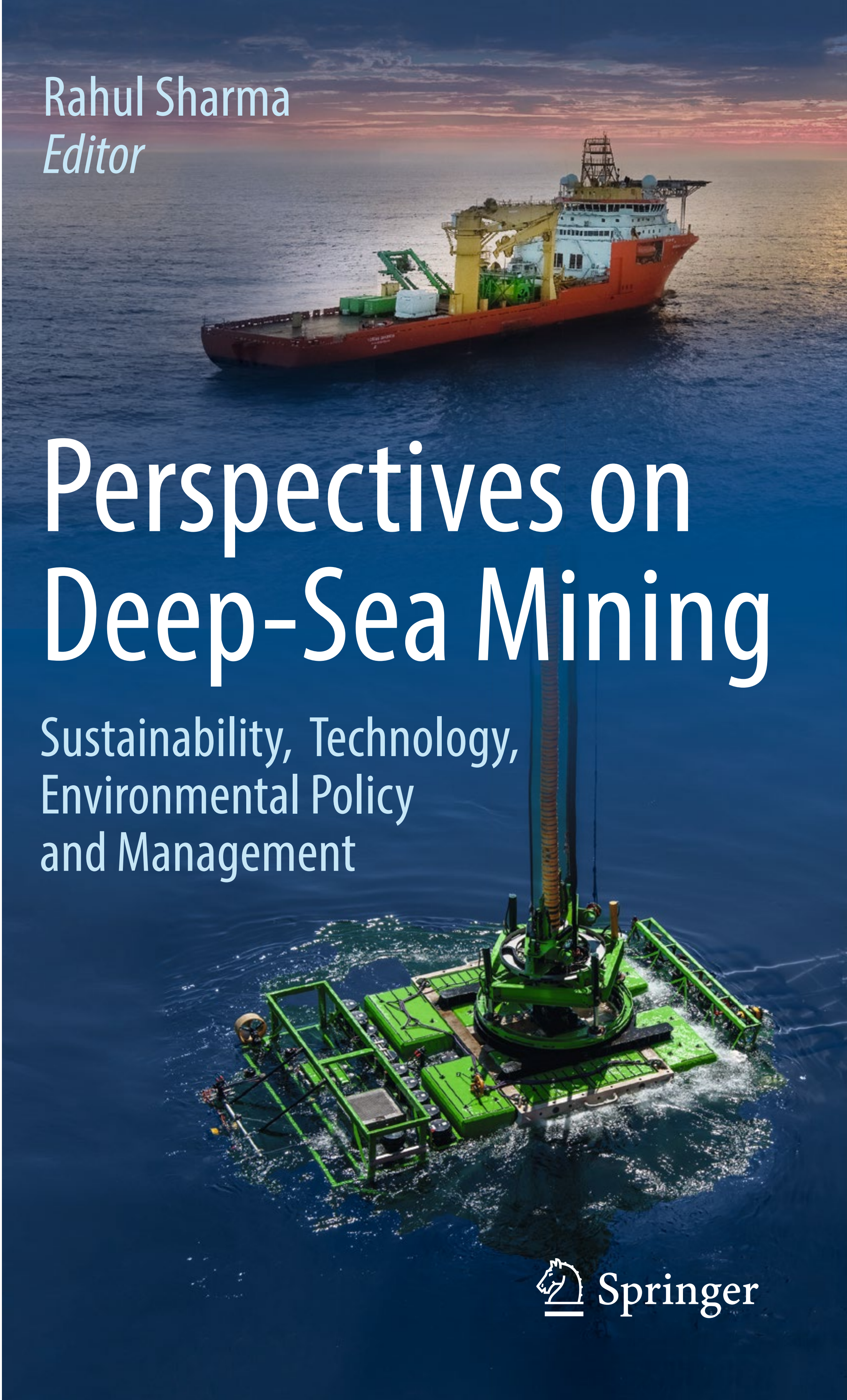
Rahul Sharma
Editor

Perspectives on Deep-Sea Mining

Sustainability, Technology, Environmental Policy and Management



Springer

Perspectives on Deep-Sea Mining

Rahul Sharma
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Cover caption: Testing of pre-prototype deep-sea mining machine Patania II from the Research Vessel Normand Energy (Courtesy of Global Sea Mineral Resources NV, Belgium).

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Foreword

This is the third occasion on which I have had the pleasure of contributing a foreword to a volume edited by Dr. Rahul Sharma. Both of his previous volumes, on the resource potential and technical considerations for deep-sea mining, and on environmental issues of deep-sea mining, made substantial contributions to the scholarly literature on the potential for marine minerals from the deep seabed to contribute to global sustainable development.

With this third volume, on sustainability, technology, environmental policy and management, Dr. Sharma has again brought together the perspectives of a number of experts in the field. Many of the authors are among the world's leading experts in their subjects, with decades of experience and accumulated wisdom. It is a pleasure to see that Dr. Sharma has also included the perspectives of younger scholars to make this volume truly intergenerational.

Since the first volume was published in 2017, the level of interest in deep-sea mining has continued to increase, driven by the increased recognition of how dramatically the extraction and processing of certain critical minerals, such as cobalt and nickel, will need to grow in order to enable the ambitions of the world's politicians to decarbonize economies by 2050. Associated with this is the fact that technological developments have made deep-sea mining feasible, just as rising demand has made investment more attractive.

Regrettably, at the same time, the public discourse around deep-sea mining has become increasingly polarized with some conservation groups seeking to block all deep-sea mining on the basis of extreme environmentalist ideology. In these circumstances, it is more important than ever that the debate is properly informed. Collectively, we need to consider long-term planetary sustainability and take a systems science perspective rather than focus on niche perceptions of risk while neglecting or, even worse, obfuscating or ignoring the other trade-offs that need to be made.

Books like this are an important contribution to this broader debate and I congratulate Dr. Sharma and all the experts who have contributed to this volume.

Michael W. Lodge
International Seabed Authority
Kingston, Jamaica

Preface

Deep-sea minerals continue to enthuse researchers involved either in ascertaining their potential as alternative sources for critical metals including those for green energy, or in technology development for their exploration and exploitation; as well as in addressing environmental, socio-economic and legal issues. With a steady increase in the number of contractors having exclusive rights over large tracts on the seafloor in the 'Area', i.e. regions beyond national jurisdictions, the International Seabed Authority that is mandated with the responsibility of regulating such activities, is in the process of developing a code for exploitation of deep-sea minerals. These coupled with growing interest among private entrepreneurs, investment companies as well as policy makers, underlines the need for updated information being available in one place on the subject of deep-sea mining, which is the objective of this volume.

This book is a sequel to the previous ones, viz. *Deep-sea mining—resource potential, technical and environmental considerations* (2017) and *Environmental issues of deep-sea mining* (2019) that had contributions from several experts on different topics associated with deep-sea mining. The overwhelming response from the deep-sea mining community to these books led us to conceive the present one that aims to bring together different perspectives from specialists around the world on various aspects of deep-sea mining.

The first section of the book *Evaluation of deep-sea mineral resources and their potential* looks at the historical as well as current status, global resources and geological characterization of deep-sea minerals. This is followed by a section on *Technology development for deep-sea mining and mineral processing* that includes recent advances and challenges in deep-sea mining technologies, exploring the use of renewable resources and a zero waste approach during mineral processing, as well as comparing them with terrestrial ores. The section on *Ecosystem studies, environmental monitoring and management* addresses issues such as natural variability versus anthropogenic impacts, besides looking at the potential impacts on pelagic, meso-pelagic and benthic ecosystems and also suggests adaptive management as well as integrated management of ecological impacts from mining of deep-sea minerals.

The section on *Techno-economic models, risk assessment and payment regimes* discusses different models for improving the feasibility of deep-sea mining, their risk assessment, 3-D modelling and taxation within national jurisdictions as well as sharing of financial benefits from deep-sea mining, whereas the section on *Legal and socio-cultural frameworks* deals with achieving effective seabed mining regulation, operational aspects of regulatory frameworks, application of cultural dimensions to seabed resource management, as well as safeguarding the interests of developing states in the context of deep-sea mining.

The information compiled in the book is expected to serve as a key reference source for all stake holders including researchers, contractors, mining companies, regulators as well as NGOs involved in deep-sea mining. The chapters have been contributed by highly acclaimed scientists, technologists, lawyers and administrators who have an experience of several decades on their respective subjects.

Besides the excellent contributions from all authors, one of the highlights of this book is that several chapters are written by authors from relatively younger age group, that being an indicator of sustained interest in the field of deep-sea mining, and a matter of satisfaction for the 'older' researchers who have been in this field through the previous century and are on the verge of retirement.

I wish to gratefully acknowledge all the authors for their contributions, the publishers for providing this platform, the reviewers for their invaluable inputs and all those directly or indirectly associated with this project. Special thanks are due to Mr. Michael Lodge, Secretary General, International Seabed Authority for graciously writing the Foreword for the book. Dr. Kris Van Nijen, Managing Director, DEME-Global Seabed Resources, Belgium, is gratefully acknowledged for sharing the pictures of the research vessel and pre-prototype mining system for the cover page of the book.

Dona Paula, Goa, India Rahul Sharma

Contents

Part I
Evaluation of Deep-Sea Mineral Resources and Their Potential

Chapter 1
Deep-Sea Mining: Historical Perspectives

David S. Cronan

Abstract The seeds of deep-sea mining were sown during the post-war boom. The massive use of raw materials and the wholescale destruction of both property and material during that war created a demand for raw materials that some thought could not be met from conventional sources. Amongst these was a group of University of California Professors who met at the Scripps Institution of Oceanography in 1957 and who initiated a programme on the evaluation of mining manganese nodules (Mero 1965). John Mero was appointed Chief Investigator of this project and went on to produce several papers on the subject (Mero 1959, 1960, 1962), and his now-classic book 'The Mineral Resources of the Sea' (1965) painted a very optimistic picture of deep-sea mining.

It was arguably the publication of Mero's book that initiated interest in the whole business of deep-sea mining. However, Mero was not the first person to recognise the future potential of manganese nodules. John Young Buchanan, ship's chemist during the Challenger Expedition (1873–1876) mentioned their possible future value in a letter to his father (Glasby 1977). Additionally, Dunham (1964) mentioned the possibility of potentially economic hydrothermal minerals occurring on the seafloor, several years before they were actually discovered.

The deep-sea minerals of interest in this Introduction are manganese (polymetallic) nodules, cobalt-rich ferromanganese oxide crusts and hydrothermal polymetallic sulphide deposits (PMS).

Keywords Deep-sea minerals · Nodules · Crusts · Sulphides · Historical perspective

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1 Manganese or Polymetallic Nodules

Industrial and political interest in manganese nodules commenced soon after the publication of John Mero's book in 1965 and has lasted to the present day, with one or two ups and downs. It was the work of Mero that engendered serious consideration being given to mining them and at least partly to the declaration by the Maltese Ambassador to the UN that the resources of the deep-sea floor should be 'the common heritage of mankind' (1967) which in turn helped lead to and underpinned the third Law of the Sea Conference and the ensuing Law of the Sea Convention in 1982. Mero (1965) considered that if only 10% of the nodule deposits on the ocean floor were to be mined, enough metals to last for thousands of years at the then rates of consumption would be recovered. He also said that the nodules were growing ocean wide at a rate faster than the metals that they contained could be consumed, which on a worldwide basis was probably true. However, subsequent work showed that only a very small proportion of all the nodules on the deep-sea floor would be mined for reasons of their grade and that those were amongst the most slowly growing, at rates of only up to a few tens of millimetres per million years.

Another point that Mero (1965) made was that manganese nodule mining could lead to the closure of environmentally polluting mines on land, a theme that was subsequently developed in regard to comparisons with nickeliferous laterite mining, its nearest terrestrial equivalent, which is a great despoiler of mainly tropical areas. This and other points in favour of deep-sea mining were made by Heydon (2012) who stated that 'in contrast to terrestrial mining, deep sea mineral extraction involves minimal overburden stripping…decreased extraction waste, no societal displacement, minimal production infrastructure, no need to build roads and railways for haulage, no blasting, no acid mine drainage and no deforestation'. Mero himself never seemed to have considered the possibility of marine environmental damage, something that has recently generated much interest and concern (Sharma 2019). Nevertheless, Mero's lasting legacy is that with only limited data he outlined the manganese nodule compositional regions of the Pacific, which remain more or less unchanged to this day in spite of many more data now being available.

Commercial interest in nodule mining commenced in the mid-1960s and by the 1970s several consortia had been formed to mine in the Clarion Clipperton Zone (CCZ) in the Pacific, which resource estimates suggested contains about 7.5 billion tonnes of Mn, and respectively 340, 265 and 78 million tonnes of Ni, Cu and Co. Large sums were spent by Industrial Consortia in exploring for future mine sites in the CCZ but most became inactive in the late 1970s and 1980s. Later, several National Consortia sponsored by countries such as France, Japan, Korea and others were formed, some of which are still active.

In the Indian Ocean, the National Institute of Oceanography, Goa, started an exploration programme for nodules in 1981 using the R.V. Gaveshani after desk-based studies on published data to identify the best areas. The first nodules were picked up from 4800 m depth on 26 January of that year on the S.W. Carlsberg Ridge. Exploration for nodules in the prime area of the Central Indian Basin identified from published data commenced in 1982. Work continued to the identification of a mine site (Qasim and Nair 1988). Indian national manganese nodule programme has been described by Valsangkar (2003) and Sharma (2010), amongst others.

In terms of the physical and chemical attributes of the nodules, by the 1970s both the abundance and distribution of nodules had been found to be very variable on an ocean wide scale and also locally on the scale of a kilometre or less (Glasby 1977). It was also realised by then that nodule distribution depends on a number of processes including the availability of nuclei on the seafloor and the rate of accumulation of the associated sediments. It was found that low sedimentation rates favour high nodule abundance. Nodules were first found to be most abundant in the CCZ (Horn et al. 1972) and later to be locally almost as abundant in the Central Pacific Basin (Usui and Moritani 1992). Subsequent research in the South Pacific found nodule distribution and abundance to be more irregular than in the North Pacific largely because of its greater topographic and sedimentological diversity, but that nodules were particularly abundant around the Cook Islands and especially in the Penrhyn Basin where abundances can locally exceed 50 kg/m^2 (Glasby et al. 1974; Cronan 1987, 2006; MMAJ 1995).

Early geochemical work on nodules (see Verlaan and Cronan, 2021 for a recent review) found that they represent a continuum exhibiting a compositional mixing from diagenetic end-members enriched in Mn, Ni and Cu to hydrogenous end-members enriched in Fe and Co. The diagenetic deposits were thought to derive their Mn, Ni and Cu in part from sediment pore waters by recycling these metals from decaying organic material. Hydrogenous deposits were thought to get their metals from normal seawater or non-metal-enriched sediment pore waters. Nickel- and Cu-rich nodules of resource interest in the CCZ fall near the diagenetic end-member in composition and are enriched in these metals up to about 3% combined but are relatively low in Co. In contrast, Co-rich nodules of resource interest in the Penrhyn Basin are hydrogenous and contain up to about 0.6% Co (Pautot and Melguen 1979). Early geochemical work on nodules also showed that some contained enrichments of many minor and rare elements up to 100 times or more over their crustal abundances (Cronan 1976). Most of these elements were for a long time thought to be of little economic interest, but in the early 2000s some of them were found to be required in emerging technology industries. Koschinsky et al. (2010) identified not only the Rare Earth Elements (REE) in this regard but also Li, Te, Pt, V, Mo and W.

One of the issues that exercised the early workers on the economics of nodule mining was the question of what reserves and resources were. After considerable discussion, Archer (1979) suggested that reserves should be defined as the recoverable elements in mineral deposits that are economically workable in the locally prevailing circumstances. By contrast, resources would then be those elements in deposits that may be workable at some time in the future. Resources may become reserves with changing economic and technological circumstances. On this basis, Archer proposed that marine mineral resources should be defined as mineral occurrences on the seafloor that are likely to become workable in the next 20 or 30 years.

General recognition of Exclusive Economic Zones (EEZs) as potential sites of marine minerals dates from the early 1980s and was given publicity by the declaration by President Reagan of a very large EEZ around the United States. EEZs are areas within 200 nautical miles of coastal states in which those states can exert jurisdiction over resources. Areas beyond 200 miles come under the jurisdiction of the International Seabed Authority (ISA). Since the early 1980s, many states have sought to exercise control over the marine resources adjacent to their coasts. However, it was realised early on that most EEZs were not deep-sea areas and thus, with one or two exceptions, would not contain typical deep-sea minerals such as manganese nodules. Indeed, it was found that the only EEZs that did contain nodules in sufficient amounts to be of economic interest in the foreseeable future were those around certain of the island states in the South Pacific (Exon 1983), most notably the Cook Islands. Glasby et al. (1974) were amongst the first to point out the importance of nodules in that part of the S W Pacific Basin that would later become part of the EEZ of the Cook Islands. This resulted in many subsequent cruises for nodule exploration in the CI EEZ, most notably by the Metal Mining Agency of Japan (MMAJ) from 1985 onwards in collaboration with CCOP/SOPAC, the then principal marine minerals authority in the South Pacific. Cronan (2013) has summarised the results of those cruises. Essentially, the North Penrhyn Basin nodules are rich in Ni and Cu, and the South Penrhyn Basin nodules are rich in Co, Ti and REE.

Between the mid-1980s and the commencement of the twenty-first century, interest in mining manganese nodules declined, and the deep-sea mining that was expected to happen in the twentieth century never occurred. There were several reasons for this. First, the prices of the main metals in the nodules either decreased or remained relatively static during the last quarter of the twentieth century. Second, the oil price increase in the mid-1970s added greatly to the processing costs for nodules. Third, the 1982 Law of the Sea Convention was widely regarded by the embryonic deep-sea mining industry as being unsatisfactory. Fourth, increasing environmental awareness in the 1970s and 1980s produced an added constraint for deep-sea mining.

Increasing metal prices at the start of the twenty-first century led to a resurgence of interest in nodule mining. This was capitalised on by the ISA who permitted contractors to work in the reserved areas of the mine sites that they had licensed and which had to be relinquished by the licensees under the provisions of the Law of the Sea Convention. One of these was Nauru Ocean Resources Inc. (NORI), and there were several others. By 2011, it had been granted exploration licenses in four parts of the CCZ between 115 and 130° west which was explored by its sub-contractor Deep Green Resources.

2 Cobalt-Rich Crusts

During the 1960s and 1970s, cobalt-rich crusts were rarely differentiated from manganese nodules when it came to resource estimates. It was not until the work in the early 1980s of Halbach, Hein and their co-workers (Halbach et al. 1982; Hein et al.

1985) that they came to be considered as a separate class of ferromanganese oxide deposits. Interest in the economic potential of Co-rich ferromanganese oxide crusts lay initially in their Co content and to a lesser extent in their Mn, Ni and Pt and later their REE content.

Once they had been recognised as a separate class of deposits from nodules, some of their specific attributes were enumerated (see Verlaan and Cronan, 2021 for a recent review). First, crusts largely occur in shallower water than nodules, in general on seamounts more than 2000 m shallower than most nodule deposits of economic interest and sometimes just within a few hundred meters of the sea surface. Second, they usually contain much more Co than nodules. Third, they often occur in EEZs as the seamount chains on which they are mainly found frequently contain islands. Most of our initial knowledge on Co-rich crusts came from the central Pacific. They were found to be mainly present on non-sedimented seamount slopes between 1000 and 3000 m depth and were especially well developed on and near the tops of guyots. The composition of the deposits was found to exhibit considerable variations, Mn from about 15–30%, Fe from 7–18%, Co up to about 2% and averaging 0.8% in the richest areas of the western central Pacific. Crust thicknesses were found to range from less than 1 cm to over 8 cm, with an average thickness of around 2.5 cm. Growth rates were found to be around 10 mm per million years. Geological stability was found to be necessary for the crusts to develop properly as slumping and erosion on seamounts can destroy or abrade crusts.

A study of the distribution of Pacific crusts in relation to latitude showed that their maximum thickness fell within 15° of the equator. Several elements in them were also found to exhibit a latitudinal variation (Hodkinson and Cronan 1991). Manganese, Co, Ni, Mo and Cd were found to be highest at low latitudes; Fe and Cu showed the opposite. Several elements also showed a relationship with depth. Manganese, Co, Ni, Mo, V, Zn and Pb all decreased with increasing depth whereas Fe showed the opposite.

Platinum was also recognised as an element of potential economic importance in the crusts (Halbach and Puteanus 1984). It generally occurred in concentrations of between 0.1 and 1 ppm but could be as much as 3 ppm. This is not much less than the Pt content of Sudbury ores (3.3 ppm) but much less than in the Bushveld Pt ores (7–10 ppm). Maximum Pt values were generally found to occur in crusts from less than 1500 m water depth.

Concerns about World Cobalt supplies developed strongly in 1978 when the principal supplier, Zaire, was aggressively invaded. The Co price increased dramatically as a result. In view of this, it is not surprising that interest in Co-rich crusts as resources commenced in the early 1980s. One Co-rich crust mining operation with an output capacity of 1 m tonnes per year would have met a significant part of US Cobalt demand, together with part of its Mn, Mo, Ni, V and Pt demand, had it taken place.

3 Hydrothermal Deposits

Potentially economic submarine hydrothermal deposits (PMS) were first discovered in the Red Sea in the 1960s (Miller et al. 1966) and were found to consist largely of sulphides of Fe, Cu and Zn. The Red Sea deposits were originally thought to be a unique isolated occurrence but were later realised to be the result of the hydrothermal activity that occurs all along the World Mid-Ocean Ridge System. Most of the other occurrences that occur on mid-ocean ridges, or at volcanically active ocean margins where they are also found, do not exhibit either the diversity or metal concentrations exhibited by the Red Sea deposits.

Most submarine hydrothermal deposits were thought to be largely formed by seawater penetrating into hot volcanic rocks and leaching metals from them thereby becoming transformed into mineralising brine which rises back to the seafloor to precipitate the metals. However, magmatic contributions to the deposits could never be ruled out.

On mid-ocean ridges, active hydrothermal venting was discovered in the Galapagos region by Oregon State University workers in 1979 (Corliss 1979). The hydrothermal mineral composition was found to depend on several factors including temperature of leaching, the composition of the rocks being leached and the amount of circulating seawater. Soon after, small amounts of gold, silver and other valuable metals were found in mid-ocean ridge sulphides (Herzig and Hannington 2000), and it was realised not long after their discovery that to be of serious economic value seafloor polymetallic sulphides should contain recoverable amounts of precious metals.

Later, submarine hydrothermal deposits were found at ocean margins both in back-arc basins and on volcanic island arcs, especially in the S W Pacific (Cronan 1983). These were found to be more compositionally variable than the mid-ocean ridge varieties. The best-studied and economically most valuable hydrothermal mineral deposits discovered were found to occur in the Bismarck Sea off Papua New Guinea (Binns and Scott 1993). One such deposit is the Solwara-1 deposit about 50 km from Rabaul. It is composed of mounds and chimneys and contains base metal sulphides plus Au and Ag and until recently was being developed for mining.

4 Recent Trends

The licensing of parts of the ISA reserved areas for commercial manganese nodule exploration has already been mentioned. Recently, the Red Sea hydrothermal muds programme has been reactivated (Hamer 2018). Although the Solwara-1 Project in the Bismarck Sea closed down in 2019, continued commercial interest in other hydrothermal mineral deposits, some licensed for exploration by the ISA on mid-ocean ridges, remains. The recent resurgence of interest in deep-sea minerals is due to not only the twenty-first century increase in commodity prices but also perceived future mineral shortages caused by traditionally mineral exporting countries becoming large importers of minerals to fuel their own industrial development. This phenomenon is particularly true in the case of REEs because they are needed for emerging ‘green’ and ‘technology’ applications. If any single group of elements can be held responsible for the resurgence of interest in marine minerals in the twenty-first century, it is arguably the REEs. However, deep-sea minerals will probably not be mined just for these elements, but REE and other rare elements will probably comprise an increasing proportion of the perceived value of deep-sea mineral deposits in the future.

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David S. Cronan is one of the longest serving marine minerals researchers. He studied at Durham, Oxford and London (Imperial College) Universities, obtaining his Ph.D. with a thesis on manganese nodules in 1967. He became interested in submarine hydrothermal deposits in the 1970s and worked in both the Red Sea and on mid-ocean ridges. One of his major contributions in the 1980s was the elucidation of the distribution of hydrothermal deposits in the arcs and back-arc basins of the SW Pacific, including, jointly with G. P. Glasby and Karin Knedler, the discovery of the first hydrothermal deposit to be found on the Tonga-Kermadec Ridge. Also in the 1980s he led the Aitutaki-Jarvis transect cruise in the Eastern Pacific which elucidated the long-sought relationship between manganese nodule composition and the calcium carbonate compensation depth. Like many academics, in his fifties he was drawn more and more into University administration but gave all that up on his 60th birthday in 2002 to concentrate on research again. Since then he has mainly worked on the behaviour of manganese nodules and other deposits in the SW Pacific in collaboration with SPC SOPAC and has written a substantial series of papers on the nature and variability of these deposits. He has published more than 150 scientific papers, given more than 50 conference presentations, written two books on marine minerals and edited two more .

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

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 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).

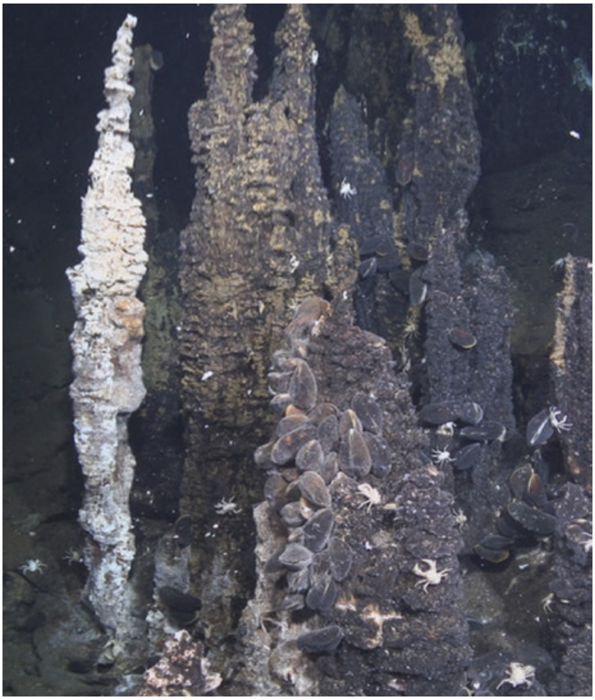


Fig. 2.2 Hydrothermal sulphide chimneys with black smokers, biological communities and microbial mats, at the Kita-Bayonnaise Caldera, Izu-Bonin Arc (JAMSTEC Cruise NT13–05 #1494 at 1370 m depth); width: approximately 2.0 m. (Photograph courtesy of Prof. A. Usui, Kochi University, Japan)

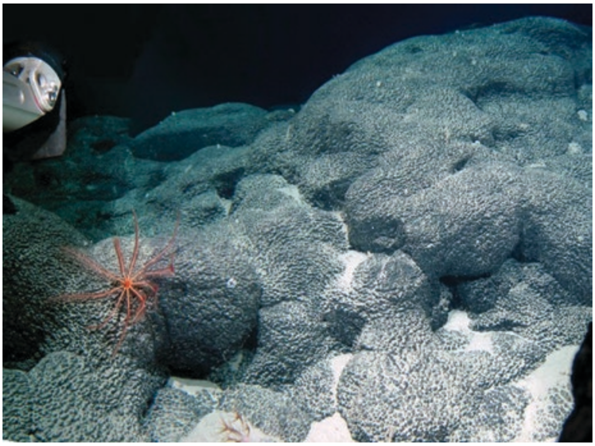


Fig. 2.3 Ferromanganese crusts near the summit of the Takuyo-Daigo seamount, NW Pacific basin (JAMSTEC Cruise KR09-02#955, at 1449 m depth); width: approximately 1.5 m. (Photograph courtesy of Prof. A. Usui, & B. Thornton)

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).

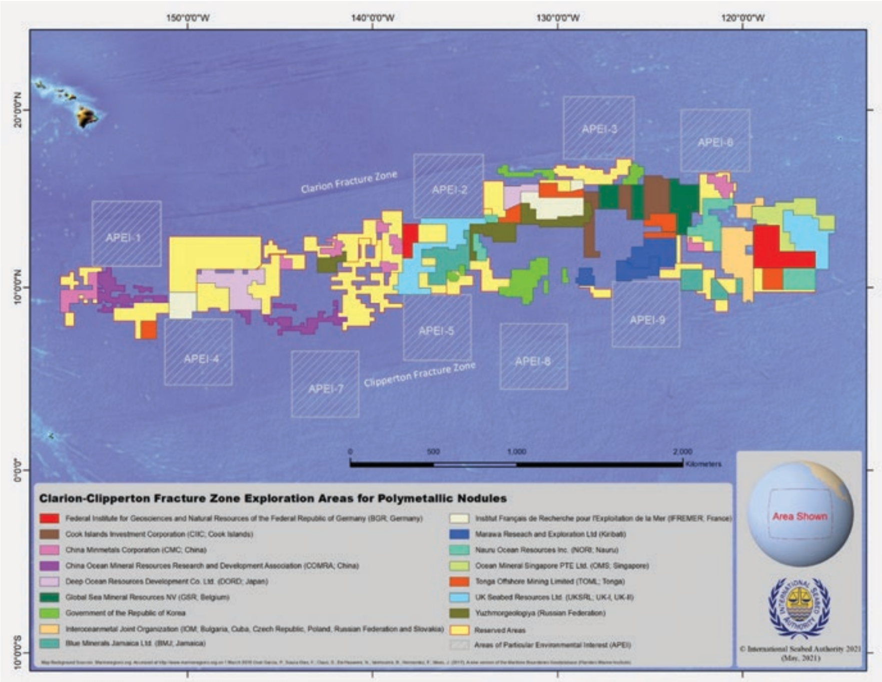
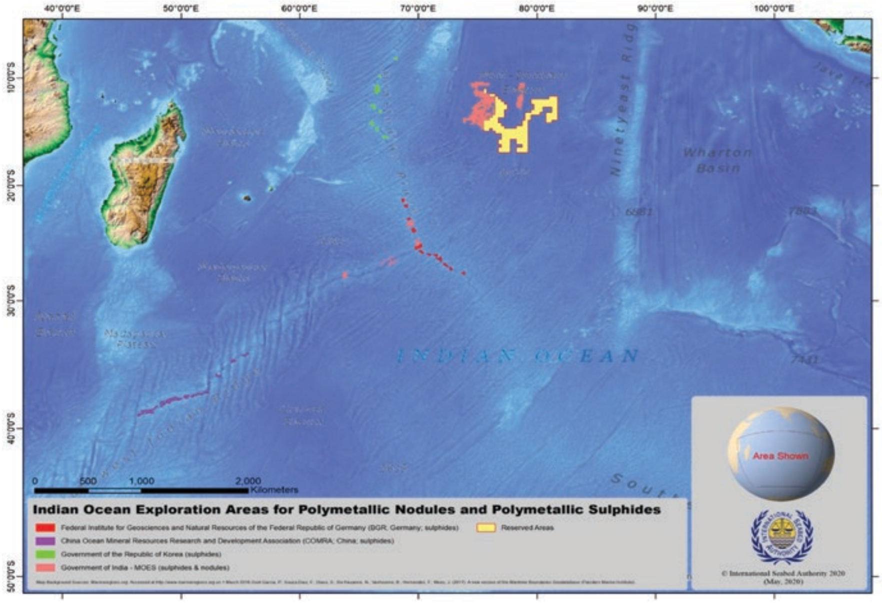


Fig. 2.4 (**a**) Exploration areas for polymetallic nodules in Clarion-Clipperton Zone. (Courtesy: International Seabed Authority, Jamaica). (**b**) Exploration areas for polymetallic nodules and sulphides in Indian Ocean. (Courtesy: International Seabed Authority, Jamaica). (**c**) Exploration areas 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)



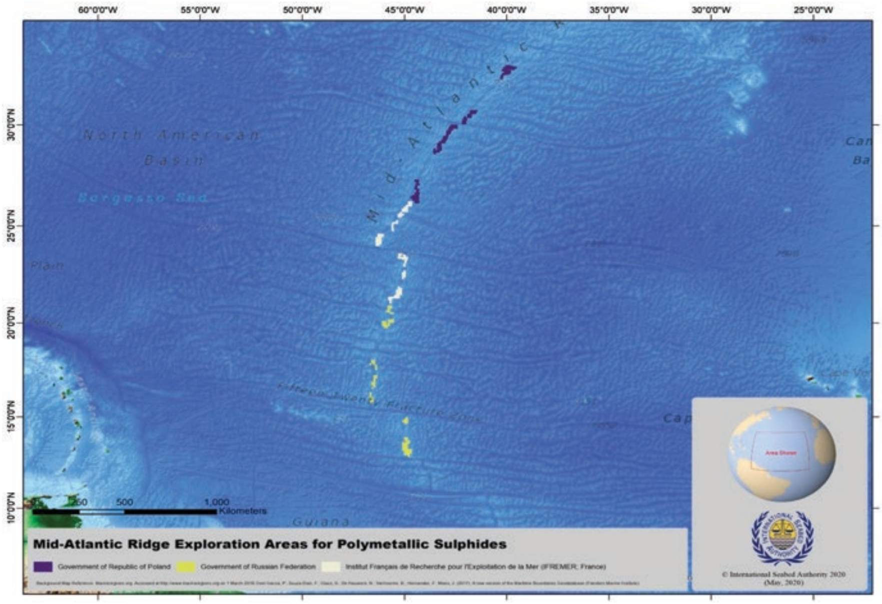
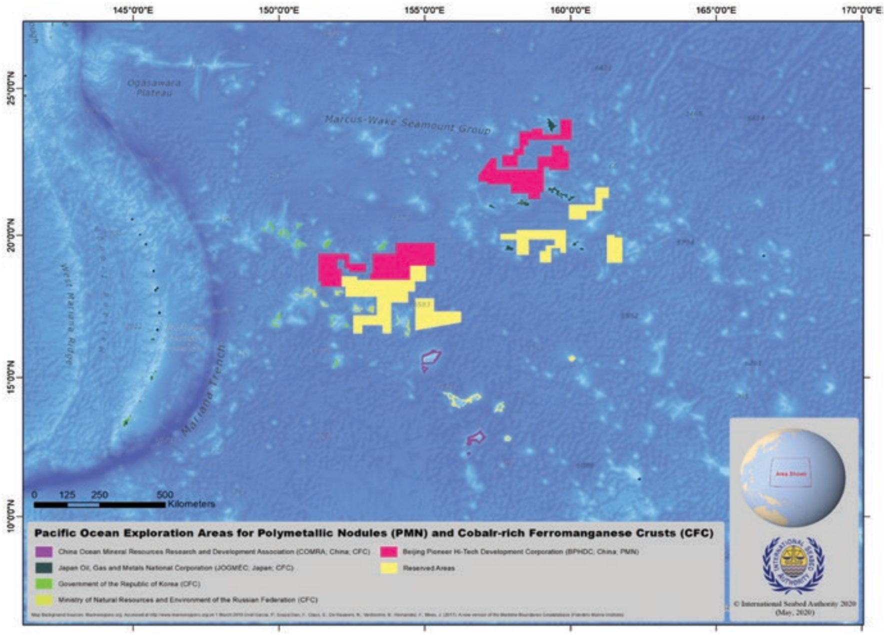


Fig. 2.4 (continued)



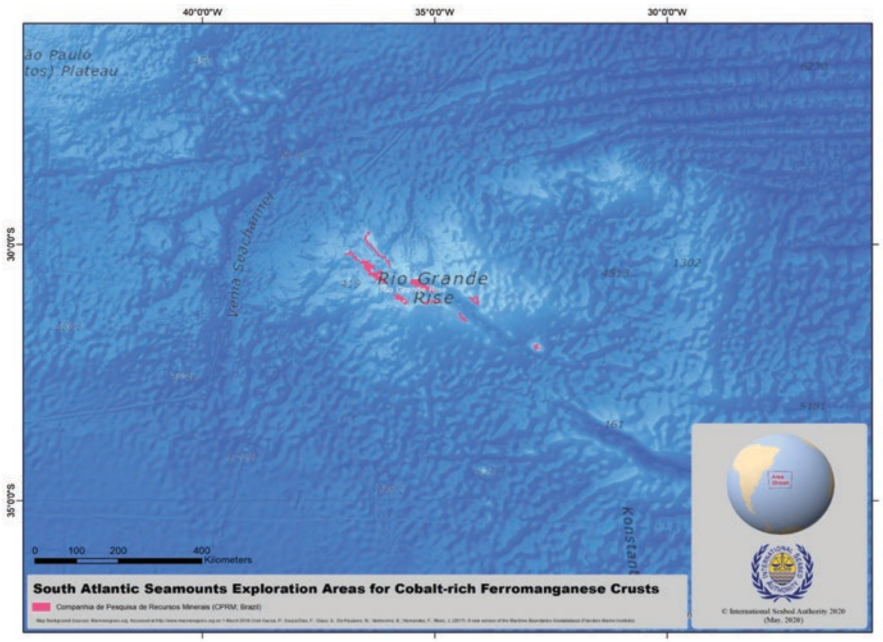


Fig. 2.4 (continued)

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 $\$4051 \times 10^6$, whereas the offshore OPEX are estimated at $\$325 \times 10^6$ annually and onshore processing at $\$688.7 \times 10^6$ 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

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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Rahul Sharma retired as Chief Scientist from the CSIR-National Institute of Oceanography in Goa, India with a career spanning more than 36 years in the field of exploration and exploitation of marine minerals. He has led a multi-disciplinary group on ‘Environmental studies for marine mining’. He has a master’s degree in Geology and a doctorate in Marine Science. His professional interests include application of exploration and environmental data to deep-sea mining.

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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 .

Chapter 3
Estimates of Metals Contained in Abyssal Manganese Nodules and Ferromanganese Crusts in the Global Ocean Based on Regional Variations and Genetic Types of Nodules

Kira Mizell, James R. Hein, Manda Au, and Amy Gartman

Abstract Deep-ocean ferromanganese crusts and manganese nodules are important marine repositories for global metals. Interest in these minerals as potential resources has led to detailed sampling in many regions of the global ocean, allowing for updated estimates of their global extent. Here, we present global estimates of total tonnage as well as contained metal concentrations and tonnages for ferromanganese crusts and manganese nodules using the most extensive compilation of geochemical data collected to date, along with updated boundaries of regions of interest for these minerals. We present results from mean composition calculated in two ways: first, a global flat average of regional mean compositions, and second, a regionally weighted average that considers differences in chemistry among genetic types and/or oceanographic and geologic settings for these mineral occurrences. For nodules, we use the three genetic types: (1) hydrogenetic, typified by nodules from the West Pacific Nodule Field and Penrhyn Basin; (2) diagenetic, typified by nodules from the Peru Basin; (3) mixed hydrogenetic-diagenetic, typified by nodules from the Clarion–Clipperton Zone and the Central Indian Ocean Basin, and Atlantic Ocean regional type hydrogenetic nodules. All crusts considered here are of hydrogenetic origin, which we divide into seven regional types that reflect a combination of ocean basin and other source inputs. Crust types include Arctic Ocean, Atlantic Ocean, Indian Ocean, Continental Margin, Prime Crust Zone (PCZ), North Pacific (non PCZ), and South Pacific. Based on our areal estimates, we find that abyssal regions likely to contain hydrogenetic-type nodules are by far the most widespread in the global ocean (47% of total area), Atlantic Ocean (28%) are next, followed by mixed diagenetic-hydrogenetic (22%) and diagenetic (3%) types. For crusts, the Prime Crust Zone is the most extensive global region (27% of total area) followed

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by South Pacific (20%), Indian Ocean (18%), North Pacific (12%), Continental Margins (11%), Atlantic Ocean (10%), and Arctic Ocean (2%) types. The global total tonnage estimates that we calculated from this method are 21×10^{10} dry tons for manganese nodules, within the range of previous estimates, and 93×10^{10}dry tons for ferromanganese crusts, which is 4.5 times higher than the 20×10^{10}dry tons reported by Hein et al. (2003). This geology and oceanography driven approach to marine mineral quantification contrasts with estimates typically carried out for terrestrial mineral resource deposits. Nevertheless, these estimates and the data that support them demonstrate that marine minerals are an impressive repository for global metals.

Keywords Metal estimates · Manganese nodules · Ferromanganese crusts · Regional variations · Genetic types · Global oceans

1 Introduction

Ferromanganese crusts and manganese nodules are extensive marine oxide occurrences. Given their insolubility in oxygenated seawater, iron and manganese precipitate ubiquitously in the global ocean. In addition to ferromanganese crusts and manganese nodules, iron and manganese oxides and oxyhydroxides precipitate local to hydrothermal systems and coat grains within sediments. Quantifying these pools of iron and manganese and associated trace metals and how they vary spatially is important for understanding global metal budgets, marine cycles, and marine mineral resources.

Quantification attempts for the total tonnage of manganese nodules have varied through time based on available data and purpose, such as prospective nodules versus total nodule tonnage (e.g., Mero 1965; Archer 1981; Sharma 2017). For ferromanganese crusts, two previous estimates are available and are within an order of magnitude of each other, 20×10^{10} dry tons as reported by Hein et al. (2003) and 3.5×10^{10} dry tons (Halbach et al. 2017). The total mineral tonnages for ferromanganese crusts and manganese nodules as well as their contained metals tonnages are important for evaluating not only resource potential but also understanding the large-scale sinks of elements in the global oceans.

A quantitative comparison between terrestrial and deep-ocean mineral deposits is not straightforward due to inconsistency between the methods used to quantify each and the physical depositional characteristics of the deposits. Terrestrial deposits are predominantly three dimensional, while crust and nodule deposits are essentially two-dimensional, occurring directly at the seabed. Therefore, to clarify and compare geologic controls, it would be useful to find ways to relate terrestrial and marine resources and the metal pools from which each mineral resource is derived.

This contribution provides updated estimates of the total tonnages and metal reservoirs for global marine ferromanganese crust and manganese nodule mineral occurrences, discusses the methods by which these estimates were made, and compares them to existing code-based marine deposit assessments and terrestrial mineral quantity and quality assessments. We further discuss differences in terminology in order to clarify discussions around marine minerals and their global context.

2 Methods for Deriving Mean Composition and Tonnage Estimates

Because marine mineral occurrences have only been seriously considered for their resource potential within the last 30 years, concepts regarding tonnage estimation have sometimes been based on or compared to long-standing methods used for terrestrial ore deposits. There are several approaches to estimate the total geologic inventory of a given metal for terrestrial deposits. Terrestrial resources and reserves are typically calculated based on drilling at regular intervals, and resources and reserves vary through time based primarily on changes (lowering) of cutoff grade and new discoveries (Jowitt et al. 2020). However, an estimate of total inventory would include quantification of what has not been identified and may be deeply buried (Arndt et al. 2017).

In contrast, iron and manganese precipitate ubiquitously as oxide and oxyhydroxide phases on hard rock and sediment surfaces in the global ocean. This precipitation occurs from basin-scale water masses and widespread sedimentary processes, resulting in significant homogeneity in the distribution and metal content from region to region, simplifying a global accounting. With these unique formation mechanisms in mind, we estimate the global tonnage and grade of crusts and nodules based on the areal extent of crust or nodule prospective regions (Figs. 3.1 and 3.2), using conservative estimates of mean seabed deposit density (kg/m^2) for each mineral type and mean element compositions based on two different calculations as described below. For both crusts and nodules, prospective region areas were calculated using Hawaii Albers Equal Area Conic projection to preserve the relative sizes of the regions across the globe and avoid overcalculating areas due to projection distortions that stretch at high latitudes. More information on the calculations for crusts and nodules follows below. The results we present here consider regions prospective for abyssal plain-type manganese nodules, which have varying amounts of hydrogenetic (derived from seawater) and diagenetic (derived from pore waters of sediment) inputs and for ferromanganese crusts in the open ocean and along continental margins. Not considered in these estimates are hydrothermal iron and manganese oxide minerals, which are currently not well constrained and, like terrestrial deposits, will require drilling to obtain grades and tonnages (Hein and Whisman 2018).

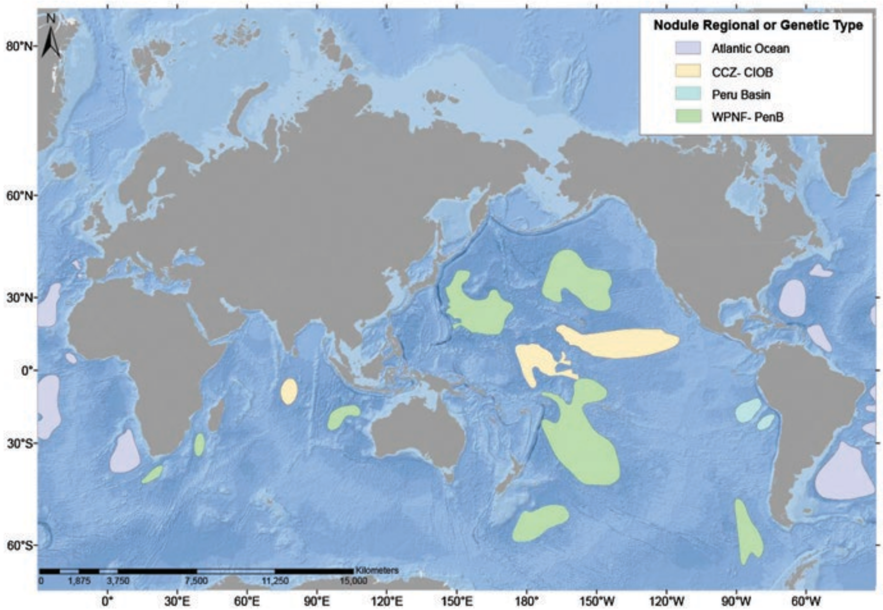

Fig. 3.1 Global nodule prospective regions illustrating the distribution of the four regional and/ or genetic types discussed in the text; CCZ-CIOB = Clarion–Clipperton Zone-Central Indian Ocean Basin combined types; WPNF-PenB = West Pacific Nodule Field-Penrhyn Basin combined types. The world ocean base-map was created by Esri, Garmin, GEBCO, NOAA NGDC, and other contributors and is shown in WGS 84/PDC Mercator projection

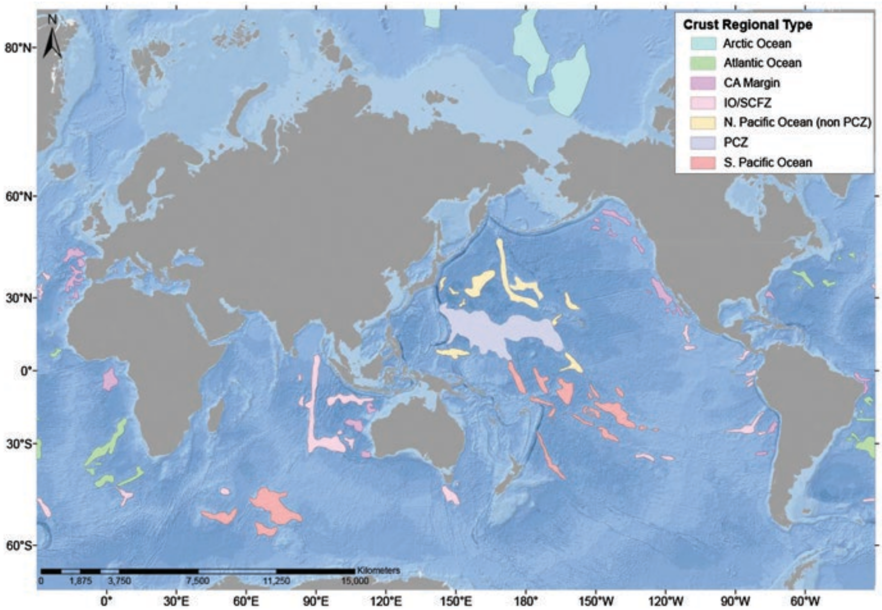

Fig. 3.2 Global crust prospective regions illustrating the distribution of the seven regional types discussed in the text; IO/SCFZ = Indian Ocean/Spreading Center Fracture Zone; PCZ = Prime Crust Zone. The world ocean base-map was created by Esri, Garmin, GEBCO, NOAA NGDC, and other contributors and is shown in WGS 84/PDC Mercator projection

2.1 Total Tonnage Calculations for Manganese Nodules

For nodules, we assume a seabed abundance of 5 kg/m^2 over these entire prospective regions (Fig. 3.1), a reduction of the projected mean density value of 6.72 kg/m^2 over 4.19×10^6 km^2 obtained for the Clarion–Clipperton Zone (CCZ; $n = 3622$, International Seabed Authority 2010). The abundance cut-off for manganese nodule resources in the CCZ used most recently is 4 kg/m^2 (Lipton et al. 2021). For the large areas delimited in our report, a systematic sampling would need to occur to better determine distribution densities and to estimate tonnages and cutoff grade. For most of these regions, such work has yet to be done or has occurred only for subregions, therefore we consider our estimates to be conservative. For example, Hein et al. (2015) determined abundances >25 kg/m^2 over ~123,844 km^2 within the Cook Islands Exclusive Economic Zone (EEZ) and 22.3 kg/m^2 for the West Pacific Nodule Field (WPNF; Li et al. 2021a, *in review*).

2.2 Total Tonnage Calculations for Ferromanganese Crusts

For crusts, there are no published code-based assessments; however, projections of potential thickness and cutoff grade information are contained within Hein et al. (2009), who suggested 3 cm of thickness as a lower limit for crusts. Our tonnage estimates are calculated using this thickness over our regions of interest and the dry bulk density of 1.3 g/cm^3 (Hein et al. 2009; Hein and Koschinsky 2014). We suggest that this thickness is conservative based on higher average crust thickness reported for seamounts, especially within the Prime Crust Zone (PCZ), where mean crust thicknesses of 5.8 and 6.2 cm were measured at two PCZ seamounts (Du et al. 2017a, 2017b). Further, whole seamount studies have also shown that even highly eroded crusts exceed 3 cm in regions of interest. For example, one study conducted on Tropic Seamount in the northeast Atlantic Ocean found that pristine crusts averaged 4.56 cm thickness and “completely eroded” crusts averaged 3.67 cm thickness (Yeo et al. 2019).

Estimates of crust tonnage are complicated by the abundance and topography of seamounts within our regions of interest. Therefore, we used some simplifications. First, the square-kilometer area of crust coverage must be estimated, and we use the entire two-dimensional footprint of the prospective area (Fig. 3.2). This may be an over-estimation since seamounts do not cover every square kilometer of seafloor in that region. For example, within one region of interest, the PCZ (Hein et al. 2009, 2013), the footprints of seamounts make up only approximately 60% of the total square-kilometer seafloor area within the region. In reality, the per-seamount-area covered by ferromanganese crusts is not identical to the footprint of the seamount; rather, it is equal to the total surface area of the seamount, which may be conical or flat-topped (guyot shaped). Moreover, the ferromanganese crusts potentially cover additional surface areas that result from the rugosity of the seamount (Li et al. 2021b, *in press*). Treating seamounts as simple cone shapes within the PCZ increases the calculated surface area by approximately a factor of 2.5, which is larger than the estimation for the PCZ region using the region's total areal extent. Given the complications of accurately parameterizing the surface area of all seamounts within our regions of interest in the global ocean, we present area calculations that represent the seafloor area of the seamount province and suggest that this approximation is on the conservative side and accurate to within a factor of 2. This is acceptable given our other uncertainties, such as amount of sediment cover, erosion, rugosity, among others.

2.3 Global Mean Composition Calculations and Rationale

To estimate the metal tonnages contained in crusts and nodules in the global ocean, we derived two values for the mean chemical composition of each deposit type, both of which utilize a broad dataset of samples from within different prospective regions (Figs. 3.1 and 3.2). Both sets of values for mean composition of crusts and nodules were calculated by first taking the weighted average of mineral data compilations from each of the regions listed in Tables 3.1 and 3.2. One set of mean composition values was then calculated using the non-weighted mean (hereafter called the flat average) of each of these regional means for crusts and for nodules. These values are an equally weighed average composition of crusts and nodules in all the considered ocean basins and settings and do not account for how much of the total prospective area may be attributed to each composition type. For comparison, we also calculated a second mean chemistry value by assigning each individual prospective region (Figs. 3.1 and 3.2) a compositional type, totaling the seafloor area attributed to each type, and finally weighted each type's contribution to the mean chemistry according to its fraction of the total seafloor area of prospective regions. The following knowledge of crusts and nodule formation was used to assign compositional type for this calculation.

Four conditions are required to form abyssal plain manganese nodules: Low sedimentation rates (<10 mm/ka), a source of material for the oxides to precipitate around (nucleus material), subdued small-scale seafloor topography, and moderate-to-low primary productivity (Morgan 2000; Kuhn et al. 2017; Hein et al. 2020). The first and fourth criteria are related in that high primary productivity produces high sedimentation rates prohibiting the formation of nodules. Hydrogenetic nodules form in regions with these four criteria, with low primary productivity, whereas diagenetic nodules form in areas with moderate primary productivity. Moderate productivity supplies enough organic matter to abyssal seafloor sediments to support diagenetic reactions in the sediment. Oxidation of the organic matter in the sediment produces suboxic conditions, which reduces the sediment-hosted Mn oxides and releases associated elements, such as Ni, Cu, Li, Mn, among others to

Table 3.1 Average manganese nodule compositions from major regions and distinctive occurrences throughout the global oceans

	CCZ[a] (n = 0–1058)	West Pacific Nodule Field[b] (n = 0–252)	Cook Islands[c] (n = 18–54)	Peru Basin[d]	Indian Ocean[e] (n = 0–1195)	Atlantic Ocean[f] (n = 0–174)	Blake Plateau[g] (n = 0–51)	Global nodules-area-normalized average	Global nodules-flat average	N
Fe (wt. %)	5.99	15.7	16.2	6.12	7.24	21.0	12.2	15.0	10.7	2735
Mn	28.4	20.8	16.9	34.2	24.5	15.7	16.5	20.1	19.8	2735
Si	6.10	7.51	7.03	4.82	8.10	10.8	2.63	8.38	6.12	946
Al	2.32	2.64	3.42	1.50	2.26	2.86	2.23	2.77	2.28	1103
Mg	1.94	1.33	1.42	1.71	1.51	1.84	2.73	1.59	1.68	1188
Ca	1.68	1.84	1.99	1.82	1.71	2.04	9.11	1.90	2.65	1159
Na	2.16	1.45	1.76	2.65	1.42	2.07	0.92	1.81	1.68	1163
K	0.98	0.61	0.90	0.81	1.00	0.71	0.48	0.80	0.81	1176
Ti	0.27	1.60	1.28	0.16	0.45	0.65	0.28	0.94	0.71	1099
P	0.16	0.33	0.34	0.15	0.15	0.24	1.25	0.26	0.45	919
Cl	0.68	–	0.42	>0.50	–	–	–	NA	0.70	591
LOI	15.7	–	27.7	16.2	–	28.5	23.6	24.9	18.8	598
H_2O^-	11.6	–	12.7	–	–	–	12.4	NA	9.42	102
H_2O^+	8.8	–	11.8	–	–	–	7.9	NA	7.36	81
CO_2	–	–	–	–	–	–	4.6	NA	4.56	6
Ag (ppm)	0.30	0.04	0.23	0.05	–	–	6.9	NA	1.4	76
As	82	238	150	65	162	137	334	158	146	652
B	–	–	–	–	250	290	81	NA	156	10
Ba	3933	1547	1160	3158	1726	1328	2235	1726	1886	1112
Be	2.2	–	3.9	1.4	10	3.8	17	4.3	5.5	110

(continued)

Table 3.1 (continued)

	CCZ[a] (n = 0–1058)	West Pacific Nodule Field[b] (n = 0–252)	Cook Islands[c] (n = 18–54)	Peru Basin[d]	Indian Ocean[e] (n = 0–1195)	Atlantic Ocean[f] (n = 0–174)	Blake Plateau[g] (n = 0–51)	Global nodules-area-normalized average	Global nodules-flat average	N
Bi	8.8	34	11	3.3	–	12	120	16	27	188
Br	–	–	–	–	–	–	54	NA	27	2
Cd	16	–	4.7	19	15	7.1	9.9	8.1	10	93
Co	1918	4709	3751	475	1152	2627	3240	3072	2234	2723
Cr	12.4	9.1	59	16	19	77	68	42	33	224
Cs	1.3	1.6	0.38	0.78	0.99	1.1	0.93	1.0	1.0	763
Cu	10,794	2527	2309	5988	10,433	1427	926	4060	4301	2721
Ge	0.70	3.3	–	0.60	–	–	–	NA	1.4	46
Hf	4.6	12	13	4.74	14	–	–	NA	8.2	955
In	0.27	–	0.78	0.08	–	–	0.37	NA	0.50	68
Li	132	38	51	311	110	82	–	80	104	994
Mo	612	388	295	547	600	341	340	406	390	1112
Nb	19	30	91	13	87	40	18	52	37	965
Ni	12785	4912	3767	13008	10983	3254	5552	5960	6783	2718
Pb	358	1098	976	121	1067	895	1102	898	702	1164
Rb	21	10	15	12	70	23	2.9	23	19	789
S	1572	–	1829	–	–	–	–	NA	1134	591
Sb	65	–	36	61	50	40	111	43	52	179
Sc	10	12	12	7.6	19	20	–	15	12	968
Se	0.72	21	0.80	0.50	–	–	543	NA	95	104
Sn	5.3	4.8	7.8	0.90	10	–	677	NA	101	107
Sr	691	1080	935	687	925	774	1335	888	803	1189
Ta	0.27	0.24	2.2	0.23	1.8	–	–	NA	0.96	919

	CCZ[a] (n = 0–1058)	West Pacific Nodule Field[b] (n = 0–252)	Cook Islands[c] (n = 18–54)	Peru Basin[d]	Indian Ocean[e] (n = 0–1195)	Atlantic Ocean[f] (n = 0–174)	Blake Plateau[g] (n = 0–51)	Global nodules-area-normalized average	Global nodules-flat average	N
Te	3.6	26	24	1.7	40	–	–	NA	16	859
Th	199	54	36	6.9	240	84	3.6	93	78	308
Tl	14	150	146	129	58	110	200	112	101	835
U	3.9	9.6	9.5	4.4	16	6.7	333	8.7	48	1055
V	591	552	504	431	502	566	802	540	493	1090
W	63	65	59	69	103	41	–	61	57	971
Zn	1509	622	492	1845	1235	810	730	846	905	1829
Zr	287	615	555	325	587	544	65	533	372	1046
La	106	227	173	68	131	172	91	170	121	951
Ce	283	1497	991	110	544	1569	795	1118	724	931
Pr	31	50	41	14	33	45	25	41	30	926
Nd	126	202	160	63	144	200	89	173	123	951
Sm	31	43	35	14	33	47	24	39	28	951
Eu	7.6	11	8.5	3.9	7.9	11	6.6	9.3	7.1	947
Gd	30.4	49	36	15.6	32	42	18	39	28	913
Tb	4.6	7.4	6.1	2.5	5.3	6.3	4.6	6.1	4.7	937
Dy	27	42	35	15.8	27	37	22	35	26	936
Y	83	158	141	69	108	133	172	130	108	940
Ho	4.9	8.4	7.2	3.4	4.9	6.8	5.2	6.8	5.2	935
Er	13.4	24	19.1	9.8	12.9	18.5	9.8	18	13.6	913
Tm	1.9	3.8	3.0	1.5	2	2.6	2.1	2.8	2.2	900
Yb	12.9	25	19.8	10.3	11.7	18.9	13.8	18	14.1	951

(continued)

Table 3.1 (continued)

	CCZ[a] (n = 0–1058)	West Pacific Nodule Field[b] (n = 0–252)	Cook Islands[c] (n = 18–54)	Peru Basin[d]	Indian Ocean[e] (n = 0–1195)	Atlantic Ocean[f] (n = 0–174)	Blake Plateau[g] (n = 0–51)	Global nodules-area-normalized average	Global nodules-flat average	N
Lu	1.9	3.9	3.0	1.6	1.9	2.3	2.2	2.7	2.23	949
ΣREY[h]	764	2153	1678	403	1074	2033	1109	1683	1151	1073
Hg (ppb)	18.0	–	36	–	–	–	–	NA	18.3	32
Au	4.5	–	6	–	–	–	–	NA	3.8	28
Ir	2.0	4.7	5	–	3.0	2.5	–	NA	3.0	68
Os	–	–	2	–	–	–	–	NA	1.5	12
Pd	7.7	4.0	7	–	8.0	2.4	–	NA	5.0	68
Pt	119	213	232	40	184	116	–	171	129	91
Rh	8.5	17	17	–	11	–	–	NA	11.0	61
Ru	11.5	18	18	–	26	15	–	NA	14.9	68
ΣPGM[i]								NA	165	–

[a]Hein et al. (2013), Pak et al. (2019), Kuhn et al. (2017; eastern and central CCZ)
[b]Li et al. (2020), Qui et al. (2020), Machida et al. (2016), Li et al. (2021a), Jiang et al. (2021)
[c]Hein et al. (2015)
[d]Hein et al. (2013)
[e]Hein et al. (2013), Kumar and Tiwary (2008), McKelvey (1986)
[f]Berezhnaya et al. (2018), Dubinin and Berezhnaya (2021), Smith et al. (1968), Mero (1962), Menendez et al. (2018), Cronan (1975), Addy (1979), Rogers (1987)
[g]Balaram et al. (2006), Glasby (1973), Mero (1965), Manheim et al. (1982), Abbey (1983), Flanagan and Gottfried (1980), Govindaraju (1994), Horn et al. (1973), Manheim et al. (1980), Manheim et al. (1989 OFR), Tarver et al. (1995)
[h]ΣREY denotes sum of the rare earth elements plus yttrium
[i]ΣPGM denotes total platinum group metals

Table 3.2 Average ferromanganese crust compositions from major regions and distinctive occurrences throughout the global oceans

	Atlantic Ocean[a] (n = 6–77)	Indian Ocean[b] (n = 0–62)	Pacific Prime Crust Zone (PCZ)[c] (n = 0–362)	North Pacific non-PCZ[d] (n = 0–70)	South Pacific[e] (n = 1–286)	California Continental Margin[f] (n = 0–225)	Arctic Ocean[g] (n = 0–50)	Global crusts-area normalized average	Global crusts, flat average	N
Fe (wt.%)	21.1	22.7	16.9	22.5	18.1	23.8	19.8	20.1	20.7	1131
Mn	15.9	14.5	22.8	23.4	21.7	19.5	7.70	19.9	17.9	1166
Si	4.56	6.79	4.05	5.88	4.75	10.8	11.0	5.84	6.84	995
Al	1.94	1.83	1.01	1.80	1.28	1.79	6.29	1.57	2.28	1036
Mg	1.54	2.22	1.10	1.37	1.32	1.26	1.68	1.45	1.50	960
Ca	4.17	1.28	4.03	2.54	3.53	2.25	1.20	3.01	2.71	1023
Na	1.26	1.55	1.64	1.98	1.52	1.97	1.61	1.64	1.65	829
K	0.50	0.62	0.55	0.78	0.63	0.85	1.14	0.65	0.72	1549
Ti	0.90	0.86	1.16	1.01	1.12	0.67	0.37	0.99	0.87	1020
P	0.72	0.39	0.96	0.95	0.78	0.57	0.53	0.74	0.70	1038
Cl	0.79	0.95	0.92	1.05	1.08	0.74	1.26	0.95	0.97	184
LOI	26.8	27.3	32.0	25.3	18.5	16.4	23.0	25.2	24.2	623
H_2O^-	11.8	14.4	19.5	17.4	19.8	18.3	9.61	17.3	15.8	792
H_2O^+	14.5	0.95	7.99	9.20	10.2	9.39	8.01	8.07	8.61	399
CO_2	4.4	–	0.74	0.69	0.83	0.37	–	NA	1.40	366
Ag (ppm)	0.19	0.37	–	1.5	0.97	0.90	0.26	NA	0.69	273
As	346	208	393	257	287	257	560	304	330	845
B	257	287	178	302	197	235	–	NA	243	159
Ba	1927	1332	1934	2267	1705	1838	451	1782	1636	931
Be	8.3	6.9	6.1	7.4	5.4	4.0	5.8	6.2	6.3	459
Bi	24	30	43	31	22	16	4.0	30	24	429
Br	36	54	28	29	30	34	–	NA	35	172

(continued)

Table 3.2 (continued)

	Atlantic Ocean[a] (n = 6–77)	Indian Ocean[b] (n = 0–62)	Pacific Prime Crust Zone (PCZ)[c] (n = 0–362)	North Pacific non-PCZ[d] (n = 0–70)	South Pacific[e] (n = 1–286)	California Continental Margin[f] (n = 0–225)	Arctic Ocean[g] (n = 0–50)	Global crusts-area normalized average	Global crusts, flat average	N
Cd	3.7	7.0	3.6	3.7	4.1	3.7	3.5	4.4	4.2	770
Co	4204	3167	6662	3733	6167	3131	1468	4847	4076	1165
Cr	44	22	28	30	35	52	43	33	36	756
Cs	0.62	5.0	3.7	5.8	1.9	0.66	3.0	3.2	3.0	250
Cu	761	680	976	1074	1082	383	652	862	801	1161
Ge	0.66	0.64	–	15	2.4	0.87	0.60	NA	3.3	198
Hf	8.3	9.2	9.4	6.9	9.2	6.1	10	8.6	8.5	440
In	0.18	0.26	0.62	0.79	0.87	0.14	0.33	0.52	0.46	268
Li	28	10	2.9	7.3	3.5	17	90	10	23	286
Mo	413	562	461	516	418	385	213	461	424	849
Nb	70	53	52	50	59	32	40	52	51	472
Ni	2759	2288	4209	3495	4643	2269	2335	3469	3143	1162
Pb	1444	1400	1641	1470	1057	1565	233	1409	1259	896
Rb	13	11	17	15	11	15	47	14	18	379
S	2568	1350	2600	1800	1700	–	2722	NA	2123	224
Sb	51	34	39	52	35	37	50	40	43	452
Sc	14	13	6.6	11	9.3	9.4	46	11	16	491
Se	0.37	4.8	15	13	5.1	2.0	0.66	7.8	5.8	303
Sn	8.1	9.7	10	9.0	11	4.3	7.7	9.1	8.5	329
Sr	1306	1203	1510	1608	1483	1302	476	1400	1270	776
Ta	1.3	1.1	2.4	3.1	1.2	0.59	0.89	1.7	1.5	331
Te	56	30	60	30	38	13	17	40	35	417
Th	60	49	11	36	15	48	63	32	40	465

	Atlantic Ocean[a] (n = 6–77)	Indian Ocean[b] (n = 0–62)	Pacific Prime Crust Zone (PCZ)[c] (n = 0–362)	North Pacific non-PCZ[d] (n = 0–70)	South Pacific[e] (n = 1–286)	California Continental Margin[f] (n = 0–225)	Arctic Ocean[g] (n = 0–50)	Global crusts-area normalized average	Global crusts, flat average	N
Tl	104	91	155	123	154	49	87	121	109	445
U	12	11	12	13	12	12	11	12	12	451
V	1182	639	641	679	660	628	936	704	766	945
W	82	80	89	87	97	66	50	85	79	447
Zn	605	844	668	673	698	554	350	683	628	987
Zr	378	629	548	724	754	464	422	598	560	446
La	283	260	339	320	204	270	152	279	261	575
Ce	1532	1033	1322	1360	818	1264	867	1179	1171	611
Pr	64	53	61	61	41	60	43	56	55	495
Nd	252	230	258	275	184	253	172	238	232	567
Sm	55	48	52	57	38	54	44	49	50	531
Eu	12.0	11.3	12.5	13.7	17.5	12.7	11.0	13.3	12.9	575
Gd	58	52	56	66	44	56	48	54	54	495
Tb	8.8	8.1	8.8	9.6	6.0	8.9	8.0	8.2	8.3	516
Dy	48	47	60.0	56	41	50	45	51	50	494
Y	184	180	221	190	177	172	197	191	189	813
Ho	9.6	9.3	10.9	10.8	8.5	10.0	9.2	9.9	9.8	505
Er	28	25	31	31	27	28	25	28	28	495
Tm	3.8	3.6	4.6	4.3	3.6	3.9	3.8	4.0	3.9	480
Yb	24	23	29	28	22	25	23	25	25	575
Lu	3.7	3.5	4.3	4.0	3.3	3.8	3.6	3.8	3.8	484
ΣREY[h]	2627	1703	2469	2488	1633	2270	1649	2143	2120	119

(continued)

Table 3.2 (continued)

	Atlantic Ocean[a] (n = 6–77)	Indian Ocean[b] (n = 0–62)	Pacific Prime Crust Zone (PCZ)[c] (n = 0–362)	North Pacific non-PCZ[d] (n = 0–70)	South Pacific[e] (n = 1–286)	California Continental Margin[f] (n = 0–225)	Arctic Ocean[g] (n = 0–50)	Global crusts-area normalized average	Global crusts, flat average	N
Hg (ppb)	86	38	9.3	28	32	11	56	30	37	347
Au	12	21	100	25	33	7.8	–	NA	33	92
Ir	5.0	6.3	13	5.3	2.5	1.8	–	NA	5.7	126
Os	1.6	4.0	2.4	7.7	2.5	3.5	–	NA	3.6	45
Pd	12	14	3.8	4.3	7.0	4.1	–	NA	7.4	154
Pt	307	194	470	228	465	70	–	NA	289	169
Rh	30	19	23	15	33	6.0	–	NA	21	160
Ru	18	19	17	16	13	9.0	–	NA	15.3	143
ΣPGM[i]	362	256	529	276	523	94	–	NA	342	–

[a]Hein et al. (2013), Goto et al. (2017), Benites et al. (2020), Marino et al. (2017), Dubinin et al. (2018), Josso et al. (2020), Koschinsky et al. (2020)
[b]Hein et al. (2013), Surya Prakash et al. (2020), Banerjee et al. (2017), Koschinsky et al. (2020)
[c]Hein et al. (2013)
[d]Hein et al. (2013)
[e]Hein et al. (2013)
[f]Conrad et al. (2017)
[g]Hein et al. (2017)
[h]ΣREY denotes sum of the rare earth elements plus yttrium
[i]ΣPGM denotes total platinum group metals

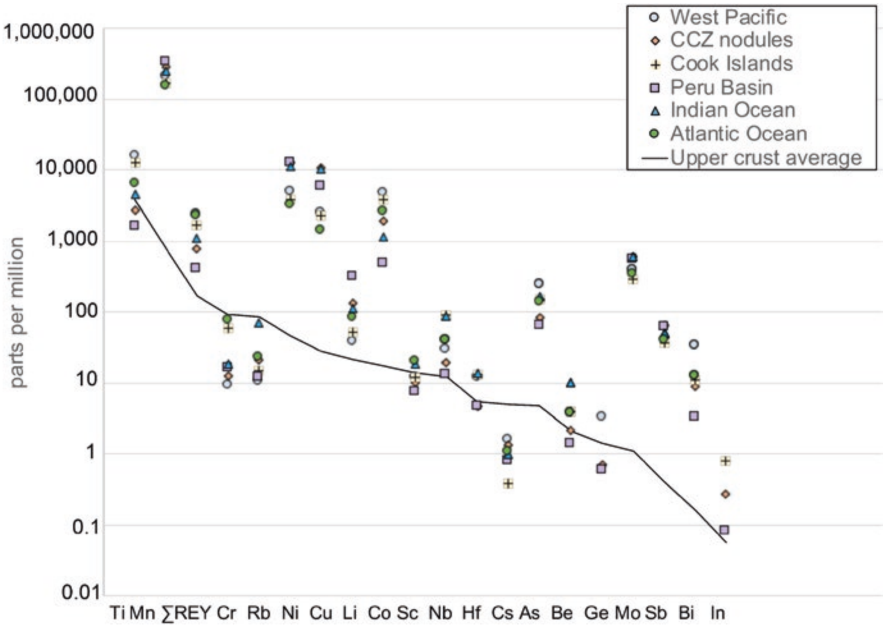

Fig. 3.3 Nodule composition plot illustrating the average concentrations in parts per million for the four regional types discussed in the text. The average values for Earth's upper crust are from Rudnick and Gao 2003

sediment pore waters that are available for sorption (Fig. 3.3 and Table 3.1). This is the mechanism by which diagenetic and mixed diagenetic-hydrogenetic nodules obtain high contents of these metals. Depending on the depth in the sediment of the suboxic recycling boundary and the metal concentration gradients in the overlying sediment, these metals can diffuse upward and on encountering oxidizing conditions near the seabed contribute specific metals to the formation of the nodules.

The moderate productivity areas typically occur adjacent to coastal and equatorial zones of high primary productivity. However, most abyssal plains where nodules form are distant from high-to-moderate productivity zones. Therefore, hydrogenetic nodule fields dominate globally. The major exceptions are the CCZ and Central Indian Ocean Basin (CIOB) regions, which are considered to have the highest resource potential for Cu, Ni, and Mn where there are 17 and 1 exploration contracts, respectively, with the International Seabed Authority.

Variations in the chemical composition of hydrogenetic nodules result from depth and location with respect to the calcite compensation depth (CCD), detrital input, and hydrothermal input, as well as redox state of the water column and bottom current activity. These factors also influence the composition of diagenetic nodules, but sediment redox conditions are of greatest importance. For mixed-origin nodules, the ratio of diagenetic to hydrogenetic layers is key. Chemical composition also depends on the mineralogy of the nodules. For example, hydrogenetic nodules are composed of amorphous ferrihydrite (FeOOH) and cryptocrystalline

Fe-vernadite (δ-MnO_2), which are precipitated and accreted solely from ocean water and therefore are rich in metals from that source such as Co, Nb, Pb, Te, V, Pt, and others. By contrast, diagenetic and mixed origin nodules are composed of 7 and 10 Å Mn oxides (disordered phyllomanganates) that are rich in metals derived from pore waters of sediment, such as Ni, Cu, Mn, Li, and others. All these factors will determine the regional variations in the composition of nodule fields. However, it is remarkable how similar the compositions of mixed-origin nodules are, for example, throughout the CCZ and between the CCZ and CIOB nodules. The compositions of hydrogenetic nodules from the WPNF and the Penrhyn Basin are also notably similar (Hein et al. 2015; Li et al. 2021a *in press*; this paper). Thus, an interesting outcome of this research exercise is that hydrogenetic nodule fields are likely the predominant type in the global ocean, which are likely well characterized by the mineralogy and geochemistry of nodules from the WPNF and Penrhyn Basin fields in the Pacific Ocean, most of the Atlantic Ocean basins, such as the Nares, Argentine, Brazil, and Cape Basins, and the Indian Ocean basins except the CIOB.

Ferromanganese crusts are all solely of hydrogenetic origin and much of what was stated above about hydrogenetic nodules applies to crusts as well. In addition to these factors, water depth of formation (e.g., Mizell et al. 2020) and phosphatization of the older part of thick crusts also influence crust composition (Koschinsky et al. 1997). Despite all crusts having a similar genetic origin, ferromanganese crusts from different regions do exhibit heterogeneous compositions (Fig. 3.4 and

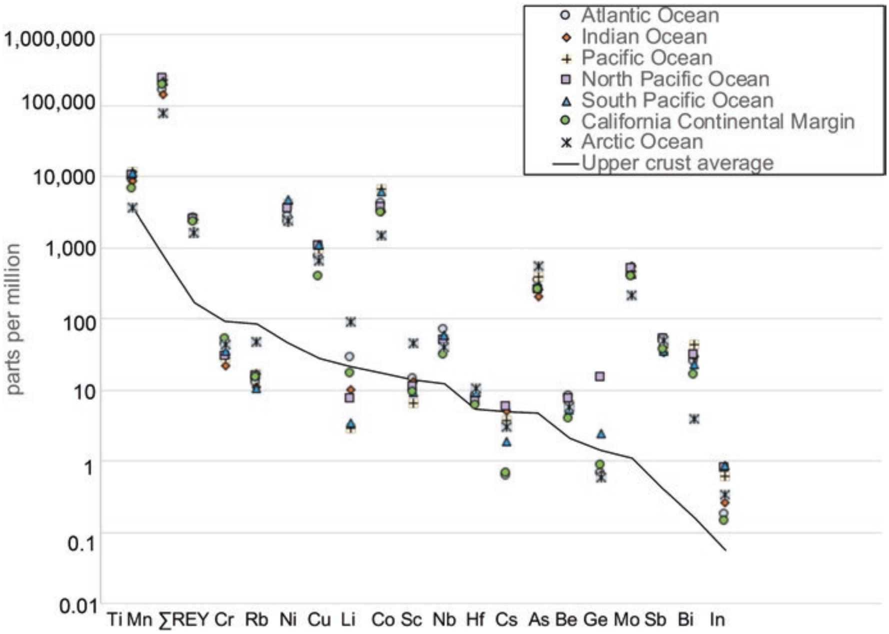

Fig. 3.4 Crust composition plot illustrating the average concentrations in parts per million for the seven regional types discussed in the text. The average values for Earth's upper crust are from Rudnick and Gao 2003

Table 3.2). One regional variation in ferromanganese crust composition is related to hydrothermal input, which can especially influence Fe/Mn ratios (more Fe rich relative to Mn) in crusts that form nearby hydrothermal systems. In the Indian Ocean, which hosts three spreading centers, crusts forming nearby can record hydrothermal input to various degrees, with weak to moderate variations in metal contents (Banerjee et al. 2017; Surya Prakash et al. 2020; this study). Therefore, in this study, all prospective regions near fracture zones and spreading ridges without available chemistry data were assumed to have a chemical composition similar to Indian Ocean crusts and were represented in the area-normalized mean by the mean Indian Ocean crust chemical composition (Fig. 3.2). We note that Atlantic Ocean nodules that form near hydrothermal systems along the MAR can also record hydrothermal input, as well as crusts formed along volcanic arcs, which could be more carefully accounted for in future refinements of mean crust and nodule composition.

3 Results and Discussion

3.1 Global Element Composition of Ferromanganese Crusts and Manganese Nodules

Contrasting flat averages versus area-weighted averages for global crust and nodule compositions yield several interesting trends (Tables 3.1 and 3.2). First, for nodules, an area-weighted average results in a much higher average Fe content (15.0 wt. % regionally weighted vs. 10.7 wt. % flat average), Fe/Mn ratio, and total Fe tonnage. Nodules with a diagenetic influence are significantly more enriched with Mn relative to Fe than hydrogenetic nodules, and the weighted average takes into account that diagenetic (e.g., Peru Basin) and mixed hydrogenetic-diagenetic (e.g., CCZ, CIOB) nodules represent a minority of global nodule fields. This shift is also apparent in increased average Co contents (3072 ppm regionally weighted vs. 2234 ppm flat average), Nb (52 ppm regionally weighted vs. 37 ppm flat average), total REY (1683 ppm regionally weighted vs. 1151 ppm flat average), and Pt (171 ppb regionally weighted vs. 129 ppb flat average), which are considered typical hydrogenetic metals. Decreased Ca (1.9 wt. % regionally weighted vs. 2.6 wt. % flat average), Be (4.3 ppm regionally weighted vs. 5.5 ppm flat average), Bi (16 ppm regionally weighted vs. 27 ppm flat average), Cd (8.1 ppm regionally weighted vs. 10 ppm flat average), Li (80 ppm regionally weighted vs. 104 ppm flat average), and U (8.7 ppm regionally weighted vs. 48 ppm flat average) are also apparent. All these differences are within an order of magnitude.

The differences for global average crust composition are less and include decreases in Al (1.6 wt. % regionally weighted vs. 2.3 wt. % flat average), Li (10 ppm regionally weighted vs. 23 ppm flat average), Rb (14 ppm regionally weighted vs. 18 ppm flat average), Sc (11 ppm regionally weighted vs. 16 ppm flat average), and Th (32 ppm regionally weighted vs. 40 ppm flat average) reflecting decreased relative influence of Arctic Ocean crusts. Interestingly, aside from the decreased influence of Arctic Ocean crusts, which make up a small proportion of global crusts (2%), the relatively similarly sized areas represented by ferromanganese crusts in other areas result in minor differences between the area-weighted average and the global average.

3.2 Total and Contained Metal Tonnage Estimates for Ferromanganese Crusts and Manganese Nodules and Comparison to Identified World Terrestrial Resources

The total global tonnage of manganese nodules determined from the prospective regions is 21×10^{10} tons, and for ferromanganese crusts is 93×10^{10} tons, making the estimated total tonnage for ferromanganese oxides in the ocean of 114×10^{10}tons (Table 3.3). Using the area-normalized mean composition of crusts and nodules, the estimated contained metal tonnages for the most commonly reported elements for these marine deposits are 22.7×10^{10} tons of Mn, 5.15×10^{9} tons of Co, 1.65×10^{9} tons of Cu, and 4.48×10^{9} tons of Ni (Table 3.3). Tonnages for additional trace metals using the area-normalized mean composition include 1.11×10^{10} tons of Ti, 2.63×10^{7} tons of Li, and 5.14×10^{8} tons of Mo. The tonnage of Te, calculated from

Table 3.3 Global contained metal tonnages for crusts and nodules based on area-normalized mean compositions[a]

	Global crust	Global nodule	Global crust + nodule
Fe	1.87E+11	3.15E+10	2.19E+11
Mn	1.85E+11	4.22E+10	2.27E+11
Si	5.43E+10	1.76E+10	7.19E+10
Al	1.46E+10	5.82E+09	2.05E+10
Mg	1.35E+10	3.34E+09	1.69E+10
Ca	2.80E+10	3.99E+09	3.20E+10
Na	1.53E+10	3.80E+09	1.91E+10
K	6.00E+09	1.68E+09	7.68E+09
Ti	9.17E+09	1.98E+09	1.11E+10
P	6.92E+09	5.55E+08	7.47E+09
Ag	NA	NA	NA
As	2.83E+08	3.32E+07	3.16E+08
B	NA	NA	NA
Ba	1.66E+09	3.62E+08	2.02E+09
Be	5.78E+06	9.00E+05	6.68E+06
Bi	2.75E+07	3.37E+06	3.09E+07
Br	NA	NA	NA
Cd	4.05E+06	1.71E+06	5.76E+06

(continued)

Table 3.3 (continued)

	Global crust	Global nodule	Global crust + nodule
Co	4.51E+09	6.45E+08	5.15E+09
Cr	3.06E+07	8.72E+06	3.93E+07
Cs	2.97E+06	2.19E+05	3.19E+06
Cu	8.02E+08	8.53E+08	1.65E+09
Ge	NA	NA	NA
Hf	7.96E+06	NA	NA
In	4.87E+05	NA	NA
Li	9.58E+06	1.67E+07	2.63E+07
Mo	4.28E+08	8.53E+07	5.14E+08
Nb	4.88E+07	1.08E+07	5.96E+07
Ni	3.23E+09	1.25E+09	4.48E+09
Pb	1.31E+09	1.89E+08	1.50E+09
Rb	1.32E+07	4.76E+06	1.80E+07
Sb	3.73E+07	8.96E+06	4.62E+07
Sc	9.82E+06	3.08E+06	1.29E+07
Se	7.22E+06	NA	NA
Sn	8.50E+06	NA	NA
Sr	1.30E+09	1.86E+08	1.49E+09
Ta	1.55E+06	NA	NA
Te	3.73E+07	NA	NA
Th	2.94E+07	1.96E+07	4.90E+07
Tl	1.13E+08	2.35E+07	1.36E+08
U	1.11E+07	1.83E+06	1.29E+07
V	6.55E+08	1.13E+08	7.68E+08
W	7.89E+07	1.28E+07	9.18E+07
Zn	6.35E+08	1.78E+08	8.13E+08
Zr	5.56E+08	1.12E+08	6.68E+08
La	2.59E+08	3.58E+07	2.95E+08
Ce	1.10E+09	2.35E+08	1.33E+09
Pr	5.17E+07	8.69E+06	6.04E+07
Nd	2.21E+08	3.63E+07	2.57E+08
Sm	4.59E+07	8.12E+06	5.40E+07
Eu	1.24E+07	1.95E+06	1.44E+07
Gd	5.04E+07	8.17E+06	5.86E+07
Tb	7.63E+06	1.28E+06	8.91E+06
Dy	4.72E+07	7.29E+06	5.44E+07
Y	1.78E+08	2.74E+07	2.05E+08
Ho	9.17E+06	1.42E+06	1.06E+07
Er	2.63E+07	3.88E+06	3.02E+07
Tm	3.71E+06	5.86E+05	4.30E+06
Yb	2.35E+07	3.93E+06	2.74E+07
Lu	3.53E+06	5.73E+05	4.11E+06
ΣREY[b]	1.99E+09	3.53E+08	2.35E+09
ΣPGM[c]	3.18E+05	3.46E+04	3.53E+05

[a]Total mineral tonnages used to calculate contained metal tonnages are 93E+10 for crusts and 21E+10 for nodules

[b]ΣREY denotes sum of the rare earth elements plus yttrium

[c]ΣPGM denotes total platinum group metals; ΣPGM values were calculated using mean global compositions from flat averages unlike the rest of the values in this table

Table 3.4 World identified terrestrial resources for select metals[a]

	Tonnage × 10^6 tons
Manganese	~5200
Cobalt	25
Copper	5600
Nickel[b]	300
Antimony	~4.3
Arsenic[c]	11
Lithium	~86
Molybdenum	25.4
Niobium	~17
PGM[d]	~0.10
REE[e]	409
Scandium	0.64
Tellurium	~0.05
Thallium[f]	0.65
Thorium	6.4
Titanium	1200
Tungsten[g]	7.0
Vanadium	~63
Yttrium	~0.94
Zirconium	~77

[a]Majority of values from U.S. Geological Survey (2021)
[b]Mudd and Jowitt (2014)
[c]U.S. Geological Survey (2016)
[d]PGM denotes platinum group metals, Pt alone would be less
[e]Zhou et al. (2017)
[f]Thallium resource 0.017 × 10^6 in Zn resources and 0.630 × 10^6 tons in coal resources
[g]Hinde (2008)

the flat average due to data availability, is 3.24 × 10^7 tons (see Table 3.3 for a complete list of elements and tonnages).

To add perspective on the magnitude of these contained metal tonnage estimates, we can compare them with available known terrestrial tonnage estimates. Compared with compiled values for the identified world terrestrial resource, there is 648 times more Te, 206 times more Co, 44 times more Mn, as well as more Y, Th, Ti, Mo, Sc, W, V, Sb, Zr, Th, Nb, As, and Ni (listed in decreasing magnitude) contained in ferromanganese crusts plus nodules (Table 3.4; U.S. Geological Survey 2014, 2016, 2021; Mudd and Jowitt 2014; Hinde 2008). However, there is 3.4 times more Cu, 3 times more Li, 2.3 times more Bi, and 1.9 times more rare earth elements (not including Y) in the identified world terrestrial resources than in global crust and nodules. Nevertheless, the terrestrial resource values are not calculated using the same methods as crust and nodule contained metal tonnages, given that likely present but non-identified terrestrial resources are not included in the reported terrestrial inventories. The comparison does, however, illustrate that the total contained metal tonnages for ferromanganese crusts and manganese nodules do constitute a significant metal reservoir on Earth.

3.3 Marine Ferromanganese Minerals in the Context of Ocean Metal Reservoirs

In addition to the seafloor minerals discussed above, ferromanganese minerals in the oceans also occur in the water column, where they contribute to the distribution of different metals between dissolved and particulate phases. The tonnages we present here can contribute to understanding the scale of the sink that ferromanganese oxides provide. For example, the primary processes responsible for the removal of Mn from the dissolved phase in the oceans are (1) biological uptake and (2) oxidation and aggregation into particles (van Hulten et al. 2017; Gartman and Findlay 2020). Sinking and burial of particulate manganese in sediments as well as the formation of ferromanganese crusts and nodules are therefore considered the consequential sinks for manganese. Here, we estimate that the total contained tonnages of manganese for manganese nodules and ferromanganese crusts of 2.27×10^{11} tons. A recent estimate using samples obtained from the South Pacific Gyre suggested that poorly crystalline manganese oxide microparticles within oxygenated sediments may contain on the order of 10^{12} tons of manganese (Uramoto et al. 2019). This estimate is just one order of magnitude higher than the total for crusts and nodules calculated here. Notably, the microparticles exhibited a Fe/Mn ratio of approximately 1, suggesting they are hydrogenetic in origin and indicating that sediment microparticles and ferromanganese crusts and nodules, in addition to contributing nearly equally to global sinks of manganese in the ocean, also have similar formation mechanisms. With a similar genesis, manganese oxide particles and mineral occurrences likely control other trace metals in similar ways, especially Co, Ni, Te, Ce, and others (Yamagata and Iwashima 1963; Koschinsky and Hein 2003; Hein et al. 2003; Bau and Koschinsky 2009).

4 Conclusions

Considering the relative areal extent of ferromanganese crust and manganese nodule occurrences in the oceans and compositional differences between the large areas over which these minerals occur reveal interesting patterns. For manganese nodules, the influence of diagenetic inputs is overestimated in global compilations that do not use regional weighting factors, leading to potential underestimation of Fe, Co, Nb, REY, Te, and Pt, and overestimation of Ca, Be, Bi, Cd, Li, and U. For ferromanganese crusts, the effect of regional weighting factors is less pronounced, and changes are minor unless Arctic Ocean crusts are included without regard for proportion.

This is not because the outlined ferromanganese crust types are compositionally similar but rather because they make up relatively equal proportions globally. Based on these new estimates, we suggest that ferromanganese crusts are a greater repository for global manganese and many associated trace metals than manganese nodules; other estimates suggest that manganese microparticles may exceed both.

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Annexure: Definitions

The terms *polymetallic nodule*, *ferromanganese nodule*, *manganese nodule*, and the shorthand *nodule* are sometimes used interchangeably. However, without context, do not have identical meanings. The term *nodule* is a morphologic term that generally refers to rounded mineral concretions. The term *ferromanganese* is a description of composition, indicating the presence of iron and manganese, which are the framework metals for marine nodules. *Ferromanganese* is often used as a descriptor for crusts, which have approximately equal Fe and Mn contributions by weight (this paper), and *manganese* is often used as a descriptor for nodules, which may have Mn contents ~2× that of Fe, although hydrogenetic nodules have a Fe/Mn ratio of approximately 1 (this paper). *Polymetallic nodule*, as defined by the International Seabed Authority (ISA), refers to "any deposit or accretion of nodules on or just below the surface of the deep seabed, which contain manganese, nickel, cobalt and copper." For instance, whereas all polymetallic nodules are also manganese nodules and in shorthand may be referred to as nodules, the opposite is not true—not all nodules are manganese nor polymetallic nodules, since *nodule* is a morphologic term that may be applied in other contexts. For instance, carbonate nodules, phosphorite nodules, and micronodules are some examples of *nodules* that occur elsewhere in the oceans and are entirely distinct from abyssal plain nodules.

Likewise, the terms *cobalt-rich ferromanganese crust* designates a specific subset of the mineral occurrence discussed as *ferromanganese crusts* for which the shorthand *crust* is often used. As defined by the ISA, *cobalt crusts* also known as *cobalt-rich ferromanganese crusts* are "hydroxide/oxide deposits formed from direct precipitation of minerals from seawater on to hard substrates containing minor but significant concentrations of cobalt, titanium, nickel, platinum, molybdenum, tellurium, cerium, other metallic, and rare earth elements." The terms *cobalt crusts* and *cobalt-rich ferromanganese crusts* both refer to minerals that are predominantly composed of iron and manganese; the cobalt contents average greater than 6500 ppm (0.65 wt. %) in the Prime Crust Zone and greater than 4000 ppm (0.40 wt. %) globally averaged. *Ferromanganese crust* refers to a chemical sedimentary rock containing iron and manganese, with trace metal contents that vary by region (e.g., Aplin and Cronan 1985; Wen et al. 1997; Hein et al. 2000; this paper); a *crust* is a morphologic description.

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Chapter 4
Geological Characterization of Ferromanganese Crust Deposits in the NW Pacific Seamounts for Prudent Deep-Sea Mining

Akira Usui and Katsuhiko Suzuki

Abstract We review recent results of onsite seabed surveys and geoscientific analyses of hydrogenetic ferromanganese crusts in the northwestern Pacific and attempt to identify the controlling parameters of the diversity of the deposits in terms of scientific understanding of processes and environments to be applied for future deep-sea mining. We ascertained that oxidizing seawater, old and stable rock substrates, and no or scarce sedimentation or productivity, are optimal conditions for high-grade abundant deposits. The following physicochemical and geological processes were verified from our observations and analyses: (1) ultra-slow and fairly continuous growth at a rate of several μm/kyr in all water-depth zones for more than 10 Myr; (2) initial precipitation of poorly crystalline vernadite (Fe/Mn around one with two diffused X-ray diffraction) now forming coccoid-like morphology as a final constituent to comprise the crusts, and (3) the highest Co concentration around the oxygen minimum zone. Moreover, the microstratigraphy of crusts indicates surprisingly similar structural zones, mineralogy, and chemistry on micron- or millimeter-scales among those from remote areas when the water-depth range is the same. Thus, continuity in abundance and grade at the regional scale can be reasonably expected. Geological characterization and consideration are essential for understanding mineral diversity and evaluating the economic potential and distribution.

Keywords Marine mineral · Ferromanganese crust · Seamount · Northwestern Pacific · Growth rate · Takuyo–Daigo · Hydrogenetic · Co-rich crust

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1 Introduction

The ferromanganese crust (hereafter called crust) is believed to be one of the most promising mineral resources in oceans, with a high abundance and moderate grade of strategic metals (Co, Ni, REE, Pt, etc.). Crust deposits are unique chemical precipitates formed in normal cold seawater (hydrogenetic) at depths of approximately 1000 m or deeper finally accumulating into a thick layer of 10 cm or more on firm rock substrates over millions of years (Hein et al. 2000; Koschinsky and Hein 2003). Exploration has been focused on the northwestern Pacific because of the abundance of high sea areas, and the four nations, Japan, China, Russia, and Korea (Kim and Wessel 2011; Yang et al. 2019; Zhao et al. 2019; Hino and Usui 2021), have a long-term contract for exploration of their exclusive mining areas with the International Seabed Authority (ISA 2012) under United Nations Convention on the Law of the Sea (UNCLOS). For the past 30 years, scientific facts regarding the crust deposits have been established due to the rapid increase in demand for metals and innovation in ocean survey techniques.

The unique geological occurrences and mineral and chemical compositions of deposits have been obtained (Halbach et al. 1989, 1982), and the economic potential of the northern Central Pacific seamount areas was first suggested in the 1980s (Halbach et al. 1989; Hein et al. 2000). Scientific and reconnaissance surveys conducted by American, Japanese, Korean, Russian, and Chinese institutions have demonstrated the distribution of similar types of deposits in the western and southern Pacific seamount areas (Halbach and Puteanus 1984; Usui and Okamoto 2010; Usui and Someya 1997; Hein et al. 2013; Jeong et al. 2000; Okamoto and Usui 2014). More recent research has revealed the ubiquitous occurrence of deposits all over the Indian (Banakar and Hein 2000; Hein et al. 2016; Glasby et al. 2010), Atlantic (Kuhn et al. 1996; González et al. 2016; Josso et al. 2019, 2020; Benites et al. 2020), and Arctic oceans (Konstantinova et al. 2017). However, the northwestern Pacific basin continues to outrank other regions in terms of abundance of distribution and grade of crusts due to its optimal geological environments, such as great water depth, the oldest age of basins, and numerous seamounts (Hein 2002; Hein et al. 2003; Rona 2003).

The crusts and nodules of the Pacific are composed of typical sedimentary deposits of Mn and Fe oxides and are unique to the Cenozoic ocean (Usui and Ito 1994). The major oxide minerals that cover or surround rock outcrops (Fig. 4.1) or fragments with porous and hydrous oxide compounds are poorly crystalline and small in size (less than 1 μm scale). The mass of the compounds can be described as a low-grade, large-scale, and 2D deposit that occurs on the deep seafloor (Hein and Petersen 2013; Usui et al. 2017). The crust deposits typically have high contents of Co, Ni, Pt, Mn, Tl, and Te (Fig. 4.2), rare earth elements, and other strategic metals (Hein et al. 2000; Bau et al. 2014; Lusty et al. 2018). Moreover, they contain the least hazardous metals and exist as stable oxide forms in the surface aqueous environments and that the content of critical metals per unit area is the highest in the crust deposits (Table 4.1).

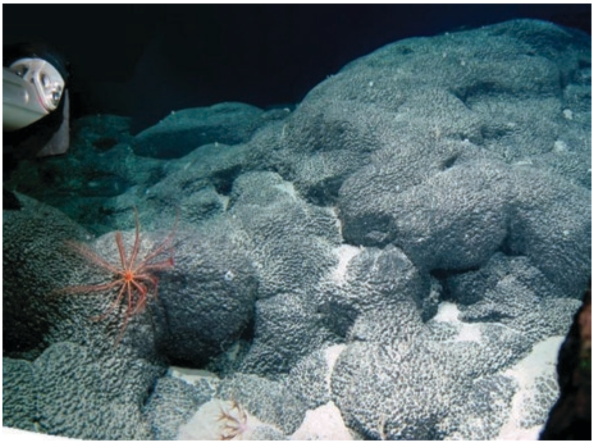

Fig. 4.1 Sea floor image of the ferromanganese crusts at 1255 m water depth with ROV HyperDolphin (JAMSTEC)

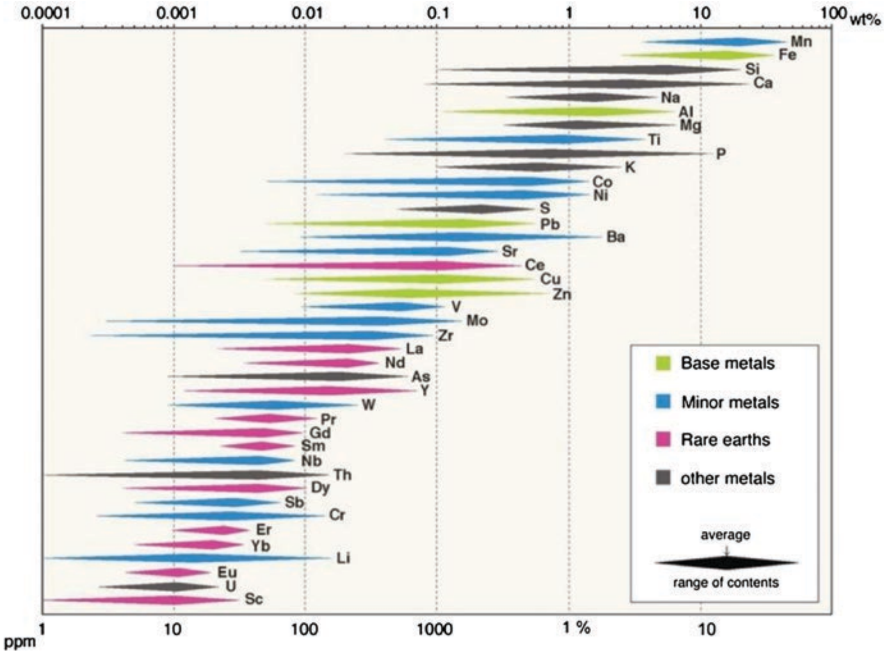

Fig. 4.2 Variation of chemical composition of marine manganese deposits in the NW Pacific [Kisimoto et al. 2017]

However, the geological properties of the deposits are yet to be determined on various scales, and the reasons for mineral diversity are not yet well understood. Thus, more careful and reliable scientific characterization is expected from geopolitical, environmental, and economic points of view (Beaudoin and Baker 2013; Lodge and Ryabinin 2019). In consideration of these requirements, Japanese

Table 4.1 Calculated total metal values assuming 10 cm thickness of crusts, 1.90 specific density, and metal price in 2018 based on Mineral Commodity Summaries (2020, USGS)

Ferromanganese crusts[a]			
	Concentration	Metal price[b]	Total value per m^2
	in ppm	US$ per kg	in US$
Pt	0.77	30,579	3.6
Co	9100	37	52.8
Ni	4500	12	8.4
Cu	1050	6	1.0
Ce	1100	2	0.3
			66.1
Manganese nodules[a]			
Pt	0.11	30,579	0.1
Co	2400	37	2.7
Ni	10,000	12	3.6
Cu	12,800	6	2.4
Ce	900	3	0.1
			8.8

[a]Calculated from Usui and Someya (1997)
[b]Calculated total values of major metallic elements assuming 10 cm thickness of crusts and 10 kg/m^2 nodules, and 1.90 specific wet density, based on the metal market price in 2018 in Mineral Commodity Summaries [USGS 2020]

organizations have focused on practical exploitation and geoscientific research on crusts, supported by technological innovation in seafloor exploration and laboratory analysis over the last few decades. For example, new exploration vessels have been used for exploration and scientific research of crusts, as have drill machines, remotely operated vehicles (ROVs), deep-tow sensors, and manned submersibles (Usui et al. 1993; Kisimoto et al. 2017). In this paper, we review the recent geological knowledge on crusts necessary for future exploration, safe and economical mining technology, and security of deep-sea environments. Herein, we describe the occurrence and properties of the deposits on regional to microscopic scales, a genetic model of the deposits, and its application to exploration. We believe that these deposits are abundant mineral deposits and also serve as important geological archives.

2 Regional Occurrence and Distribution

Ferromanganese oxide deposits often form thick crusts over rock outcrops and scattered nodule pavements on unconsolidated sediments. The thickness of the oxide layers ranges from zero to approximately 15 cm (Fig. 4.3). Some of the northwestern Pacific seamounts typically yield widely extended ferromanganese crust deposits of >100 kg ferromanganese crust per square meter. Hydrogenetic crusts are

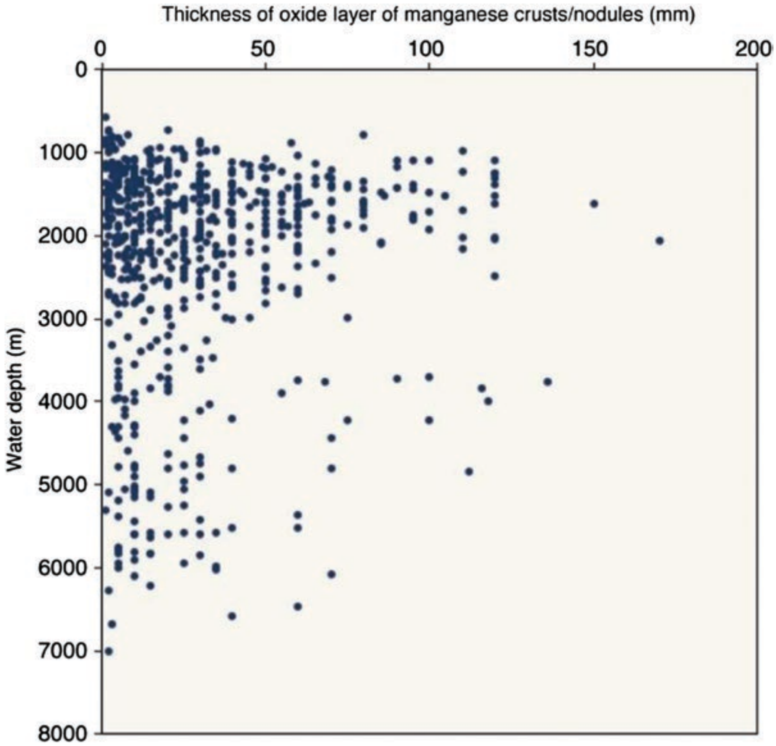

Fig. 4.3 Thickness of marine manganese deposits and water depth in the NW Pacific [Kisimoto et al. 2017]

believed to grow at a rate of several millimeters per million years through the accumulation of iron and manganese oxide precipitates and the absorption of various types of dissolved cations and anions (Hein et al. 2000; Koschinsky and Halbach 1995). Old and firm substrates, such as phosphatized limestone and volcanic rocks, often yield thick ferromanganese crusts and reveal a complicated evolutionary history of the volcanoes, such as eruption, erosion, subsidence, reef-building, collapse, mass wasting, and pelagic sedimentation and may determine the configuration and thickness of the deposits (Glasby et al. 2007; Hein and Morgan 1999). The growth of hydrogenetic ferromanganese crusts or nodules was promoted in oxygenated water (Fig. 4.4), whereas high rates of sedimentation, volcanic activity, high bioproductivity, terrigenous supply, and mass wasting commonly restrain the growth of hydrogenetic crusts.

Simple statistics of the thickness of crusts and nodules and the age of basement rocks (Kisimoto et al. 2017) exhibit a clear relationship between the maximum thickness at every station and the age of the basement rocks (Fig. 4.5). The occurrence of increasingly thick ferromanganese crusts indicates the older age of the substrate rocks. The thickest crusts occur in the Jurassic to Cretaceous seamounts of the northwestern Pacific, whereas modern sediments, reefs, and volcanic rocks are

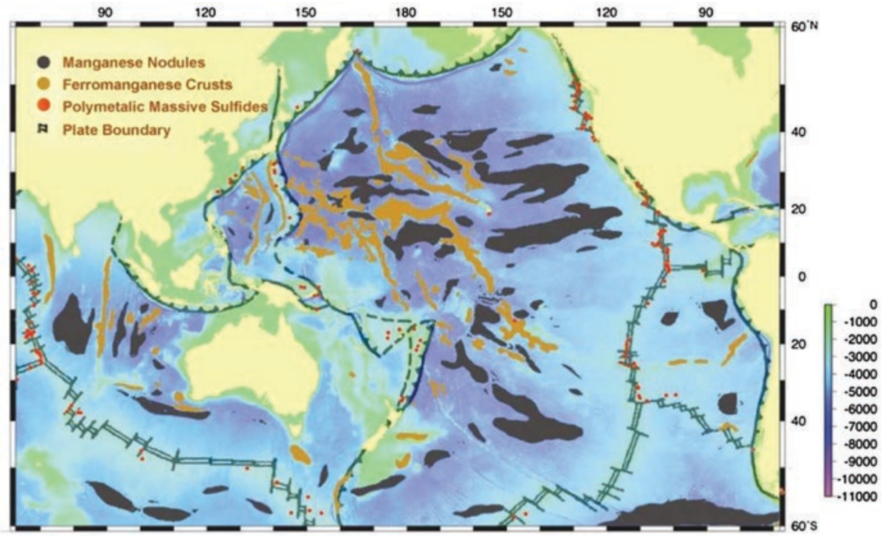

Fig. 4.4 Distribution map of marine mineral resources and water depth

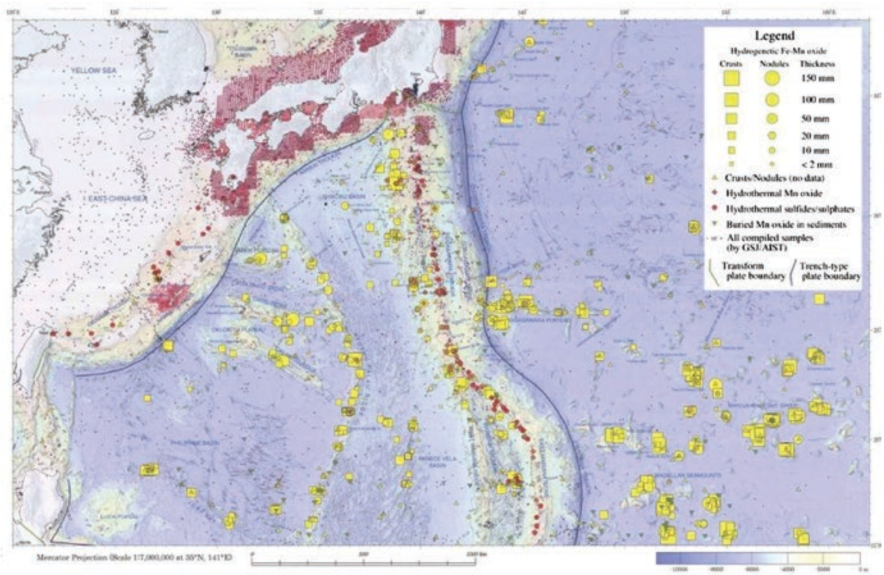

Fig. 4.5 Distribution map of marine mineral resources [Kisimoto et al. 2017]

never associated with thick crusts. As shown in Fig. 4.6, the prime ferromanganese deposits are related to the Cretaceous seamount over the Pacific Plate, whereas the scarce areas are correlated with younger terrigenous sediments, thick biogenic sediments, or modern submarine volcanism. A similar occurrence was reported in crusts from the Hawaiian Ridge (Moore and Clague 2004).

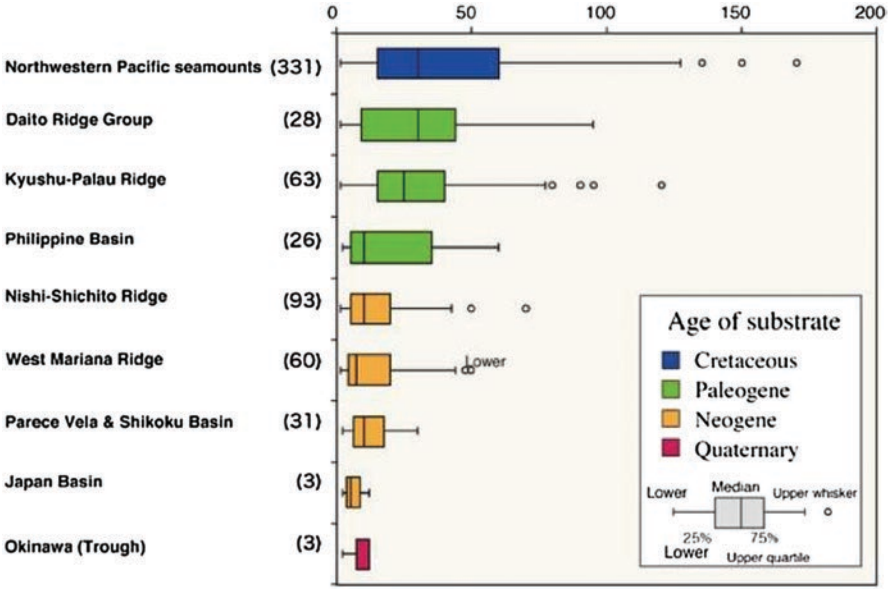

Fig. 4.6 Thickness of marine manganese deposits by the geological environment in the NW Pacific [Kisimoto et al. 2017]

Hydrogenetic ferromanganese crusts are believed to have been growing very slowly for several millions of years since the Paleogene period (Hein et al. 2000; Klemm et al. 2005; Goto et al. 2014) or even the Cretaceous Era (Josso et al. 2019). Thick crusts are also important long-range geological archives (Hein et al. 1992, 2000; Kim et al. 2006). It is important to characterize the origin and formation environments of this metallic deposit; however, comparison against genetic analogs of metallic deposits on land is a challenging task. The controlling geological parameters have not yet been determined (Bogdanov et al. 1995; Hein et al. 2009).

This study aims to characterize the various features of extensive deposits around the northwestern Pacific seamount area. The patterns of regional and fine-scale variability in thickness and chemical composition have been documented (Usui and Someya 1997; Hein et al. 2016; Marino et al. 2018), and innovative high-resolution acoustic mapping and video imaging of seafloors have recently been attempted (Bodenmann et al. 2017; Du et al. 2017; Yeo et al. 2019; Yang et al. 2020; Joo et al. 2020).

Small-Scale Variation Over Seamount Areas.

The patterns of small-scale variation in the occurrence, morphology, and composition of the crusts within a seamount (Fig. 4.7) are poorly understood or reported because of the difficulty in positioning vehicles, sampling of bottom materials, and scarce geological information. To characterize the small-scale patterns of variation in grade and abundance and to correlate them with the water depth, geomorphology, and sedimentary conditions, we surveyed the sea floors and associated crusts in a model seamount, the Takuyo–Daigo seamount (see Fig. 4.8), a type of large flat-top

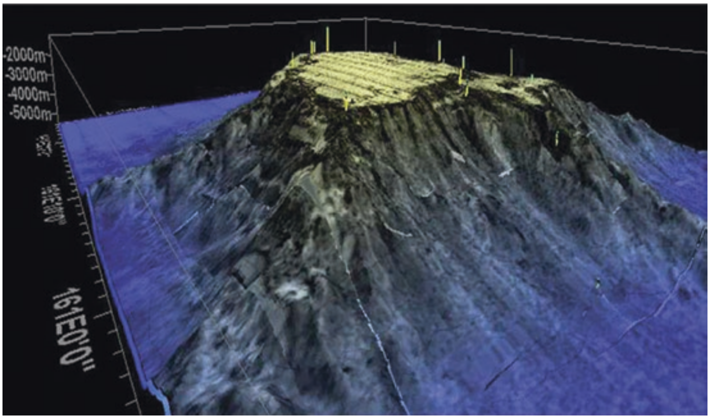

Fig. 4.7 Topography of a flat top seamount in the Marshall sea area and thickness of crust. Bright area shows low acoustic impedance (Usui et al. 2015)

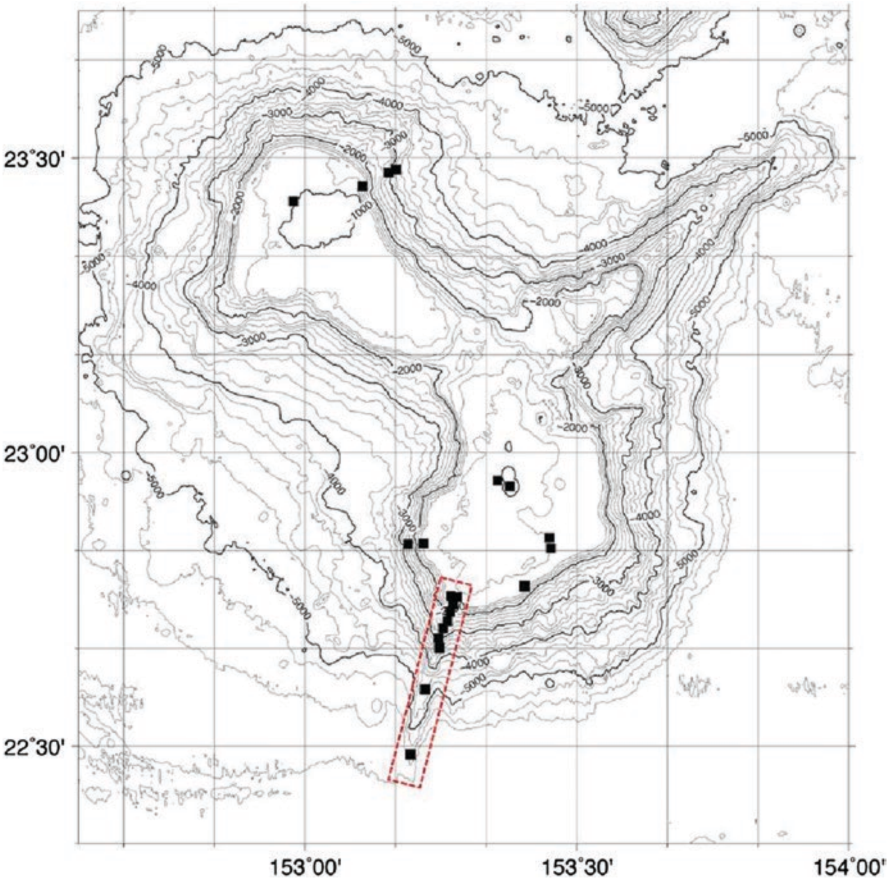

Fig. 4.8 Topography of the Takuyo–Daigo seamount and sample location of the crusts. The southern ridge shows a ROV survey line

seamount (Guyot), using the ROV robots (HyperDolphin and Kaiko, JAMSEC) and a newly innovated acoustic probe sensor (Thornton et al. 2012) along a line from the foot to the top of the seamount. Usui et al. (2017) summarized the general pattern of small-scale occurrence and distribution of the crusts within 1000–5500 m water-depth range, based on small-scale observations and careful sampling performed with the ROVs, HyperDolphin, and Kaiko during more than five cruises of R/V Natsushima and Kairei (e.g., NT09-02 and KR16-01) from the deep-sea floor to the top.

We observed the bottom material and crusts on the seafloor (Fig. 4.9a and b) and collected samples at approximately 100 m depth intervals after continuous observation and measurement at the bottom. Generally, stable outcrops of substrates with gradients greater than 15° are commonly covered with thick ferromanganese crusts.

Physicochemical parameters (temperature, salinity, depth, and dissolved oxygen) were measured on the line. High-resolution photographs were obtained (Fig. 4.1), and the thickness of the crusts was measured for the collected samples. Petrographic descriptions were carried out for the crusts and substrate rocks on the shore.

Based on the *in situ* observation, sampling, and onshore analyses of four dives with RV Natsushima-ROV HyperDolphin-4 K and ROV Kaiko MK-V, we found the following on-site facts and ideas. (1) Hydrogenetic precipitation of iron and manganese oxide has taken place continuously at a constant rate during the Neogene period since approximately 20 Ma over a wide water-depth range (900–5500 m), including the oxygen minimum zone (OMZ), from the foot to the top of the seamount (Fig. 4.10), unless covered with sediments. (2) The thickness of the crusts is generally controlled by the time of exposure (age) to bottom water, but minor variations are affected by sedimentary input and post-depositional non-tectonic movement, which may have changed during the growth period. (3) The chemistry of modern precipitates (very surface of the crusts) is well correlated with water depth, probably because the redox conditions of seawater affect the process of incorporation and chemical form of metallic elements (Usui et al. 2017; Kashiwabara et al. 2013; Takahashi et al. 2007). Most metallic elements (Mn, Fe, Co, Ce, and Mo) have a strong water-depth dependency (Fig. 4.10). (4) The thickness is the result of the integrated accumulation of Fe–Mn oxides and other polygenetic particulate materials, such as biogenic, volcanogenic, terrigenous, and cosmogenic origins. (5) A remarkable diversity of microbes was observed associated with redox conditions. Thus, microbial metabolism probably affects the precipitation of manganese oxide and the growth of the crusts (Kato et al. 2018). (6) Thornton et al. (2012) attempted to obtain automated acoustic-sensor observation of the internal structure of crusts using a 200 kHz acoustic beam and estimate the thickness of the ferromanganese crust. This technology is expected for future remote sensing of the exploration of crusts. Another new technique for measuring the thickness of crusts is an ROV-mounted drilling device that was tested by JAMSTEC on the seafloor to be used for future exploration.

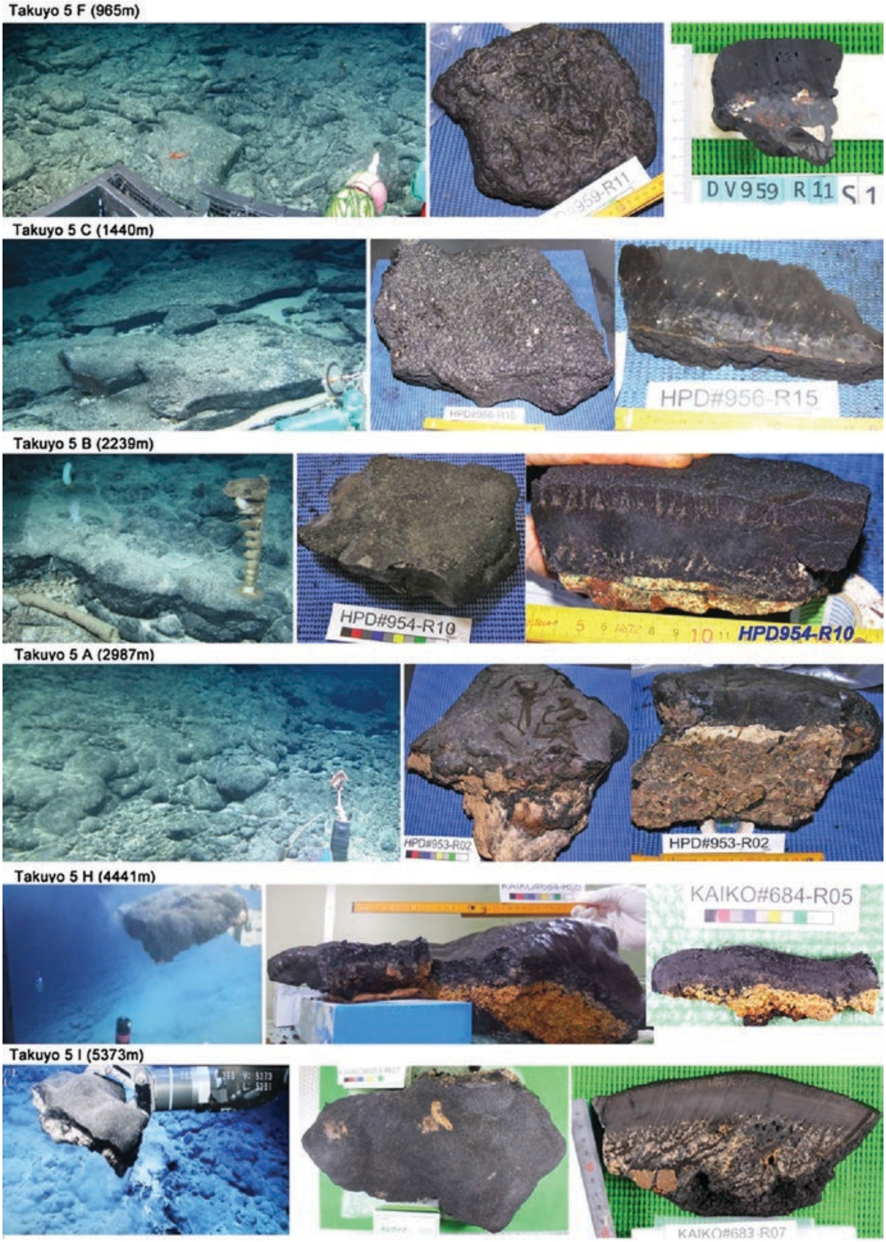

Fig. 4.9 (**a**) Seafloor image, morphology, and cross section of crusts from foot to top in the Takuyo–Daigo seamount [Usui and Suzuki 2019]. (**b**) Seafloor image, morphology, and cross section of crusts from foot to top in the Takuyo–Daisan seamount [Usui and Suzuki 2019]

Fig. 4.9 (continued)

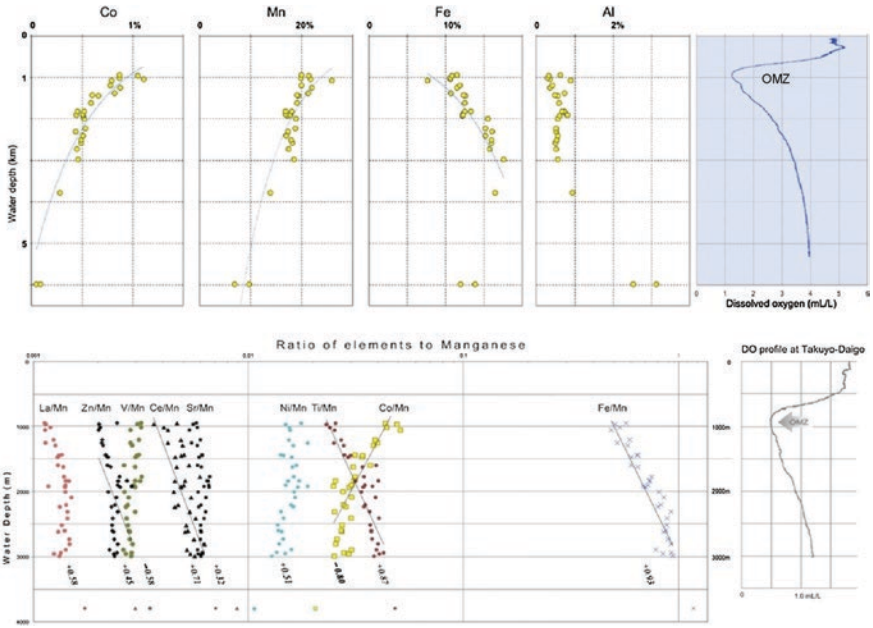

Fig. 4.10 Water-depth dependent variation of chemical composition in the Takuyo–Daigo seamount [Usui et al. 2017]

3 Geological Background of the Seamount Areas

The northwestern Pacific seafloor is characterized by the complex morphology of abundant and large seamounts (Kim and Wessel 2011), where extensive hydrogenetic ferromanganese crusts commonly occur (Glasby et al. 2007). The age of basement oceanic crusts goes back to the Late Jurassic, and the later large-scale volcanic eruption took place from the Middle to Late Cretaceous. The eruption formed a large number of seamounts and guyots (flat-top seamounts) at 10–20° S in the Southern Hemisphere during the Cretaceous period (Nakanishi and Gee 1995; Whitechurch et al. 1992) and then moved to the northwestern Pacific (Smoot 1989; Smith et al. 1989). The volcanic islands were wave-cut and traversed the equator as carbonate reefs, followed by subsidence (Lincoln et al. 1993; Winterer et al. 1993; Van Waasberge and Winterer 1993; Larson et al. 1995). Plate motion also formed several hotspot seamount chains (Fig. 4.11) between the East Pacific Rise and the northwest Pacific margin (Koppers et al. 1998, 2003).

The ferromanganese crusts may have started to grow after complete submergence below a water depth of approximately 1 km, without pelagic sedimentation over the firm rock substrates. The estimated history of a model seamount, Takuyo–Daigo seamount, and the formation of ferromanganese crusts are illustrated in Fig. 4.12.

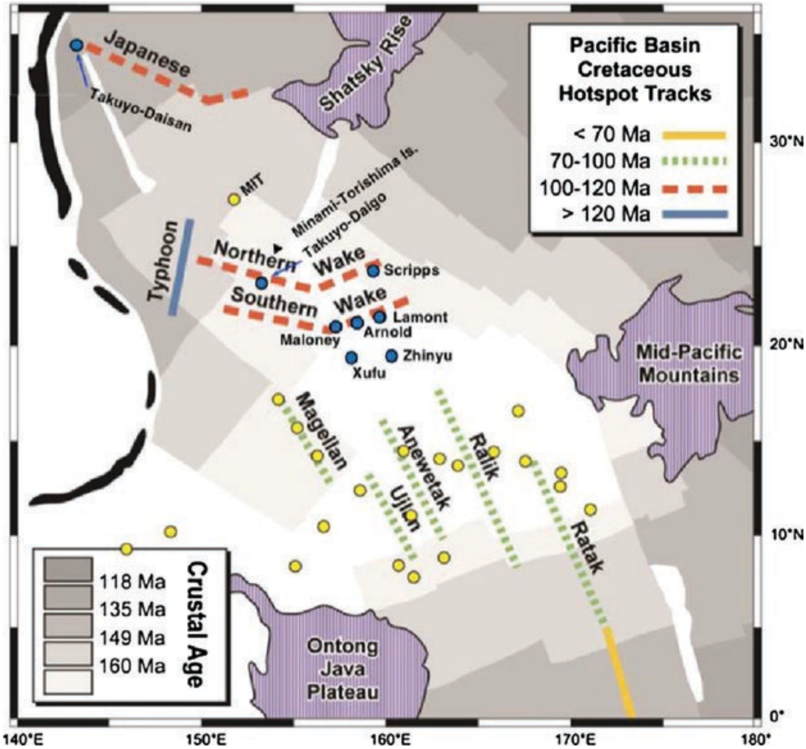

Fig. 4.11 Simplified tectonic map and survey areas for crusts [modified from Koppers et al. 2003]

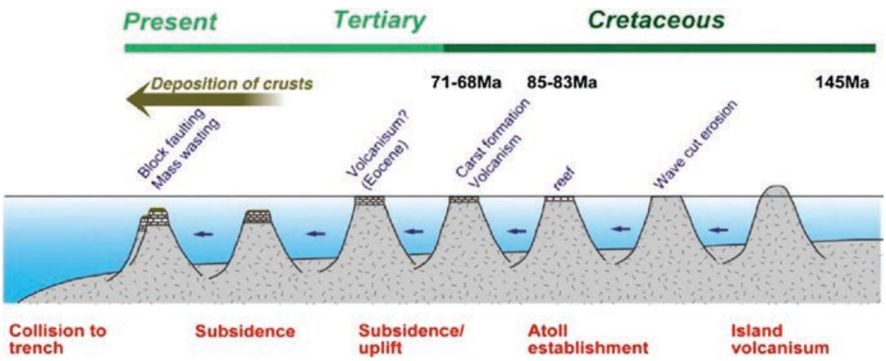

Fig. 4.12 Schematic model of seamount evolution and formation of crusts over the Pacific plate

The basement basalt at the Takuyo–Daigo seamount was dated 100 Ma using the Ar-Ar method (Tokumaru et al. 2015), Takuyo–Daisan seamount as 118 Ma (Pringle and Duncan 1995; Wilson et al. 1998), and Iwaki seamount as approximately 140 Ma (Nakanishi et al. 1999). The seamount is estimated to be drowned in the southern hemisphere (3°S) at 112 Ma (Albian, Cretaceous), and the flat tops are partly covered with foraminiferal pelagic ooze sediments, but most are outcropped with the Cretaceous limestone and basalt basement. The steep slopes near the edges of the tops are hard phosphatized limestone with a gradient of 20°or greater, where most of the outcrops are commonly covered with thick ferromanganese crusts. Mass wasting has occurred since the flat-top seamounts were drowned and started subsidence for more than 1000 m or more. Figure 4.12 shows the schematic history of the evolution of the seamount and related deposition timing of the ferromanganese crusts.

The morphology of the seamount suggests a complicated evolutionary history from the Early Cretaceous to the present (Koppers et al. 2003; Tokumaru et al. 2015). The seamount is a composite volcano that erupted as a member of the hot spot chain, forming subaerial island volcanoes and then eroded at sea level. The seamount started to subsidize, followed by reef-building atolls, submerged as a flat-top seamount, and pelagic sedimentation began. The steep slopes were affected by mass wasting during subsidence and drifting, forming minor ridges, sediment pools, independent blocks, scours, and fans.

3.1 Microscopical-Scale Variations Within the Crusts

Hydrogenetic ferromanganese crusts are long-range chemical sedimentary rocks that form several millimeters per million years. Thus, a thick crust is an integrated pile due to the accumulation of tiny particles or thin layers (Fig. 4.13). The bulk concentration of metals (grade) and the variation within the ore deposit were affected by the temporal change in the mass accumulation rates or each fraction (Fig. 4.14). The fractions are major submicron-scale ferromanganese oxide particles, volcanic fragments or sands, biogenetic skeletons, terrigenous particles, eolian dusts, and cosmic spherules, thus determining physical and compositional lamination and banding (Figs. 4.15 and 4.16).

The crusts in the Takuyo–Daigo seamount contain a maximum of 1.1% Co, 0.5% Ni, and 0.2% total REE, but the secular distributions of metals show considerable ranges (Ren et al. 2007; Nozaki et al. 2016; Usui et al. 2017; Yeo et al. 2018). Notably, the patterns of secular variation are similar within the area, indicating similar paleoenvironmental and sedimentological changes during the formation for millions of years.

Microscopical description and X-ray fluorescence (XRF) chemical analysis suggest that apparent banding, such as the alternation of dense/black and porous/brownish layers, is principally due to the microstructure and abundance of detrital particles and not directly due to variation within the oxide minerals. Thus, stratigraphic correlations based on visible characteristics among ferromanganese crust cores are often poor because of the localized (detrital, volcanogenic, and biogenic)

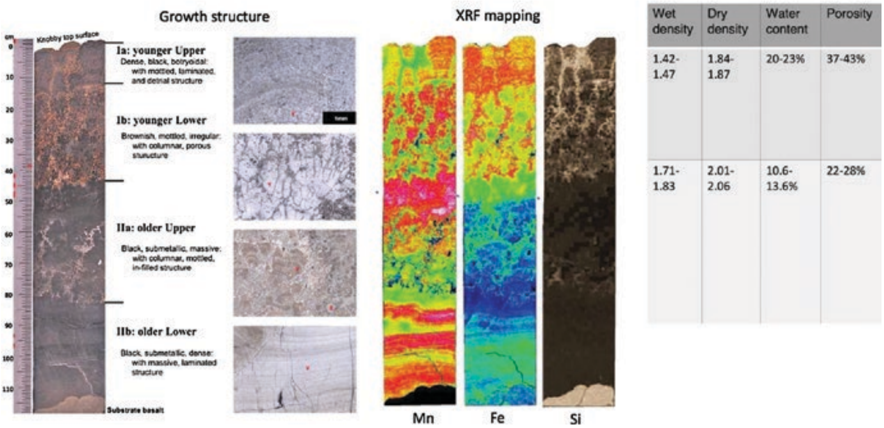

Fig. 4.13 Microstratigraphy and different properties in structure and composition of the growth zones in the crusts. [Hino and Usui 2021]

sources of mineral particles. The variable contents of the major elements (Mn, Fe, and Si) are the most important factors in discussing the relationships to regional and global environments. The secular element profiles in the ferromanganese crusts from the two remote stations are often correlated if the water-depth zones are similar. However, when compared to a crust from different water depths, the secular trend is not always comparable. This implies that both regional and local geological and oceanographic environments influence the temporal chemical and mineralogical variations within crusts.

Among the patterns of elemental distribution reported for the crusts (Halbach et al. 1989; Nishi et al. 2017), the clearest change in composition and appearance is the dual structure (older and younger generations) divided by a marked change in physical and mineralogical properties (Fig. 4.14). The dominant dual structure (showing a younger earthy black, apatite-free, friable zone, and an older submetallic apatite-rich, hard, phosphatized generation), first described by Halbach et al. (1989), was observed in all crusts of this study thicker than approximately 5 cm at all depths and seamounts. This microstratigraphic correlation suggests a regional-scale global change in the oceanographic redox environment, such as ocean circulation or climate (Halbach et al. 1982, 1989).

Thus, the microstratigraphic correlation between the crusts from different areas is most important when describing the geochemical characteristics of the ore deposits and the interpolation and extrapolation of the ore grade and the abundance of the deposits. Our data for the Takuyo–Daigo seamount indicate that the distinct changes within the crusts are (1) higher Fe/Mn and higher Co in the younger layers, but higher total REE, P, and Pt in the older layers, and (2) higher contents of detrital minerals in the younger layers, such as quartz and plagioclases.

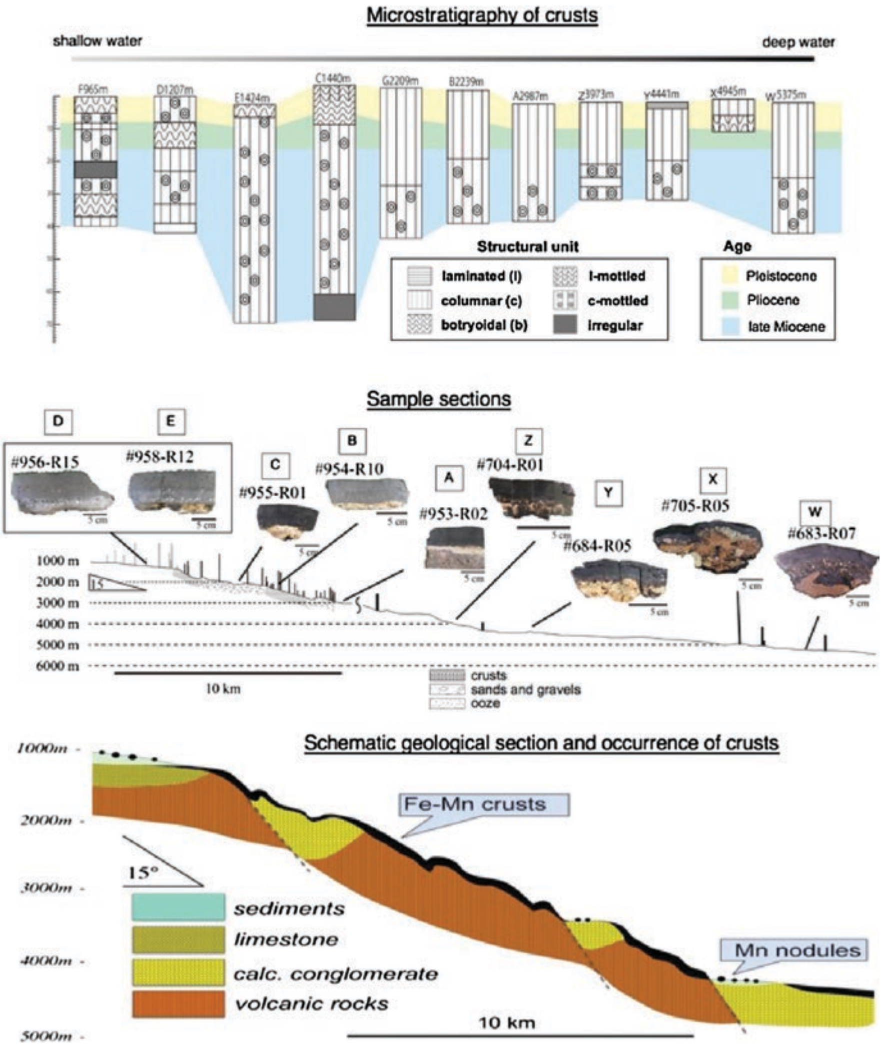

Fig. 4.14 Microstratigraphic correlations along the southern ridge of the Takuyo–Daigo seamount [A. Nagaoka, pers. com., 2020]

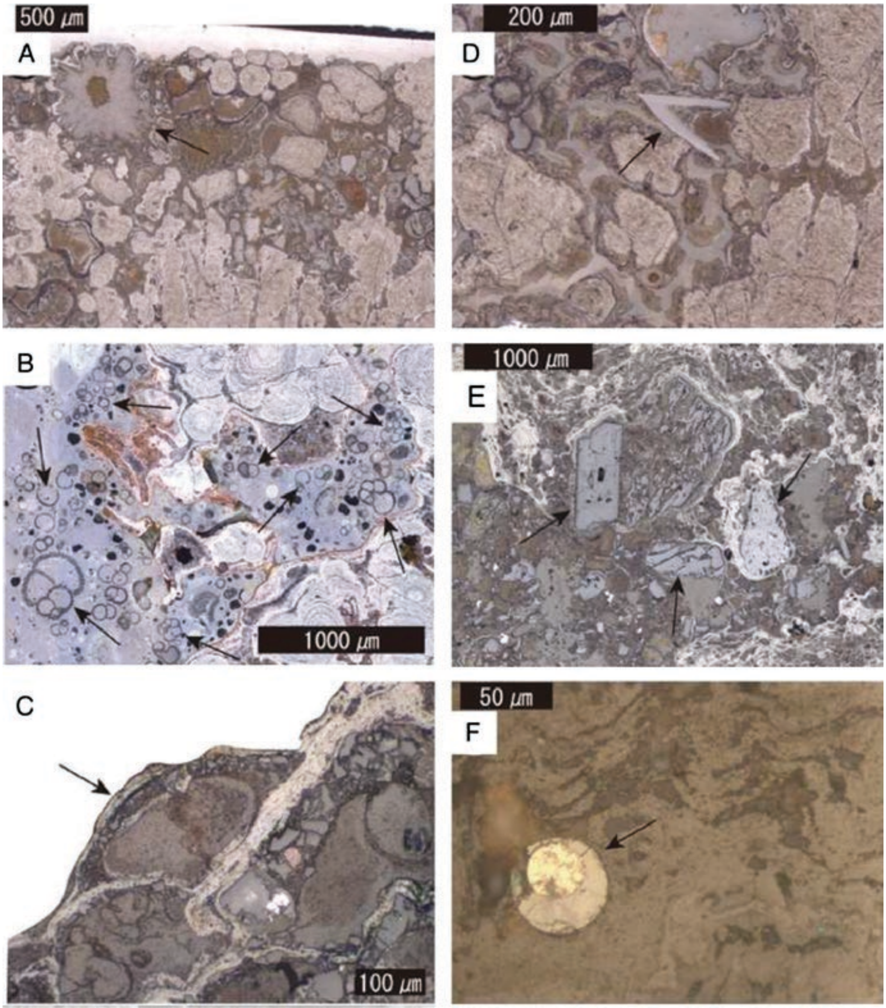

Fig. 4.15 Hard mineral particles included within growth structure of the crusts in the Takuyo–Daisan seamount. Arrows show zeolites (**A**), foraminifera (**B**), benthic foraminifera (**C**), fish tooth (**D**), plagioclase (**E**), cosmic spherule (**F**) [A. Nagaoka, pers. com., 2020]

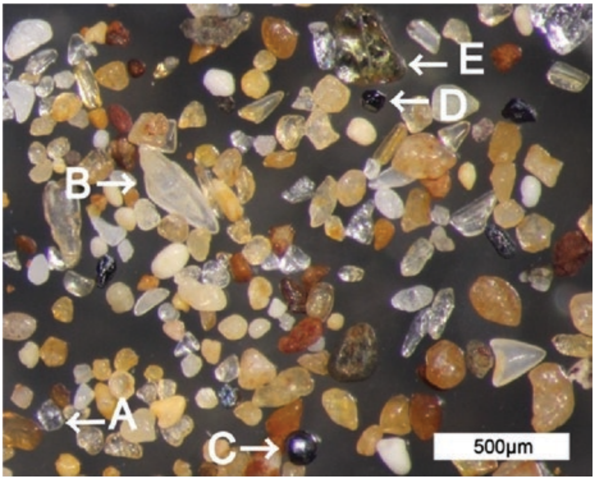

Fig. 4.16 Mineral particles extracted from the crusts in the Takuyo–Daigo seamount. Arrows indicate a phosphate grain (**A**), fish tooth (**B**), cosmic spherule (**C**), magnetite (**D**), and pyroxene (**E**) [E. Shimizu, pers. com., 2018]

4 Recent Progress in Genetic Models for Growth Processes and Environments

The origin of ferromanganese crusts is described simply as hydrogenetic. However, the extreme origin of elements, pathways, chemical forms in seawater, oxidation processes of Fe and Mn, mechanism of absorption of metals, and process of growth structure are poorly understood. Here, we summarize our recent ideas and facts on the growth and formation of crusts based on our onsite observations, onsite experiments, and in-laboratory analyses. The relationship between regional, small, and fine-scale variabilities to environments is as follows:

1. The Cretaceous hotspot submarine volcanoes (partly subaerial) provide optimal geological platforms for the long-term accumulation of crusts. The volcanic islands subsequently subside and then submerged to form a flat-top seamount after erosion and reef-building, then traversed the equator toward the northwest, where less pelagic sedimentation took place at the summit and sustained broad rock outcrops. Hard rock substrates are necessary for building thick ferromanganese crusts, such as volcanic rocks or phosphatized reef limestones (Yamazaki and Sharma 1998; Hein and Morgan 1999).
2. Major elements, Mn, Fe, and Si, of the crusts were directly supplied from normal seawater, primarily transported via the continental shelves and by currents, rivers, and winds, and dispersed into the ocean floors (Halbach et al. 1989; Hein et al. 2013). The Nd isotopes of the surface of the ferromanganese crusts from the Takuyo–Daigo seamount agree with the adjacent seawater, which implies that the Nd (and probably other REEs) is derived from seawater (Amakawa et al. 2017). OMZ is believed to be a significant reservoir of dissolved Mn to form abundant oxide particles after mixing with dissolved oxygen in deeper water (Hein et al. 1992, 2000). Our recent results (Fig. 4.17) over 1–15 years of onsite

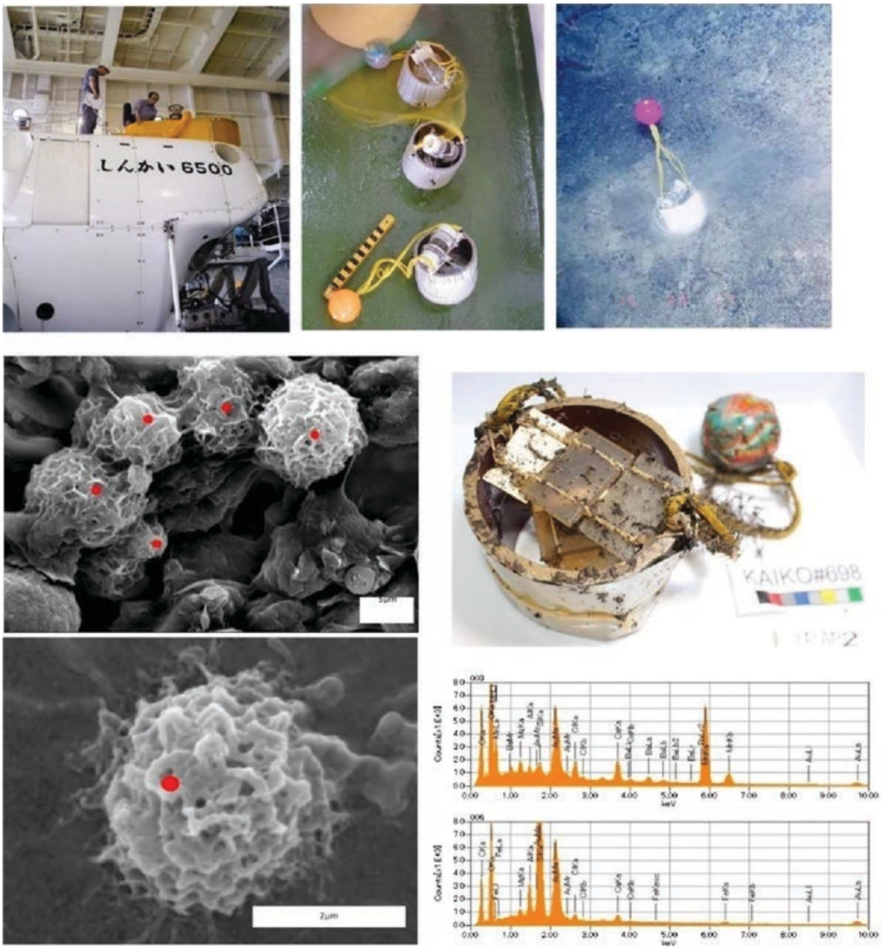

Fig. 4.17 Onsite precipitation experiments for 15 years, showing coccoid-like aggregates of ferromanganese oxide [Usui et al. 2020]

experiments (Usui et al. 2020) at 1–5 km water depths suggest that OMZ is not a reservoir of dissolved Mn but instead an area of oxidation. The results suggest that the ferromanganese oxide minerals are probably stable at all depths in normal seawater as tiny (1–2 μm) coccoid-like oxide particles, which are deposited on any hard objects at 6 km water depths and form a patina and crusts at a rate of μm per 1000 years (Usui et al. 2020), finally forming a complicated submicron-scale microstructure. The particles look like microbe but do not show evidence of any metabolic activity yet (Kato et al. 2018; Nitahara et al. 2017), in which iron and manganese exist as particulate oxides (vernadite minerals) even in the OMZ. Finally, the crusts grew for millions of years at variable flux rates (Figs. 4.18 and 4.19); thus, microstratigraphy is often correlated among the

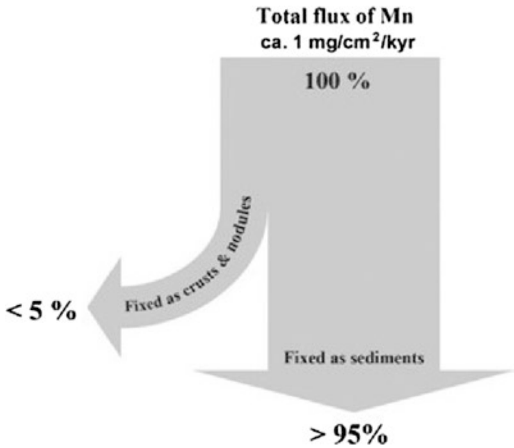

Fig. 4.18 Flux of manganese towards the sea floor and crusts [Sato and Usui 2018]

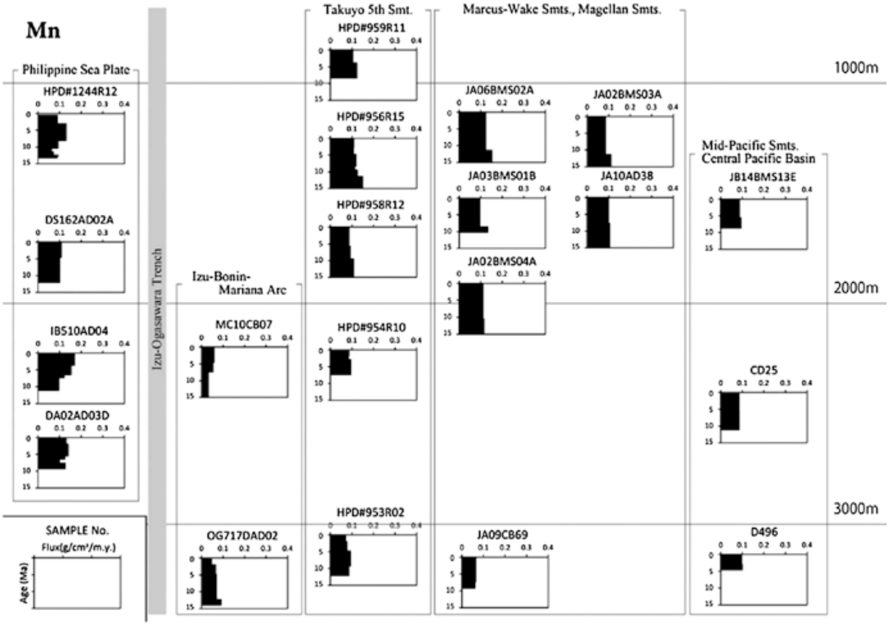

Fig. 4.19 Variation of manganese flux in time and in water depth into the crusts [Sato and Usui 2018]

remote crust cores (Sato and Usui 2018; Usui and Suzuki 2018; Nishi et al. 2017; Usui et al. 2017, 2020). This model suggests a reconsideration of the chemical forms of Mn and Fe in normal seawater.

3. The concentration and chemical form of some minor elements (Co, Ce, Eu) in seawater columns are often sensitive to redox environments and the absorption structure of iron and manganese oxides (Amakawa et al. 2017; Kashiwabara

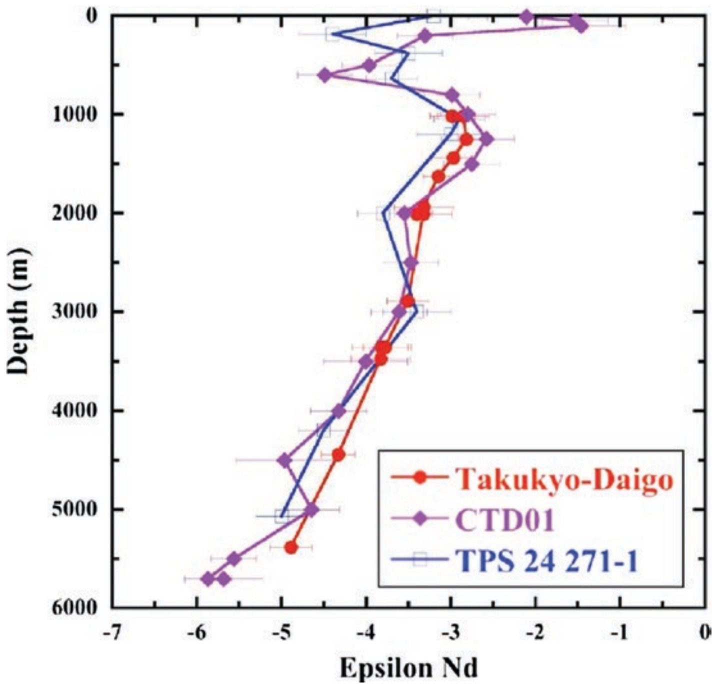

Fig. 4.20 Nd isotope ratio for the crust surface and nearly ambient sea water [Amakawa et al. 2017]

et al. 2013; Takahashi et al. 2007), and the hydrogenetic crust is consequently correlated with the water depth (Fig. 4.20) of deposition. The variability of the chemical composition of crusts is closely related to the water depth; for example, the water-depth trends of Co and Ce are clear, which is probably related to their chemical form and state in seawater (Usui et al. 2017). A common stratigraphic variation in composition and structure is presumed between the crust cores at the seafloor of a water depth. The genetic model was supported by earlier onsite observations and experiments during several research cruises, high-resolution analytical techniques, and newly developed paleomagnetic (Fig. 4.21) and dating methods (Oda et al. 2011; Noguchi et al. 2017). The molecular adsorption structure of manganese and iron oxides with the elements, based on XAFS methods using high brightness X-ray produced in synchrotron were used to control the variable concentration of minor elements such as W, Mo, and Te (Kashiwabara et al. 2011, 2013, 2014; Takahashi et al. 2015).

4. The slow accumulation of ferromanganese crusts was ascertained by several dating methods, Os and Be isotope stratigraphy, paleomagnetography, and conventional microfossil method. The high Os concentrations and Os isotope ratios ($^{187}Os/^{188}Os$) in the crusts and the present-day seawater indicate that Os in seawater is directly concentrated in the ferromanganese crust. Thus, the obtained Os isotopic compositions of the crust can be fit to the chronological Os isotopic

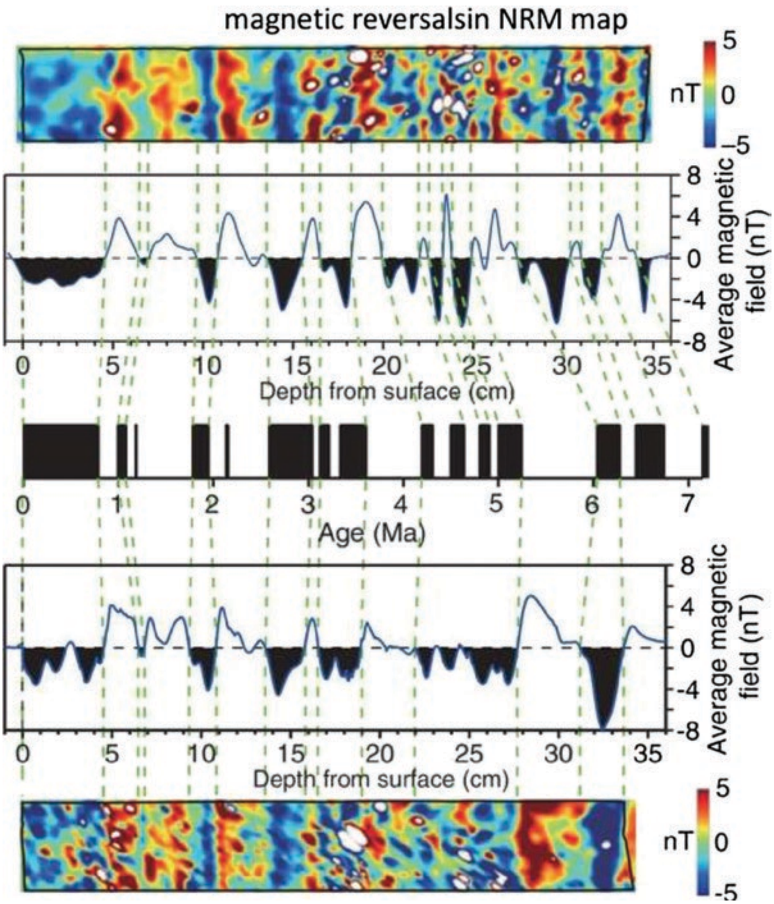

Fig. 4.21 Results of paleomagnetic age dating using SQUID magnetometer [Oda et al. 2011]

variation curve of seawater (Os isotope stratigraphy) and used to estimate the growth rate of the crusts (e.g., Goto et al. 2014).

5. The surface of ferromanganese crusts is characterized by diverse microorganisms (Nitahara et al. 2011, 2017). Although little information is currently available on the function of each microbe inhabiting the crusts, they are possibly related to the depositional and growth process (Kato et al. 2018). We are currently working on the microbial investigation, such as the DNA analyses, to reveal specific function on their growth, accumulation, and concentration.
6. Long-term slow accumulation (Fig. 4.22) of Fe-Mn oxide finally results in the formation of crusts up to 10 cm in thickness, including detrital, biogenic, terrigenous, and volcanogenic materials, unless sustainable growth is arrested by a rapid supply of pelagic sedimentation or slumping deposits on the seafloor (Usui and Ito 1994).

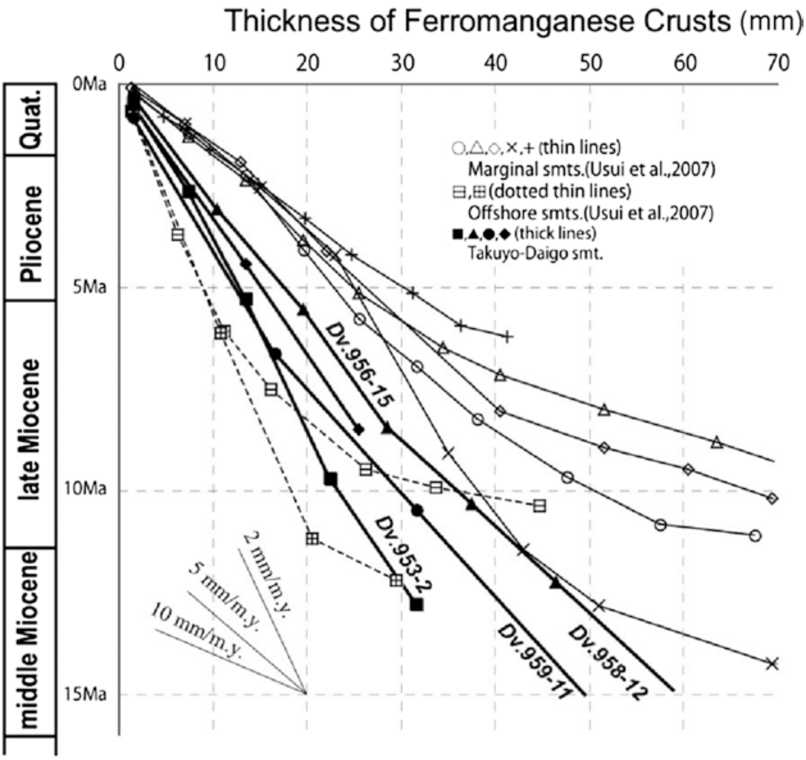

Fig. 4.22 Growth curves of the crusts in the NW Pacific determined by Be isotope [Usui et al. 2007, 2017] corrected by half age for B-10 (Nishiizumi et al. 2007)

5 Inferences of Geological Models to Exploration

As shown during our onsite observations and fine-scale stratigraphic characterization, the crust deposits have been growing ubiquitously at all depths greater than 1 km in the Cretaceous seamounts. A common correlation between microstratigraphy and consistent age models among the crust cores supports the spatiotemporal connectivity of depositional environments. Consequently, the stratigraphic characterization supports the interpolation and extrapolation of the bulk chemical composition of the cores, suggesting a similar age of formation, similar metal flux, and similar mineral diversity; the rock outcrop is commonly covered with a layer of 10 cm or thicker, but sensitive to sedimentation and substrate stability.

The flat summits that are scarcely covered with pelagic sediments are likely to yield the thick (>10 cm) hydrogenetic ferromanganese crusts underlain mostly by firm basement rocks. The stratigraphic geochemical and mineralogical features of the crust revealed similar secular variation patterns common to the crust cores from the northwestern Pacific seamounts (Figs. 4.23a and b) over Cretaceous oceanic crusts of approximately 1000 km or wider (Hino and Usui 2021). The stratigraphic

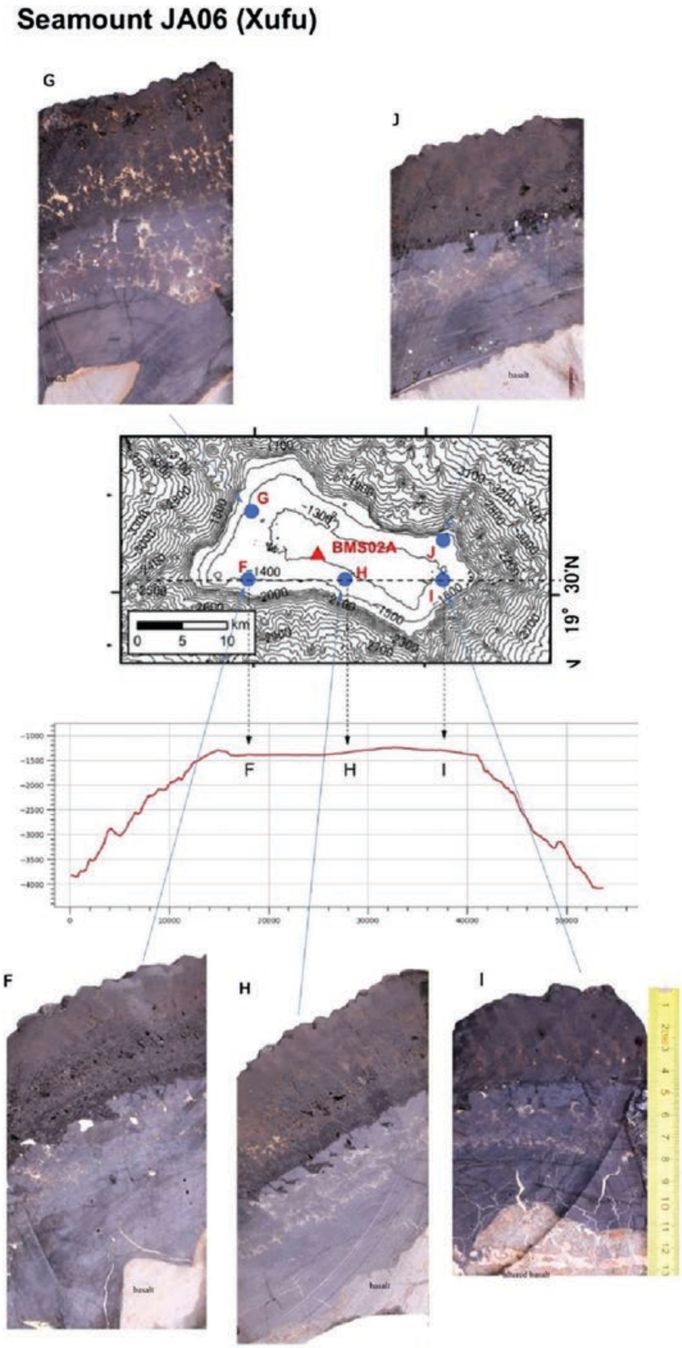

Fig. 4.23 (**a**) Example of well-correlated crust cores taken from the flat top of the Xufusmt. Compare with a similar stratigraphy to that in Fig. 4.13 [Hino and Usui 2021]. (**b**) Example of well-correlated crust cores taken from the flat top of the Lamont smt. Compare with a similar stratigraphy to that in Fig. 4.13 [Hino and Usui 2021]

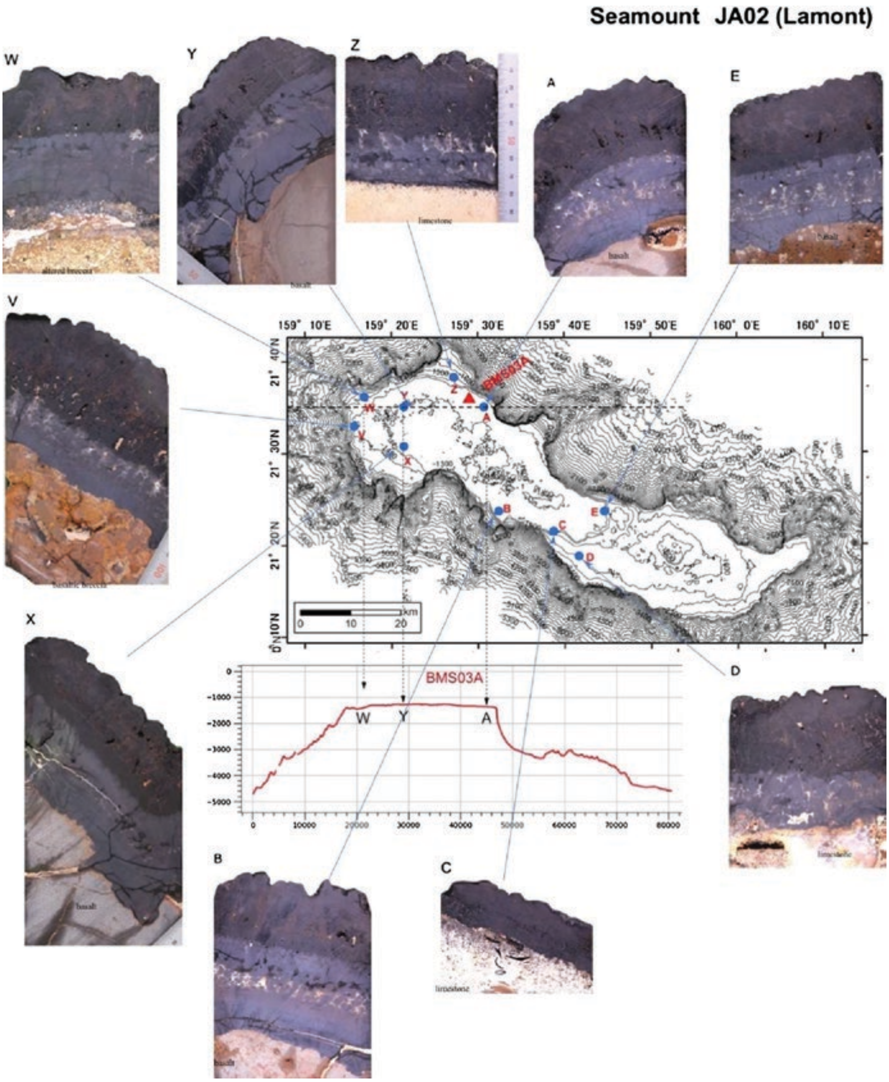

Fig. 4.23 (continued)

description indicated a continuous and fairly constant growth for millions of years, although the growth may have been interrupted in places by rapid pelagic sedimentation and destructive mass wasting. The fine and regional variabilities of ferromanganese crusts in composition and structure were well explained by our hypothetical genetic model established in the model seamount Takuyo–Daigo: (1) slow, constant, and continuous growth since the Neogene or older at all water depths, (2) optimal precipitation of ferromanganese oxide within normal sea waters including OMZ, and 3) concentration of some redox-sensitive metals, Co and Ce, at water depths at

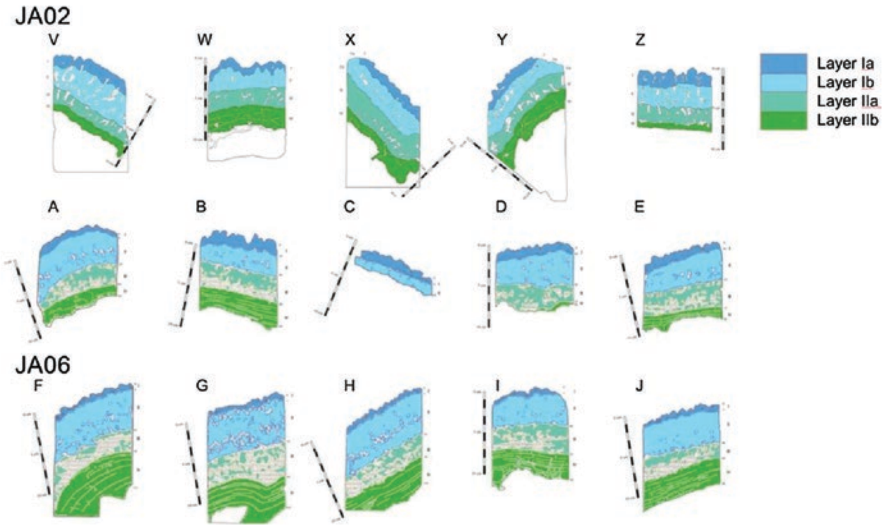

Fig. 4.24 Sketch of the well-correlated crust cores from the two seamounts with occasional lack of growth layers on the top or bottom [Hino and Usui 2021]

the summits. Such a stratigraphic description proved crucial to the characterization of the regional and fine-scale variability of crusts in the northwestern Pacific.

We applied this genetic model to consider the factors controlling the variability in abundance on the Marcus-Wake seamount area, including Japan's allocated area. The crust shows a similar stratigraphy (Fig. 4.24) but is associated with periods of missing growth locally, that is, the reset of the substrate and younger sedimentation, assuming a similar history of the evolution of the seamounts, such as eruptions, erosion, reef-building, subsidence, and submergence. Missing growth yields thinner crusts than continuous growth. A slight difference in Be-10 growth rates (Graham et al. 2004; Usui et al. 2007; Nishiizumi et al. 2007) between 2 and 4 mm/My (Fig. 4.22) was interpreted as a dilution of detrital flux. Some cores indicate missing younger layers. Other minor changes in the growth rate may be related to changes in the metal flux (mass accumulation) with time.

Thus, the principal parameters controlling the composition and thickness are the age of the crust and the secular change in metal flux. The similarities in microstratigraphy, such as clear dual structure, ensure a uniform composition in space; however, the shorter growth age, by contrast, yields less abundant deposits when the top is buried with sediment by the collapse of substrates due to mass wasting. This correlation is useful for characterizing the compositional variability of the deposits. A comparison of the geological and geochemical characteristics of the crusts and the evolutionary history of seamounts is essential for reliable extrapolation and interpolation of their abundance and grade. Thus, geological and geochemical characterization is strongly recommended for selecting mining blocks for the deposits, as suggested by Hein et al. (2009).

6 Conclusions

A review of the geological characterization of the ferromanganese crusts ascertained ubiquitous distribution and diversity on various scales in the northwestern Pacific based on a recent shipboard survey and in-laboratory analyses, primarily by Japanese institutions.

1. Our onsite exposure experiment, small-scale geological observation, and microstratigraphic description indicated that the crust is a chemical precipitate that has been formed continuously at all deep waters below 1000 m as aggregate in cold normal seawater and finally yields a 10-cm thickness over firm rock substrates.
2. The optimal conditions for high-grade and abundant deposits are: oxidizing seawater conditions, old and stable rock substrates, and no or scarce sedimentation or productivity. Microscopic-scale chemical and mineralogical analyses suggested that the diversity in grade and abundance is controlled by the water depth of precipitation, age of the crusts, the geological history of seamounts, and sedimentology at the seafloor. The following physicochemical and geological processes were verified from our observations and analyses: (a) ultra-slow and continuous growth at all water depths, (b) initial precipitation of poorly crystalline vernadite (Fe/Mn = 1), and (c) the maximum high Co concentration around the OMZ.
3. A well-correlated microstratigraphy in the ferromanganese crusts, showing similar structural, mineralogical, and chemical zoning and fine-scale lamination, is a good indicator for the continuous abundance and grade in exploration and economic evaluation. Such geological characterization and considerations are essential for the search for new deposits in the future.

Finally, we learned from our geoscientific characterization of the ferromanganese deposits in the northwestern Pacific seamounts that this type of scientific information is critical for prudent and sustainable development of our ocean resources from environmental, technological, and economic points of view, in future. The International Marine Minerals Society (https://www.underwaterminerals.org/) and International Seabed Authority (www.isa.org.jm) also state that advancements in marine scientific research in the deep seabed are required and will be the key to the sustainable development of the ocean (Lodge and Ryabinin 2019; IMMS 2021).

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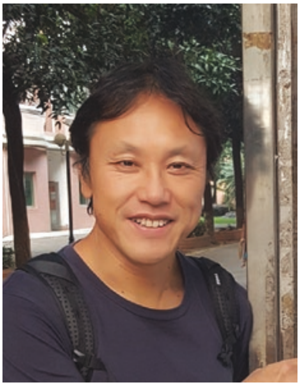

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Chapter 5
Secondary Ion Mass Spectrometry Microanalysis of Platinum in Hydrogenetic Ferromanganese Crusts

Yuichi Morishita, Akira Usui, Naoto Takahata, and Yuji Sano

Abstract The fine-scale concentration of platinum in a hydrogenetic ferromanganese crust (Takuyo-Daigo Seamount 2987 m water depth) was determined using secondary ion mass spectrometry (SIMS). The crust was analyzed chronologically, and the spatial resolution of the SIMS depth profiling was 0.013 µm, corresponding to 5 years of the crust growth. SIMS depth profiling is the only feature that is not found in other analytical methods. Platinum (Pt) concentration in vernadite of the crust ranges from 0.14 to 0.31 ppm, and it finely fluctuated along the growth direction. Little Pt was found in a brown matrix that exists among columnar vernadite. Our results showed that SIMS is a powerful and promising tool for Pt microanalysis to understand crust characterization and the environment for selective accumulation of seawater-dissolved Pt into crusts.

Keywords Ferromanganese crust · Platinum · SIMS · Microanalysis · Depth profile · Takuyo-Daigo Seamount

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1 Introduction

The ferromanganese deposit is one of the major chemical precipitates which often covers the seafloor of the world's deep oceans as crusts on rock outcrops or nodules on unconsolidated sediments. Some of the hydrogenetic ferromanganese crusts and nodules contain as high as 1% cobalt and 1 ppm platinum (Manheim 1986; Halbach et al. 1984). In particular, the Co- and Pt-rich ferromanganese crusts have been noted as future seabed mineral resources. The deposit is also expected as a significant long-range geological and palaeoceanographic archive for tens of millions of years (Hein et al. 2000). However, their geological occurrences and geochemical properties vary greatly on micron- to global scales, resulting in a wide range of grade and abundance (Usuai and Suzuki 2022, this book). Recent progress in exploration technology and high-resolution analyses has characterized their nature and origin in the world oceans (Hein et al. 2013, 2016; Wiltshire et al. 1999; Muiños et al. 2013), but the chemical, mineralogical nature of platinum and its selective enrichment are yet poorly understood.

The resources of platinum group metals (PGM) including Pt are unevenly distributed on earth, and more than 90% of the world PGM reserve exists in South Africa (USGS 2021). Pt in ferromanganese crusts is much more widely distributed, and therefore it attracts considerable attention. The Pt concentration has been reported in the range of 0.1 to 1 ppm. Platinum is one of the rarest elements in the earth's crust, but its relative abundance in the ferromanganese crusts is very high (Marino et al. 2017). The first analysis started with the atomic absorption method for acid-digested solution (Manheim 1986; Terashima et al. 1988). Recently, inductively coupled plasma mass spectrometry (ICP-MS) is the most common method for PGE estimation (Balaram 1999) because of its high accuracy and high sensitivity. LA(laser ablation)-ICP-MS (Garbe-Schönberg and McMurtry 1994; Vonderhaar et al. 2000) is another advanced method for characterizing the temporal/secular change in Pt concentration.

The objectives of chemical analysis of crusts are to understand the mechanism of selective concentration of Pt, physicochemical condition of formation of high-Pt ferromanganese oxide, and environmental factors of temporal variation. The valence state of Pt is poorly determined in sea water (Jacinto and van den Berg 1989) or in the ferromanganese oxide deposits (Vonderhaar et al. 2000), but the change of state from 0 to +II on Fe or Mn oxide compound has been proposed (Banakar et al. 2007; Koschinsky et al. 2020; Berezhnaya et al. 2018). Effect of organic carbon (Kubrakova et al. 2010) or influence of cosmic dust (Sano et al. 1985; Savelyev et al. 2020) or mantle source (Baker and Jensen 2004) is suggested.

Although the secular variability within microscopical stratigraphic zones is the most important objective in understanding the process and environments of Pt deposition, very little has been reported (Asavin et al. 2010; Vonderhaar et al. 2000). A unique feature of secondary ion mass spectrometry (SIMS) is a very high spatial resolution in-depth profiling analysis. SIMS has originally been developed in the semiconductor community to analyze nanoscale concentration gradients of trace elements in semiconductor materials. As the analytical ability of SIMS has become recognized in earth and planetary sciences, plenty of applications have been made even in mineral resources fields (e.g., Morishita et al. 2018). Au nanoparticles were found in sulfide minerals in SIMS depth profiles (Morishita et al. 2019), and we thought that SIMS depth profiling ability was suitable for analyzing ferromanganese crusts. Morishita and Usui (2015) first demonstrated preliminary results of SIMS crust analysis, though several analytical problems remained. Here we present comprehensive analytical methods for Pt microanalysis of ferromanganese crust using SIMS.

2 Materials and Methods

2.1 Materials

The ferromanganese crust used in this study is HPD#953-R02 that was collected from the Takuyo-Daigo Seamount, a member of the Marcus-Wake seamounts group, located about 150 km southwest of the Minamitorishima Island in the northwestern Pacific Ocean. The water depth of the sampling location (22°41’N, 153°15′E) was 2987 m. The ferromanganese crust consists of vernadite, rock fragments, fossils, and clay minerals. The thickness of the crust is about 35 mm (Fig. 5.1), and the ^{10}Be-dated growth rate is about 2.5 mm/m.y. (Usui et al. 2017).

The crust was sliced into four pieces (A1/B1, A2/B2, A3/B3, and A4/B4) parallel to the crust surface that is perpendicular to the growth direction (Fig. 5.1; Table 5.1). When SIMS analyses were performed on the surface, Pt concentration was obtained in a chronological direction. The upper surface of the A1/B1 slice is 4.5 mm from the crust surface (Fig. 5.1; Table 5.1), and it corresponds to 1.5 Ma of age (Usui et al. 2017). Each Ax/Bx (x = 1–4) slice has the same age (The estimated age of each sample surface is shown in Table 5.1). Then A1/B1 slice, for example, was cut into A1 and B1 perpendicular to the slice surface. Now we have eight samples, and they were mounted onto two (A and B) of 12.6 mm diameter glass discs (disc A contains A1 to A4 and disc B contains B1 to B4), and the surface of discs A and B was diamond polished. The polished glass disc of A was used as the SIMS standard (mentioned later in the standardization section). The polished glass disc of B (Fig. 5.2) was analyzed for its platinum concentration using SIMS. Both discs were carbon coated for charge compensation during the SIMS analysis. A sample just above A1/B1 slice (the youngest part among samples used in this study) was taken for bulk analysis. The bulk Pt and Pd concentrations analyzed by the fire assay–ICP-MS method at Actlabs were 0.095 and 0.002 ppm, respectively.

Fig. 5.1 Cross-section of the studied ferromanganese crust (35 mm thick) on phosphatized limestone and altered basalt. A monotonous structure of earthy black compact layers is observed

Table 5.1 Depth and age of crust samples

Slice name	Depth from the crust surface	Age of the sample surface
A1/B1	4.5 mm	1.5 Ma
A2/B2	7.5 mm	2.5 Ma
A3/B3	13.5 mm	5.1 Ma
A4/B4	19.5 mm	8.0 Ma

Sample locality is shown in Fig. 5.1. The age of the crust surface was interpolated from the Be-isotope dating (Usui et al. 2017)

2.2 Analytical Methods

We determined Pt concentrations of ferromanganese crust using a NanoSIMS 50 at the Atmosphere and Ocean Research Institute (AORI) of the University of Tokyo. Cs^+ primary ion beam was scanned over the sample surface. Negative secondary ions were extracted by an accelerating voltage of 8 kV and introduced into the mass spectrometer. An electron flood gun was used for charge compensation. The entrance slit was set to a width of approximately 40 μm, and the exit slits for each electron

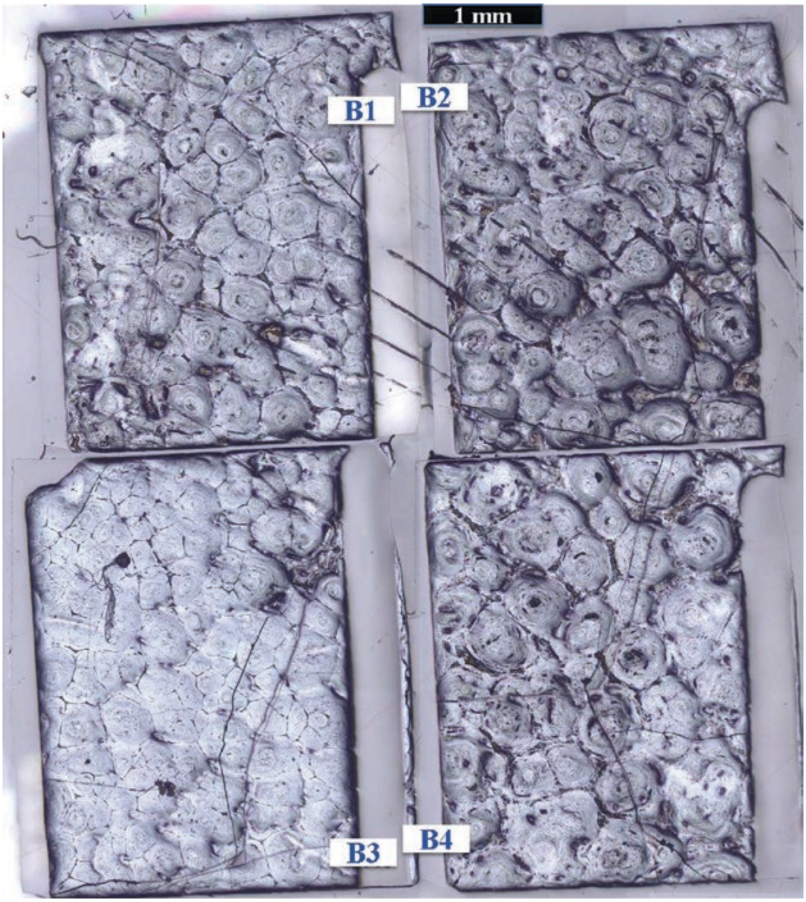

Fig. 5.2 Four crust samples on glass disc B. The formation ages are described in Table 5.1

multiplier (EM) were set to a width of 75 μm. A mass-resolving power of 8000 was attained with adequate flat-topped peaks. The matrix $^{30}Si^-$, $^{55}Mn^-$,$^{54}Fe^{16}O^-$, and the targeted $^{195}Pt^-$ ions were measured simultaneously using multicollectors with EMs. Measuring ^{56}Fe (not ^{54}Fe) without overlapping isobaric interferences is possible, but it is impossible to arrange the detector for ^{56}Fe in the multicollectors because ^{55}Mn and ^{56}Fe detectors would be very close to fit the detectors into the rail of the multicollection system. Thus $^{54}Fe^{16}O^-$ was measured for Fe abundance. $^{30}Si^-$was measured to monitor the system stability. Figure 5.3 shows ^{195}Pt peak shape with a flat top (blue line) for Pt metal foil measurement at the mass of 195. As the interfering molecule ions (orange line) might affect the center position (green line) of the ^{195}Pt peak, measurement was performed on the right side of the flat top with +2.0 V addition (red line). The reason for measuring $^{195}Pt^-$ ions of six Pt isotopes is to eliminate isobaric interferences on $^{195}Pt^-$without using energy filtering. It is fairly difficult to eliminate interference molecular ions from the other five Pt isotopes. The EM noise

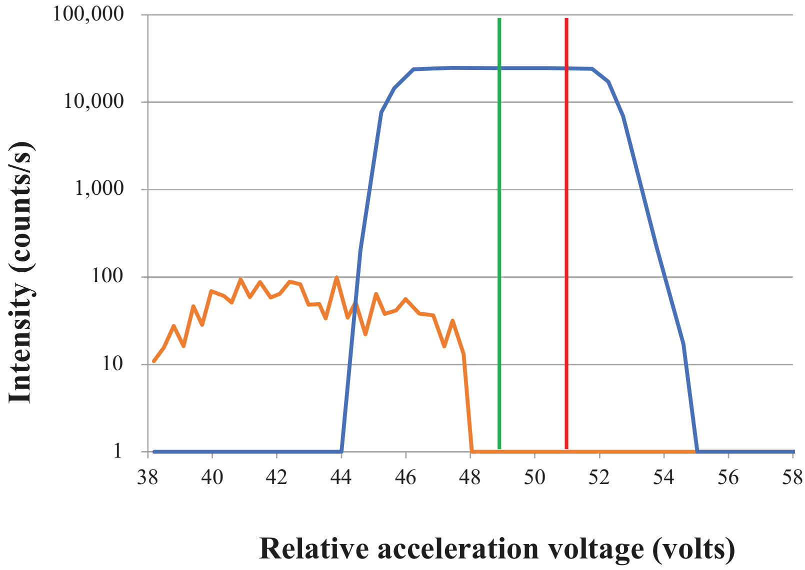

Fig. 5.3 ^{195}Pt peak with interfering peak. The horizontal axis shows relative acceleration voltage, and the vertical axis represents the intensity on a logarithmic scale in counts per second. Isobaric interference peak (orange) from ferromanganese matrix is superimposed on ^{195}Pt peak (blue) from Pt metal foil. Pt measurement was performed on 2 V higher (red) than the peak center (green) to eliminate the interference

of 0.0022 cps was measured. We have performed SIMS Pt analysis with two experimental specifications as follows.

2.2.1 Experimental Specification 1

After presputtering with a 0.5 nA Cs^+ raster beam over a 30 μm × 30 μm area for 6 min to remove the carbon coat from the sample surface and stabilize the secondary ion intensity by Cs^+ irradiation, a focused 0.1 nA Cs^+ primary ion beam was scanned over the inner 20 μm × 20 μm area for analysis. To reduce contamination from the area surrounding the analyzed part, beam blanking was adopted. Only the inner 10 μm × 10 μm area of the scanned area was measured (32 × 32 pixels out of 64 × 64 pixels), resulted in 25% of the total secondary ions were counted. A cycle of measurement was 20 s, so the EM noise was 0.011 count per cycle on average.

The depth of the sputtered borehole that was excavated by a 200 cycles B4–13 SIMS analysis was measured using a surface profiler, and it was 2.53 μm. Thus the depth of one cycle measurement was 12.7 nm, which corresponds to 5 years of crust growth because the growth rate was about 2.5 mm/m.y. (Usui et al. 2017). The growth rate was almost constant during the entire crust growth (Usui et al. 2017).

2.2.2 Experimental Specification 2

When we analyze a low concentration element like Pt, a low detection limit is necessary. To achieve it, much more secondary ions should be measured. However, an increase in the primary ion current may cause charge-up on the sample surface, though the surface was carbon coated and an electron flood gun is used. Then experimental specification 2 increases both the primary ion current and ion bombardment area. Even when the primary ion current increases, the ion density does not increase if the ion bombardment area is enlarged. In addition to that, the spatial resolution of the analysis decreases with the increasing primary current. Note that the reliable data with a low detection limit and the spatial resolution are in a trade-off relationship.

After presputtering with a 2 nA Cs^+ raster beam over a 60 μm × 60 μm area for 3 min to remove the carbon coat from the sample surface and stabilize the secondary ion intensity by Cs^+ irradiation, a focused 1 nA Cs^+ primary ion beam was scanned over the inner 40 μm × 40 μm area for analysis. To reduce contamination from the area surrounding the analyzed part, beam blanking was adopted. Only the inner approximately 28 μm × 28 μm area of the scanned area was measured (44 × 44 pixels out of 64 × 64 pixels), resulted in 47% of the total secondary ions were counted. A cycle of measurement was 20 s, so the EM noise per cycle was calculated to be 0.021 counts. The primary beam intensity of 1 nA was chosen so that the maximum secondary beam intensity ($^{54}Fe^{16}O^-$) was reasonably lower than the EM measurement limit (~10^6 cps).

The depth of the sputtered borehole that was excavated by a 200 cycles analysis was 3.98 μm. So, the depth of one cycle was 19.9 nm, which corresponds to 8 years of crust growth because the growth rate was about 2.5 mm/m.y. (Usui et al. 2017).

2.3 Standardization

Quantitative SIMS analysis requires an appropriate standard sample. Although doped standard glasses with known concentrations are normally used for geochemical research, it is difficult to obtain homogeneous distributions of trace elements in standard samples since precious metals like Pt commonly disperse heterogeneously. Therefore, ion implantation (an ion beam of the desired element is accelerated to implant itself into the sample surface of the standard) was performed. Although the standard sample should have a similar chemical composition and crystallographic structure to the target minerals, the main constituent mineral of ferromanganese crust is vernadite with low crystallinity. It is very difficult to prepare a single crystal of vernadite. Therefore we tried to find the next best candidate to serve as a SIMS standard sample, and the idea of using ferromanganese crust itself as a standard sample was obtained.

Since Ax/Bx (x = 1–4) slice was divided into Ax and Bx (x = 1–4), Ax and Bx were adjacent. Disc A was used as standard, and disc B was analyzed by SIMS. Disc

A was implanted with Pt ions at 1.2 MeV and a density of 2 E14 atoms/cm^2 by the Tandetron Accelerator Laboratory, Department of Physics & Astronomy, Western University, Canada to produce a Pt standard disc. A Si wafer was also implanted with Pt ions at the same time as disc A to find out the implanted Pt isotope composition. The natural isotope abundance of ^{195}Pt is 0.338 (Table 5.2), but isotope discrimination occurs in the tandetron accelerator. As described in the analytical methods section, many interference molecular ions overlap on Pt isotope ions, but Pt implanted Si wafer does not produce such high mass interference molecular ions on Pt ions. Table 5.2 shows SIMS measurement of the Pt implanted Si wafer for Pt isotope abundance and shows that the abundance of ^{195}Pt in the implanted Pt is 0.389, which is higher than that of natural Pt.

2.4 Relative Sensitivity Factor (RSF) Calculations

Quantitative analysis by SIMS requires a relative sensitivity factor (RSF) defined in Appendix 1. The RSF for a specific matrix element was used to calculate the concentration in the unknown sample. Mn and Fe were selected to be matrix elements because the major constituent elements of the crust are Mn and Fe. Chemical analysis of the crust sample was analyzed by XRF method at Actlabs, and Mn and Fe concentrations were 17.10% and 16.04%, respectively. They were close to those for HPD#953-R01 crust Mn and Fe (next to the crust in this study), which were 18.7% and 17.6%, respectively (Usui et al. 2017).

The ^{195}Pt concentration in vernadite from the Pt implanted A4 crust of standard disc A was analyzed by SIMS (analysis no. 1024-6). It varied with depth and had a Gaussian distribution as a whole (Fig. 5.4). The measured ^{195}Pt is not equal to the implanted ^{195}Pt because originally existed natural ^{195}Pt abundance was included in the data. We analyzed ^{195}Pt abundance in vernadite from B4 that is originally the same crust sample as A4. The ^{195}Pt concentration of B4 was then deducted from the A4 data, and the modified data correspond to the amount of the implanted ^{195}Pt. The deduction was reflected in the following RSF calculations, but its influence is less than 0.1% because the amount of implanted Pt was overwhelmingly large compared

Table 5.2 Comparison of both natural and implanted isotope abundances of Pt

Mass number	Natural (%)	Implanted (%)
190	0.01	0.002
192	0.79	0.548
194	32.9	39.966
195	33.8	38.859
196	25.3	20.582
198	7.2	0.043

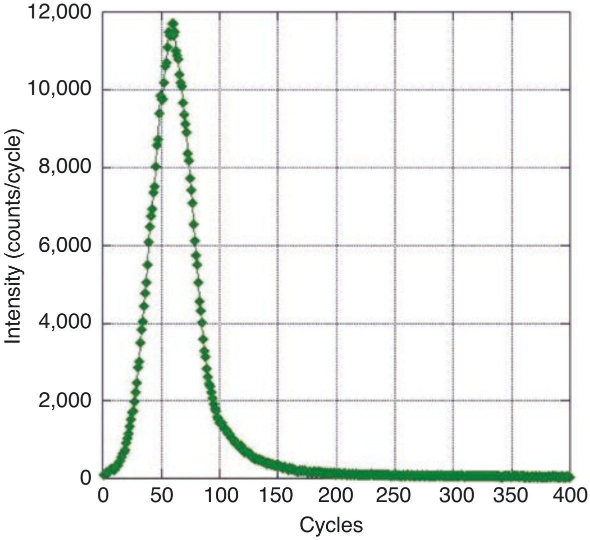

Fig. 5.4 SIMS analysis of Pt implanted vernadite. The horizontal axis indicates the measurement cycle, and the vertical axis represents the ^{195}Pt intensity in counts per cycle

to that of natural Pt. $^{55}Mn^{-}$and $^{54}Fe^{16}O^{-}$were also analyzed at the same time of ^{195}Pt analysis (1024-6). Since Pt ion implantation density F (Appendix 1) was 2 E14 atoms/cm^2 (Standardization section), ^{195}Pt density was calculated to be 7.77 E13 ions/cm^2. Other than above, crater depth d is necessary to calculate RSF (Appendix 1). The depth of the sputtered borehole that was excavated at the SIMS analysis 1024-6 was measured to be 4.54 µm using a surface profiler.

Using the equation in Appendix 1, the ^{195}Pt RSF value for Mn matrix, which is RSF_{195Pt} (Mn), is calculated to be 2.8 E17 (atoms/cm^3), and that for $^{54}Fe^{16}O$ matrix, which is RSF_{195Pt} (Fe), was 2.2 E19 (atoms/cm^3). As we like to know Pt concentration rather than ^{195}Pt concentration in the crust, RSF_{195Pt} values were converted using the natural abundance of Pt (Table 5.2). RSF_{Pt} (Mn) and RSF_{Pt} (Fe) were calculated to be 8.4E+17 and 6.6E+19, respectively. The Pt concentration (atoms/cm^3) can be calculated using the following equation:

$$\mathrm{Pt}\left(\mathrm{atoms/cm^3}\right) = \mathrm{RSF_{Pt}}\left(\mathrm{M}\right) \times {}^{195}\mathrm{Pt_i} / \mathrm{M_i} \quad (5.1)$$

where M is Mn or $^{54}Fe^{16}O$ matrix as a reference,$^{195}Pt_i$ or M_i is the intensity of ^{195}Pt or the reference Mn or $^{54}Fe^{16}O$, respectively. The Pt concentration (ppm) is then calculated using the following equation with the conversion factor of 6.17 E15 that was obtained from Appendix 2:

$$\mathrm{Pt}\left(\mathrm{ppm}\right) = \mathrm{RSF_{Pt}}\left(\mathrm{M}\right) / \left(6.17\,\mathrm{E15}\right) \times {}^{195}\mathrm{Pt_i} / \mathrm{M_i} \quad (5.2)$$

3 Results and Discussion

3.1 Results of Experimental Specification 1

SIMS Pt microanalysis was performed on the B1 to B4 crust surfaces in disc B, and Pt concentration was obtained along a chronological direction. Table 5.3 shows the target description and the analytical results. ^{195}Pt (c/c), Mn (c/c), and FeO (c/c) are the average analytical counts per cycle for ^{195}Pt, ^{55}Mn, and ^{54}Fe^{16}O ions. The EM noise of 0.0011 (mean) was already subtracted from the ^{195}Pt (c/c). Pt concentration for reference Mn or Fe is abbreviated as Pt (Mn) or Pt (Fe), respectively. Pt concentration of Pt (Mn) or Pt (Fe) is calculated using ^{195}Pt (c/c) and Mn (c/c) or FeO (c/c)

Table 5.3 SIMS Pt analysis in ferromanganese crust (Disc B)

Crust	Age (Ma)	Target	File no.	Cycles	^{195}Pt (c/c)	Mn (c/c)	FeO (c/c)	Pt (Mn) (ppm)	Pt (Fe) (ppm)
B1–11	1.5	Vernadite center	1024_7	200	0.78	3.62E+02	4.81E+04	0.29	0.17
B1–12	1.5	Vernadite rim	1025_1	200	0.89	4.43E+02	5.26E+04	0.27	0.18
B2–2	2.5	Vernadite center	1024_2	200	0.71	3.93E+02	2.46E+04	0.24	0.30
B2–13	2.5	Vernadite center	1023_10	200	1.25	5.16E+02	6.48E+04	0.31	0.20
B2–13			1023_10	201–400	0.71	3.34E+02	3.13E+04	0.29	0.24
B2–15	2.5	Vernadite rim	1024_3	200	0.86	7.28E+02	8.77E+04	0.16	0.11
B3–12	5.1	Vernadite center	1025_4	200	1.37	7.99E+02	1.14E+05	0.23	0.13
B3–13	5.1	Black recess	1025_5	40	0.64	7.31E+02	4.01E+04	0.12	0.17
B3–14	5.1	Vernadite center	1025_8	200	1.46	5.66E+02	1.25E+05	0.35	0.12
B3–14			1025_8	2000	1.07	4.33E+02	5.88E+04	0.34	0.19
B4–12	8.0	Vernadite shoulder	1023_8	200	0.85	5.31E+02	4.11E+04	0.20	0.21
B4–13	8.0	Vernadite center	1024_4	200	1.01	4.95E+02	6.20E+04	0.28	0.17
B4–14	8.0	Vernadite center	1025_6	200	0.66	3.80E+02	4.20E+04	0.24	0.17
B4–15	8.0	Vernadite rim	1025_7	200	1.41	6.72E+02	9.74E+04	0.29	0.15
Average					0.98	5.27E+02	6.35E+04	0.26	0.18

c/c: counts per cycle; Pt (Mn): calculated using Mn (c/c) as reference matrix; Pt (Fe): calculated using FeO (c/c) as a reference matrix; vernadite center, rim or shoulder: center, rim, or shoulder of columnar vernadite; black recess: the boundary between columnar vernadite as a matrix, respectively. The Mn concentration in vernadite is higher than Fe, however, Mn sensitivity is lower than Fe (e.g., Storms et al. 1977). Moreover, the sensitivity of oxide FeO is higher than that of Fe, resulting in a lower Mn intensity compared to FeO (Table 5.3). Pt concentration ranges between 0.16 and 0.35 ppm for Mn reference and ranges between 0.11 and 0.31 ppm for Fe reference. The detection limit is usually defined as three times the standard deviation of the background noise in addition to the mean background noise. As Table 5.3 already deducts the mean EM noise from the Pt concentrations, three times the standard deviation of the EM noise is the detection limit here. As it depends on the intensity of reference Mn or Fe, we chose the average intensity of Mn or Fe in Table 5.3. Then the detection limit was 0.08 ppm for Pt (Mn) and it was 0.05 ppm for Pt (Fe) under the condition of 5.3E2 counts per cycle Mn and 6.4E4 counts per cycle FeO. The difference in Pt concentrations between Pt (Mn) and Pt (Fe) might partly be reflected by Mn or Fe fluctuation in the vernadite. Mn is mainly used as the reference matrix in this study, despite FeO also being suitable for such use (Table 5.3). The question "which is a better reference?" might depend on the targeted material, and it is left as a future issue.

One of the purposes of this study was that we might obtain cycle by cycle analysis along a chronological direction, and then we could obtain Pt concentration from 5 years crust growth per cycle. Figure 5.5 shows depth profiles of B4–12 (Table 5.3) analysis. The average Pt (Mn) is 0.20 ppm and that for Pt(Fe) is 0.21 ppm, and they finely fluctuate. Since the depth of one cycle measurement that corresponds to

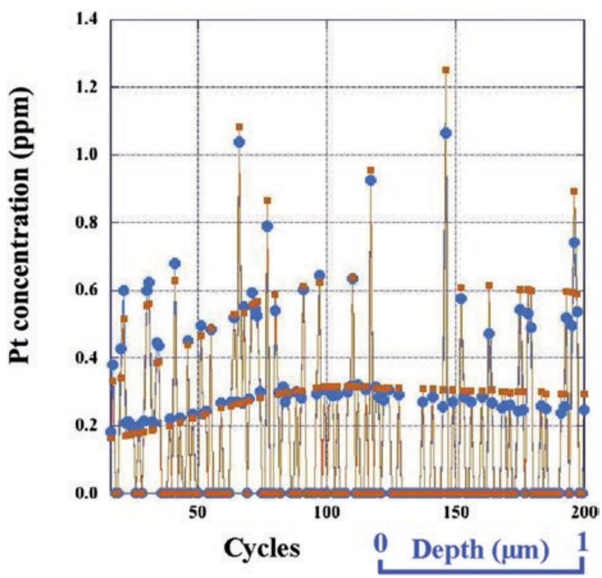

Fig. 5.5 Pt (Mn) and Pt (Fe) depth profiles of B4–12. The horizontal axis indicates the measurement cycle (from cycle 16 to 200), and the vertical axis represents the Pt concentration in ppm. The blue symbol is for Pt (Mn) and the brown symbol is for Pt (Fe)

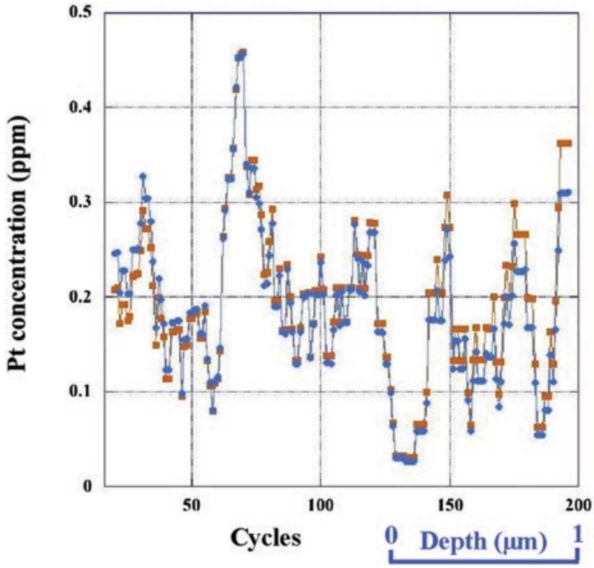

Fig. 5.6 Nine-data moving average for Pt (Mn) and Pt (Fe) depth profiles of B4–12. The analytical data are the same as Fig. 5.5. The horizontal axis indicates the measurement cycle (from cycle 16 to 200, obviously the first 4 and last 4 points do not exist), and the vertical axis represents the Pt concentration in ppm. The blue symbol is for Pt (Mn) and the brown symbol is for Pt (Fe)

5 years of crust growth was extremely thin (12.7 nm), the analyzed data were scattered (Fig. 5.5) because the Pt count accumulation was very low. Another way to display slightly larger fluctuations is by calculating the moving average of Pt concentration with nine adjacent data (Fig. 5.6). This 9-data moving average is averaging from point 1 to point 9 at point 5, and then averaging from point 2 to point 10 at point 6, and so on. Although Fig. 5.5 shows Pt fluctuations, several Pt peaks are visible in Fig. 5.6.

Figure 5.7 shows a Pt (Mn) depth profile of B2–13 (Table 5.3) analysis. The average Pt (Mn) concentration is 0.29 ppm for 201–400 cycles, and it fluctuates. Nine-data moving average has a similar shape to Fig. 5.7, and it is not shown here.

Figure 5.8 shows three-data moving average for Pt (Mn) depth profile of B4–13 (Table 5.3) analysis. The three-data moving average clearly shows several Pt enrichments rather than using the nine-data moving average. The average Pt (Mn) concentration from cycle 201 to 400 is 0.28 ppm. The sputtered borehole is shown in Fig. 5.9.

Since increasing the reference ion intensity makes the detection limit lower, it is important to increase the secondary ion yield. Then we will show such examples in the next experiments.

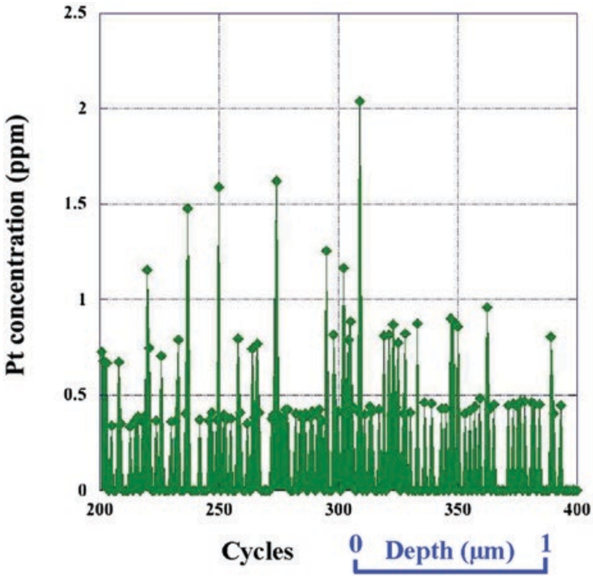

Fig. 5.7 Pt (Mn) depth profile of B2–13. The horizontal axis indicates the measurement cycle (from cycle 201 to 400), and the vertical axis represents the Pt (Mn) concentration in ppm

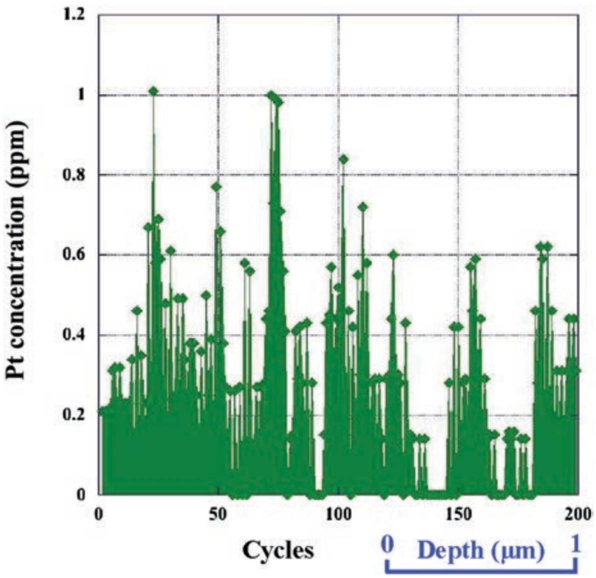

Fig. 5.8 Three-data moving average for Pt (Mn) depth profile of B4–13. The horizontal axis indicates the measurement cycle, and the vertical axis represents the Pt concentration in ppm. Several Pt peaks are found in the figure

3.2 Results of Experimental Specification 2

SIMS Pt microanalysis under the experimental specification 2 was performed on the B1 to B4 crust surfaces in disc B. Experimental specification 2 increases secondary ion intensities 10 times compared with experimental specification 1; because of this,

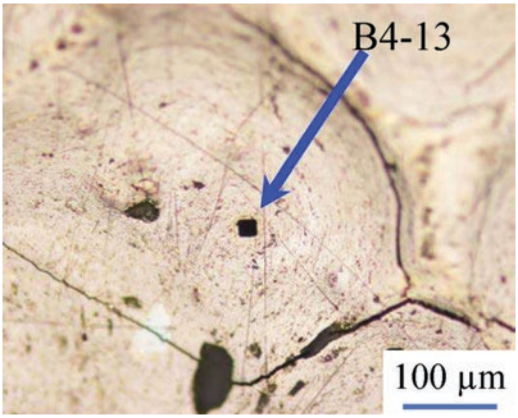

Fig. 5.9 The borehole that was produced during the B4–13 analysis in a vernadite columnar

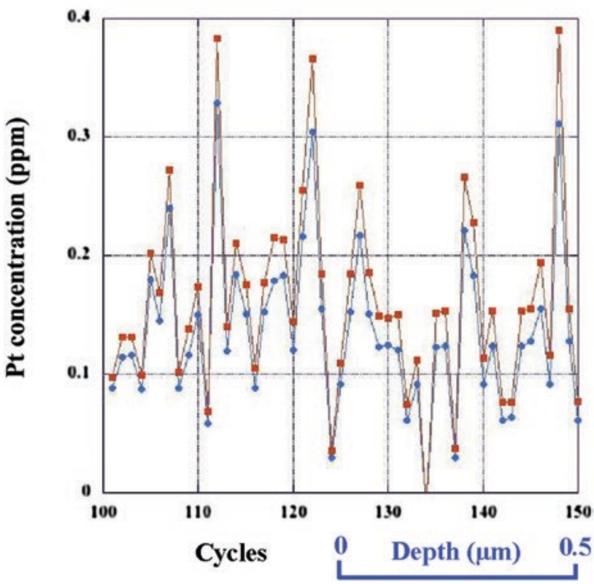

Fig. 5.10 Pt (Mn) and Pt (Fe) depth profiles of 0311_4 in B3. The horizontal axis indicates the measurement cycle (from cycle 101 to 150), and the vertical axis represents the Pt concentrations in ppm. The blue symbol is for Pt (Mn) and the brown symbol is for Pt (Fe)

the detection limit of specification 2 was lowered to 0.01 ppm for Pt (Mn) analysis under the condition of 5.7E3 counts of Mn per cycle. It was also 0.01 ppm for Pt (Fe) analysis under the condition of 3.8E5 counts of FeO per cycle. Pt concentration was obtained along a chronological direction, and several depth profiles are shown below.

Figure 5.10 shows depth profiles of Pt from cycle 101 to cycle 150 in B3. The average concentration is 0.14 ppm for Pt (Mn) and it is 0.16 ppm for Pt (Fe), and there appear several Pt enrichments in Fig. 5.10.

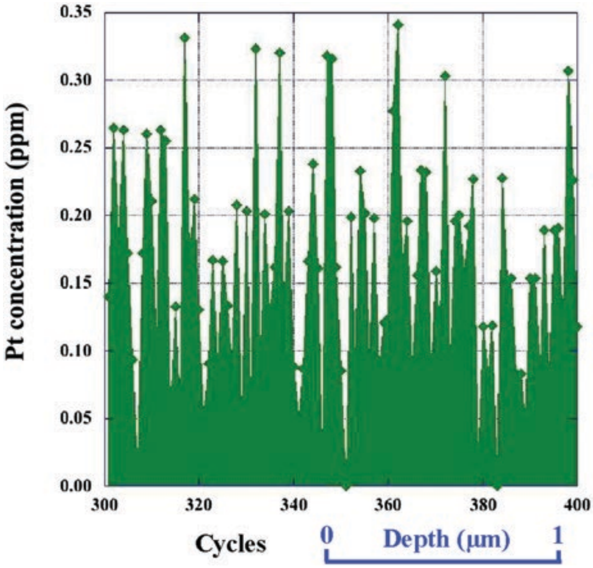

Fig. 5.11 Pt (Mn) depth profile of 0312_1 in B4. The horizontal axis indicates the measurement cycle (from cycle 301 to 400), and the vertical axis represents the Pt (Mn) concentration in ppm

Figure 5.11 shows a depth profile of Pt (Mn) from cycle 301 to cycle 400 of 0312_1 in B4. The average Pt (Mn) concentration is 0.18 ppm, and it highly fluctuates.

Brown matrix, which exists among columnar vernadite, was determined. The average Pt concentration is 0.03 ppm, and it is sporadically very low. Figure 5.12 shows a three-data moving average of Pt (Mn) depth profile from cycle 51 to cycle 100 on the brown matrix in B1. Although analyses of the experimental specification 2 produce sufficient reliable data, the phenomenon here shows large-scale fluctuations at lower concentrations, so a three-data moving average is calculated, and it represents the feature better than the raw data. A low abundance of Pt in the brown matrix was also reported in Morishita and Usui (2015).

SIMS depth profiles of the hydrogenetic ferromanganese crust show submicroscopic fluctuations in Pt concentration, though the average Pt concentration of vernadite is not so variable. The depth profiling analyses show that microscopic variations in Pt concentration are remarkable. The reason is that trace elements like Pt cannot exist homogeneously (nanoscale nugget effect) unless it is a constituent of a crystal lattice. The SIMS analysis methods proposed in this study demonstrated that SIMS is a powerful tool for Pt microanalysis to understand crust characterization. Experimental specification 1 has a very high spatial resolution, but statistical reliability is low in some cases. The experimental specification 2 increases the statistical reliability, and it is promising to apply for several problems that occurred in the crusts studies.

In the future, several processes of trial and error were required to meet the researcher's demand because the reliable data with a low detection limit and the spatial resolution are in a trade-off relationship. The high-resolution and fine-scale variation of Pt concentration help to understand (1) mineralogical and chemical

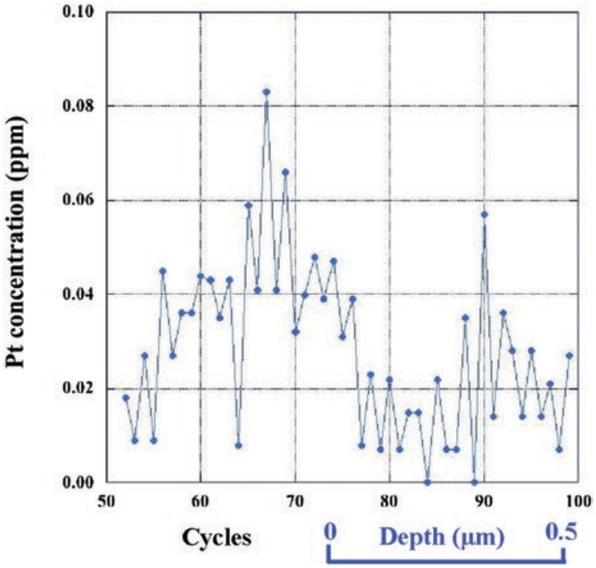

Fig. 5.12 Three-data moving average for Pt (Mn) depth profile of 0312_4 in B1. The horizontal axis indicates the measurement cycle, and the vertical axis represents the Pt concentration in ppm. Large-scale fluctuations at lower concentrations are found in the figure

form of Pt in the crusts, and (2) process and environment for selective accumulation of seawater-dissolved Pt into crusts.

4 Conclusions

We present analytical methods for Pt microanalysis of hydrogenetic ferromanganese crust using SIMS. The crust was analyzed along the crust growth direction, and the spatial resolution of the SIMS depth profiling was 0.013 µm, which corresponds to 5 years of crust growth using experimental specification 1. Another experimental condition (experimental specification 2) was also performed to increase the secondary intensity and accuracy of the Pt analysis. Pt concentration in vernadite from the Takuyo-Daigo Seamount 2987 m water depth ranged from 0.14 to 0.31 ppm, and little Pt was found in the brown matrix that exists among columnar vernadite. The SIMS depth profiling is the only feature not found in other analytical methods. Submicroscopic variations in Pt concentration along crust growth direction were clearly observed in the SIMS depth profiles. As the analyses were performed well under certain conditions in this study, the basis of the SIMS analytical method was described in detail for performing a new analytical experiment for the future. Our results indicate that SIMS is one of the most promising and powerful tools for Pt microanalysis ~~to~~ that can be applied to on-site geological exploration and extraction technology.

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Appendix 1: Calculation of RSF

RSF (relative sensitivity factor) is defined by the following equation (e.g., Wilson et al. 1989);

$$\mathrm{RSF}\left(\mathrm{atoms}/\mathrm{cm}^3\right) = \mathrm{F}/\mathrm{d}\left(\mathrm{C\,IM\,t}\right)/\left(\Sigma IE - \mathrm{Ibkg\,C}\right)$$

where F is the ion implantation density (atoms/cm^2),

C is the number of measurement cycles,
IM is the matrix ion intensity (counts/s),
t is the analysis time in a cycle (s/cycle),
d is the crater depth (cm),
ΣIE is the sum of the targeted ion counts (counts),
Ibkg is the background ion intensity (counts/cycle).

After the SIMS depth profiling analysis of the A4 standard for its Pt concentration, the depth of the sputtered borehole (d) was measured using a surface profiler to determine the RSF.

Appendix 2: Calculation of Conversion Factor

The density of in-situ vernadite is 2.0 g/cm^3 (Hein et al. 2000), so vernadite containing 1 ppm Pt by weight has Pt of 2.0 × 1E-6 g/cm^3 and the number of Pt atoms in 1 g is 3.087 E21 atoms/g. Thus 1 ppm of Pt equals to 2.0 × 1E-6 g/cm^3 × 3.087 E21 atoms/g = 6.17E15 (atoms/cm^3). This value is used as a conversion factor (Larocque and Cabri 1998) for RSF normalization of the SIMS data.

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Part II
Technology Development for Deep-Sea Mining and Mineral Processing

Chapter 6
A Precautionary Approach to Developing Nodule Collector Technology

Kris De Bruyne, Harmen Stoffers, Stéphane Flamen, Hendrik De Beuf, Céline Taymans, Samantha Smith, and Kris Van Nijen

Abstract Global Sea Mineral Resources NV (GSR) holds an exploration contract with the International Seabed Authority (ISA) established under UNLOS to explore for polymetallic nodules on the seafloor of the Clarion Clipperton Zone (CCZ) in the Pacific Ocean.

The basis of GSR's research and development (R&D) strategy was developed in 2013 following a desktop study that defined an integrated concept of operation. By performing this integrated study, it was possible to identify all systems and related subsystems and define an overall architectural diagram. A key component of the deep seabed mining system is the seafloor nodule collector (SNC).

The SNC has a significant influence on the overall operational environmental impact and on the achievable production rate, two criteria that are critical in developing a responsible mining operation. Additionally, given commercial deep-seabed mining operations are unprecedented, the SNC is the subsystem involving the highest number of information and knowledge gaps, such as the environmental impacts and effects, its response to soil characteristics, trafficability, and nodule collection methodology.

Hence, from all the systems and subsystems identified, GSR decided to focus its first efforts on the SNC system and more specifically on a pre-prototype of an SNC. This feasibility study, called ProCat (derived from "Prototype Caterpillar") extended from 2015 to 2021 and consisted of a step-by-step approach and culminated in the design, building, and testing of a pre-prototype SNC, called Patania II (PATII).

Following the successful trials conducted with Patania II at 4500 m water depth in the CCZ in 2021, the final phase will commence, which will culminate in the design, building, and trial of a commercial-scale SNC.

GSR remains committed to responsible deep-sea research and technology development, one step at a time.

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Keywords Polymetallic nodules · Nodule collection system · Propulsion system · Seabed Nodule Collector · Patania I · Patania II · Technological development · Environmental impacts · Effects

1 Introduction

Of all the marine mineral resources, polymetallic nodules are probably the most likely commodity to be developed in the short to medium term. Global Sea Mineral Resources (GSR), a subsidiary of the DEME Group, was established to explore the possibilities for deep seabed mining of polymetallic nodules.

In 2013, the International Seabed Authority (ISA) and GSR signed a 15-year exploration contract (ISA 2012). Under the contract, GSR has exclusive rights for the exploration of 75,000 km^2 of seabed in the Clarion Clipperton Zone (CCZ) of the Pacific Ocean, an area known for vast quantities of polymetallic nodules that are strewn across the ocean floor. The nodules contain important metals such as nickel, cobalt, copper, and manganese and are found on the surface of the seabed at 4500 m water depth (Hein et al. 2020).

This chapter describes GSR's technology development program, which began in 2015. Given significant learnings can be obtained from a robust testing and trial program, GSR has favored a step-by-step, precautionary approach to the development of the nodule collector technology (Weilkiens et al. 2015). At each step, learnings are realized and implemented into the next step, consequently reducing the risks, environmental impacts and effects, and (operational) uncertainties. With each step, GSR scaled up its technology.

Section 2 describes GSR's technology development strategy. Additionally, it provides insight into the general concept of operations and the step-by-step de-risking strategy of the seabed nodule collector (SNC). Subsequently, Section 3 describes these developments in more detail and specifically addresses two main research topics: the vehicle's propulsion system and the nodule collection system. Section 4 describes the integrated development, namely the design and building of GSR's Pre-Prototype Vehicle Patania II (PATII). Section 5 describes the offshore campaign of 2021, conducted in CCZ, where PATII was tested in situ. Section 6 concludes and provides an outlook for the future.

This chapter assumes the reader has some basic background knowledge about the operations conducted by GSR in the CCZ (also available on www.deme-gsr.com/). Consequently, it does not define all aspects of the operation in detail. Note that the nomenclature GSR uses for its offshore campaigns is GSRNODXX, whereby the last two digits refer to the year of the campaign (e.g., GSRNOD21 refers to GSR's campaign conducted in the CCZ in 2021).

2 GSR's Seabed Nodule Collector Development Strategy (2015–2021)

The basis of GSR's research and development (R&D) strategy was developed in 2013 following a desktop study that defined an integrated concept of operation. Additionally, by performing an integrated study, it was possible to identify all systems and related subsystems and define an overall architectural diagram.

There are different ways to organize systems and subsystems in order to develop a holistic architecture. GSR has opted to define the system based on the physical location of the components. Six elements have been defined of which five are tangible systems (System 1–5) and one intangible (System 6). In general, the tangible systems relate to the physical location of subsystems and are ordered to be consistent with the value chain:

1. The **seabed nodule collection system (SNCS)** consists among others of the mining vehicle or seabed nodule collector (SNC).
2. The **vertical transport system (VTS)** transports the nodules to the sea surface. The VTS includes among others the riser and the pumping system, and also the equipment used for the deployment and recovery of the VTS.
3. The **surface operating system (SOS)** primarily consists of the surface operating vessel (SOV) from where all operations are conducted.
4. The **environmental monitoring and survey system (EMSS)**: this system includes all equipment related to the environmental monitoring and (operational) survey such as ROVs, AUVs, sensors, sampling devices, landers, or dedicated environmental monitoring vessels.
5. The **horizontal transport system (HTS)** includes the bulk carriers that bring the nodules to the onshore processing plants and all the necessary auxiliary equipment.

The sixth system relates to specific (operational) strategies, methodologies, procedures, or algorithms.

6. **Mining operations** include the environmental monitoring and management plan (EMMP) and the operational mining plan.

The above system architecture is the framework of GSR's technical development program.

The SNC has a significant influence on the overall operational environmental impact and on the achievable production rate, two criteria that are critical in developing a responsible mining operation. Simultaneously, as commercial deep-sea mining operations are unprecedented, the SNC is the subsystem involving the highest number of information- and knowledge gaps, such as the environmental impacts and effects, its response to soil characteristics, trafficability, nodule collection methodology, and so on.

Hence, from all the systems and subsystems described earlier, GSR decided to focus its first endeavors on the SNCS and more specifically on a pre-prototype of an

SNC. This feasibility study, called ProCat (derived from “Prototype Caterpillar”) that was conducted from 2015 to mid-2021, consisted of a step-by-step approach and culminated in the design, building, and testing of a pre-prototype SNC, called Patania II (PATII).

3 Seabed Nodule Collector: Propulsion and Nodule Collection

The main objective of the SNC is to collect polymetallic nodules while adhering to certain environmental-, economic-, and operational requirements. The SNC consists of a nodule collection system, and the means to maneuver on the seabed, referred to as the propulsion system. The nodule collection system and the propulsion system encompass, directly or indirectly, a large number of information- and knowledge gaps that were identified during the prefeasibility phase. Both research topics have been addressed in GSR’s ProCat project since 2015. In 2019, system dynamics was added as a third fundamental research topic (Fig. 6.1).

ProCat is considered to be a subsystem feasibility study, in line with the definition and the system architecture described earlier. Not all subsystems have immediately been the subject of a feasibility study. If information-, knowledge-, or technology gaps attributed to certain topics are limited or at least manageable through engineering or design, it has not been prioritized after the initial prefeasibility study.

GSR has opted for a step-by-step, parallel de-risking strategy with regard to the development of the SNC in the ProCat project as follows:

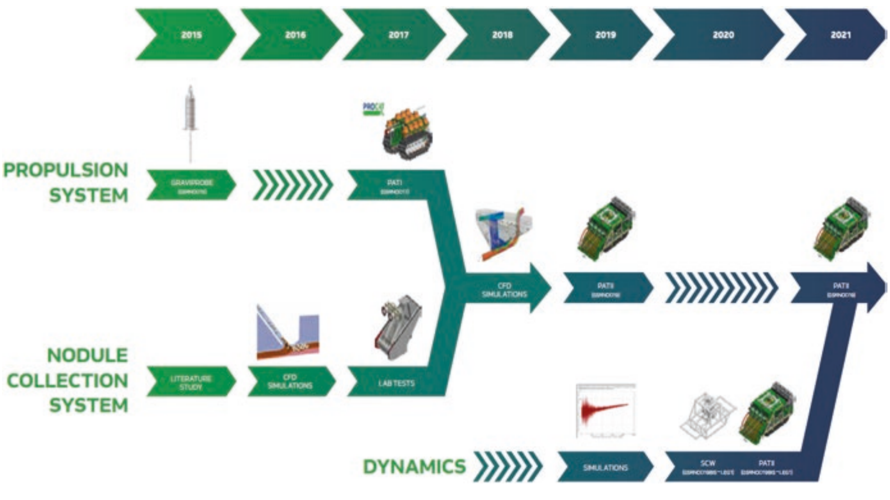

Fig. 6.1 GSR’s SNC subsystem feasibility study

- **ProCat#1 [2015–2017]**: Separate parallel testing of the collection mechanism and propulsion mechanism (TSTD PATI). ProCat#1 was successfully completed in September 2017.
- **ProCat#2 [2018–2021]**: The knowledge acquired during the first phase was applied in this second phase. The collection mechanism and propulsion mechanism were integrated into the design of a pre-prototype SNC called Patania II. This vehicle was used for pilot mining trials in Q2 2019 and Q2 2021 in the GSR exploration license area.

A detailed breakdown of the work performed with regard to the SNC during this feasibility stage and the corresponding R&D strategy is provided in subsequent sections.

3.1 Propulsion System

In general, the different vehicle propulsion concepts that were considered can be divided into three different categories: (1) Towed vehicles; (2) Noncontact suspended vehicles (similar to ROVs), and (3) Terramechanical propelled vehicles (Archimedes screws, caterpillar tracks, wheels).

GSR pursued the design option of caterpillar tracks for its propulsion system. Basically, there are two different ways to approach the design of a tracked undercarriage:

1. Optimized design in the laboratory: In the (recent) past, several research groups have designed tracked systems for deep seabed mining applications solely based on experiments in a laboratory. This typically involves simulated soil, such as bentonite–water mixtures.
2. Optimized design based on in situ measurements: Unlike the first approach where the investigation is focused on the design of the tracked undercarriage itself, the focus here is on acquiring reliable and statistically relevant in situ soil characteristics. This information can subsequently be used in a terramechanical, field-specific desktop study for the design of the propulsion system. This approach is more cost-intensive as it involves an offshore test campaign.

Both approaches have advantages and disadvantages. The main disadvantages of the lab approach are the unknown soil conditions and the measurement errors introduced when replicating the in situ soil characteristics. There is limited dedicated terramechanical literature publicly available on the soil conditions in the CCZ. Additionally, spatial variance and measuring methodology (accuracy, test depth, statistical deviations, and so on) play an important role in defining these characteristics. If the values used in the calculations and experiments are not in line with the actual in situ data, this could result in a track design that is not appropriate for the soft soil conditions of the CCZ.

Given DEME's expertise in dredging technologies, the importance of reliable in situ soil measurements was considered critical. Hence, GSR decided to approach the problem like any conventional dredging project and started with acquiring reliable, in situ soil data. With the results from these measurements, a subsea propulsion system was developed based on standard land-based track design theory.

3.2 GraviProbe

Most dredging projects start with an on-site, geological investigation campaign whereby a cone penetrometer test (CPT) is one of the measurement tools that are deployed. A CPT is a standardized, common method used to determine the geotechnical- and engineering characteristics of soil and to differentiate between sediment layers (Lietaert et al. 2016). This is particularly interesting for the design of a tracked propulsion system.

Unfortunately, no CPT devise existed that was suitable for the envisaged in situ measurement campaign. Therefore, GSR and DotOcean developed and tested a soil strength measuring device, called the GraviProbe, at 4500 m water depth (during GSRNOD15) (Fig. 6.2). The GraviProbe is a free-fall impact instrument, analyzing the underwater sediment layers during the intrusion. The measuring probe was attached to a 4-m-long shaft, thereby acquiring in situ shear strength up to 4 m depth. The soil characteristics retrieved from the GraviProbe and the additional geotechnical tests performed on box cores were used to proceed to the next step in the propulsion development that is, design and building of a dedicated research tool to perform in situ terramechanical research.

3.2.1 Dedicated Terramechanical Research Tool: TSTD Patania I (PATI)

"TSTD" is the short form for Tracked Soil Testing Device, with the emphasis on the "Soil Testing Device": PATI did not collect any nodules or soil samples. The main objective of PATI was to acquire in situ terramechanical parameters that would

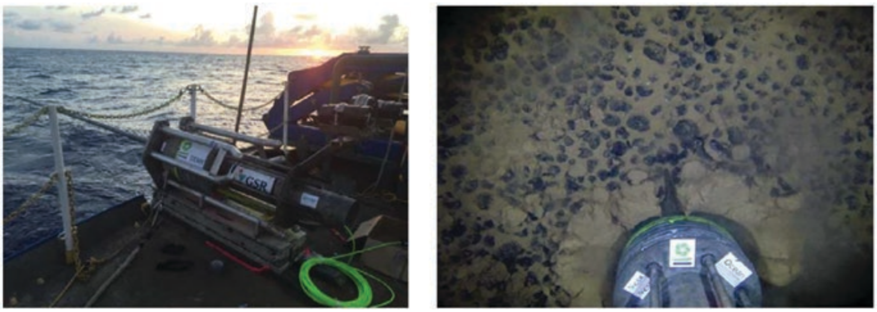

Fig. 6.2 GraviProbe (September 2015)

allow GSR to optimize the design of its pre-prototype Patania II (PATII), so that engineering and operational uncertainties would be de-risked stage by stage (Wong 2009).

An initial track-based undercarriage was designed, combining land-based theories with the geotechnical data collected during GSRNOD15. The design of PATI's track system assumed a rather conservative soil bearing capacity and incorporated many safety margins.

Three main kinds of test objectives were predefined:

- **General trafficability objectives**: Demonstrate that vehicles can maneuver by means of a track-based undercarriage on this type of soil. The achievable speed and performance variability, as a result of different seabed conditions, were key objectives.
- **Terramechanical objectives:** Provide solid terramechanical input data to enable the design of PATII. This includes establishing the pressure–sinkage relationship (bearing capacity), the thrust–slip relationship (drawbar pull), and the shear stress–shear strain relationship (Wong 2009).
- **Environmental objectives:** Gain insight into soil disruption and generated sediment plume, mainly as a result of the tracked propulsion system.

A shear test, measuring the stress–shear displacement relationship and the shear strength of the terrain, consists out of a shear ring or a shear plate and is used to simulate the shearing action of the tracks. However, performing in situ vane tests implies a meticulous rotary system that is difficult to implement on a subsea vehicle, especially considering the high amount of technical uncertainties that were already present. For that reason, it was decided to measure the shearing characteristics using a vane tester on soil samples ex-situ. The vane tests were performed on box cores as soon as they came on deck to get the most accurate ex-situ measurements on the least disturbed samples.

For the pressure–sinkage relationship, two discs of different diameter are pushed into the seabed while measuring the pressure and penetration depth at every test location (plate measurements) (Figs. 6.3 and 6.4).

The thrust–slip relationship will indicate the real tractive performance of the vehicle on the seabed. The associated drawbar pull will indicate the amount of effort available to push or pull hardware, climbing abilities, and so on. For that reason, an anchor (drawbar) was mounted at the back of the vehicle (Figs. 6.5 and 6.6).

In total, PATI performed 13 dives during the GSRNOD17 campaign, reaching the seabed on 19 June 2017, after 25 days at sea. The lessons learned from the GSRNOD17 campaign have had a direct impact on the component selection, de-risking, and testing program of PATII.

In general, all major objectives set forward were achieved. An overview of the most important (nonconfidential) results obtained with PATI, quantitative and qualitative, is given in the table below (Table 6.1).

Fig. 6.3 Pressure plates mounted on Patania I (June 2017)

Fig. 6.4 Imprints in the soil from the pressure plates (June 2017)

Fig. 6.5 Anchor for thrust–slip measurements (February 2017)

Fig. 6.6 PATI being deployed during GSRNOD17 (June 2017)

Table 6.1 Result overview TSTD Patania

Parameter	Measured value
Maximum speed driven on the seabed	0.65 m/s
Total distance traveled on the seabed	14.5 km
Total time on the seabed	>30 h
Maximum slope	>15%
Number of in situ pressure–sinkage measurements (a set of plate measurements)	23 sets
Shear strength–shear displacement measurements (ex situ samples)	42 [−]

3.3 Nodule Collection System (Laboratory Tests)

Nodule collection systems have extensively been investigated and tested in the past. Collectors can generally be divided into two main classes, active and passive (ISA 2001). Passive collectors, which are towed systems, have not been investigated by GSR because these are not fully controllable with regard to positioning and behavior on the seabed and are deemed less efficient. Moreover, passive collectors do not comply with the current environmental design philosophy on minimizing the area of impact. Active collector concepts require external power to collect nodules, whereby hydraulic and mechanical principles (or a combination of both) are most commonly used.

The approach used for the development of the nodule collection system is different than the one used for the propulsion system. While the design choice for a tracked propulsion system was rather straightforward, the choice of an appropriate nodule collection system is more complex as it encompassed more fundamental uncertainties. Design drivers needed to be defined in order to objectively compare different concepts.

3.3.1 Design Drivers

The main objective was to develop a nodule collection system that has an appropriate production capacity combined with minimal environmental impact and an optimal pickup efficiency. Several parameters were identified as drivers for the design of the collection head:

1. Pickup efficiency ($\eta_{\text{pick up}}$): The pickup efficiency is defined as the ratio of nodules collected in a certain area over the total amount of nodules available in the same area. This parameter needs to be maximized.
2. Production: Annual production figures determine economically viable operations. Productions figures range between 2.8 million and 3.0 million tons of dry nodules per year.
3. Water flow: Hydraulic collector concepts require a certain water flow to pick up the nodules ($Q_{\text{pick up}}$). Mechanical collectors also need a water flow to separate and clean the nodules from the sediment ($Q_{\text{separation}}$). The water flow should be minimized as it is reasonable to assume it is directly proportional to the generated sediment plume.
4. Environmental pressures: Minimizing the environmental impact and effects is an important factor to be considered when designing a nodule collection system. Three parameters have been defined:

    - Turbidity: All engineered solutions should aim to keep turbidity as low as possible. The turbidity originates either from the nodule collection system ($T_{\text{collection}}$), the separation and cleaning system ($T_{\text{separation}}$), or the propulsion system (T_{driving}).
    - Seafloor disturbance: The physical disturbance of the seafloor is a factor that should be minimized at all times. Seabed penetration should be avoided by design.
    - Noise: Noise levels should be minimized.

5. Seafloor interaction: The collector head should have minimal seafloor interaction, mainly to avoid clogging and blockage as the soil is known to be soft and sticky. Soil that does get picked up should be separated from the nodules early in the process.
6. Reliability: The nodule collection system should have a minimal amount of active parts. This can either be a rotating drum, a conveyor belt, scoops, or something else. The more active (moving) components, the higher the risks of failure and corresponding downtime.
7. Lifetime: Lifetime of the collector should be maximized. The design should incorporate components with high wear resistance.

These design drivers are used to evaluate different nodule collection systems.

3.3.2 GSR's Nodule Collection System Development: Trade-Off

GSR looked at mechanical and hydraulic concepts for nodule collection. After an initial exploratory concept study and small-scale laboratory tests, extensive laboratory tests were conducted using only a hydraulic lift collector.

Mechanical collection concepts, regardless of the geometrical configuration, generally use the same principle that creates a significant top-layer disturbance wherefrom nodules are removed (a "slice" of soil and nodules is being scraped off). The nodule pickup efficiency, despite possible bulldozing effects and side-spills, is consequently relatively high. However, by slicing off a layer of the upper seabed, a significant amount of sediment is added into the process flow. While hydraulic systems only fluidize the sediment surrounding the nodules, in the case of mechanical collection, it might be possible that entire chunks of clay are being collected. This significantly increases the risk of clogging and blockage downstream of the collector's head.

For the mechanical collection system, the principle of the fenestrated ramp was the preferred option because of its widespread application in the potato-harvesting industry. On the other hand, the hydraulic lift concept was put forward as the most promising hydraulic concept largely because of its simplicity.

The trade-off using the design drivers as defined above is shown in Table 6.2. The fields with shading are considered least favorable. Considering the design drivers defined above, it is evident that there is an inherent advantage for hydraulic nodule collection systems.

Certain assumptions have been made when comparing both systems.

Assumption 1: A near 100% pickup efficiency of the mechanical collector implies for comparative reasons (especially energy consumption), also a near 100% pickup efficiency of the hydraulic lift collection system;

Assumption 2: In order to pump the nodules to the SOV at the sea surface through the riser, a fluidized mixture needs to leave the mining vehicle. Essentially, in the case of the mechanical collector, this implies having to fluidize the layer of nodules.

As such, the research question changed into: "how does the waterflow, the consequential power requirements and generated sediment plume used for nodule pickup with hydraulic collection systems compare to the waterflow (and consequential power and generated sediment plume) used for separating and the subsequent fluidization of the nodules when using mechanical collection systems?"

The hydraulic lift concept, although tested in the 1970s and 1980s by various consortia, encompasses many more fundamental uncertainties as compared with the mechanical concept. Before an informed decision could be taken between the two concepts, some clarification was needed for the following.

1. How high is the pickup efficiency and how much energy (and thus water) is required to reach a near 100% efficiency for hydraulic collectors (reference is made to the first assumption)?

Table 6.2 Collection principle trade-off (shading = less favorable)

Driver	Symbol	Hydraulic collector	Mechanical collector ("scraper" system)
Pickup efficiency	$\eta_{\text{pick up}}$	To be determined during laboratory tests	Assumed to be relatively high if compared to land-based harvesting systems (~100%)
Production	P	To be determined during laboratory tests	To be determined during laboratory tests
Water flow	$Q_{\text{pick up}}$	High—To be determined during laboratory tests	N/A
	$Q_{\text{separation}}$	N/A	High—To be determined during laboratory tests
Environmental impact	$T_{\text{pick up}}$	High (~ $Q_{\text{pick up}}$)	Low
	$T_{\text{separation}}$	Low	High (~ $Q_{\text{separation}}$)
	T_{driving}	Equal (Tracks)	Equal (Tracks)
	Seabed disturbance	Water flow parallel to the seabed	Slice of seabed scraped away
	Noise	Water pumps	Waterpumps and mechanical drive
Seafloor interaction	–	Low(er)—Top layer affected by the water flow: fluidization and dragging of nodules	High(er)—Entire top layer is being removed and processed in situ
Reliability	–	High(er)—Minimal moving parts: only water pumps are required for the collection and separation	Low(er)—Water pumps are required for the nodule separation; a mechanical drive is required for the nodule collection method
Lifetime	–	To be determined.	To be determined.

2. How is the seabed affected by the hydraulic lift collector and what is the expected depth of penetration?

In order to provide an answer to these fundamental questions, an extensive test program was developed and implemented.

3.3.3 Nodule Collection System Development

Unlike the propulsion design that has been developed in situ, the test program for the nodule collection system was initially performed in a controlled environment. The major advantage of a laboratory environment for this kind of work is the ability to control and adequately measure every variable that is required for a proper assessment. As such, the research can focus solely on optimizing the nodule collection system, instead of adding the hyperbaric complexity associated with in situ testing.

The collector's head has two major functions (1) pickup function (PU), that is, picking up the nodules at the entrance of the collector by means of an active jet system and (2) transport function (TR), that is, the transport of the nodules for further handling. All design parameters have an influence on either just one of these functions or on both. Subsequently, parameters can be divided among these two functional categories. Within these two functional categories, parameters can further be categorized as either **process control** parameters, **geometrical** parameters, or **environmental** parameters.

Process control parameters are the parameters with which the collection process is monitored and controlled. These parameters determine the production rates and can be varied during the process. On the contrary, geometrical parameters are optimized through design. These can only be changed by physically modifying the nodule collection heads on the vehicle. The seabed flatness (unevenness) is an external environmental parameter that cannot be directly controlled, though it has a significant influence on the efficiency of the pickup process. Other environmental parameters include (but are not limited to) the abundance of nodules (kg/m^2), the particle size distribution (PSD) of the nodules, and the burial of the nodules into the seabed. All the aforementioned parameters are the subject of the nodule collection head design program.

Nodule Collection Head: CFD Simulations

The engineering program started with a detailed literature study of all the hydraulic collectors and their respective working principles. It was decided to optimize the geometric design using computational fluid dynamics (CFD) simulations first before the design and build of an actual collection head to be tested in the laboratory. The main benefit of this approach is the possibility of validating several geometric design variations before any construction takes place. In addition to being more cost effective, it also increases the success rate of the laboratory tests.

The main objectives of the CFD analysis were to (1) validate the working principle of the hydraulic lift system; (2) theoretically optimize the collector head geometry, and (3) perform a parameter sensitivity analysis. The CFD analysis was split into two separate parts. The first part optimizes the geometry of the head as much as possible to obtain an even and uniform inlet jet flow. On the other hand, the second part defines the parameters (geometrical and process control) that maximize the nodule pickup efficiencies. An illustrative example of the result of both parts is provided in Figs. 6.7 and 6.8 below.

Based on the results of extensive CFD analysis, the geometrical design of the collector's head was optimized. Additionally, these results provided valuable input for the laboratory test setup such as necessary flows (and required pump power) and traveling carriage speed set points.

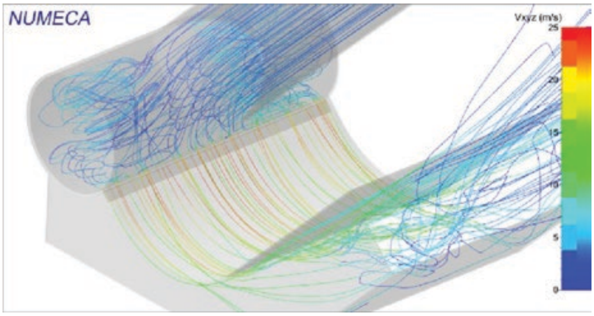

Fig. 6.7 CFD simulations (example only)

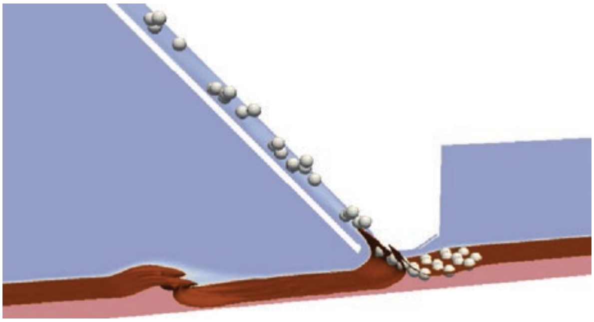

Fig. 6.8 CFD simulations (example only)

Nodule Collection Head: Laboratory Test

Although the design of the collection head was optimized with CFD, the collector head used for the laboratory tests needed to be as modular as possible in order to allow certain geometrical variations. Within every geometrical configuration, test runs were performed by varying the process control parameters.

The tests were done in collaboration with the Flanders Hydraulic Research Laboratory in Antwerp, Belgium. The test tank was 70-m long and separated into two interconnected channels: a channel of 1.07 m wide for the hydraulic collector and one channel of approximately 2.5 m for the water pumps. The pumps were selected based on the CFD analysis. The feeding pipes and collector itself were equipped with pressure, water flow, and velocity sensors. The artificial testbed inside the collector channel was approximately 250 mm thick. To avoid start-up and end variances in the measurements, a length of 22 m of the total 70 m was effectively used for the measurements. Nodule abundance ranged from 15 kg/m^2 to 35 kg/m^2 resulting in a net mass of 330 kg to 700 kg of nodules (Figs. 6.9 and 6.10).

A traveling carriage was used to move the collector forward through the channel at various speeds. The water pumps used to feed the jets were also mounted on the same traveling carriage.

Fig. 6.9 Test tank (May 2017)

Fig. 6.10 Artificial testbed with nodule collector (May 2017)

Tumbled lava stones were used as artificial nodules; these have similar characteristics (weight, density, shape, and so on) but are much harder and less brittle than actual nodules. This is important for the statistical reproducibility of different tests.

The seabed of the CCZ has some particular characteristics. Analysis on undisturbed samples has been carried out by Ghent University and the Hydraulic Research Laboratory in Antwerp. Comparative geotechnical tests were performed on in situ samples and on different kinds of artificial soils (loam, clay, and bentonite). Based on these analyses, diluted loam was used to simulate the seabed.

In order to maximize the amount of test runs, some engineering assumptions had to be taken with regard to the testbed. An important one was to disregard the top layer for the tests. This loose, “fluffy” layer that is present in the CCZ was not considered in the laboratory as it was assumed it does not affect the nodule collection process. Additionally, disregarding the top “fluffy” layer reduced the sediment settling time in between test runs.

In total, 101 test runs were performed over a period of 3 months, of which 72 were parametric test runs, 9 testbed clean-up runs and 20 were visualization runs (without sediment). In total, seven different geometrical variations have been tested, primarily related to the shape of the water jet inlet. In addition to the standard efficiency performance tests using tumbled lava stones, validation runs have been performed with real polymetallic nodules. Finally, as mentioned before, test runs were performed without the test bed in order to have a better visual indication of the nodule collection process.

4 Seabed Nodule Collector: Integrated Design

This section describes the second step in GSR’s SNC de-risking strategy, the integrated design of the Pre-Prototype Vehicle Patania II (PPV PATII). This development integrates the results of the in situ terramechanical research obtained with PATI and the optimized nodule collection system as tested in the laboratory. The development program of PATII started in September 2017, after the GSRNOD17 campaign, and was successfully completed in May 2021 with the trials during GSRNOD21 in the CCZ.

4.1 PVV Patania II: Functional Description

The main objective was to develop and construct a pre-prototype vehicle (PVV), integrating the hydraulic collector on the tracked chassis and to develop a vehicle causing minimal environmental impact hereby validating the requirements for a full-scale polymetallic nodule collection system in the actual operational environment of the CCZ (Fig. 6.11).

From the start, it was the intention to use PATII for creating a disturbance on the seabed and to perform environmental impact monitoring. Operations with PATII were a major opportunity to improve the understanding of the impact and effects of seabed mining activities. A collaboration was established with an international consortium of scientists through the “Joint Programming Initiative Healthy and Productive Seas and Oceans” (JPI Oceans) program called MiningImpact 2 (MI2).

Fig. 6.11 PATII terminology

4.1.1 Nodule Collection and Storage System

A commercial-scale seabed nodule collector was envisaged which would comprise several nodule collection modules. These modules were installed in front of the vehicle and comprise a collector head at the lower end, a discharge duct, water pumps and hoses, and a system for active height control. PATII is equipped with four of these modules. Every module is 1 m wide, which leads to a total vehicle width of approximately 4 m. Every collector module is, from a dimensional point of view, similar to the design which has been tested and validated in the laboratory environment.

For the nodule collection system, four water jet pumps (one pump per module) are mounted on top of the vehicle. A Y-piece distributes the flow in two flexible hoses. These flexible hoses are designed to allow the collector heads some variation in height above the seabed. Additionally, four other water pumps are installed on the vehicle to generate the necessary flow to transport the nodules internally and toward the bucket.

After being collected, the nodules move up the discharge duct and fall into a single trough, called the hopper. The majority of the initial pickup water flow is also used to transport the nodules up the duct, flushes through the hopper, and is discharged through the diffusor exhaust. As such, this sediment-laden water is immediately released on the seabed before it enters the subsequent transport and processing systems (in commercial operations, that is, the vertical transport system).

From the hopper, the nodules are subsequently transported to the bucket at the back. For the purpose of the MI2 experiments, given there was no VTS, PATII was equipped with a temporary storage bucket at the back. The bucket hatch can be opened or closed depending on the operating mode, and whether the nodules need to be stored or dumped at a different location. The water that is used to entrain the nodules is new process water.

4.1.2 Propulsion System

Just like PATI, standard land-based track components have been used for PATII's propulsion system, consisting of track chains, road and idler wheels, gearboxes, and trackpads. The geometry of the trackpads is specifically designed for PATII operating on the CCZ seabed and derived from the measurements obtained using PATI during the GSRNOD17 campaign.

The bearing capacity of the CCZ seabed is rather limited. This implies that the subsea weight of PATII needs to be distributed over a large surface in order to minimize (static) sinkage, excessive slip and to guarantee maximum traction performances. This has been an important design parameter. Lightweight materials, like aluminum and HDPE, are used to keep the in-air and submerged weight as low as possible. By minimizing the subsea weight, the required total track surface could be reduced, and consequently, results in a less voluminous vehicle which is also beneficial for the design of the launch and recovery system (LARS).

As the soil parameters vary significantly along the seabed, PATII can be equipped with a variable amount of buoyancy, so that as per the local seabed condition, additional buoyancy can be added or removed, allowing flexibility.

4.1.3 Survey and Telemetry system

The PATII equipment spread is equipped with more than 170 sensors, primarily used to know the status of the different constituting active components. Examples are (hydraulic) pressure sensors, water ingress sensors, temperature sensors, proximity switches, and others. A different sensor suite is used for operational purposes such as the positioning or maneuvering on the seabed (survey), the quantification of nodule throughput (production), and dedicated environmental sensors.

Survey System

A HiPAP ultra short baseline (USBL) system was used for positioning on the seabed. The HiPAP is an acoustic transmitter-receiver device that is installed below the vessel. In this particular application, it makes use of transponders installed on PATII and the umbilical to determine their position.

The second important survey device is the PHINS, installed in front of PATII. It is an inertial navigation system (INS) for measuring accelerations, motion, and heading. The PHINS was coupled to a Doppler velocity log (DVL) for measuring the altitude above the seabed and the relative speed and course over the ground.

Other devices such as a long baseline (LBL) and a current, temperature and depth (CTD) sensor were used in conjunction with the above-mentioned sensors to further improve the positioning accuracy.

Production System

A sensor crucial for defining the production is the multibeam acoustic system mounted at the front of the vehicle. The main purpose of the multibeam system was to measure the height of the seabed relative to the vehicle and activate the collector heads accordingly to maintain the ideal gap for optimized nodule collection. Additionally, the multibeam was used for determining the seabed disturbance, specifically the thickness of the sediment layer removed by the collector heads (including the nodules).

Commercial nodule mining operations are unprecedented. As a consequence, there is no equipment readily available for measuring production and dedicated equipment had to be designed and built. A density meter, of which the measuring principle is based on electrical resistance tomography (ERT), was developed and tested. ERT is a measurement method that utilizes the electrical properties of the material for understanding, measuring, and controlling processes. The purpose of the density meter is to measure the mixture composition pumped towards the nodule bucket on PATII (or toward a riser). In future operations, production could be optimized in real-time using the aforementioned control process parameters.

4.1.4 Dedicated Environmental Monitoring System

The environmental sensor suite installed on PATII is primarily used for quantifying and assessing the behavior of the sediment plume. Besides the equipment installed on PATII, GSR deployed other sensors such as an autonomous underwater vehicle (AUV) and sediment traps, current profilers, and turbidity sensors, all installed on deepwater moorings.

For the purpose of monitoring the sediment plume, four arrays of five remotely triggered sampling bottles (Niskin bottles) are installed on top of PATII (20 bottles in total). Niskin bottles are able to take a water sample at a certain moment during the operations. In addition to the Niskin bottles, 10 turbidity sensors are installed at different locations on PATII. These miniature sensors detect light scattered by particles that are suspended in the surrounding water, generating an output voltage proportional to turbidity or suspended solids.

In addition to the sampling bottles and the turbidity sensors, multiple acoustic Doppler current profilers (ADCPs) are installed on the vehicle, facing forward, upwards, and backwards. ADCPs are able to detect and measure current velocities and directions. The data are used for validating the near-field hydrodynamic models.

Lastly, a prototype of a real-time size and settling velocity (RTSSV) particle size analyzer was mounted in the back of the vehicle. This instrument, the only one of its kind, was codeveloped by Sequoia Scientific, the Massachusetts Institute of Technology (MIT), and Scripps Institution of Oceanography. It measures suspended sediment concentration, which is a valuable information for increasing the understanding of the characteristics of the near-field sediment plume.

Fig. 6.12 Environmental sensor suite terminology

Fig. 6.13 Sampling bottles installed on top of PATII

Five low definition cameras and one high definition (HD) camera were installed on PATII. The HD camera was specifically used for biological observations (primarily megafauna). Two laser beams were used to establish distances and sizes on the seabed (Figs. 6.12, 6.13, and 6.14).

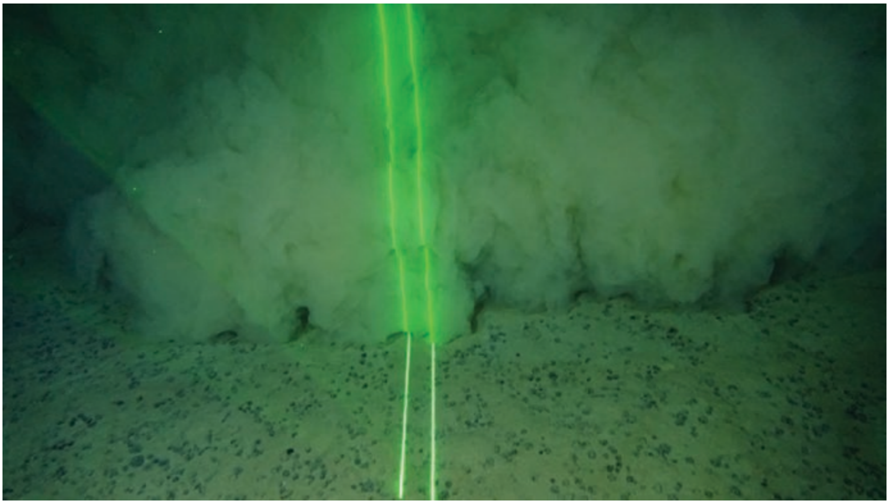

Fig. 6.14 Image of the laser beams on the head of the plume created behind PATII (April 2021)

Fig. 6.15 PATII's launch and recovery system (A-frame and umbilical winch) (July 2020)

4.1.5 Launch and Recovery System

The launch and recovery system (LARS) consisted of an A-frame, and umbilical spooled onto an umbilical winch, and all the necessary auxiliary equipment such as a control container, hydraulic power unit (HPU) to operate the hydraulic systems of the LARS and a power distribution unit (PDU). All of these systems were custom built and tailor-made for deep-water operations (Fig. 6.15).

4.2 Sediment Plume Behavior Study

In parallel with the technical and equipment developments, a hydrodynamic model has been developed to better understand the behavior of the sediment plume that is generated by the operations (GSR 2018). GSR collaborates with different expert groups in the development of hydrodynamic models such as International Marine and Dredging Consultants (IMDC) and Massachusetts Institute of Technology (MIT).

4.2.1 The Far-Field Ocean Hydrodynamic Model

The far-field ocean hydrodynamic model has been under development since 2017 and has been continuously improved and validated with updated measurements and data sets. In addition to desktop studies, GSR has deployed oceanographic moorings in its license area for continuous long-term environmental data collection.

The numerical hydrodynamic model takes the following physical processes into account: barotropic forces, wind stresses and atmospheric pressure gradients, bed friction, Coriolis force, horizontal and vertical turbulent diffusion, baroclinic forces due to salinity and temperature gradients, and tidal body forces. The domain of the model is restricted to a rectangular area of approximately 870,000 km^2 around the GSR license area (excluding GSR's B2 area).

4.2.2 The Near-Field Plume Model

The near-field, computational fluid dynamics (CFD) plume model describes the dynamics of the water–sediment mixture in the first few hundred meters of the water column, and specifically the complex particle motions occurring in the first few meters behind the vehicle. The in situ trials with PATII have been used to validate these theoretical models. The environmental sensor suite that has been described in earlier sections is specifically set up for this purpose.

The goal of the model is primarily to gain a better understanding of the behavior and dispersion of the sediment plume around the vehicle. A better understanding of the source term will improve the accuracy of the far-field hydrodynamic model. Additionally, the results of the modeling and field trials will contribute to the optimization of the design of the diffusor to minimize sediment plume dispersion (Fig. 6.16).

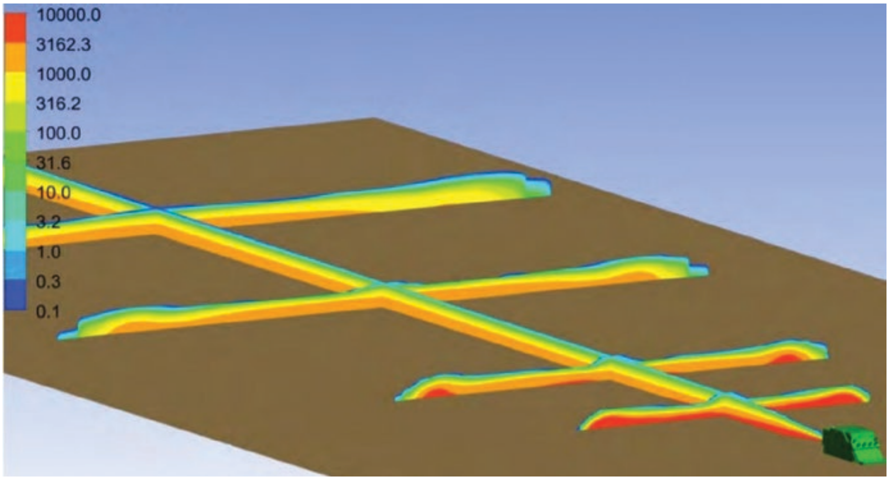

Fig. 6.16 Contours of sediment concentration (mg/l) along the central and lateral symmetry planes

5 GSRNOD21 Campaign: PATANIA II trials in the CCZ

5.1 GSRNOD21 Campaign Objectives

Prior to the campaign, GSR defined several objectives which were mostly focused on the technical performances of PATII and the monitoring of the environmental response. A brief explanation of what has been performed is listed below:

1. **PATII functional testing (propulsion and nodule collection systems):** In situ validation and optimization of the technologies and different working principles developed under ProCat#1 (increasing to TRL7). Additionally, purpose-built measurement equipment was installed on PATII that provided insight into the functioning of the collection system and how it influences its surrounding environment. Generally, a functional distinction can be made between systems related to the nodule collection process (focused on collection efficiencies $\eta\%$), the overall maneuvering of the vehicle (speed, traction, turning radius, slippage, and so on), and the vehicle condition and production monitoring sensor suite (such as the multibeam, density meter or beacons to measure the deflection of the umbilical).
2. **Mining trials and associated environmental monitoring (JPIO MI2 project scope):** The trials with PATII were a major opportunity to improve the understanding of the impact and effects of deep seabed mining. Two field trials were conducted in the GSR and BGR license areas. The potential geophysical, biogeochemical, and biological effects were monitored from a second ship (M/V Island Pride) involving equipment spread consisting of ROVs and AUVs (for

far-field sediment plume monitoring) among others. An AUV was also installed on the ship that hosted PATII (M/V Normand Energy).

3. **Acoustic and sediment plume assessment (near- and far-field plume):** The aforementioned environmental tools installed on the PATII have been used to study the sediment plume behavior in the near field, in collaboration with the Environmental Dynamics Laboratory (END Lab) of MIT. These experiments included driving perpendicular to a previous track and through the self-generated plume ("selfie experiment"). Additionally, oceanographic moorings with environmental sensors were installed near the test site for the same purpose (drive-by experiment whereby PATII drove as close as possible to a mooring). The size, concentration, and behavior of the suspended sediment generated by PATII were measured during different operational scenarios. The results lead to the optimized design of a discharge system and an optimized mining pattern to minimize the environmental impacts.
4. **Retrieval of measured environmental data from moorings:** GSR has had environmental moorings in the CCZ since 2017 for continuous physical oceanographic recordings (current, turbidity, and so on). Some shorter moorings have been recovered and redeployed in 2018. However, during GSRNOD21, all the moorings had to be recovered and redeployed, including the 4000 m-long moorings.
5. **Nodule sampling**: Nodules were sampled for further study related to metallurgical processes.
6. **Megafauna observation**: Several transects to make megafauna observations were conducted using PATII. In addition, several transects to observe megafauna were performed with the AUV.

5.2 GSRNOD21 Experiences

5.2.1 Course of Events

The mobilization of GSRNOD21 started on 18 February 2021 in the port of Vlissingen (The Netherlands). After several logistical challenges brought on by the global COVID-19 pandemic, the vessel M/V Normand Energy eventually departed for the CCZ on 2 April (Fig. 6.17).

During the transit toward the CCZ, PATII was deployed two times for hyperbaric proofing up to a maximum depth of 3830 m, well above the seabed. The vessel arrived in the GSR license area on 8 April after which it commenced with the recovery of the previously installed oceanographic moorings.

In total, M/V Normand Energy stayed 43 days offshore. Finally, after 4 years of development, PATII reached the seabed on 10 April, early in the morning.

Fig. 6.17 M/V Normand Energy with M/V Island Pride in the background during the MI2 experiments

Table 6.3 Result overview PATII

Parameter	Measured value
Total dive time with PATII	227 h
Total time on the seabed	> 107 h
Average launching time	3 h 43 min
Average recovery time	4 h 14 min
Total distance driven on the seabed	54.3 km
Self-logging sediment plume characterization experiments ("selfieexperiment")	8 experiments
Mooring drive-by experiments	3.5 experiments
Megafauna transect	> 4.5 km
Estimated theoretical throughput of nodules ("buckethatch open" operatingmode)	~2000 T
Total surface cleared of nodule for MI2 experiment in GSR area	30,899 m^2
Total surface cleared of nodule for MI2 experiment in BGR area	23,400 m^2

5.2.2 GSRNOD21: Main Results

In total, 15 dives were performed with PATII during GSRNOD21. All major objectives were achieved. An overview of the most important (nonconfidential) results of the PATII trial, quantitative and qualitative, is provided in the table below (Table 6.3).

Approximately 660 h of video data were recorded while driving on the seabed. This proved to be a valuable source of qualitative information for various purposes,

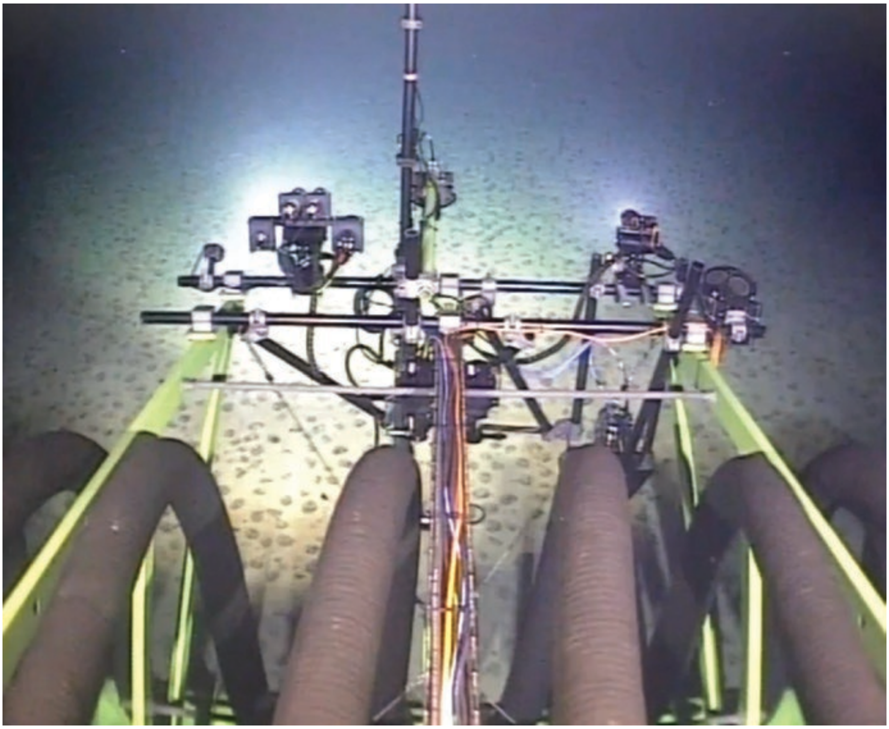

Fig. 6.18 PATII on the seabed (April 2021)

such as megafauna observations, assessment of the local variability of the terrain, sediment plume behavior, and nodule collection efficiencies (Fig. 6.18).

The background oceanographic data collected from the moorings installed since 2017 (and 2018) seems to be very promising. A significant data set, over an extended period in time, has been retrieved from the different sensors. The results, still being processed at the moment of writing, will be used for the improvement of the hydrodynamic model.

6 Conclusion

With the successful ProCat program, GSR's solution for responsible deep seabed mining has taken a giant leap forward. From a technological, operational, and environmental perspective, there is sufficient confidence to proceed to the next phase, the system integration phase (SIP). The SIP will culminate in a system integration test (SIT), whereby a commercial scale seabed nodule collector, Patania III, and vertical transport system (VTS), including all necessary auxiliary (deck) equipment, will be integrated and tested in the CCZ. With regard to the SIT, GSR will continue to advocate a step-by-step development strategy using the best available technologies, in collaboration with world-leading experts, scientists, and universities, while simultaneously adhering to all the relevant environmental considerations.

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Kris De Bruyne joined GSR in 2015 as a technical engineer and was actively involved in developing GSR's R&D strategy. Mr. De Bruyne was the lead engineer on board of the vessel conducting the trafficability trials in 2017 in the CCZ with the tracked soil testing device (TSTD) Patania I. In parallel, he organized and facilitated fundamental research on the nodule collection system performed at the Flanders Hydraulic Research Institute in Antwerp. Since then, as a project manager, Mr. De Bruyne has been responsible for the development, build and test of the Pre-Prototype Vehicle (PPV) Patania II. For the offshore trials in 2019, 2020, and 2021, Mr. De Bruyne was responsible for all operations with PPV Patania II. Mr. De Bruyne obtained a master's degree in Mechanical Engineering-Naval Architecture in 2010 at the University of Ghent, along with a master's degree in Organizational Management at the University of Antwerp in 2011.

Harmen Stoffers has spent the last 13 years designing and building large complex equipment used in the maritime and offshore industry in his role as lead engineer and project manager. Mr. Stoffers joined GSR in 2016 as lead project engineer and has since then been involved in the equipment development program, specifically focused on the propulsion system and on the subsequent design and build of the tracked soil testing device (TSTD) Patania I. After the successful completion of the offshore trials in 2017, Mr. Stoffers initiated the development of the Pre-Prototype Vehicle (PPV) Patania II as design manager. Since then, Mr. Stoffers has had a leading role in the development, build, and offshore trials of Patania II in 2019, 2020, and 2021. Mr. Stoffers has a degree in Mechanical Engineering, along with a degree in Industrial Engineering & Management (NL).

Stéphane Flamen started in 2011 as a technical superintendent on board of several dredging vessels across multiple projects worldwide. Mr. Flamen joined GSR in 2016 as a technical engineer and was responsible for the technical development of the nodule collection system for the Pre-Prototype Vehicle (PPV) Patania II. After the offshore trial of 2019, Mr. Flamen's expanded his expertise in the field of offshore system dynamics and associated launch and recovery systems. Mr. Flamen has joined GSR's offshore campaigns in 2019, 2020, and 2021. In his current role as a design manager, he is involved in GSR's developments for future deep-sea mining technologies. Mr. Flamen obtained a master's degree in Civil Engineering from the University of Ghent (BE) and is specialized in Maritime Engineering.

Hendrik De Beuf joined GSR as a surveyor in 2017 after working on several complex positioning systems within the DEME Group. He has been involved in the design and build of the Tracked Soil Testing Device (TSTD) Patania I and the Pre-Prototype Vehicle (PPV) Patania II. Mr. De Beuf was specifically involved in the development of technologies to optimize the nodule collection system and the position accuracy of the vehicles on the seabed. As chief surveyor, Mr. De Beuf has since 2019 been responsible for the electronic system integration, data management, and positioning systems on all GSR's offshore campaigns. Mr. De Beuf has a B.Sc. from the University College of Ghent (BE) as a Land Surveyor but his lifelong passion for the oceans made him pursue this path towards the deep sea.

Céline Taymans joined GSR as Marine Environmental Engineer in 2017. Since then, she was involved in GSR's multidisciplinary environmental baseline studies and participated in associated offshore campaigns. Additionally, she was involved in the development of the Pre-Prototype Vehicle (PPV) Patania II, specially focused on monitoring the environmental impacts and effects associated with the trials of the 2021 campaign. She is part of the team developing GSR's Environmental Monitoring and Management Plans. Ms. Taymans obtained a master's degree in Bioscience Engineering from the University of Louvain (BE), along with a master's degree in Oceanography from the University of Liège (BE) where she specialized in complex hydrodynamic modeling.

Samantha Smith has 20 years' experience conducting environmental assessments in a number of countries, covering four continents, and has 15 years' experience working with the deep seafloor minerals sector. Dr. Smith's background is in strategic environmental and social performance planning, is a coauthor of several papers related to environmental management considerations for the deep ocean and is a recognized and respected expert in her field. Dr. Smith has a B.Sc. (Hons) from McMaster University in Canada which focused on aquatic ecology and a Ph.D. in Environmental Biology & Biogeochemistry from the University of Bristol (UK). Dr. Smith is a director and president of the International Marine Minerals Society and a Fellow of AusIMM (Australasian Institute for Mining and Metallurgy).

Kris Van Nijen has spent the last 20 years overseeing marine engineering projects across continents, and has a track record of successfully balancing economic, environmental and social considerations for sustainable growth. Dr. Van Nijen has been the head of the GSR team since 2010, working on developing ultradeep ocean technologies and focused on recovering critical metals needed for sustainable development and ultimately for the future benefit of humankind. Dr. Van Nijen is an active participant and presenter in meetings with regional (EU) and international (UN) intergovernmental bodies charged with regulating the marine minerals sector. Dr. Van Nijen has been quoted in the Economist, Time Magazine, Financial Times & Nature and was interviewed for CBS 60 min. Dr. Van Nijen has a Ph.D. in applied economics and holds a master's degree in construction engineering from the University of Antwerp (BE), along with an MBA from the Vlerick Business School (BE).

Chapter 7
Mining and Processing of Seafloor Massive Sulfides: Experiences and Challenges

Seiya Kawano and Hisatoshi Furuya

Abstract The Japan Oil, Gas and Metals National Corporation (JOGMEC) has been working toward developing seafloor polymetallic sulfide deposits. As part of its achievement, in 2017, it successfully tested continuous lifting of ore from the seabed in Exclusive Economic Zone (EEZ) of Japan near Okinawa. It is the first successful attempt in the world for sulfide mining. Furthermore, by the flotation test using 15 tons of ore, 2 tons of the concentrate with a sufficient grade of zinc were recovered and charged into the furnace of the existing domestic smelter. In this chapter, these results and remaining challenges toward the commercialization of the project are discussed.

Keywords Seafloor Massive Sulfide · Mining · Ore-lifting test · Mineral processing

1 Introduction

Over a period of last decade, it has become evident that there are many seafloor massive sulfide deposits (SMS) in the exclusive economic zone of Japan (Okinawa, Izu, and Ogasawara seas). SMS have been found to contain more copper, lead, zinc, gold, silver, and other useful metals than those found in onshore mines and are expected to be an advantageous resource for development because of their relatively shallow depths (approximately 500–2000 m depth) among marine mineral resources. Since Japan relies on imports from abroad for most of its metal resource needs,

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SMS are expected to be a new source of resources for Japan. However, the technology for mining and ore-lifting on a commercial scale has not yet been established.

JOGMEC, commissioned by the Ministry of Economy, Trade and Industry (METI), in cooperation with research institutes, universities, and private companies, has been carrying out studies on SMS in four areas: exploration, mining and ore-lifting technology, ore processing and smelting technology, and environmental impact assessment.

The development of marine mineral resources has been attracting attention not only in Japan but also around the world. As for the development of mining and ore-lifting technology, Nautilus Minerals, a Canadian company that attempted to develop SMS in the territorial waters of Papua New Guinea (PNG), had completed the construction of three types of commercial machines (Nautilus Minerals Inc. 2018). As for manganese nodules, China, Korea, and India have developed mining machines and conducted self-propelled tests in shallow waters (Hong et al. 2010; Hong 2016; Liu et al. 2010; Janarthanan et al. 2018). In addition, the Korea Institute of Ocean Science and Technology had developed a buffer system, which is an important technology to adjust the slurry concentration. As a result in 2015, the lifting test using this buffer system was conducted in the shallow water of 500 m depth (Hong 2016). In addition, GSR successfully conducted a collection test at a water depth of 4500 m in April 2021 (GSR 2021).

On the other hand, there have been few studies on mineral processing technology in the world (Golder association report 2012). It was assumed to be similar to that of Japanese Kuroko based on the formation of SMS, but as the crystal structure is very fine, there are issues in improving the recovery rate and concentrate grade.

This chapter reports on the experience and results of the development of mining and ore-lifting technology since 2008, with a focus on the world's first pilot test conducted for ore-lifting of SMS in 2017. Furthermore, with regard to mineral processing, an optimum flotation system has been investigated and it has been researched whether the concentrates obtained from the flotation tests could be charged into the furnace at the existing domestic smelting plant.

2 Seafloor Massive sulfides in Japan EEZ

As shown by Tivey (2007) and Halbach et al. (1989), it is known that the sites of hydrothermal venting distribute along mid-ocean ridges, in back-arc basins, rifted arcs, and at submerged island-arc volcanoes. As shown in Table 7.1 (Morozumi et al. 2020), SMS mainly contain copper (Cu), lead (Pb), zinc (Zn), gold (Au), and silver (Ag). SMS in EEZ of Japan are mainly discovered at the Okinawa trough back-arc basin and the Izu-Bonin back-arc rift in the depths of 700 to 1600 m. JOGMEC has actually confirmed hydrothermal activities in these areas by observing and sampling with remotely operated vehicle (ROV). As shown in Fig. 7.1 (Morozumi et al. 2020), there are two forms of ore bodies at the Hakurei site. One is exposed on the seafloor and the other is below the seafloor.

Table 7.1 List of SMS deposits reported by JOGMEC

Name	Average ore grades Cu (%)	Pb (%)	Zn (%)	Au (g/t)	Ag (g/t)	As (%)	Data to calculate average grades	Date of news release [1]	T (°C) [3]
Okinawa area									
Hakurei site	0.41	1.44	5.75	1.45	95.6	0.26	Ore reserves of 7.4 million tons.	May 26, 2016	[4]
No ho site	0.53	7.81	12.03	3.26	911	[2]	6 samples taken from seafloor	December 4, 2014	350
Gondou site	3.38	2.39	6.39	0.97	62.6	[2]	153 samples taken from drill cores.	May 26, 2016	[4]
Dana site	3.70	8.14	24.01	3.90	525	[2]	5 samples taken from seafloor.	February 17, 2016	400
Higa site	0.27	29.00	33.41	0.05	212	[2]	2 samples taken from seafloor.	February 17, 2016	300
Kumi site	4.7	7.6	6.0	2.9	842	[2]	4 samples taken from seafloor.	July 21, 2017	350
Ginsui site	0.8	13.9	17.5	13.6	1061	[2]	8 samples taken from seafloor.	July 21, 2017	220
Izu-Ogasawara area									
Hakurei deposit	0.82	1.30	15.84	8.63	294.2	0.14	Ore reserves of 0.1 million tons.	May 26, 2016	150
Higashi-Aogashima deposit	1.00	6.21	23.91	17.02	1300	[2]	33 samples taken from seafloor.	December 27, 2018	267

[1] http://www.jogmec.go.jp/
[2] Arsenic contents are not reported
[3] Measured maximam temperature of hydrothermal water
[4] No data

3 Mining and Ore-Lifting Technology

Figure 7.2 shows a roadmap of R&D project for the 10 years to 2017. The main target for this decade is the ore-lifting test in 2017. Towards the realization of the main target, subsystem tests were carried out step by step to accumulate experience and knowledge.

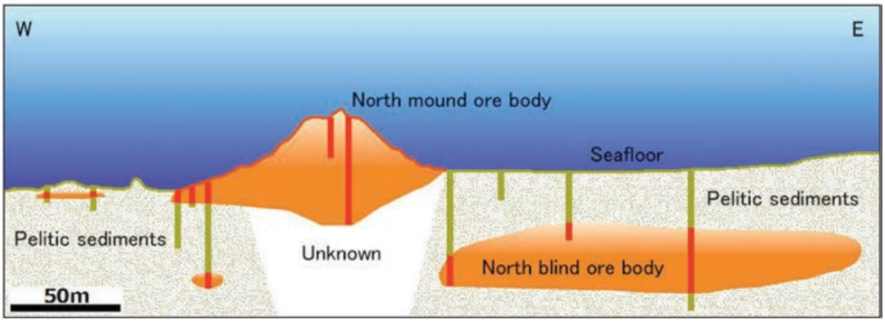

Fig. 7.1 Geological section of the north part of the Hakurei site in E–W direction. Vertical lines mean the drill holes. Pelitic sediments are partially consolidated

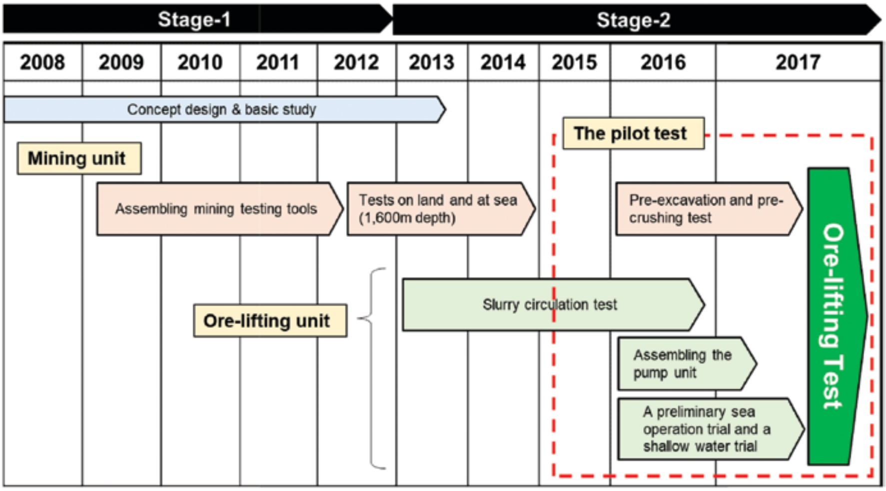

Fig. 7.2 Roadmap of JOGMEC's R&D project

3.1 Setting of Mining Conditions

For considering the mining system, it was necessary to assume the model to be developed and the mining method. Based on our previous knowledge of SMS, the mining conditions (ex. shape and physical properties of the SMS), mining method, and commercial production scale were set as shown in Table 7.2.

However, as a result of borehole investigations and various sampling using the marine research vessel Hakurei built by JOGMEC in 2012, the geotechnical characteristics of the mound have gradually become clear in recent years, such as the mound is steeper, the internal strength is not homogeneous, and the strength varies depending on the fill between each block of sulfide ore and the sulfide minerals that comprise it.

Table 7.2 Mining conditions

Item	Specifications
Mining target	A mound raisad from the seabed with a diameter of about 100 m and a specific height of about 20 m
Mound surface	Covered by gravel of several tens of centimeters to one meter in diameter
Top of the mound	Chimneys are present.
Uniaxial compressive strength of the ore	average of about 20 MPa (maximum 50 MPa)
Effective porosity of the ore	10–40%.
Spacific gravity of the ore	3–4
Mining method	Bench cut by mechanical excavation from the top downward
Maximum grain size of excavated product	50 mm or less
Mining rate per day	5000 tons wet weight

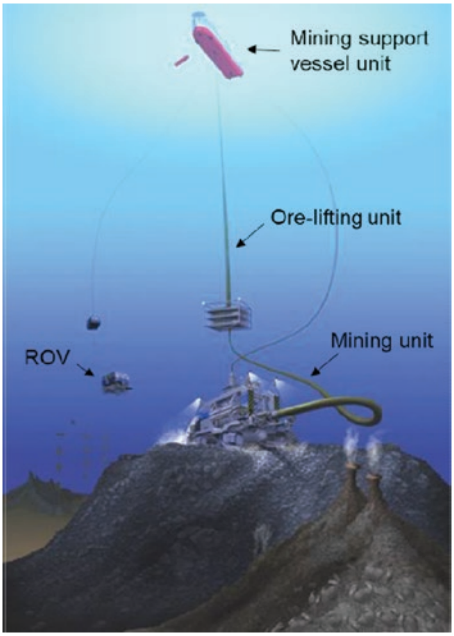

Fig. 7.3 Commercial mining system concept design

3.2 Development of the Mining and Ore-Lifting System

Figure 7.3 shows the configuration of the mining and lifting method for a model mound of SMS (METI 2013). The system consists of a mining unit, an ore-lifting unit, and a mining support vessel unit. In the mining unit, a self-propelled mining machine and collector excavate the mound to collect ore, which is then sent through a flexible pipe to a pump in the ore-lifting unit. In the ore-lifting unit, which consists of a pump and a lifting pipe (riser pipe), the ore sent from the submersible pump is lifted to the sea surface (to the ship). In the mining support vessel unit, the slurry of ore and seawater is separated into solid and liquid, and the ore is discharged to the shuttle ship for transportation to land. For each of these units, mining testing tools were designed, manufactured, and demonstrated.

3.2.1 Mining Unit

As shown in Fig. 7.4, two types of small mining testing tools were manufactured for the purpose of conducting technical evaluations of its subsystems for moving on mounds, excavation, and ore collection. Tests for these purposes were conducted on land, in a tank, and on the seafloor at 1600 m depth.

(A) Mining testing tool A: Four crawler system with multiaxis cutter head (Fig. 7.4a):

The tool A is designed to excavate and collect ores by one vehicle. Two types of cutter heads are used for different purposes: a biaxial type for leveling mounds and a drum type for efficiently excavating the leveled surface downward. The moving method is self-propelled by four crawlers, and each crawler is individually controlled by a cylinder to adjust the height and tilt of the crawler back and forth or left and right according to the condition of the seabed.

(B) Mining testing tool B: Two crawler system with road header (Fig. 7.4b):

The tool B is designed to excavate and collect ores with different vehicles. Thus, the head of this tool can be replaced to the excavation or collecting head. For the excavation, the road-header type, which is mainly used for coal mines and tunnels construction, was used.

These two tools were mounted on Hakurei to conduct mining tests in order to confirm and obtain data on different subsystems such as excavation and collecting conditions, moving conditions, operation techniques, and visibility improvement at

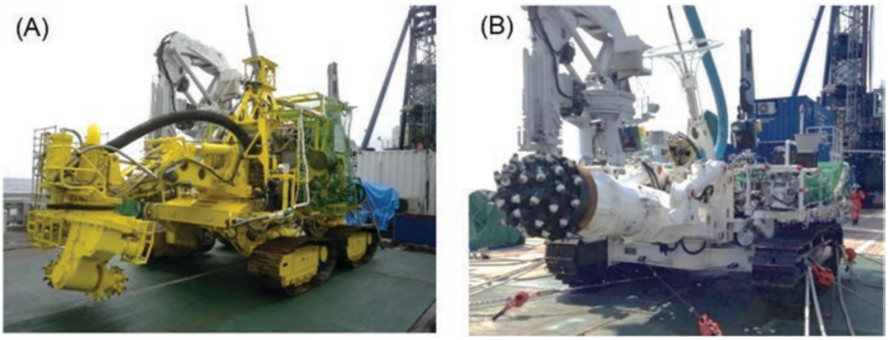

Fig. 7.4 Mining testing tools

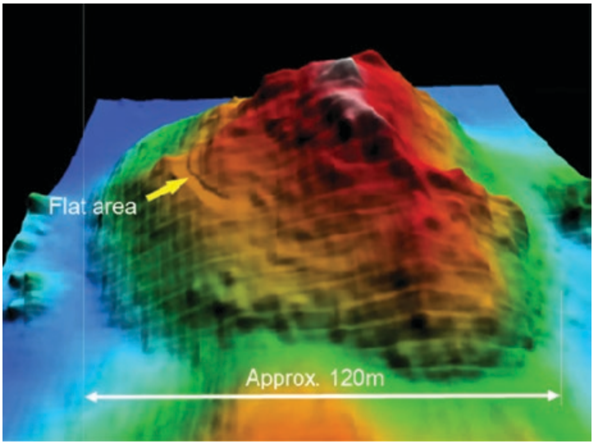

Fig. 7.5 The flat area created by the tool B on the mid-slope of the mound

a depth of approximately 1600 m in SMS area from 2012 to 2014. In these tests, the cutting efficiency of each cutterhead type, the particle size distribution of the cut ore, the wear condition of the bit, the movement performance, the visual capability in poor visibility conditions using 3D acoustic sonar, the series of on-board operations from launching to the recovery of the tools, and the remote operation were confirmed.

In the mining test using the tool B, 24-h continuous excavation was achieved, and a flat area (bench surface) was also created on the mid-slope of the mound (Fig. 7.5). There had been concerns about movement on that slope since it was thought that there were voids and soft fillings inside the mound, but there was no problem in the movement of the crawlers.

In these mining tests, environmental monitoring measurements of turbidity and underwater noise were also conducted before, during, and after the test to understand and evaluate the impact of excavation on the surrounding environment.

3.2.2 Ore Lifting Unit

The pump method, the airlift method, and the bucket method are often used for designing the ore-lifting systems. Here, the advantages and disadvantages of these are evaluated. The airlift method uses a three-phase flow of gas, liquid, and solid. So, it is difficult to predict whether its performance and productivity are consistent. The bucket method is inexpensive, technically established, and easy to maintain. But its productivity is low. Therefore, the pump system was selected because it was considered to have high productivity and ease of operation although it was not easy to maintain.

Then, the specifications of several combinations of riser systems, including rigid and flexible risers, diaphragm and turbo submersible pumps, and submersible pumps suspended from the hull and free-standing, were examined and compared for

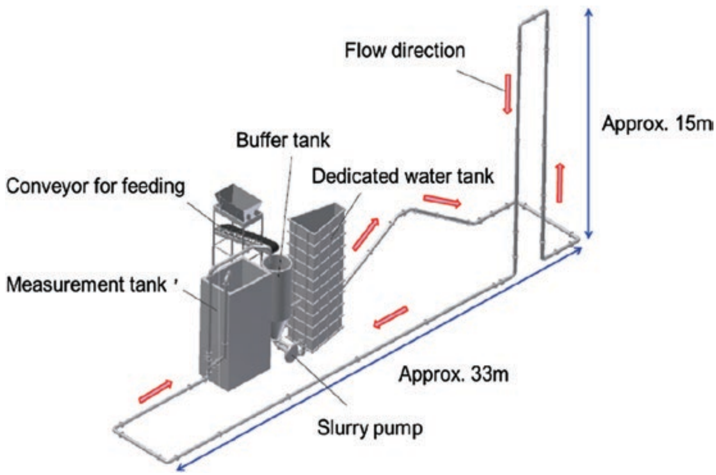

Fig. 7.6 Schematic diagram of the slurry circulation test

evaluation. The flexible riser, which could not be subjected to a large bending load, required a huge handling device, and the system weight and price were higher than those of the rigid riser. In addition, it was considered that there would be problems in installation and recovery work such as difficulty in tying the umbilical cable for the submersible pump. As for the submersible pump, the turbo type was considered to be more advantageous than the diaphragm type in terms of weight, power requirements, reliability, and price. Therefore, it was finally decided to adopt the rigid riser/turbo-type pump system.

For preparation for the pilot test, a slurry circulation test, as shown in Fig. 7.6, was conducted to develop an equation to estimate the pressure loss for designing the submersible pump (Hayashi et al. 2018) and to determine the amount of wear of the ore-lifting pipe (Takano et al. 2018).

The slurry circulation test was conducted to obtain an equation relating to the Froude number, which is the ratio of fluid inertia and gravity, to the density of the ore in SMS (3.5 g/cm^3), the density of the seawater to be pumped with the ore (1.037 g/cm^3), the inner diameters (D) (0.11 m and 0.20 m), and the slurry flow velocity (3.5–7.5 m/s). Slurry concentration (Cs) in the pipe was assumed to be 5%, 10%, and 15%. Hayashi et al. (2018) estimated the pressure loss of the ore-lifting pipe with a length of 2000 m (Fig.7.7, Hayashi et al. 2018).

3.2.3 Mining Support Vessel

There are two methods to keep the mining mother ship at the mining position: one is by using a dynamic positioning system (DPS), and the other is by using mooring cables. The DPS method was preferred as it does not require prior preparation work for positioning. Moreover changing the location of the mother ship is easier than by

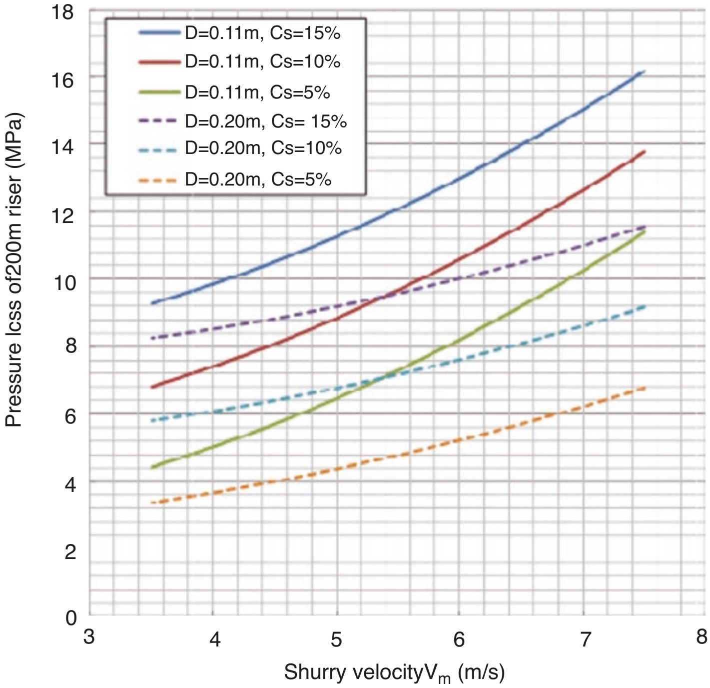

Fig. 7.7 Relationship between slurry velocity and pressure loss of 2000 m riser

using mooring cables. However, in the case of the DPS, the fuel consumption is more and the cost is high because of the need to constantly operate a large thruster.

3.3 Pilot Test of Excavation and Ore-Lifting

3.3.1 Purpose of the Pilot Test

The pilot test was planned to establish a comprehensive set of subsystems for mining and ore-lifting that will be necessary for the commercial exploitation of SMS. Moreover, it will be useful to identify issues such as technologies and costs that will contribute to the consideration of economic feasibility in preparation for the start of a project aimed at commercialization. For these purposes, the basic conditions were set as shown in Table 7.3.

A series of at-sea tests were conducted from 2015 to 2017 to verify the system from mining to ore-lifting, based on the results of the tests and equipment validation carried out until 2014. The tests were divided into three phases: the excavation, in which a mound of SMS was excavated in advance; the crushing, in which excavated fragments were crushed to a certain particle size or smaller and accumulated; and the ore-lifting, in which the accumulated fragments were lifted to the ship by a

Table 7.3 Basic conditions for the ore-lifting test

Item	Condition
Test area	Sea near Okinawa
Test period	August 22–September 23, 2017
Test depth	Approx. 1600 m
Slurry flow velocity	3.8 m/s
Slurry concentration target	3–5 vol.% (MAX 10 vol.%)
Maximum ore particle size	30 mm (long diameter)
Diameter of lifting pipe	Approx. 100 mm
Actual ore density	3.2 g/cm^3
Lifting method	Pump lift (lift pipe suspended)
Pump type	Multi-step centrifugal pump
Lifting pipe	Rigid

submersible pump. In particular, the final stage of the pilot test, that is, the ore-lifting test, was aimed not only at technical verification of continuous lifting but also the acquisition of various measurement data of the series of systems from ore collection to lifting, and the extraction and understanding of issues related to individual subsystems.

In the ore-lifting test, the main objective was to verify what could not be clearly proven in the land-based test. These include whether or not the rotation speed control could be reduced in the required discharge flow rate of the submersible pump, the understanding of the ore flow condition in the 1600 m vertical lifting pipe, and the operating condition and overall operation of the total system combining all the equipments.

3.3.2 Approaches to Ore-Lifting Test

In order to proceed with the pilot test, a 3-year plan was first prepared. After that, the test items were reviewed on the basis of the results of various tests. In order to conduct the ore-lifting test, the amount of ore required for the series of tests (excavation, crushing, ore collection, and lifting) was determined, and the mining plan including each method and procedure was studied. In the pilot test, the excavation test and the crushing test were conducted by using the tool B for excavation with the road header installed as the "excavation machine" and with the excavation head replaced by a crusher (bucket with a small jaw crusher) as the "crushing machine." The tool A was used as the "ore-collecting test machine" to conduct the collection work during the ore-lifting test.

3.3.3 Excavation and Crushing

In order to secure the SMS ore to be pumped in the ore-lifting test, the excavation test was conducted using the tool B in 2016 at the bench surface opened by the tool B in 2014. Operational test of the crushing tool on shore was conducted during 2017. Then, the crushing test in deep water was conducted prior to the ore-lifting test in 2017 to crush ores to less than 30 mm in length. The test result shows that the required amount of SMS ore was successfully secured. The crushed SMS ore was stored in a container to prevent contamination of large ore particles on the bench surface. This container is equipped with a screen to remove large particles. Thus, the risk of blockage of ore in the ore-collecting test machine and riser pipe is reduced.

3.3.4 Development of Submersible Pump System

The submersible pump unit is shown in Fig. 7.8. The pump unit is suspended from the vessel. The main specifications are shown in Table 7.4. It is a multistage centrifugal pump with a width of 3 m, a depth of 3 m, a height of 7 m, and a weight of about 30 tons. A flexible hose connects the bottom of the pump is connected to the ore-collecting test machine. The discharge flow rate of the pumps was set to 137 m^3/h by considering the pressure loss in the lift pipe at about 1600 m.

Two pumps were installed in the pump unit. The reason for using two pumps is that they are arranged in parallel with forward and reverse rotation to cancel out the rotational inertia acting on the pump units.

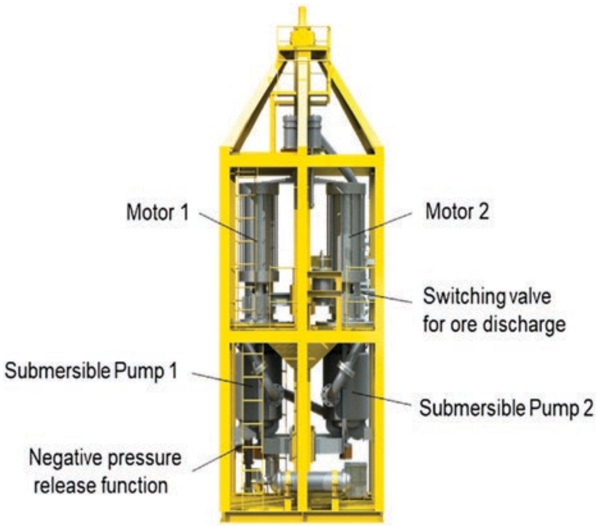

Fig. 7.8 Submersible pump unit

Table 7.4 Main specifications of the submersible pump unit

Item	Specifications
Discharge flow rate	137 m^3/h
Slurry volume density	Maximum of about 10
Ore density	Average 3.2; Maximum 4.0
Ore particle size	Less than 30 mm in length
Pumped liquid	Seawater containing ore
Minimum channel size	50 mm
Main dimensions (L × W × H)	Approx. 3.0 × 3.0 × 7.0 m
Weight in air/water	Approx. 28 t/approx. 24 t
Drive system	Inverter control/Approx. 250 kW motor

The submersible pump unit was completed in 2016 after conducting water performance tests, ore passage tests, slurry performance tests, pump performance tests, material wear tests, bearing tests, and seal friction tests at the factory. In the ore passage test, it was found that the ore stagnated inside the pump. Thus, an antirotation plate was installed at the impeller inlet side. As a result, the stagnation time of the ore was greatly reduced. During these tests, two conditions were found to prevent ore blockage, based on the experience of large diameter ore blocking the flow path in the pump. The first one is that the maximum diameter of the ore would be 30 mm or less. The second one is that the volume concentration of the slurry of ore and seawater would be controlled to 15% or less in order to allow the ore to pass through the flow path in the pump without blockage.

The negative pressure in the flexible hose due to the failure in the pump of the ore-collecting test machine may crush the hose. Therefore, a function to relieve the negative pressure was installed. Moreover, the riser pipe and pump may get blocked due to the falling of ores in the pipe when the pump is suddenly stopped. To prevent blockage of the pump and the pipe, an ore discharge switching valve is installed.

Prior to the ore-lifting test, the operation of the pump was checked at a depth of approximately 500 m. By comparing the data with the water performance test, it was confirmed that there were no abnormalities in the operating condition or performance even underwater pressure conditions.

3.3.5 Development of Ore-Lifting System

The ore-lifting pipe is used in the corrosive and abrasive environment of ore slurry transportation in seawater. Therefore various abrasion tests were conducted. Then, the duplex stainless steel was selected as the material for the ore-lifting pipe because of its high corrosion and abrasion resistance. However, the oil well pipe (SM-125S), which has excellent wear resistance among carbon steel pipes, was selected because it was used for a short time in the ore-lifting test and the effects of corrosion and wear were small.

For designing the lifting pipes, the required strength and working limits of the lifting pipes were calculated by the overall analysis of the lifting pipes based on the schematic design of the lifting system and the sea and atmospheric conditions. A slurry transfer analysis method that is effective for estimating the phenomenon of solid-liquid two-phase flow in the lifting pipe was developed. Then, a monitoring system was developed and manufactured to monitor and record the behavior of the lifting pipe and the slurry transfer condition in the lifting pipe.

3.3.6 Operability Evaluation and Safety Evaluation

A series of model tests (in wave generating pool) in 2016 and operation window analysis were conducted to examine the influence of the sea condition on the execution of the ore-lifting test. The allowable wave height obtained by the model tests of the lifting pipe strength as the threshold was used for the operation window analysis. In addition, the number of days of continuous operation was calculated by the operation window analysis using the allowable wave height obtained by the analysis of the lifting pipe strength as the threshold, and the basic plan of the ore-lifting test and the operation conditions were examined.

In order to give sufficient consideration to the safety aspects in the operation of the ore-lifting test, a Hazard-Identification (HAZID) was conducted in the initial stage of the pilot test planning. In 2016, Hazard and Operability Study (HAZOP) was held for all the processes extracted by HAZID, and 353 deviations from the design intent that were considered to cause accidents were identified, and countermeasures were discussed for each of them.

3.3.7 A Preliminary Sea Operation Trial and a Shallow Water Trial

A preliminary sea operation trial was conducted in 2016 to confirm the operation procedures, understand the time required for the operation, improve the operation rate by understanding the operation, acquire various data and identify issues that would contribute to the planning of the ore-lifting test. In addition, a shallow water trial at an about 500 m depth in 1 month before the ore-lifting test was conducted to confirm the overall functions of the submersible pump unit and ore separation equipment and to further train the proficiency of the operation. Through these tests, the time required for operation was greatly reduced. Moreover, safe and efficient operation procedures during the ore-lifting test were established.

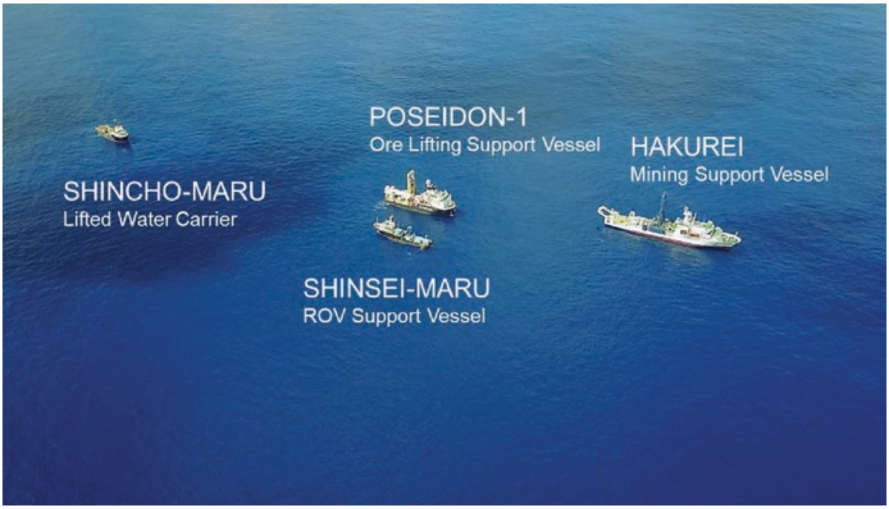

Fig. 7.9 Vessel operation work during the ore-lifting test

3.3.8 Outline of the Ore-Lifting Test

The ore-lifting test was conducted in the sea around Okinawa several times from August 22 to September 23, 2017, when the sea condition was favorable. The test sites were selected after a preliminary investigation of the topography, hydrothermal activity, and environmental characteristics.

Four vessels shown in Fig. 7.9 were used for the ore-lifting test. The first one is the mining support vessel (Hakurei), which operates the ore-collecting test machines. The second one is the ore-lifting support vessel (POSEIDON-1), which is responsible for launching and recovering submersible pump units, connecting mining pipes, and separating ores. The third one is the ROV support vessel (Shinsei-Maru), which supports underwater operations using ROV. The last one is the lifted water carrier (Shincho-Maru), which transports seawater (lifted water) after removing ores from the slurry to shore. Moreover, an information-sharing system was established to check the working status of each vessel to distribute and share key data such as ROV images and fluctuations of slurry concentration in the lifting pipe to all vessels.

The ore-collecting test machine (Fig. 7.10), the submersible pump, and the lifting pipe were installed on the seafloor in parallel. Then, the flexible hose under the submersible pump was connected at a depth of about 1600 m by the operation of the DPS, based on the real-time images transmitted from the ore-collecting test machine and ROV. The equipment layout for the ore-lifting test is shown in Fig. 7.11.

After connecting the ore-collecting test machine to the submersible pump, the ore stored in the container was collected along with seawater by remotely operating the collecting head of the machine from Hakurei, by changing the number of swings of the collecting head and the height of the head (digging depth). The ore was

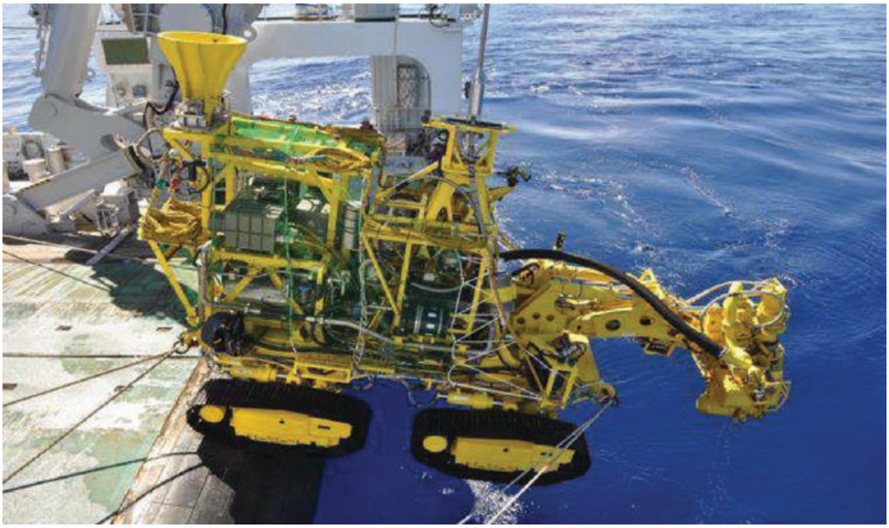

Fig. 7.10 Ore-collecting test machine launched from the deck of "Hakurei" (METI 2017; Okamoto et al. 2019)

pumped with seawater continuously in slurry form from the seabed to the ship using a submersible pump controlled from the top of POSEIDON-1. For the first test run using artificial ore was used, since it was considered better to use an ore of uniform particle size. The artificial ore is ferronickel slag, which is chosen because it does not leach heavy metal components into seawater. First test run was conducted, with a small turning speed and a shallow digging depth. Then, the swing speed and the digging depth were gradually increased. In the process, the relationship among the swing speed, digging depth, and slurry concentration, the condition of the submersible pump rotation speed control, and the condition of slurry transfer in the lifting pipe was collected. Then, the results were reflected in the next test plan, which enabled smooth test execution and reliable and appropriate data acquisition. These were based on the results and achievements of several tests using artificial ores. It was a challenge to lift SMS ore and highly concentrated slurry for a long period of time.

The pumped ore was separated from seawater by an ore separator installed onboard POSEIDON-1, and then stored in an onboard tank. The water that was lifted with the ore was transported to the water carrier. After the ore-lifting test, the entire amount collected was treated at a treatment facility on land.

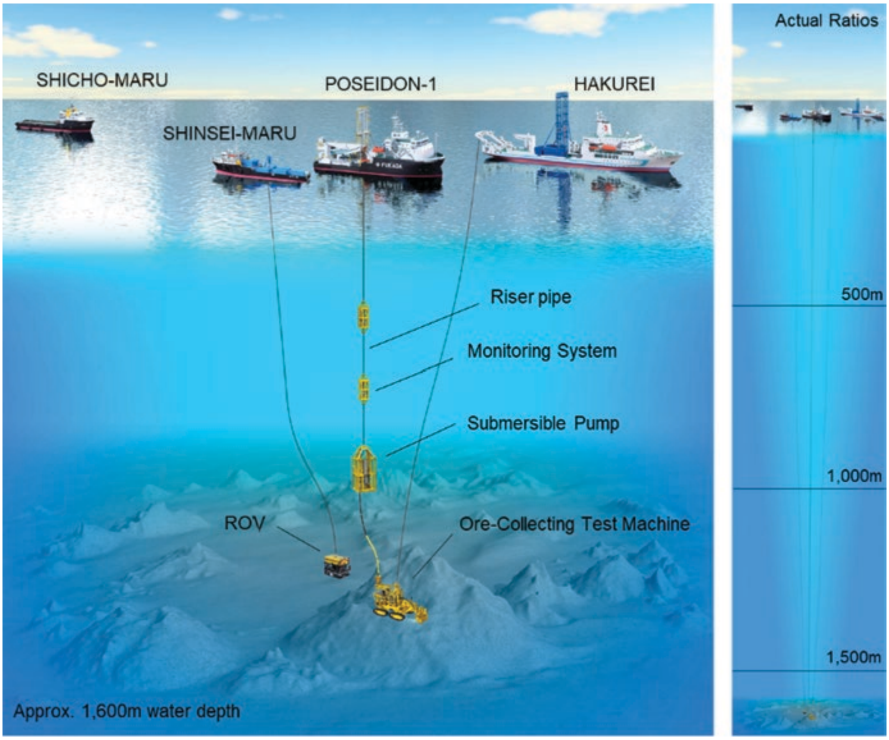

Fig. 7.11 Diagram of the ore-lifting test

3.3.9 Results of the Ore-Lifting Test

The slurry concentration, flow rate, and pressure during the test were monitored by a monitoring system installed in the ore-collecting test machine, the submersible pump, the lifting pipe, and onboard pipes. Through these tests, the excavation machine, the crushing machine, the ore-collecting test machine, and the submersible pumps were able to operate for long periods of time at the bottom of the deep sea. Moreover, very valuable information including technical verification of the series of systems from the ore-collecting test machine to the ore separator was successfully obtained. Data acquired during the operations are shown in Table 7.5.

Achievement of the ore-lifting test is shown in Table 7.6. In the ore-lifting test, no blockage occurred in the pump and the pipe. A total of 16 tests (10 for artificial ore and 6 for SMS ore) were successfully conducted. As a result, a total of about 16.4 tons of ore was achieved. A lifted ore photo after the separation from seawater is shown in Fig. 7.12.

The average ore concentration in the slurry during different tests is shown in Fig. 7.13. In the tests, the rotation speed of the submersible pump was controlled by an inverter to maintain a constant flow rate. Therefore, the control was carried out while carefully checking whether it could follow the fluctuation of slurry

Table 7.5 Data acquisition during/after the test

Item	Data acquisition
Monitoring System (on deck)	Slurry concentration(on deck), flow velocity, weight of lifted ore, temperature, pump discharge and so on
Monitoring System (riser system)	Slurry concentration (inner slurry pipe), deferential pressure, positioning, video, riser pipe acceleration motion and so on
Submersible Pump	Navigation, depth, deferential pressure, temperature, power supply and so on
Collector	Power supply, hydraulic data, navigation, depth, pitch and roll, boom angle, deferential pressure of in-line pump and so on

Table 7.6 Ore-lifting test achievement

	Date of test	Lifted ore	No. of test condition	Total operation time	Total lifted time	Amount of lifted ore
1	25 Aug. to 26 Aug. 2017	Artificial ore	8	4 h 21 min 40s	35 min 51 s	5668 kg
2	27 Aug. to 28 Aug. 2017	Sulphide ore	6	3 h 13 min 12 s	38 min 35 s	4140 kg
3	20 Sep. 2017	Artificial ore	2	1 h 35 min 04 s	22 min 28 s	6587 kg
			16	8 h 9 min 56 s	96 min 14 s	16,395 kg

Fig. 7.12 Lifted ore after the separation (on deck)

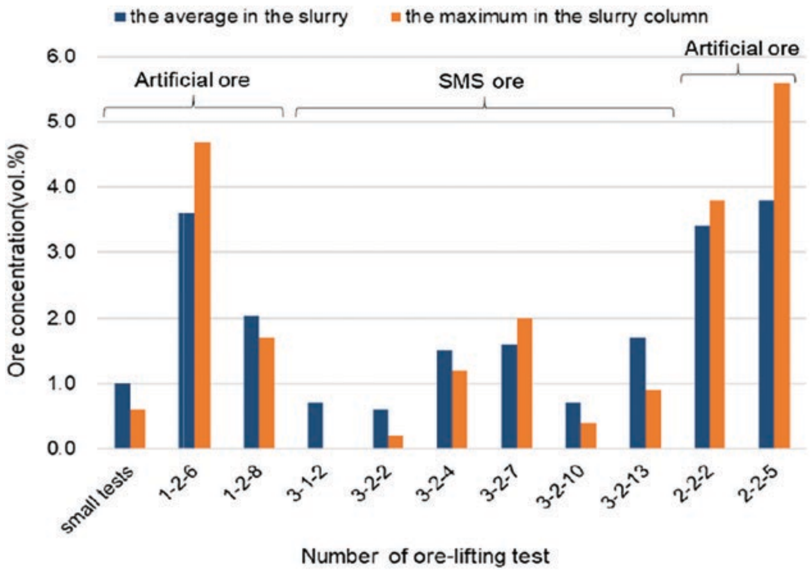

Fig. 7.13 Ore concentration

concentration. As a result, the average ore concentration in the slurry in one ore-lifting test was 3.8%, and the maximum ore concentration in the slurry column (the average concentration in the pipe when the pumped ore reaches the ship and the lifting pipe is filled with slurry from the outlet of the submersible pump to the ship) was 5.6%. The test using artificial ores resulted in higher concentrations than the test using SMS ores since the particle size of artificial ores was uniform. The test of deeper digging condition could be set without much risk of blockage.

Figure 7.14 shows the slurry density data from the monitoring device. Although some variation in slurry concentration occurred, the variation was maintained at depths of 900 m, 500 m, and at the sea surface with little change in condition. Therefore, it was found that there was no extreme concentration or dispersion of the high concentration area in the long-distance vertical lifting.

The regulations for the development of marine mineral resources are still under discussion internationally. An environmental baseline study was conducted in accordance with the ISA environmental guidelines prior to the implementation of this study. It was carefully confirmed beforehand that there would be no serious impact by numerical simulation prediction of the diffusion of the turbidity using a model developed for this test (Fig. 7.15). Environmental monitoring was also conducted during the test. After the test, the environmental impact will continuously be monitored.

The temperature of seawater lifted with the ore was 15 °C although it is 4 °C at the 1600 m depth. This means that the seawater was warmed for 11 °C during lifting. Okamoto et al. 2019 have indicated that 15 °C corresponds to a water depth of about 400 m when calculated from the existing CTD data (Fig. 7.16). This is the

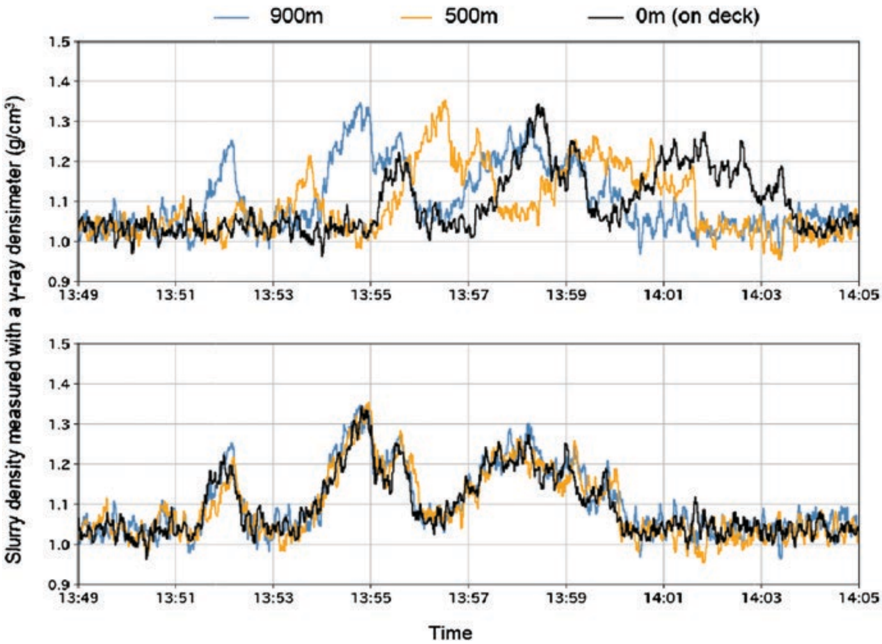

Fig. 7.14 Slurry density data from the monitoring device at each depth. The upper graph is for the same time at each depth. The bottom is time-shifted to a depth of 900 m

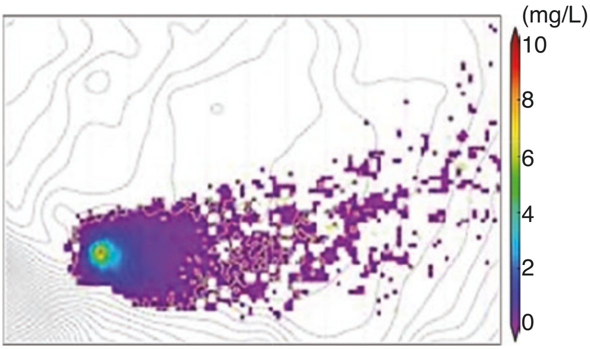

Fig. 7.15 Simulation result example of the distribution of resedimentation thickness of suspended particles by the predictive simulation model

temperature immediately after being lifted. It is necessary to consider the temperature after the separation and purification process for commercialization; however, this information is very useful for considering the depth of water discharge in the future.

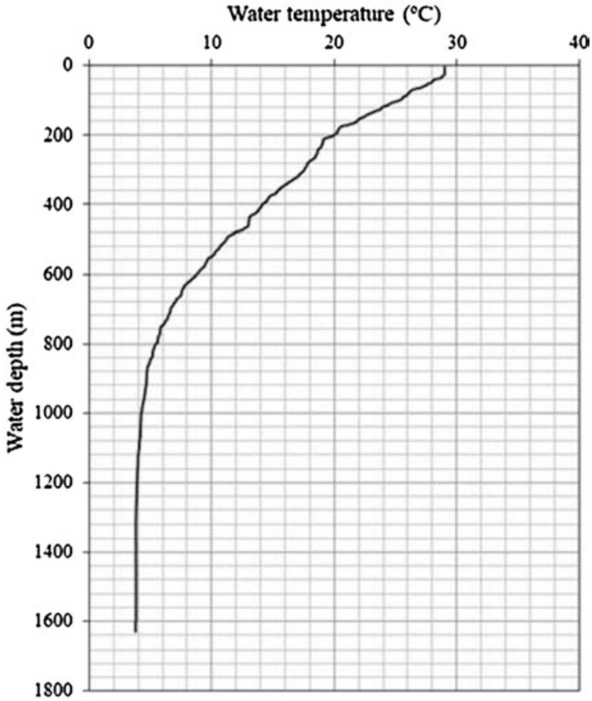

Fig. 7.16 CTD data (water temperature) in Okinawa area (Okamoto et al. 2019)

3.3.10 Summary of Pilot Test

The evaluation of the results of this pilot test revealed several issues to be addressed for achieving stable operations. The most important one is restructuring the entire mining and ore-lifting system by reviewing the mining plan. Specific examples are the method to adjust the ore particle size and ore concentration in the pipe system. For this purpose, a grinding system to make large ore into small particle and a buffer system to supply ore to a pipe system without fluctuation should be developed. There are many other technical issues that need to be resolved, such as improving the durability and maintainability of equipment and components during continuous operation, improving monitoring and simulation technology, and improving the efficiency and optimization of the entire system. The optimization of the system must be considered in conjunction with the reliability of the equipment and the redundancy and availability of the entire system.

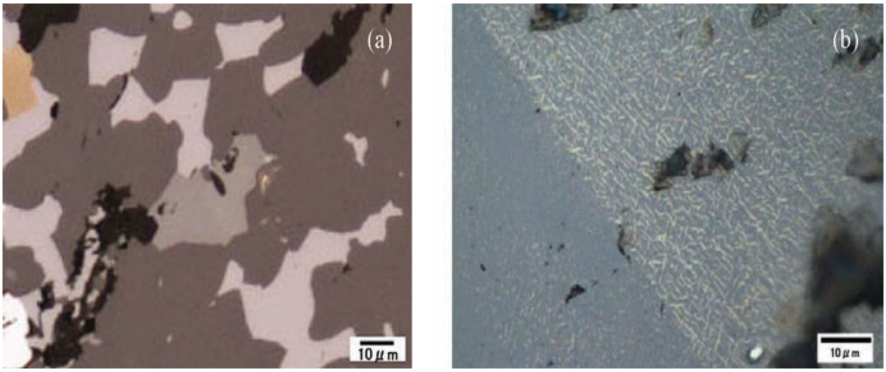

Fig. 7.17 Microscopic observation results of Kuroko (**a**) and SMS (**b**)

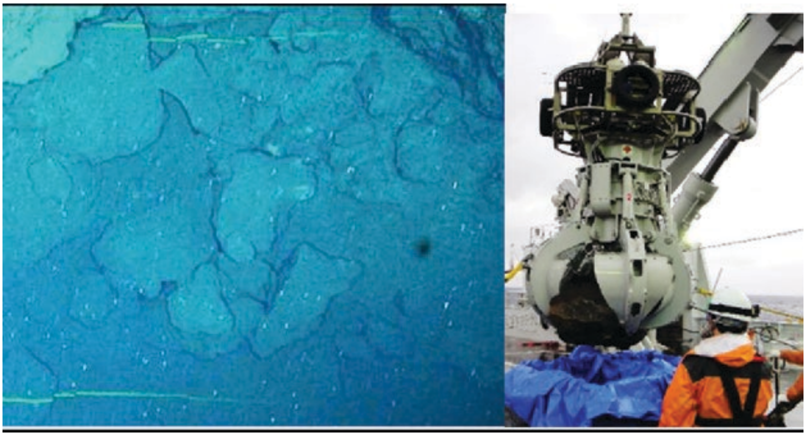

Fig. 7.18 SMS ores on the surface of the seafloor in Okinawa trough and Finder-installed Power grab

4 Mineral Processing Technology

4.1 Mineral Characteristics

SMS is a complex sulfide ore and it is known that the origin of SMS is similar to that of the Kuroko ore which has been mined and processed earlier mainly in the northern part of Japan. However, some properties such as mineral composition, mineral grain size, and crystallinity of SMS are totally different from the Kuroko deposits. Regarding SMS, the content ratio of iron sulfides is very high and that of gangue components such as silica (Si) is low. Furthermore, mineral grain size is minute as shown in Fig. 7.17, and the crystallinity of minerals is generally low. Therefore, the mineral separation and concentration process of SMS becomes much more complicated and would be a unique one.

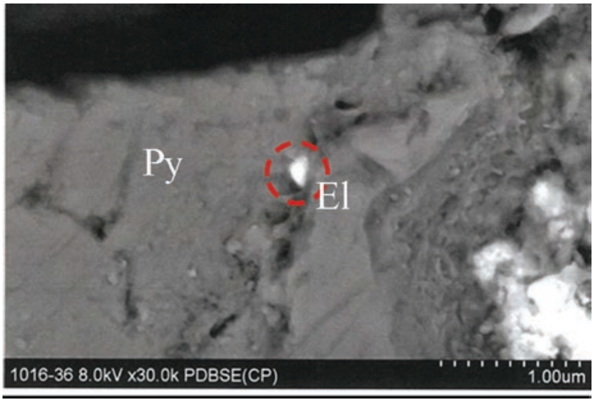

Fig. 7.19 Au observation result by Transmission Electron Microscope

Table 7.7 Dissolved ion concentration in the mixture of SMS ore and water with 20 wt% pulp

	Cu	Pb	Zn	Fe	S	As	Cd
Dissolved metal ion conc.	mg/L						
Kuroko	N.D.	2.5	38.9	29.9	75.2	N.D.	N.D.
SPS	N.D.	2.1	2027	602.9	1292	0.2	0.6

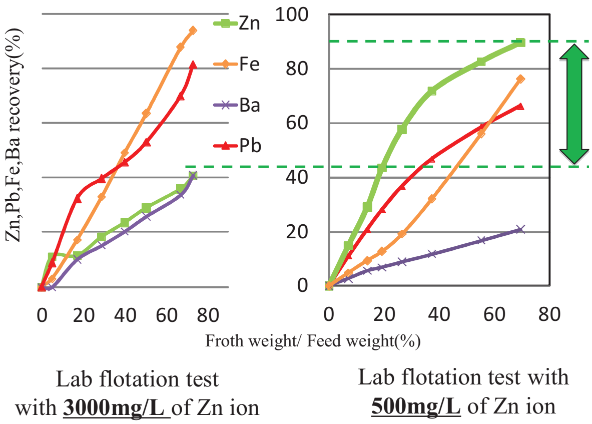

Fig. 7.20 Difference in zinc recovery by flotation depending on the zinc ion concentration in the ore pulp

In the research by JOGMEC, 15 tons of the SMS ore were sampled by Finder-installed Power Grab (FPG), shown in Fig. 7.18, from the surface layer of Izena Cauldron located in Okinawa Trough and some processing tests were conducted. The samples contain mainly Au, Ag, Cu, Zn, Pb, Fe, Si, and barium (Ba). The average grades of Au, Ag, Cu, Zn, and Pb were 2.6 g/t, 216 g/t, 0.3%, 7.3%, 2.5% respectively. Large quantity of Zn and Fe existed as sphalerite and pyrite, respectively. On the other hand, the majority of Pb in the ore was presented in the form of anglesite, not galena. In order to separate these minerals, the SMS ore sample had to be ground to a mean particle size of less than 20 micrometer because of very fine

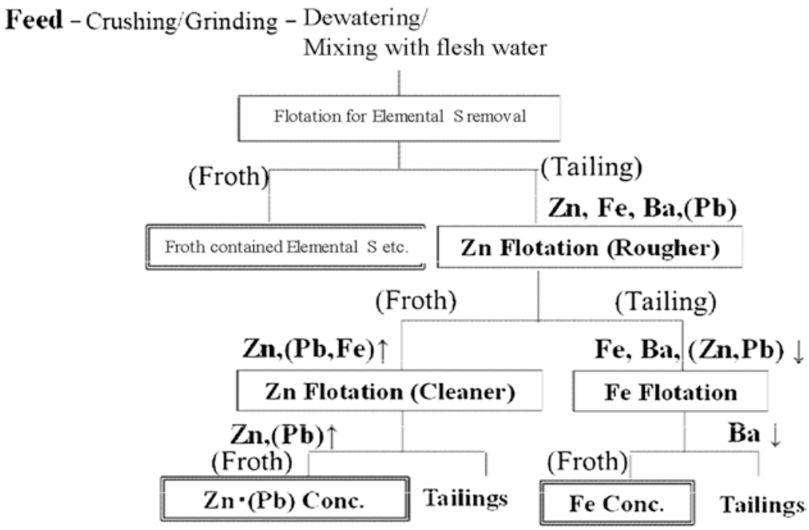

Fig. 7.21 Intended flotation process for SMS ore

mineral grain size. In addition, as shown in Fig. 7.19, Au was found in pyrite in the form of electrum with submicron particle size. Furthermore, it was very unique that the ore sample contained some elemental sulfur which was not often found in the Kuroko deposits.

Another feature of this SMS ore sample was its susceptibility to surface alteration. The SMS ore sampled from the seafloor was crushed into about 5 cm pieces and stored in 1 m3 polypropylene bags in the air for several months before the start of the test. When the ground ore sample and water were mixed with a pulp concentration of 20%, 2000 mg/L of Zn ion was detected from the pulp. Table 7.7 shows a remarkable difference in the concentration of ions leached from the Kuroko deposits. Although metal sulfides from on-land ores are generally insoluble in water, a large amount of metal ion was leached out from the SMS ore sample because its surface was easily oxidized in the air.

It is known that Zn ion works as a depressant in the flotation process and so a large amount of Zn ion makes it difficult to recover metal sulfides as froth. Figure 7.20 indicates the results of the lab flotation test using Zn ion solution (mass concentration of 500 mg/L and 3000 mg/L) and the mixture of mineral specimens such as sphalerite, pyrite, galena, and gypsum. From the result, it was found that the lower the concentration of zinc ion in the solution, the more sphalerite could be recovered and that zinc ion had to be removed before the flotation process.

Fig. 7.22 Lab flotation test equipment

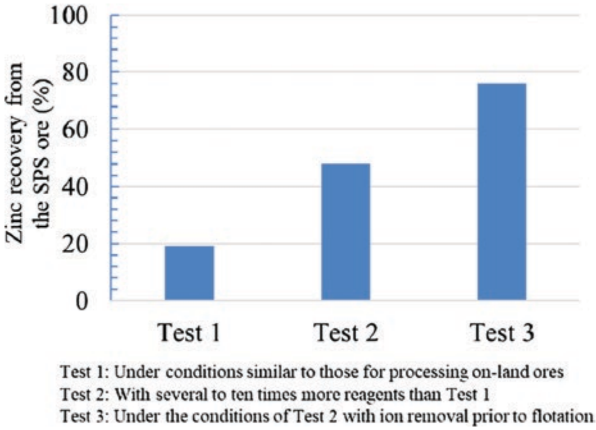

Fig. 7.23 Lab flotation test results

4.2 Development of Mineral Processing System

Based on these characteristics, a mineral processing system for SMS was developed. The system consists of crushing, grinding, dewatering (to remove metal ions), and multistep flotation. The process flow-sheet, which is based on the existing one for complex sulfide ores, is shown in Fig. 7.21. By this process, Zn, Pb, and Fe can be recovered as bulk concentrates.

With the test equipment shown in Fig. 7.22, the lab floatation tests were conducted using the SMS ore from Okinawa Trough as a feed sample in order to research an optimum flotation condition where more than 70% of zinc contained in the ore could be recovered as a concentrate with zinc grade of more than 40%. In the flotation tests, the ore was crushed and ground to a mean particle size of around 15 micrometers. Potassium amyl xanthate as a collector, sodium sulfite as a depressant, copper sulfate solution as an activator, and DOW250 as a frother were used at various dosages and pH was controlled between 6 and 12. Furthermore, to reconfirm the

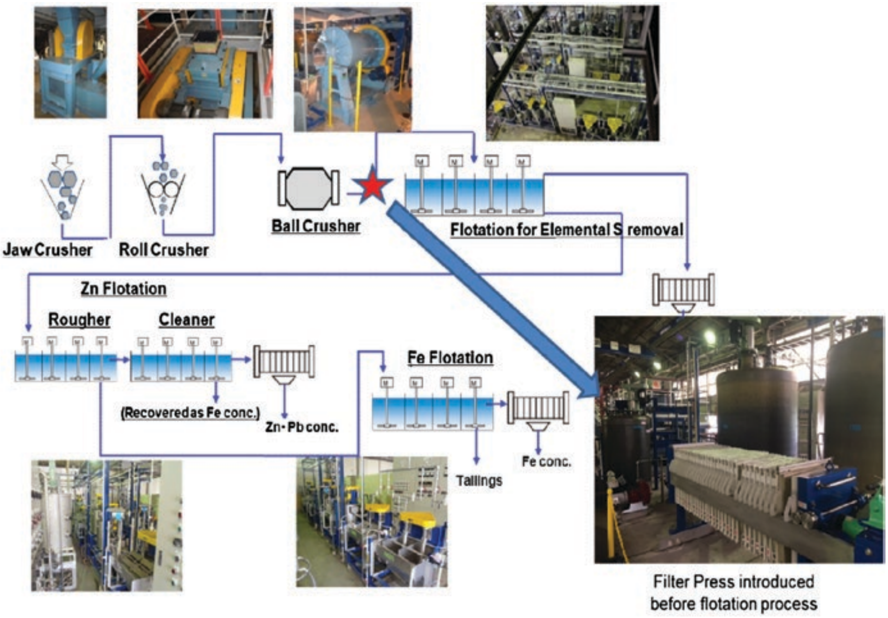

Fig. 7.24 Schematic design of the test plant for continuous flotation test

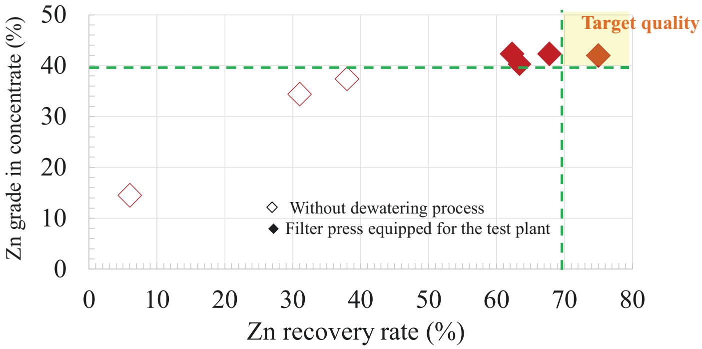

Fig. 7.25 Zinc grade and recovery of Zn/Pb bulk concentrate obtained by scale-up flotation test

influence of zinc ion in the ore pulp on zinc mineral recovery, flotation tests with/without the dewatering process were conducted. The test results are shown in Fig. 7.23. In order to achieve a zinc recovery rate close to the target of 70%, it was necessary to remove ions from the ore pulp before flotation and to add several ten times more reagents (especially depressants) than when processing on-land ores.

For the next step, the scale-up flotation test plant shown in Fig. 7.24 was constructed in order to demonstrate the performance of the mineral processing system with the conditions researched in lab flotation tests. The plant, which could process 200 kg of the ore per hour, was equipped with a jaw crusher, ball mill, filter press,

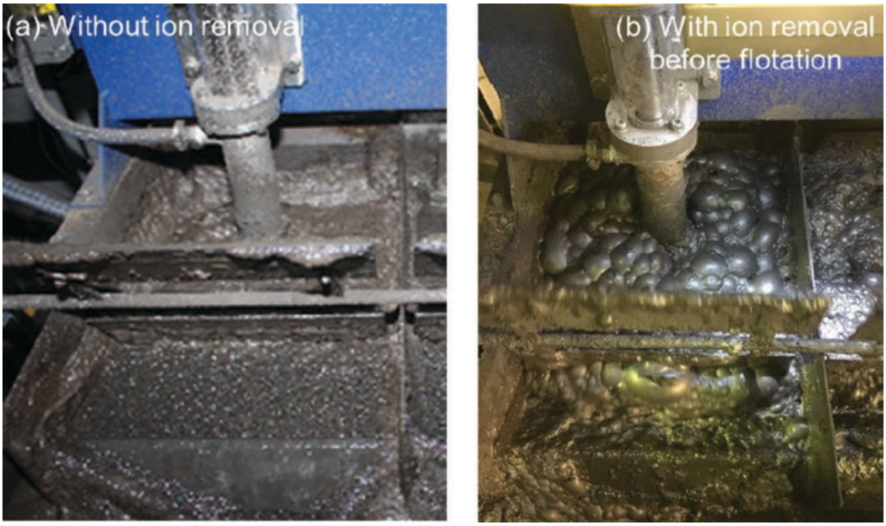

Fig. 7.26 Difference in zinc froth formation

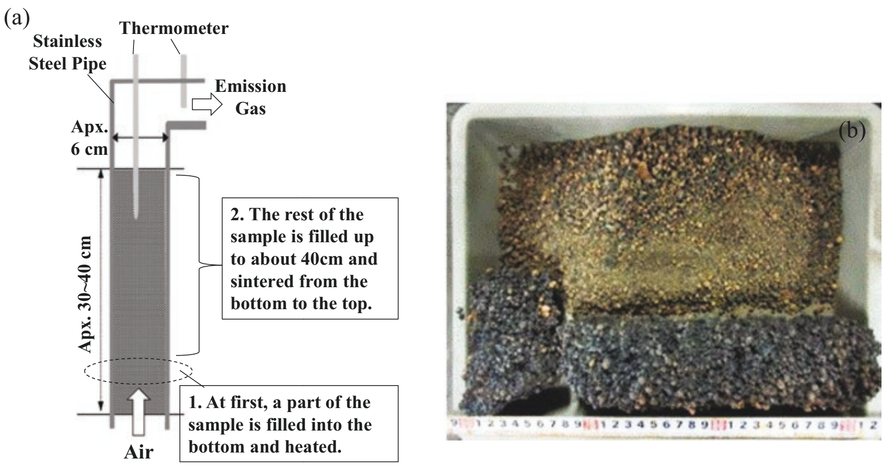

Fig. 7.27 Schematic design of the test equipment (**a**) and sintered test sample (**b**)

and some conventional flotation machines. First, the preliminary flotation tests without the dewatering process were conducted. In the test, only a little amount of froth was generated during the flotation process and the zinc recovery rate was less than 40%. On the other hand, in the test with dewatering process by the filter press, zinc recovery rate improved to more than 70% at maximum, where zinc grade of the concentrate was around 40% as shown in Figs. 7.25 and 7.26. In the case where the ore pulp is filtered before flotation, more froth was generated. Finally, 2 tons of the

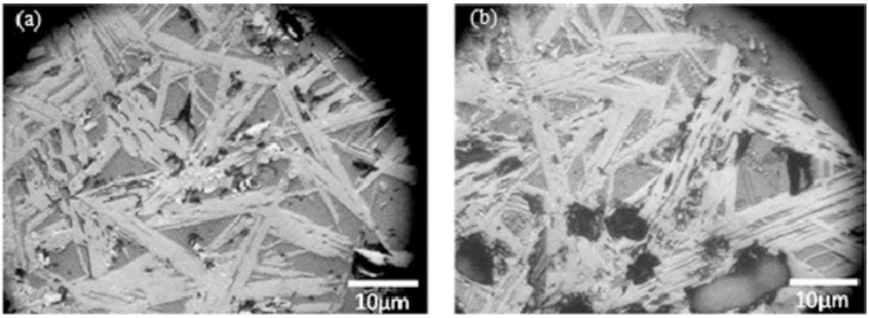

Fig. 7.28 Crystal structure of zinc oxide in the actual sintered Zn/Pb bulk concentrate produced by the existing domestic smelter (**a**) and the one mixed with the SMS concentrate (**b**)

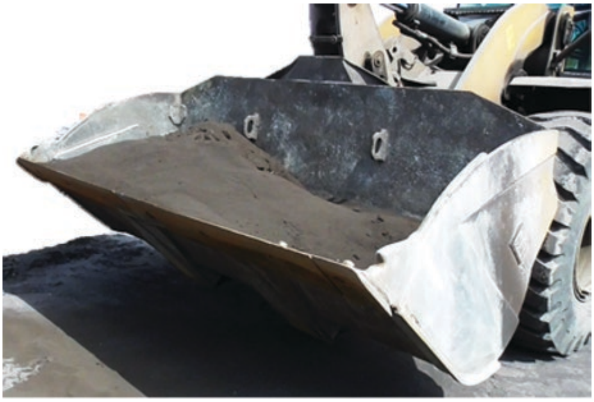

Fig. 7.29 The Zn/Pb bulk concentrate derived from the SMS ore actually charged into the furnace at the domestic smelter

Zn/Pb bulk concentrate with a sufficient grade of zinc for the existing domestic smelter was obtained from 15 tons of the SMS ore.

4.3 Applicability of Zn/Pb Bulk Concentration to the Smelter

Regarding the Zn/Pb bulk concentrate obtained by the scale-up flotation test described above, its sinterability as well as elemental composition to evaluate the acceptability of the concentrate to the existing domestic smelter was investigated. In the Zn/Pb simultaneous smelting process, fine and powdery concentrates are not put directly into the furnace. It is once pelletized and sintered in order to form a lump and then charged into the blast furnace. This pretreatment creates sufficient space in the furnace and promotes effective smelting. Therefore, the concentrates that cannot be made into a large lump are not preferable. In the JOGMEC's research, sintering pot tests were conducted. The schematic design of the test equipment is shown in Fig. 7.27(a). The test sample was the mixture of the concentrate, which was

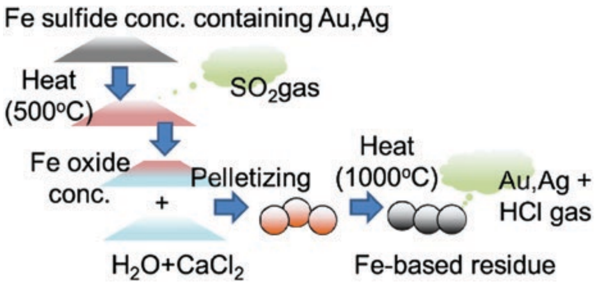

Fig. 7.30 Schematic design of the chloride volatilization test for iron sulfide concentrate

currently processed at the existing Zn/Pb smelter in Japan, and the one obtained by scale-up flotation test. Duration of the test was 30 min and the maximum temperature of the inside of the pot reached to 1300 °C. Compared the sintered test sample shown in Fig.7.27(b) with the actual sintered concentrate produced at the smelter, there was almost no difference in quality such as metal grades, the weight ratio of sintered concentrate to unsintered one as well as the crystal structure of zinc oxide in the sintered concentrate shown in Fig. 7.28. These results indicate that the Zn/Pb bulk concentrate from the SMS ore could be processed by the existing Zn/Pb smelting method. Finally, as shown in Fig. 7.29, 2 tons of the concentrate, equivalent to about 800 kg of zinc metal was charged into the actual production line at the smelter.

4.4 Processing Method of Iron Sulfide Concentration

Based on the material balance obtained from the flotation test, the weight ratio of Zn/Pb bulk concentrate to the SMS ore feed was about 15%. On the other hand, the weight ratio of iron sulfide concentrate, which could be obtained by Fe flotation after Zn recovery, was about 60%. The problem is that 50% of Au in the SMS ore tended to be contained in the iron sulfides concentrate. In this research, in order to recover the precious metal, the applicability of the chloride volatilization method was investigated. This method is commercially available technology and is also effective for the recovery of other nonferrous metal components. Furthermore, if volatilization of these components is successful, the iron-based residue left after volatilization could be utilized as an iron raw material.

The schematic design of the chloride volatilization test for iron sulfide concentrate is shown in Fig. 7.30. After removing sulfur at 500 °C, iron oxide concentrate is mixed with calcium chloride and calcinated at 1000 °C to volatilize nonferrous elements, including precious metals, with hydrogen chloride gas. From the test results, it was found that 95–99% of Au and Ag contained in the concentrate could be selectively recovered.

5 Conclusions

5.1 Mining and Ore-Lifting Technology Development

The success of the ore-lifting test was a major step toward establishing the technology necessary for the development of marine mineral resources. However, there are still many issues to be addressed for development. It is necessary to fully analyze and evaluate the data obtained from this pilot test in order to correctly recognize various issues. Then, it is important to continue the efforts toward the commercialization of SMS from a long-term and comprehensive perspective.

Furthermore, there are still some issues to be addressed in terms of the environment. JOGMEC will continue to assess the environmental impact of the project and use the environmental data and assessment results obtained so far to contribute to the development of a sustainable international standard for marine mineral resources based on scientific data.

5.2 Mineral Processing Technology Development

SMS contains more iron sulfides compared to on-land ores. Grain size of each mineral in the SMS ore is minute and not sufficiently liberated. The surface of the material is easily altered when stored in the air, and just by mixing it with water, a large amount of metal ions are dissolved, which adversely affect flotation performance.

Based on these characteristics, in order to develop the processing system, the flotation tests were conducted using the ore mainly containing Zn, Pb, and Fe from Izena Cauldron, Okinawa Trough. By adjusting the quantity of the agents and removing zinc ion with filtration before flotation, the zinc grade and recovery rate of the concentrate reached around 40% and 70%, respectively. Furthermore, it was confirmed that the Zn/Pb bulk concentrate had enough sinterability. From these results, 2 tons of the concentrate equivalent to about 800 kg of zinc metal was charged into the actual production line at the domestic Zn/Pb smelter.

However, in order to obtain sufficient zinc recovery, the flotation process requires several to a dozen times more reagents than when processing land ores, which is a problem and further improvement is required. Moreover, because of impurities content such as As and Hg, the charging amount of the concentrate to the smelter would be limited, so that the research for removal of these toxic elements would be required in future works. In addition, the flotation tests for the SMS mainly containing Cu are currently being conducted, with the goal of developing a flotation process that can be applied to various types of ores.

Regarding iron sulfide concentrate which could be obtained by Fe flotation after Zn recovery, the applicability of the chloride volatilization method was investigated in order to recover the precious metals contained in the concentrate. From the test results, it was found that 95–99% of Au and Ag contained in the concentrate could be selectively recovered. However, it was the technical issue that volatility of Cu and Zn was relatively low, at 89%. Practical issues also remain, such as how to treat sulfurous acid gas (sulfuric acid) generated by desulfurization before chloride volatilization. Thus, it is necessary to continue to study not only for further improvement of the volatility of nonferrous metal components in the chloride volatilization process but also for more feasible methods of processing iron sulfide concentrates.

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Chapter 8
Comparative Advantages of the Mineral Processing of Deep-Sea Polymetallic Nodules over Terrestrial Ores

Chris Duhayon and Simon Boel

Abstract A review of comparative advantages of mineral processing of deep-sea polymetallic nodules over terrestrial ores is attempted. The work conducted as part of Global Sea Mineral Resources' onshore processing development strategy has contributed to answer the critical questions related to the choice of the flow sheet, the adequateness of the beneficiation of polymetallic nodules, the behavior of nodules with regard to comminution, and how it compares to land-based ores in terms of energy intensity. The results suggest there is an undisputable environmental advantage associated with the comminution of polymetallic nodules as compared to conventional (monometallic) land-based ores, due to their higher grade, polymetallic character, and comminution behavior.

Keywords Polymetallic nodules · Mineral processing · Beneficiation · Comminution · Metal-specific energy · Manganese · Nickel · Copper · Cobalt

1 Introduction

This chapter proposes a view of the comparative advantages of mineral processing of deep-sea polymetallic nodules over terrestrial ores. As Global Sea Mineral Resources (GSR) incorporated the onshore processing of nodules in its development strategy, critical questions related to mineral processing were raised: What should the process flow-sheet look like? Is the beneficiation of polymetallic nodules to be ruled out upfront? What is the comminution behavior of nodules, and how does it compare to land-based ores? Is there a gain in energy intensity related to the mineral processing of nodules compared to terrestrial ores, and if so, what are the drivers? As the work progressed toward finding an answer to these questions,

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advantages started to emerge, which required to be formalized and put into perspective. The present work is a contribution to that purpose.

The first part provides a brief reminder on the deep-sea polymetallic nodules characteristics that are relevant to our discussion. A short review on the manganese ore beneficiation processes is then proposed and used in a discussion about their restricted application to polymetallic nodules. This is put into perspective in the light of the results of a nodules sample preparation, which concludes this part.

The second part briefly reviews the literature treating comminution characteristics of polymetallic nodules and shares chosen data from a study on the grindability of the polymetallic nodules. The results of the Bond Ball Mill Work Index and Abrasion Index test-work are discussed and compared with land-based ores. Useful considerations related to comminution equipment wear rates are shown. It concludes by showing the results of a comparison of metal-specific energy, a metrics that take the grade and the polymetallic character of ore into account when comparing the comminution energy intensity.

2 Polymetallic Nodules Beneficiation

2.1 Deep-Sea Polymetallic Nodules Characteristics

Deep-sea polymetallic nodules and their physicochemical characteristics have been exhaustively studied in the past, (Burns and Fuerstenau 1966; Barnes 1967; Fuerstenau and Han 1977, 1983; Mukherjee et al. 2004; Wang et al. 2009; Hesse and Schacht 2011; Dreiseitl and Bednarek 2011; Kuhn et al. 2017). This section refreshes the necessary aspects for the following discussion and presents results from a study carried out for GSR by a specialized partner.

In their seminal work, Burns and Fuerstenau (1966) observed the manganese phase as δ-MnO_2, 7 Å manganite and 10 Å manganite, and an iron-rich amorphous phase believed to contain hydrated FeOOH. Nickel, copper, magnesium, aluminum, and potassium are deported in the manganese phase, and cobalt, titanium, calcium, and silicon are deported in the iron phase (Burns and Fuerstenau 1966). The manganese oxides were later identified as birnessite, todorokite, s-birnessite (Giovanoli et al. 1970), hydrohausmanite, and vernadite (Post 1999). Fuerstenau et al. note that nodules consist of 100 Å–500 Å colloidal particles as evidenced by the internal pore size distribution and by the electron probe and scanning electron microscopy studies (Fuerstenau and Han 1977, 1983). The nodule samples mentioned in their work originate from the Mexican coast, Polynesia, and one from the UKSR contract zone, and the gangue characteristics are not discussed in detail. It is therefore arguable that the presented results would be valid for nodules originating from other parts of the CCFZ.

In terms of species deportment, the results obtained by our specialized partner are in agreement with previous observations (Burns and Fuerstenau 1966; Fuerstenau and Han 1983) and indicate that manganese is unevenly deported in the manganese-rich and iron-rich phases, cobalt is only present in the iron-rich phase and nickel and copper are mainly present in the manganese-rich phase. No deportment of metal of interest (Ni, Co, and Cu) is observed in the gangue. The gangue represents 30% by weight of the dry nodules and has been observed as free grains and fine inclusions in the manganese and iron phases, with d_{50} of 16 μm for the quartz, 17 μm for the feldspars, and 21 μm for the micas present in the manganese-rich phase but also in a smaller proportion (<20%) in the iron-rich phase. The CCFZ polymetallic nodules bear some similarities with the terrestrial manganese oxide ores as they are in the oxidized form and with their manganese grade of 30% wt. and iron grade around 5% wt., their Mn/Fe ratio is around 6, which is much lower than 11.3, an Mn/Fe average based on a sample of low-, medium-, and high-grade ores from diverse origins (South Africa, Australia, West Africa, Latin America, Eastern Europe, and India), and also lower than 8.8, an Mn/Fe average based on a subset sample of high-grade ores (grades > 40% wt.) from the previous sample.

2.2 Presentation of the Manganese Oxide Ore Beneficiation Processes

As the beneficiation options for polymetallic nodules are discussed, it is adequate to mention the processes applied to manganese ores: the low and medium grade manganese ores are usually upgraded by beneficiation processes, which after crushing and screening would include jigging, spirals, dense media separation, flotation, or a combination thereof (Singh et al. 2019). The choice of the beneficiation process depends on the nature of the ore (siliceous, carbonate, or oxide). For the oxide ores, the goal is not only to upgrade the ore but also to ensure an adequate Mn/Fe ratio, as the ferruginous ores with an Mn/Fe ratio lower than 1.5 are not suitable for metallurgical processing. The main manganese oxide ore beneficiation plants such as those found in GEMCO in Australia (Groote Eylandt Mining Company, part of the South 32 group) and COMILOG in Gabon (part of the Eramet group) use gravity separation methods, such as dense media techniques and jigging (Singh et al. 2019).

The specific gravity of iron-bearing impurities in these ores varies between 4 and 5.2, whereas the manganese oxide minerals have a specific gravity higher than 4, which complicates the gravity separation process (Singh et al. 2019). The gangue minerals such as quartz, gibbsite, and kaolinite have a lower density and can therefore be removed by gravity separation, in which case the upgraded mineral flow will still contain manganese and iron species.

Magnetic separation is another method used to sort the ores. It is based on their magnetic properties such as permeability and susceptibility. Ores containing ferromagnetic minerals (e.g., magnetite) can be separated or enriched with low-intensity magnetic separators, while paramagnetic or weakly magnetic particles require higher flux densities found in high-intensity magnetic separators, typically ten times those of low-intensity magnetic separators (Fuerstenau and Han 2003). However, the paramagnetic iron minerals such as hematite and goethite offer only a narrow difference in magnetic properties from the also paramagnetic manganese minerals (Gao et al. 2019). In the latter case, a solution to circumvent the limited success of the habitual magnetic separation process is to perform a preliminary reduction roasting. The reduction of the paramagnetic hematite to ferromagnetic magnetite widens the difference in magnetic susceptibility and allows an efficient magnetic separation. An increase of manganese grades from 36% wt. to 44% wt. with limited loss of manganese and increase in Mn/Fe (Gao et al. 2012), and an increase of manganese grades from 30% wt. to 56% wt. with a 71% recovery yield of manganese and an increase in Mn/Fe from 1.04 to 10.85 (Gao et al. 2019) have been reported.

Flotation has previously been studied in the context of manganese oxide ore beneficiation (Fuerstenau et al. 1986). It is generally observed that flotation of oxide minerals can upgrade the ore by removal of gangue minerals (Mehdilo and Irannajad 2014; Rahimi et al. 2017), but the selective separation of manganese and iron is poor (Bayat et al. 2013; Singh et al. 2019). One of the reasons is the ambiguity of the ranges of point of zero charge of hematite (pH 4.0–8.9) and pyrolusite (pH 4.2–7.4), which seem to be highly dependent on the origin of the mineral (Parrent 2012). The consequence is a limited increase in the Mn/Fe ratio by flotation itself.

2.3 Discussion of the Beneficiation Processes for Polymetallic Nodules

Although both the Mn grade and the Mn/Fe ratio of polymetallic nodules would suggest the benefit of upgrading them, the dissemination of metals of interest and their intricate structure question both the possibility and the attractiveness of beneficiation: the mineralized fraction represents the major part of the ore and the metals of interest are deported and finely disseminated in the manganese and iron-bearing phases; the gangue particle sizes and the particle density differences are at the lower end of the size range of common size-separating and gravity-separating devices, except in special circumstances (Fuerstenau and Han 2003). Preconcentration of deep-sea polymetallic nodules via density separation, flotation, and magnetic separation is commonly considered to be impossible (Wegorzewski 2018).

It is known that separation by density difference under gravity becomes less efficient for fine particle sizes, and that flotation becomes the dominant separation process with this regard (Gupta and Yan 2016). However, gravity separation usually exhibits advantages over flotation: a lower installed cost and power requirement per ton of throughput, and the absence or reduction of expensive organic reagents. Two main methods can be used to evaluate the effectiveness of gravity separation: the evaluation of the ±0.1 specific gravity, and the calculation of the equal settling ratio (Fuerstenau and Han 2003; Gupta and Yan 2016). Depending on the methods to be

Table 8.1 Densities of manganese/iron mineral and gangue species

	Species	Density (–)
Manganese/iron minerals	Vernadite	2.9–3.0
	Birnessite	3.0
Gangue	Quartz	2.7
	Albite	2.6
	Mica	2.8–3.0
	Feldspath	2.6–2.8

used, the determination of the respective densities of the species to be separated and a sink-float analysis are recommended. As shown in Table 8.1, the manganese/iron mineral species and the gangue species have similar densities. The gangue density was estimated at 2.7 by using its weight composition and the density of its mineral components.

Heavy media separation would require the use of a solid heavier than the mineral to be floated to produce a quasi-stable suspension which density is intermediate between the manganese-rich phases (density range: 2.9–3.0) and the gangue (density 2.7). Heavy media vessels can handle tonnages as high as 700–800 tph, however with coarse material (Fuerstenau and Han 2003). Instead of carrying out a sink-float analysis on nodules crushed and ground to #100, a preliminary evaluation of the criteria used by the two methods was performed. An ideal scenario was assumed by considering that the gangue particles and the Mn-rich particles are perfectly liberated and have respective densities of 2.7 and 2.9. These assumptions lead to the hypothetical sink-float test data shown in Table 8.2. They clearly illustrate the difficulty to find an adequate heavy liquid for a sink-float separation. Tribromomethane (density of 2.87) would be a candidate but is a Group 3 carcinogen and linked to liver toxicity (Gupta and Yan 2016), so a pseudo heavy liquid with adequate density could be used. The case is too simplified to represent washability curves inferred from the data in Table 8.2, but the examination of the ±0.1 specific gravity distribution shows values higher than 25, which is considered as a threshold value for gravity separation feasibility (Gupta and Yan 2016). The hypothesis of an ideal scenario is not restrictive in our case, as a distribution of particles composed of gangue and Mn-rich minerals would always exhibit ±0.1 specific gravity values higher than the ideal case represented in Table 8.2. It can be concluded that the implementation of the sink-float separation method for polymetallic nodules is impossible in the current technological context.

In the same conditions, the equal settling ratio d_L/d_H (also known as the concentration criterion) was evaluated using Eq. (8.1) for the manganese mineral species (vernadite, birnessite) and the gangue, considering water as the fluid used for separation. In Eq. (8.1), ρ_H is the specific gravity of heavy particles, ρ_L is the specific gravity of light particles, ρ' is the apparent specific gravity of the fluid or the suspension (in case of hindered settling), and the exponent n depends on the regime (Newtonian or Stokesian).

Table 8.2 Hypothetical sink-float test data related to the ideal situation involving perfectly liberated gangue particles (30 wt%) and Mn-rich particles (70 wt%) with respective specific gravities of 2.7 and 2.9

Specific gravity range	Mass (wt%)	Cumulative float mass (%)	Cumulative sink mass (%)	±0.1 Specific gravity distribution
F2.7	0	0	100	–
S2.7–F2.8	30	30	100	30
S2.8–F2.9	0	30	70	70
S2.9–F3.0	70	100	70	70
S3.0	0	100	0	–

$$d_L / d_H = \frac{(\rho_H - \rho')^n}{(\rho_L - \rho')^n} \tag{8.1}$$

Three sets of assumptions considered as limiting cases were used:

(a) Free settling, the solids concentration in water being neglected ($\rho' = 1$ g/cm^3) and Newtonian conditions ($n = 1$).
(b) Hindered settling, 25% solids in water ($\rho' = 1.45$ g/cm^3) and Newtonian conditions ($n = 1$).
(c) Hindered settling, 50% solids in water ($\rho' = 1.65$ g/cm^3) and Stokesian conditions ($n = 0.5$), which seems realistic for a slurry containing fine particles.

The range of values of the equal settling ratio obtained is 1.1–1.2 in all three cases, which indicates an almost impossible separation at any size as the range is lower than the threshold value of 1.25 (Gupta and Yan 2016). In this range of values, however, it is suggested that flotation films or flowing films concentrators could be implemented (Fuerstenau and Han 2003).

Flowing film concentrators, like the tilting frame and the spiral concentrator, use the differential speed of particles in a thin film of water and fine particles going down a slightly inclined plane. As the technique requires a large flowing film surface area, its development is aimed at decreasing its footprint (Fuerstenau and Han 2003). With a usual capacity of 1 t/day/m^2, the footprint of a tilting frame for a 375 tph dry nodules would be in the order of magnitude 9000 m^2, which is clearly impracticable. While the implementation of a tilting frame is not impossible, the previous considerations question the size and economics of the equipment that would be used for a polymetallic nodules commercial operation.

On the other hand, the option of a spiral separator seems more viable for throughput of 3×10^6 ton of dry polymetallic nodules per year. Considering 12-spiral modules of triple-start spirals (Gupta and Yan 2016) including a rougher, a scavenger, and a cleaner at a 3 tph feed rate per spiral, a feed size range of 45–850 µm and a 16 m^2 footprint for each module, 32 modules would be required. A total footprint of the spiral concentrators of 2800 m^2 is then calculated following habitual rules used to evaluate the footprint of industrial facilities (Caceres et al. 2020). This value is high but more in line with current industrial practice and could mandate further investigation of the application of spiral separator in combination with other screening methods for polymetallic nodules.

As mentioned in the previous section, magnetic separation methods have been applied to low-grade manganese ores, optionally with a preliminary reduction roasting step. This mineral processing route was not investigated, but recent attempts based on earlier work (Leonhardt 1979) have shown the interest in pursuing this option. The preliminary reduction roasting step is crucial in the process, as the small particle size, the heterogeneous distribution of the metals in the nodules, and the fact that the different Mn–Fe (oxy) hydroxides are epitaxially intergrown with each other, make a direct magnetic separation process impossible (Wegorzewski 2018). The reduction roasting step was tested with some success with the addition of coke, quartz, and elementary sulfur to a rotary kiln at 1050–1100 °C for 2 h. This produced metal-rich particles with a D90 < 12.71 μm, which is too small for usual beneficiation methods. These metal-rich particles contain Fe, Ni, and Cu. Other phases are present as well, that is, MnS, and a slag of Mn-oxide and Mn-silicates (Wegorzewski 2018). Another attempt used nodules from the China Ocean Sample Repository and the addition of anthracite, quartz, calcium fluoride, and iron sulfide (II) to a crucible in a muffle furnace at 1100 °C for 0.5–4 h (Zhao et al. 2020). The metals of interest (copper, nickel, and cobalt), as well as iron, were reduced to their metallic form in a magnetic phase, while a small fraction of the manganese was reduced to the metal. The obtained particle sizes were D90 < 100 μm, which allowed a magnetic separation step to follow. The overall recoveries were around 80–85% for nickel, copper, cobalt, 91% for iron, and 5.6% for manganese. The Mn/Fe ratio in the nonmagnetic phases was not mentioned as manganese is mainly present in three different phases (ferromanganese sulfide phase, manganese olivine phase, and a glass phase), but the prevalent glass phase seems to have an Mn/Fe ratio of 4.7 based on the SEM imagery and the electron-probe analysis, while the initial Mn/Fe ratio of the nodules is 4.1. This questions the prospect of the downstream valorization of the manganese in this process and suggests a three-metal business case (i.e. excluding the valorization of manganese in the flow-sheet).

With regard to flotation, it is known that the technique is not efficient for metal beneficiation when applied to nonchemically processed nodules (Fuerstenau and Han 1983; Wegorzewski 2018). No application to polymetallic nodules seems to have been investigated, although the flotation of manganese carbonate from the Cuprion ammoniacal leach tailings has been evoked (Haynes 1985). It can also be applied to nodules which have undergone the reduction roasting process previously mentioned, in which case it has been found that the flotation of the product from the reduction roasting with a sulfur addition higher than 2% in weight leads to higher metal recoveries than the magnetic separation, probably due to the formation of easily floated sulfides (Sridhar 1974). The segregation process (using coke and chloride salts) has also been reported to allow for a downstream flotation (Fuerstenau and Han 1977).

However, a desliming test work was recently subcontracted to a specialized partner. The desliming step was carried out with a Mozley hydrocyclone kit as a basis for a custom-built apparatus and took place after crushing and grinding polymetallic nodules to #100 (P80 148 μm). Qualitative mineralogical observations were made before and after the desliming test with a Zeiss binocular microscope under reflected light. They showed that the feed contained a lot of agglomerated fines identified as clays and micas. Following the hydrocyclone separation, a major fraction of the micas and clay minerals seem to have been removed under the optimal condition test work, which is the one producing a P80 181 μm for the underflow of the hydrocyclone. The XRF and ICP analysis of metals of interest in the feed and the product showed a limited upgrade ratio of 1.15. The results of this test work suggest that the crushing and grinding process preferentially liberates gangue in the fine particles, which confirms a previous similar observation (Yoon et al. 2015). This suggests that a size classification with the purpose of desliming is possible, and even recommendable for further hydrometallurgical processing.

To summarize, it has been shown that the beneficiation of deep-sea polymetallic nodules is challenging but not impossible. There is evidence that reduction roasting preceding a separation process such as flotation or magnetic separation could be implemented in the future, most probably for the three-metal business case. On the other hand, even if the gangue particle sizes and the particle density differences are at the lower end of the size range of common size-separating and gravity-separating devices, there is an advantage in studying further the size classification (with hydrocyclones) or gravity separation (with spiral concentrators) opportunities for polymetallic nodules, as a four-metal processing option can benefit from a desliming and improve the feed upgrade for the hydrometallurgical operations.

3 Polymetallic Nodules Comminution

3.1 Introduction

The comminution of polymetallic nodules is not well covered by literature. It is generally assumed that the nodules would be crushed and milled before any metallurgical processing (Fuerstenau and Han 1977). Among the parameters related to comminution, the Bond Ball Mill Work Index BWi is a convenient way to report the grindability of the ore and has been widely used for equipment design (Fuerstenau and Han 2003; Wills and Napier-Munn 2006). While the values of the Bond Work Indices are fairly documented for terrestrial ores, it is not the case for polymetallic nodules. Fuerstenau and Han (1977) noted that in the case of processing of soft nodules, the size reduction may be carried out simply in hammer mills and that energy consumption for size reduction in nodule processing should not be large. The only values reported are mentioned in Table 8.3 (Brooke and Prosser 1969).

The values reported for the Bond Work Indices (BWi) show a high variability depending on the geographical origin of the nodules, which can be correlated to their composition, structure, and formation mechanism. These aspects have been already exhaustively discussed (Kuhn et al. 2017). Except for the values of the Bond

Table 8.3 Bond ball mill work indices and sampling location of polymetallic nodules (Brooke and Prosser 1969)

Sample reference	BWi (kWh/t)	Coordinates and depth	Approximate location
2P-52	13.7	9°57'N, 137°47'W, 4930 m	UKSR CCFZ exploration zone
2P-50	7.7	13°53'S, 150°35'W, 3623 m	French Polynesia EEZ
DH-2	8.8	21°50'N, 115°12'W, 3430 m	Mexican EEZ
Average	**10.1**		

Ball Mill Index BWi 9.4 kWh/t and the Abrasion Index Ai 0.0047 g reported by Deep Green in its technical report (DeWolfe and Ling 2018), no data have been found in relation to the Bond Low Energy Work Index, the Rod Mill Grindability Work Index, or the abrasion characteristics of the nodules in the context of the comminution operations.

The lack of information on the nodule's comminution prompted GSR to de-risk the development of the comminution operations. With that regard, a study on the grindability of the polymetallic nodules was commissioned to a specialized partner. The sample used for the study was combined from subsamples obtained by GSR during successive cruises in its exploration contract area in the CCFZ.

3.2 Results of the Investigation of the Grindability of the CCFZ Polymetallic Nodules

The panel of tests included among others: a determination of the PSD of the sample, an SMC test (SAG Mill Comminution), a Bond Low Energy Impact test (CWi), a Bond Rod Mill Grindability test (RWi), a Bond Ball Mill Grindability test (BWi), and a Bond Abrasion test (Ai). The test work allowed the assessment of the comminution parameters of the polymetallic nodules and confirmed the energy requirements, and established the SAB flow sheet (semiautogenous/ball mill) as the optimum comminution circuit preceding the metallurgical process (using the JKSimMet software and Bond's third theory of comminution). The particle size distribution of the nodule feed is presented in Fig. 8.1.

The Bond Low Energy Impact test is used to evaluate the power requirements for crusher sizing. The test returned a CWi work index of 0.5 kWh/t,[1] which is very soft, and no crusher is considered in the circuit. The sample is very soft at coarse and moderate grinding sizes (Rod Mill Work index RWi 6.5 kWh/t[1], SPI 10.4 min), and soft at finer grindability sizes with a BWi 10.1 kWh/t[1], which is incidentally equal to the average of BWi reported in Table 8.3. The comparison of the Rod Mill Work index with the Ball Mill Work index confirms the intuition that the ore is indeed very soft but hardens with size reduction, a trend that may be reconciled with the

[1] For the comminution results, masses are expressed in short tons. We use "metric ton" when necessary to show the difference.

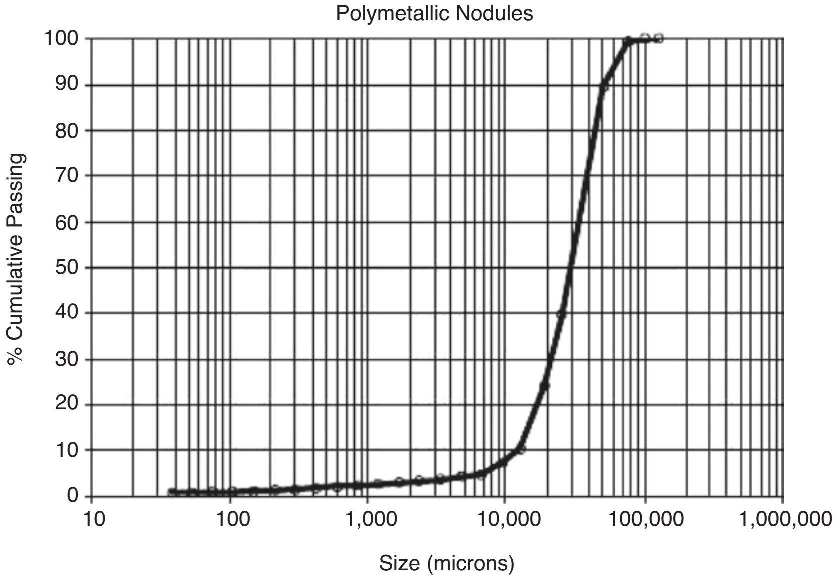

Fig. 8.1 Particle size distribution of the GSR CCFZ nodule sample used in the comminution testwork by our specialized partner

relationship between the uniaxial compressive strength of the nodules and their size distribution (Dreiseitl 2017; Van Wijk and Hoog 2020). Due to a lack of references to use as a point of comparison, the Low Energy Impact index and the Rod Mill Work index will not be discussed further in the present paper.

Figure 8.2 proposes a comparison between the Bond Ball Mill Work Index BWi average of polymetallic nodules, and copper, manganese, and nickel land-based ores. The graph shows the range of the historical values from Brooke and Prosser (1969) from Table 8.3, and the GSR, Deep Green, and land-based ores BWi values from Table 8.4. The differences between the average BWi of the polymetallic nodules on one hand, and between the polymetallic nodules and the copper ores on the other, do not seem statistically significant. However, on average manganese ore and nickel ore require, respectively, 27% and 33% more energy to grind the ore to P_{80} minus #100. The results should be considered with a critical perspective as the GSR value is a BWi point value, the historical range is constituted of 3 values, and the values for copper, manganese, and nickel are the averages of a large sample of ores. The Deep Green value is probably also a point value.

Nevertheless, if the trend would be confirmed for the BWi of the CCFZ nodules, and considering the absence of a requirement of primary or secondary crushing, this result is indicative of substantial energy savings for the mineral processing of CCFZ polymetallic nodules in comparison with terrestrial ores. The envisioned power density of the SAG mill (the ratio of the power of the mill to its diameter, in MW/ft) to be used for the comminution of nodules in the SAB flow sheet is far below the

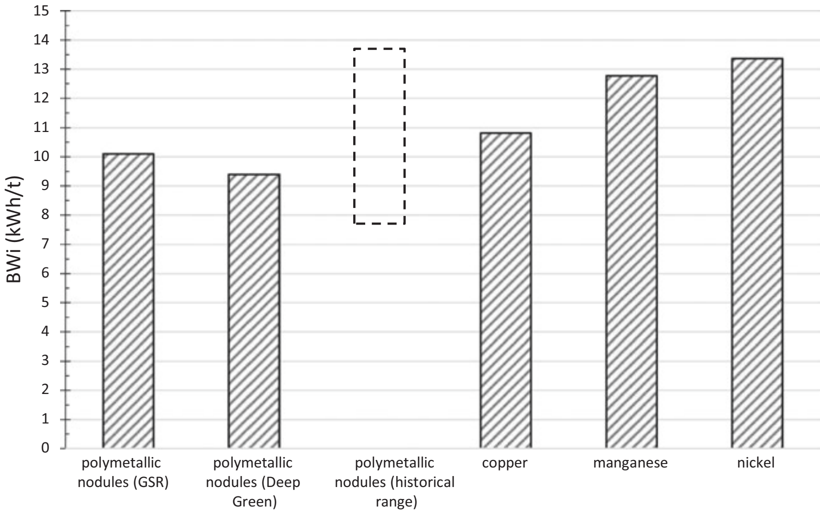

Fig. 8.2 Bond ball mill work index comparison of different ores: polymetallic nodules (GSR), polymetallic nodules from Deep Green (DeWolfe and Ling 2018)) and copper, manganese, and nickel ores

Table 8.4 Synthesis of the BWi found in literature for CCFZ polymetallic nodules and land-based ores

Dataset	BWi (kWh/t)	Source
GSR polymetallic nodules	10.1	Study by our specialized partner
Deep green polymetallic nodules	9.4	DeWolfe and Ling (2018)
Land-based manganese ore	12.8	C.f supplementary information
Land-based nickel ore	13.4	C.f supplementary information
Land-based copper ore	10.8	C.f supplementary information

power density range of 0.35–0.80 MW/ft. of the SAG mills installed by ABB in the 1995–2010 period (van de Vijfeijken 2010).

3.3 Comminution Equipment Wear Rates

Bond's abrasion test method is generally accepted as the basis for an evaluation of the attrition of metals by minerals in crushing and grinding operations (Gupta and Yan 2016). A number of correlations between the abrasion index Ai and metal wear of the liner and grinding media are used in practice. Equation (8.2) predicts the wear rate (in lb/kWh) for the balls, and Eq. (8.3) predicts the wear rate (also in lb/kWh) for the liners, both in a wet ball mill operation (Bond 1963):

$$R_{\text{balls}}\left[\frac{\text{lb}}{\text{kWh}}\right]=0.35\times\left(A_i-0.015\right)^{0.33} \quad (8.2)$$

$$R_{\text{liners}}\left[\frac{\text{lb}}{\text{kWh}}\right]=0.026\times\left(A_i-0.015\right)^{0.30} \quad (8.3)$$

The result of the test for the nodule sample abrasion index Ai is 0.001 g, which is of the same order of magnitude as the 0.0047 g value reported by Deep Green (DeWolfe and Ling 2018). This value is in the lower range of what is considered nonabrasive (Dunne et al. 2019). This characteristic is desirable to ensure the extended life of the mill linings and attrition media, and decrease the operating costs of the comminution operation (Fuerstenau and Han 2003). The nodule Ai values are so low that crusher and mill wear rates cannot be predicted with the usual empirical formulas presented in Eqs. (8.2) and (8.3).

Figure 8.3 proposes a comparison of the abrasion index value of the GSR CCFZ polymetallic nodules with typical values for nickel, copper, and manganese ores (Bond 1961a, b; Gupta and Yan 2016).

The terrestrial ore Abrasion Index values all fall under the moderately abrasive category, while the nickel ores are in the lower range of this category, and the copper and manganese ores are in the upper range (Dunne et al. 2019). The polymetallic nodules value is one to two orders of magnitude smaller than terrestrial ores, this fact being confirmed by the position of the nodules' value in the third percentile of the abrasion index database from our specialized partner. Due to their mathematical form, Eqs. (8.2 and 8.3) do not allow to predict the ball and liner wear rates for the CCFZ polymetallic nodules, but it is reasonable to assume that their wear rates would be well below 0.07 lb/kWh (for the balls) and 0.006 lb/kWh (for the liners). These are the values predicted for the nickel terrestrial ores, which are the lowest of

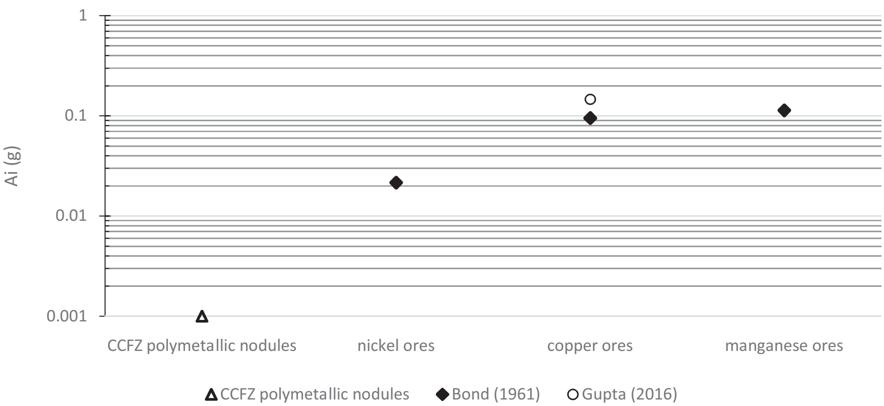

Fig. 8.3 Abrasion index comparison of polymetallic nodules and copper, nickel and manganese ores

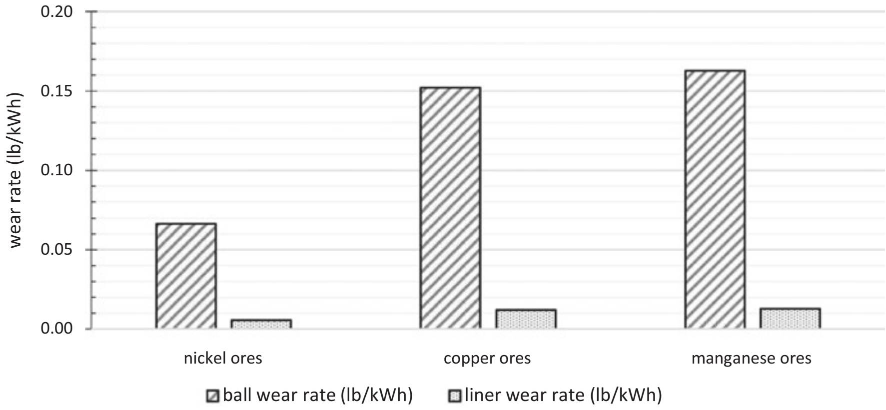

Fig. 8.4 Predicted ball wear rates for nickel, copper, and manganese ores

the set. Figure 8.4 shows the ball and liners wear rates (in lb/kWh) predicted by using the Bond abrasion index for the terrestrial ores.

This observation has important consequences: the equipment wear rates impact not only the costs due to the replacement of grinding media and worn equipment parts and the loss of production due to maintenance downtime, but also impact the pollution and contamination on the processing site, and finally, the energy that was spent for the production of the wear parts (Fuerstenau 1981). The reduced wear rate observed in the case of nodules thus considerately benefits the comminution operation.

3.4 *Metal-Specific Energy*

Comminution was already identified as a major energy consumer 40 years ago: it consumed 1% to 4% of all electrical power generated in the world (Fuerstenau 1981). Depending on the considered methodology and system boundaries, comminution represents 25% to 50% of the mine-site energy consumption (Napier-Munn 2013; Ballantyne and Powell 2014), and it is well known that comminution has a very low efficiency (3–5%) (Napier-Munn 2013). On the other hand, the energy requirement for comminution and the particle size reduction follows a Bond-like relationship depicted by Eq. (8.4).

$$W = 10\,W_{\mathrm{I}}\left(\frac{1}{\sqrt{P_{80}}} - \frac{1}{\sqrt{F_{80}}}\right) \tag{8.4}$$

where W is the comminution energy requirement (in KWh/t), W_I is the Bond work index (in KWh/t), and F_{80} and P_{80} are the 80% passing sizes of the feed and product (Bond 1961a, b).

In practical terms, this relationship means that the energy requirement will increase in a hyperbolic way with the size reduction, as one of the trends in the mining industry is to fine-grind to reach smaller liberation sizes (De Bakker 2014). Another well-known trend is the ore grade decrease (Mudd 2010; Northey et al. 2018; Rötzer and Schmidt 2020). The combination of these two trends has the potential to increase the energy requirements for comminution in a tremendous way (Napier-Munn 2013). The Bond Work Indices report the energy requirements in kWh/t, which does not incorporate the influence of the grade. Another way to report this energy requirement as a metal-specific energy per ton of final product (MSE, in kWh/ton metal) is driven by ore competence, fineness of grind, comminution efficiency, the grade of the deposit, and the separation recovery (Ballantyne and Powell 2014). This presents a totally different picture of the comminution energy requirement in the sense that the energy requirement for low-grade ores has a higher impact than for high-grade ores, a trend that will be exacerbated by the polymetallic character of the ore. In order to show that trend, we used the BWi values reported in Table 8.4 and calculated the MSE according to Eq. (8.5).

$$\text{MSE}_{\text{metal}}\left(\frac{\text{kWh}}{\text{ton metal}}\right) = BW_i\left(\frac{\text{kWh}}{\text{ton ore}}\right) \times \frac{\text{metal allocation factor}\,(\%)}{\text{grade}\,(\%\text{wt.})} \tag{8.5}$$

The grade (% wt.) parameter allows to convert the value expressed per ton of ore to one expressed per ton of considered metal. The metal allocation factor allows to take into account the polymetallic character of the ore. In the case of a polymetallic ore, this metal allocation factor should represent the weight allocated to the particular metal in the basket of products, with the condition that the sum of the individual contributions of the metals would be equal to 100%. In the case of a monometallic ore, the allocation factor equals 100%. In the present paper, we used a mass allocation factor, but the method could be used with economic allocation to show a better representation of the metal-specific energy in relation to the value of the ores or metals.

In our case, we considered nickel, copper, and manganese for a comparison of the polymetallic nodules against monometallic ores, and deliberately excluded cobalt from the comparison as it is almost never a primary product (Anonymous 2019). This opens the question of the final purpose of the comparison, as individual ores could be compared using this framework, or a higher-level comparison involving a global allocation factor for nickel, copper, and cobalt as a by-product of the associated minerals could be considered as well.

For the sake of the demonstration, we used grade values reported in the literature for nickel, copper, and manganese, and the actual grades of GSR polymetallic nodules. We also used a mass allocation for the polymetallic nodules as a simple approach, however the choice of an economic allocation would not invalidate the conclusions of this discussion. Table 8.5 shows the data and the assumptions used

Table 8.5 Data and assumptions used to calculate the MSE of the polymetallic nodules and monometallic ores. A mass allocation factor of 10.9% has been considered for the cobalt in the polymetallic nodules, but the MSE_{cobalt} has not been calculated as it has been excluded from the comparison

Ore	Metal	Grade (% wt.)	Mass allocation factor (%)	BWi (kWh/ton ore)	MSE (kWh/ton metal)
Polymetallic nodules	Ni	1.3%	28.6%	10.1	221
	Cu	1.1%	10.9%	10.1	98
	Mn	27%	48.6%	10.1	18
	(Co)	(0.2%)	(10.9%)	10.1	–
Nickel ore	Ni	0.73%	100%	13.4	1830
Copper ore	Cu	0.65%	100%	10.8	1660
Manganese ore	Mn	38.7%	100%	12.8	33

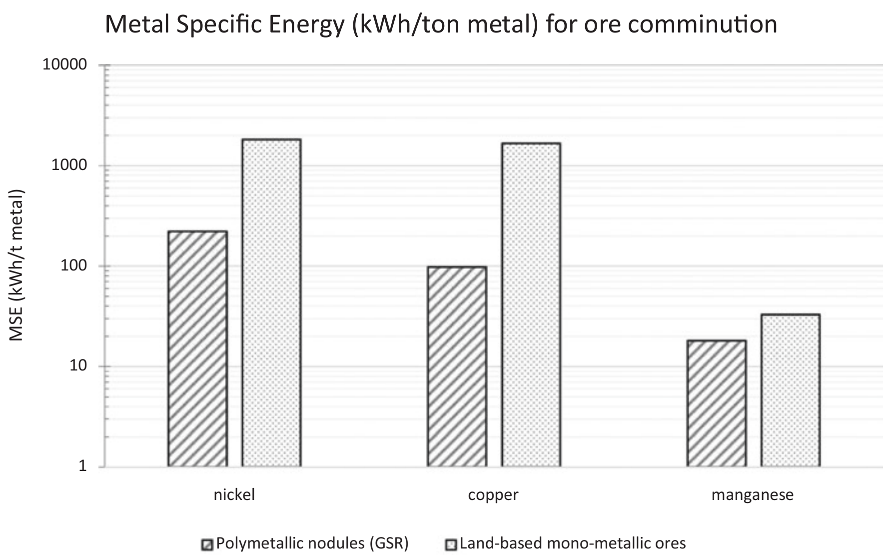

Fig. 8.5 Comparison of the nickel, copper, and manganese MSE for the polymetallic nodules and the land-based monometallic ores. Note: the vertical axis is logarithmic

for the calculations and the obtained values for the MSE of the metals associated with the considered ores.

Figure 8.5 shows the results presented in Table 8.5. It clearly shows that there is up to one order of magnitude gain that can be observed when comparing the MSE of the metals for the polymetallic nodules to the monometallic ores, whereas the BWi values in Fig. 8.2 showed a gain of 27–33% at best. This observation results from the relatively high grades and polymetallic character of the nodules, both factors that magnify the advantage of a lower BWi for the nodules in comparison with terrestrial ores.

4 Conclusion

In this chapter, a brief discussion of the relevant characteristics of deep-sea polymetallic nodules characteristics is provided, followed by a review and discussion of the manganese ore beneficiation processes and their restricted application to polymetallic nodules. It has been shown that the beneficiation of deep-sea polymetallic nodules is challenging but not impossible. There is evidence that reduction roasting preceding a separation process such as flotation or magnetic separation could be implemented in the future, most probably for three-metal business scenarios. Despite the identified limitations, there is an advantage in studying the size classification (with hydrocyclones) or gravity separation (with spiral concentrators) for polymetallic nodules in a four-metal business scenario, as the processing option can benefit from desliming and feed upgrade for the hydrometallurgical operations.

In terms of comminution of polymetallic nodules, a brief literature review is provided, putting into perspective the data obtained in a study of grindability of polymetallic nodules. The comminution study results clearly show that Bond Ball Mill Work Index and Abrasion Index values are lower than the terrestrial equivalent ores for the metals of interest. The advantage is twofold. First, the energy intensity of comminution is lower for polymetallic nodules, which leads to differences of one order of magnitude in favor of polymetallic nodules when showing the results of a comparison of metal-specific energy, a metrics that takes the grade and the polymetallic character of an ore into account. Second, values determined for the abrasion index are one to two orders of magnitude in favor of polymetallic nodules, which leads to assuming that the wear rates of the industrial comminution equipment used for nodules would be well below the values predicted for terrestrial ores.

To summarize, these results suggest there is an undisputable environmental advantage associated with the comminution of polymetallic nodules as compared to conventional (monometallic) land-based ores, due to their higher grade, polymetallic character, and comminution behavior.

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Chapter 9
Exploring the Use of Renewable Resources for Processing of Deep-Sea Minerals

P. K. Sen

Abstract Assessment of deep-sea polymetallic nodules processing technologies has assumed renewed importance in the context of the current thrust for supply of metals such as Cu, Ni, Co, and Mn that are required for clean energy transition processes. Because of similarity of suggested nodules processing operations to nickel laterite processing from land ores, the energy intensity of the operations is high. Process energy consumption data are scarce although process energy costs have been referred. The chapter elaborates an approach for minimum gross energy estimation (GER) and subsequent CO_2 emissions based on key process steps of existing flow sheets based on both foreground and background processes. For example, for hydrometallurgical processes, estimated emissions for slurry heating may vary between 0.11 T CO_2/T and 0.34 T CO_2/T nodules, with addition of 0.25 T CO_2/T nodules for downstream process using electricity to produce metals and a marketable manganese slag product. Key process emission for pyrometallurgical process is estimated at 0.67 T CO_2/T nodules. The chapter examines the possibilities of lowering such process emissions by replacing fossil fuel-based reductants with less carbon intensive inputs such as methane and renewable hydrogen, recycling CO_2 and other innovative options of using renewable energy. For hydrometallurgical flow sheets, minimizing reagent recycle such as ammonia, use of lower temperature sulfuric acid leach, combination of multiple input reactants are the possible options. Use of grid electricity with lower emission value and use of renewable electricity such as hydropower for meeting electrical energy requirements will play important role in future plant flow sheet design. The chapter provides estimates of energy and emission values for integration of renewable energy options for existing flow sheets. Although there is considerable potential for use of renewable energy for a hypothetical polymetallic nodules plant design, additional data based on industry parallels/experiments need to be generated.

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Keywords Polymetallic nodules · Process energy · Emissions · Renewable resource · Flow sheet design

1 Introduction

Assessment of new mineral resources assume importance in the context of the current thrust on locating sources that can be exploited for supply of metals such as Ni, Cu, Co, and Mn that are typically required for clean energy transition processes. Production of metals is energy-intensive, the required energy being dependent on grade of the metal bearing source as well as the technology used for extraction. In the Sustainable Development Scenario, global direct CO_2 emissions from fossil fuel use in the transport sector are expected to fall by almost 90% from 8.1 Gt in 2019 to 1 Gt by 2070 (Energy Technology Perspectives, IEA 2020). This primarily reflects a widespread shift to electric cars powered by decarbonized electricity. This fact is also a potent driver of additional demand of battery metals such as Ni, Cu, Co, and Mn leading to possible exploration of newer resources for these metals.

Reducing CO_2 emissions from heavy industries is far from straight forward (Energy Technology Perspectives, IEA 2020). The UNEP Emissions Gap Report (UNEP 2016) focuses on the 2 °C goal, as well as on the implications for limiting the temperature increase to 1.5 °C requiring stronger short-term action and deeper cuts in the medium and longer term, as the remaining carbon dioxide budget is now considerably lower. The assessment is based on Intended Nationally Determined Contributions submitted by almost all countries in the world. The industry sector of which the metal production sector is a part consumed around 3900 million tons of oil equivalent (Mtoe) of energy in 2019, accounting for just over one-quarter of total primary energy demand. Industry is currently highly reliant on fossil fuels, which account for nearly 70% of the energy supplied to the sector. About a quarter of industry sector emissions are process emissions that result from chemical reactions inherent to industrial production processes accounting for about 9 gigatons. Indirect emissions resulting from power and heat generation for use in the industrial sector account for a further 7 $GtCO_2$. Several metal production technologies require high-temperature heat for many of its processes, which today is almost exclusively provided by burning fossil fuels. Generating high-temperature heat from electricity, especially on a large scale and for electrically non-conductive applications, is impractical and costly with today's commercial technologies. Also, several metal production processes result in emissions from chemical reactions that are inherent in the production processes. Thus, emissions for metal production are hard to abate because of these factors. Deep reductions in metal sector CO_2 emissions will ultimately require the decoupling of emissions from metal production output, and new technologies will have an essential role to play in making this happen.

Choice of alternative single source for simultaneously extracting metals required for clean energy transition such as Ni, Cu, Co, and Mn is rather limited. Although terrestrial resources can readily be used, multiple sources for individual metal recovery processes may not be environmentally acceptable because of higher cumulative emissions from multiple resources being exploited for metal production. Choice of a single resource for producing the clean energy transition metals needs to be supported by energy requirements of the suggested metal production processes along with associated emissions. A single resource that can lead to production of the clean energy metals is the deep-seabed ferromanganese nodules, with possible lower energy requirements to produce metals and lower emissions. Comparison of such a single resource with alternative terrestrial resources can lead to an appropriate technology choice for reducing carbon emissions in the context of global objectives, as discussed below.

2 Assessment of Polymetallic Nodules as a Resource to Generate Sustainable Technology

Deep-seabed ferromanganese nodules have been regarded as having a major economic potential of industrial metals like nickel, copper, cobalt in addition to manganese in the last few decades by Mero (1977). Halbach et al. (1980) have cited that the ratio of metal reserves on land (approved, probable, and possible reserves) and metal amounts held by the nodules is comparable for nickel and manganese and substantially lower for cobalt. Although the above figures are subject to revision in absolute terms, the fact remains that polymetallic nodules could behave as an exploitable manganese resource depending on the price ratios of the associated metals with respect to manganese as well as the recovery factors of the various metals. The available combination of the various metals in a single source makes this resource well worthy of additional analysis of its potential as a possible driver of green economy. Thus, in addition to the existing thrust on utilization of low and medium grade of terrestrial manganese ores, utilization of additional manganese-bearing resources from the sea resembling low-grade manganese ores but with added values has been critically examined in several countries. The renewed interest in this resource has been highlighted earlier (Abramowski and Stoyanova 2012; Delucchi et al. 2014) and also in recent literature (Paulikas and Katona 2020). It has been found that polymetallic nodules have the potential to become a major source of metals, required by electronics and emerging technologies such as battery systems, hybrid cars, wind turbines, and other renewable green energy technologies that will require increasing amounts of Ni, Co, Cu, Mn. Research of alternative energy shows that Green Energy technology is far more Ni- and Cu-intensive than traditional form of energy. It is cited that a single wind turbine may require several folds more Cu to produce 1 kW than conventional power generation; similarly, an electric car could require much more Cu than a conventional car (Delucchi et al.

2014). Estimates for the amount of Ni contained in NiMH batteries used in the hybrid electric vehicle was estimated to increase by a factor of 10 between 2003 and 2010, what represented about 1.5% of total Ni apparent consumption in the United States in 2010. However, it needs to be also mentioned that the potential of polymetallic nodules to supply Ni, Cu, Co, and Mn for the Li batteries needs to be supplemented by other metals such as Neodymium for electric motors in the vehicle power train as well as Platinum for fuel cell vehicles to promote fuel cell vehicles in the context of materials required to promote renewable energy in the vehicle sector. For ease of comparison across the different metals important for renewable technologies, some key information on available resources has been presented in the context of the role that polymetallic nodules may play in shaping up future resource availability for renewable technologies (Teske et al. 2016). Recycling of metals may underscore the importance of using polymetallic nodules as a resource of choice. In the context of the present chapter, it is felt that accelerated primary metal resource demand may not be fulfilled by recycling alone.

With a prime focus on environmental assessment related to use of metal resources, Life Cycle Analysis based for a large number of metal extraction processes from different resources has been in the limelight. Life cycle analysis-based environmental impact analysis has been applied to seven major terrestrial metal production processes (Van der Voet and Van Oers 2018). Technology-specific supply scenarios and future time series of environmental impacts have been estimated encompassing effects of recyclingrates, energy system transformation, efficiency improvement, and ore grade decline. Earlier, Nuss and Matthew (2014) provided environmental impact estimates for several metals based on Life Cycle Analysis (LCA). Traditionally, for processing of polymetallic nodules, only flow sheet versions similar to exploitation of terrestrial ores like laterites have been looked at. Laterite processing is energy-intensive; this limits the potential of current flow sheet versions for polymetallic nodules resource to lower greenhouse gas (GHG) emissions. Recent LCA studies (Wei et al. 2020) based on site-specific data for laterite ore provide information on pyro metallurgical practices, confirming high energy and emissions during processing. Specific laterite process LCA information pertaining to Australian ores published earlier by Norgate and Jahanshahi (2011) suggested that although high pressure acid leach process may lead to lower GHG emissions, the advantage could be offset by high acid consumption necessitating the use of large quantities of elemental sulfur. Recent research has advocated the advantages of considering seabed nodules for possible exploitation based on life cycle analysis (Paulikas and Katona 2020) because of estimates of lower GHG emissions; this indeed is a prime requirement of novel technologies. However, these studies pertain to a specific polymetallic nodules source using pyro metallurgical processing route with a preferred input of renewable energy basket such as hydropower. Although renewed interest in polymetallic nodules metal resources can be attributed to the recent focus on green energy initiatives, general considerations of alternative technology paths of exploitation of polymetallic nodule resources have not been studied in literature since nodules extraction processes have largely been adapted to laterite processing approaches. Such alternative paths may provide the basis of new LCA studies and may lead to lower GHG emissions. In this sense, polymetallic nodule resources need to be analyzed further, not only as an alternative resource of energy metals but also with respect to its potential of lowering emissions in the current global scenario. Currently, limited information is available on the second aspect.

2.1 Resource Characterization: Energy Used, Emissions, and Economic Value

Environmental impacts are not only conditioned by changes in demand for metals, but also affected by changes in ore grades as well as efficiency improvements in the foreground and background systems of the process technology being used. Furthermore, a successful business case leading to exploitation will require minimization of climate impacts consistent with an adequate return for the business wishing to exploit an alternative resource. Some of the issues that allow an investor take an appropriate decision are discussed below.

1. The use of energy for several metal resources has been well quantified by several researchers. It is to be noted that the greenhouse gas (GHG) emissions bear a direct relationship with the gross energy requirement (GER) to produce the metal (Nuss and Matthew 2014) as brought out in Table 9.1.
2. It is also interesting to observe that the GER values depend on the energy requirements associated with different phases of extraction, such as mining, beneficiation, and processing as shown in Table 9.2 (Rankin 2014).

   Table 9.2 brings out that the grade of the deposit affects the upstream energy consumption values, particularly the mining energy consumption values (compare steel and aluminum with copper and nickel). Similar studies have pointed out the energy used in mineral extraction is inversely related to the mineral grade (Bardi 2013). For sulfide deposits (copper pyro and nickel pyro), the exothermic heat of sulfur oxidation can be gainfully used to lower the overall energy consumption, and hence the embodied energy. The CO_2 emissions are also regulated accordingly.
3. Broader characterization of such alternative resources like polymetallic nodules as a possible low GHG emission resource for metal extraction can only be supported through additional analysis of process flow sheets. For a multi metal deposit like polymetallic nodules, the gross energy consumption for *an equivalent weight of the valuable metal/100 kg of the deposit* (say nickel, normalized

Table 9.1 Gross energy requirement and greenhouse gas emissions

	Copper	Nickel	Lead	Zinc	Aluminum	Steel	Cement
GER (GJ/ton metal)	64.5	193.08	19.6	48.4	211.5	22.7	5.6
GHG (CO_2/ton of metal)	6.16	16.08	2.07	4.61	22.7	2.19	0.9
Solid waste burden (kg/kg)	125	351	14.8	29.3	4.5	2.4	–

Table 9.2 Variation of gross energy requirement with phases of metal extraction

Gross energy requirement (MJ/kg metal produced)	Al	Cu(Hydro)	Cu(Pyro)	Steel	Nickel (Pyro)	Nickel (Hydro)
Mining	0.18	16.59	7.91	0.11	11.52	9.3
Beneficiation	0.18	1.58	11.69	0.45	19.23	
Chemical processing I	30.58	46.29	10.33	21.21	33.33	184.47
Chemical processing II	180.57			0.93	49.44	
Embodied energy	211.51	64.46	33.02	22.7	113.52	193.77

by the price ratio of various constituents) can be compared to gross energy consumptions of land-based nickel metal extraction deposits. Gross energy consumption for polymetallic nodules exploitation has not been explicitly reported in literature. The cumulative *equivalent grade* of nickel, considering copper, cobalt, and recoverable manganese of a deep-sea nodule deposit may be higher than 2.5% that is better than lean grade nickel metal land-based deposits with the added benefit of copper, cobalt, and manganese recovery. The specific energy consumption of individual metal extraction processes is identical/lower than nickel metal for pyro metallurgical/hydrometallurgical extraction (Nuss and Matthew 2014) and the cumulative energy consumption per 100 kg of the deposit with an equivalent grade of nickel can be estimated. The process CO_2 emissions can be readily correlated with the energy consumption and may be partitioned based on weight allocation/economic allocation. These values may be compared with land-based resource exploitation. A multi-product metal recovery process with equivalent/lesser energy consumption per 100 kg of the deposit on dry basis, as compared to land-based ores, will offer good prospects of recovery of EV metals such as nickel, cobalt, manganese, and copper, as resource for battery metals as well as general low GHG metal extraction resource.

4. For a business venture requiring more than one metal for a single product, exploitation of multiple metals from a single resource may be advantageous, if both capital costs as well as variable operating costs provide an economic advantage as compared to sourcing separate metals required for the product from different resources. The direct variable costs in several metal extraction technologies are often largely dependent on the quantum of energy required for extraction. This is true of several commodity metals.
5. In a majority of metallurgical processes, the direct operating cost is related to the total energy used for the process and also the energy cost/unit of energy. The energy cost of a hydrometallurgical nickel, copper, cobalt, and manganese recovery process is cited to be as high as 60% for a polymetallic nodules metal recovery process (Van Nijen et al. 2018). Although the total energy used is not elaborated, electricity costs are cited to be the major component of the operating cost. Variable cost components related to energy use for polymetallic nodules processing technologies have been elaborated in earlier cost reports as well (Little 1977). It is likely that the profitability of a polymetallic nodules venture will be influenced in a major way by the energy costs by way of direct operating

costs. The profitability will be enhanced if the nickel equivalent for the deposit is high since this parameter is a direct measure of revenues.

6. Although energy cost data can be accessed, process energy consumption has rarely been reported. Reducing energy consumption is a prime requirement of lowering GHG emissions while ensuring profitability. Reduction of energy consumption is promoted by identification of a high energy consuming steps in a flow sheet. Lowering energy consumption may also happen through change in the nature of marketable outputs that may fetch lower revenues (lower nickel equivalent for a given capacity of operation). A novel flow sheet aims to lower energy consumption without changing the nature of outputs, for example, by change of nature of energy inputs.
7. There are several tested processes for polymetallic nodules processing, each with different fuel and energy inputs. Input energy variations have been reported; thus, the profiles for energy consumptions and process GHG emissions are likely to be different for individual processes. For a cradle-to-gate gross energy requirement analysis, the mining energies need to be discussed further. With mining operations at sea, the mining energy/GHG profiles are transport destination-dependent (Heinrich et al. 2019) and large-scale variations have been reported. Since such profiles are site-specific (an authorized contractor working on allocated exploitation zones by International Sea Bed Authority have specific destination plans), energy/emissions required in mining the polymetallic nodules are not discussed in this chapter. Rather, the discussions on gross energy requirement are limited to energy considerations related to process technology for a land-based plant operation for a chosen metal extraction flow sheet.

3 Energy Use and Emissions in Nodule Processing

Because of similarity of nodules processing operations to nickel laterite processing from land ores, the energy intensity of the operations is high as discussed earlier. A higher energy intensity with a greater share of fossil fuel inputs will lead to higher CO_2 emissions. Although profitability of operation can be enhanced by reducing energy intensity through increasing process efficiency, a critical analysis of substitution possibilities of the given energy mix by renewable energy for achieving emission reduction needs to be looked at. For a technology where energy intensity and emissions are high, but the operation is profitable, a redesign of the input energy mix using larger share of renewable energy will lead to reduced GHG emissions if renewable energy costs are not unusually high.

Attempts have been made to examine alternative pyro-metallurgical and hydrometallurgical process options using the concepts of lower carbon content input of replacement fossil fuels, renewable energy sources such as hydrogen, alternative reagent inputs to hydrometallurgical processes for lowering low temperature energy consumption, and use of low emission electrical energy. The process energy of process alternatives is to be interpreted as minimum since this is computed based on key process steps. The computed energy values can be directly correlated to GHG emissions as these are related to the energy mix employed to satisfy the energy demand.

Although process energy costs have been referred in other publications as discussed subsequently, process energy consumption data are scarce. It is therefore proposed to develop methodology for estimation of the energy consumptions of some standard flow sheet configurations and look at energy input substitution possibilities for a given flow sheet configuration. Discussions on energy estimations in the chapter will be primarily based on existing processing steps of technology suggested by the different contractors of International Seabed Authority, backed up by bench scale/pilot scale experimental work. Subsequently, the possibilities of alternative energy sources will be explored in the chapter for their effects on the proposed flow sheets. The emission profiles for alternative scenarios proposed will also be estimated.

Regarding profitability of operation in connection with energy requirement, the concept of nickel equivalent is useful as mentioned earlier and further taken up in a later section. High nickel equivalents can result if all components are recovered with the highest fetching market price that may also entail higher energy consumption. For reduction of energy consumed, metals may be recovered in a lower priced form with identical gross recoveries. This however will reduce the nickel equivalent of the venture and may require higher capacity operation for chosen returns with reduced energy expenditure, as explained subsequently. For comparison of alternative process flow sheets, energy consumption at identical nickel equivalent needs to be assessed.

4 Approach for Energy Estimation: Key Process Step Evaluation

Several cost estimates have been made based on a variety of process routes studied for polymetallic nodules exploitation as summarized in recent publication (Van Nijen et al. 2018). The cost estimates of the cited reference are based on CUPRION process that is based on aqueous phase gas reduction with production of a carbonated manganese product for electrolytic manganese metal recovery. General process routes have been described aptly described in earlier Bureau of Mines publications (Haynes et al. 1985) comprising of gas reduction and ammoniacal process, Cuprion ammoniacal leach, high temperature high pressure sulfuric acid leach, reduction and hydrochloric acid leach, and smelting and sulfuric acid leach. Majority of the process routes bear similarity with laterite processing routes. Cost estimates on selected process routes are reported in different publications (Johnson and Otto 1986; Lenoble 1992; Little 1977) that include operating costs along with process variants. In all the publications, operating costs have been predominantly reported rather than the total energy requirements/consumption.

In the present chapter, the primary focus is to assess the energy requirements for key process steps of the diverse process routes for *a given metal recovery profile with identical product specifications and nickel equivalent.* The total energy thus computed for the key process steps is the minimum GER of the flow sheet. The energy costs would be related to the unit energy costs prevalent for a site for the type of energy source chosen. Energy requirements for alternative scenarios have been estimated. Again, for these scenarios, energy costs would be different and the plant then needs to work out total energy costs and operating costs for a given nickel equivalent.

A closer look at the suggested flow sheets for the different process routes indicates a wide variety of inputs that are not only fuel, steam, and electricity, but also diverse reactants such as ammonia, sulfuric acid, hydrochloric acid, oxygen. In terms of Life Cycle Analysis for estimating GHG emissions, the emissions associated with the use of input chemicals also need to be considered as emissions associated to “background process energy,” also labeled as upstream energy with its associated emissions attributable to the process under consideration. The upstream energy requirements are in addition to the input fuel, steam, and electricity energy inputs. Energy credits that may be associated with the product streams of a core process are debited, giving rise to “Cumulative energy demand” of a process route, as explained below.

4.1 Cumulative Energy Demand for Key Steps

The cumulative energy demand (CED) of a product comprises of the direct and indirect energy use in units of MJ throughout the entire product life cycle, which includes energy consumed during the extraction, processing and manufacturing, and disposal of the raw and auxiliary materials (Huijbregts and Hellweg 2010). The CED is estimated based on fossil cumulative energy demand (i.e., from coal, natural gas, oil, and nuclear) and the renewable sources energy demand comprising of biomass, water, wind, and solar energy in the life cycle. In our approach, CED is estimated for the key process steps pertaining to a selected flow scheme rather than the entire flow sheet. The key steps chosen are representative of energy consumption nodes of different processes.

In the context of the present chapter, a first approach in estimating CED would be to consider from cradle to gate that would include mining the ore till delivery of the metallic product for further use. The discussions below refer to cradle-to-gate stages (primary metal production from raw material extraction) for which environmental burdens are worked out. Implications for cradle-to-grave stages (finished product from raw material extraction) are product-specific. Sometimes gate-to-gate (chosen entry point to chosen exit point) analyses are made for specific contexts such as comparative energy analysis.

An additional point where clarity is required is definition of foreground and background systems for energy estimations.

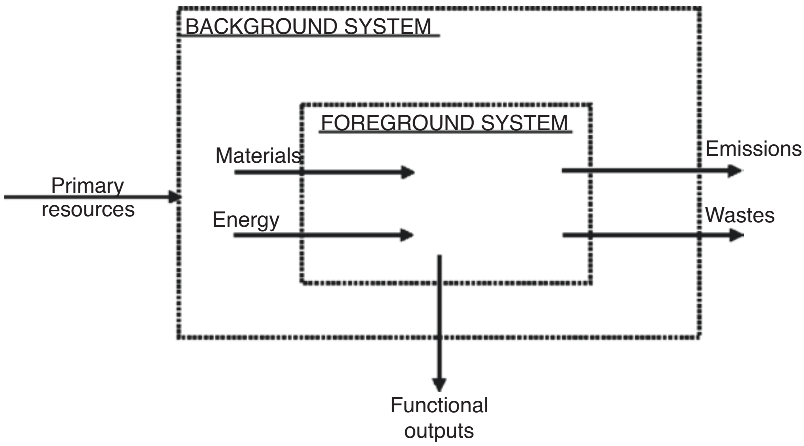

Fig. 9.1 Foreground and background systems for emission and energy accounting (after Azapagic and Cliff 1999)

Life Cycle Assessment depends on the availability of Life Cycle Inventory data for material and energy inputs (Azapagic and Cliff 1999). Figure 9.1 summarizes an approach that has been found useful in applying LCA in the process and waste management contexts. The processes that are the focus of the analysis—usually those which are directly affected by any decision based on the study—constitute the Foreground. The Background represents other economic activities that provide materials or energy to the Foreground (along with other functional outputs). The resource usages and environmental emissions associated with supplying these inputs have often been described by generic industry-average data. The materials or energy, recovered or produced in the Foreground and fed into the Background, receive "environmental credits" for the industry-average activities displaced.

In the present chapter, background energy usages by mining activities of the natural resources are excluded from context of this chapter, as described previously. All materials and energy inputs (Fig. 9.1) are considered with associated energy values to enable process energy consumption without considering mining and transportation of the raw materials to the foreground system. Such computed energy values refer to our CED estimation of the process.

Consideration of the various polymetallic nodules processing flow sheets, discussed earlier in this section, shows diverse types of inputs with which energy values can be associated. These are not only primary non-renewable energy resources such as fossil fuels but also several chemicals (NH_3, HCl, H_2SO_4, etc.) with associated energy values that need to be considered from the point of view of primary resource depletion (Utrecht University, IKARUS database 1998).

Thus, energy requirements for a chosen process step need to consider both energy actually consumed in the flow sheet using direct fossil fuel/derivatives in a flow sheet and also associated upstream energy associated with the use of chemicals. Several flow sheets consider use of ammonia, HCl, etc. (Haynes et al. 1985), but all of them focus on reagent recycle as a focus area to cut down operating costs, which translates in terms of our discussions to reduction of energy costs. The use of upstream sources energy equivalent is an established practice in WSA (World Steel Association 2021) documents for comparing emissions of commercial units. With reference to Fig. 9.1, it becomes important to draw the boundary of the foreground system: for example, for plant using H_2SO_4 as an input, sulfur will be considered as an energy source if it is within the foreground system. The cumulative energy demand of a process may then be easily worked out by considering all foreground energy consumption processes as well as upstream energy sources including fossil fuel derivatives as well as chemicals.

The cumulative energy demand has been satisfactorily correlated with climate foot print, reported as CO_2eq/kg of functional unit (Huijbregts and Hellweg 2010) for the European plastic industry. Other industry correlations can be similarly made using the approach and techniques described in the reference.

Comparison of energy requirements of a polymetallic nodules plant operation with similar land-based operations is a guiding index of the energy spent for the proposed technology and also the process emissions. For land-based nickel laterite ores, the energy requirement/t Ni shows a large variation depending on the adopted technology: 150–550 GJ/t Ni, laterite ore (Norgate and Jahanshahi 2011), 175–600 GJ/t contained nickel, various sources and products (Wei et al. 2020). The energy requirements have been directly correlated to the ore grade of nickel and are high for laterite ores with leaner grade ores requiring higher energy consumption for all chosen process routes of laterite processing. The large-scale similarity of the polymetallic nodules processing flow sheets with land-based laterite processing approaches is apparent for pyro metallurgical as well as hydrometallurgical approaches and is also suggestive of similar energy consumption patterns. Pyro metallurgical approaches are similar to ferronickel production involving roast reduction followed by smelting (similar to ferronickel production) with an added step of manganese bearing slag treatment. The reduced alloy has also been treated using hydrometallurgical approach (similar to Caron process, see Haynes et al. 1985). Hydrometallurgical approaches also include high pressure acid leaching processes that have been followed for laterites as well as low temperature variants with/without fuel gas reductions. In all the approaches, conventional reductants/reactants have been used.

Although energy consumptions for land-based laterite ores are available, literature available for polymetallic nodules processing indicates energy costs rather than energy expenditure profiles. Thus, developing procedure for energy estimation pertaining to *key process steps* for different nodules processing operation is important. Also, for reducing the high energy consumption profiles (also GHG emissions), it is necessary to develop alternate input energy sources and also different flow sheet applications. No work has been reported on polymetallic nodules using alternative energy.

4.2 Cumulative Energy Demand, Nickel Equivalent, and Profitability

The cumulative energy demand thus worked out becomes a ready reference for comparison of alternative metal sources, considering a unit quantity of the resource and the CED for recovering the metals targeted from the resource. As profitability of exploiting the resource needs to be considered as well, the estimated resource net revenue generation expressed on the basis of a single metal needs to be compared with revenue generation from a land based resource containing the same metal. Because of resource similarity with land based nickel ores, nickel metal serves as the comparison basis between sea based resource and a land based resource. More specifically, the following requirements need to be addressed once the CED for an alternative has been worked out.

1. What is the probability of achieving an investor's minimum return considering the risks of seabed mining under different commodity forecast scenarios?
2. What are the most important external cost drivers associated with a seabed mining project?
3. What is the role of energy cost in the context of operating costs?

External cost drivers will include royalty payable to International Sea Bed Authority (ISA) and environmental costs payable as dictated by policy requirements (Van Nijen et al. 2018). In addition to operating costs, these factors need to be translated to profitability estimations along with minimum returns. Projections of prices of metals are important considerations on profitability. Instead of predictions on profitability of a new resource venture, we have taken the approach to compare the energy requirements for a given target revenue since our prime intention is to consider alternative resources that can be sustainably exploited in relation to primary energy consumption. Such a comparison may subsequently lead to detailed return calculations for a business case.

Nickel equivalent and revenue To simplify resource comparisons based on revenue, the amounts of all metals to be produced may be converted into nickel equivalents. For estimation, the metals nickel, cobalt, and copper are considered to be obtained as metals, whereas manganese is either in reduced form as a ferroalloy or a manganese bearing enriched product such as slag, manganese dioxide with different unit prices. This permits us later to compare deep-sea mining with land-based lateritic nickel ore mining. The amount produced of a selected metal, measured in nickel equivalents, corresponds to the amount of nickel that would be needed to achieve the same revenue that is obtained from the sale of this amount of the selected metal for a given nickel price as well as price ratios of other metals with respect to nickel. Therefore, the price relationship of the selected metal to nickel is important for calculating the nickel equivalents. This is further elaborated below.

The function Ni Equivalent (Ni Eqv t/h) can be defined as:

$$\text{NiEqv}, \text{t} / \text{h} = \sum_{4}^{i=1} \frac{P_i M_i}{P_{\text{Ni}}} \tag{9.1}$$

where

P_i denotes price of metals/kg for recovered metal from nodules
M_i is Metals recovered, ton/h
P_{Ni} is Price of the Nickel/kg

(Index "*i*" refers to the four metals considered in this study, namely Mn, Cu, Ni, and Co.)

The Nickel Equivalent function is thus a direct measure of the sales revenue of processing scheme employed for metal recovery from a similar resource and would form the basis of revenue comparison with a land-based resource (Biswas et al. 2009).

Nickel equivalent and returns The use of Ni equivalent is also of relevance for estimation of gross economic returns of alternative processing schemes for a given resource such as polymetallic nodules is explained below. The specific energy of production of the desired metals/compounds from an alternative scheme would be dependent on (a) process route chosen and (b) final product delivered at the gate of foreground process. Required equivalent nickel production rate for an acceptable profit of operation and an internal rate of return may be estimated using the following expressions (Biswas et al. 2009).

$$E_{\text{Ni}} = C_{\text{opmin.}} + C_{\text{opmetal}} - \sum_{i=N}^{i=1} P_i * R_i + C_{\text{capexmin}} / \text{POP} + C_{\text{capexmetal}} / \text{POP} \tag{9.2}$$

$$\text{PAT} = \left(E_{\text{Ni}} + \sum_{i=1} P_{i*} R_i - C_{\text{opmin.}} - C_{\text{opmetal}} \right) * \text{Ni}\left(\text{kg} / \text{yr}\right) * \left(1 - \text{Trate}\right) \tag{9.3}$$

$$\text{NPV} = \text{PAT} * \frac{\left(1+i\right)^n - 1}{i.\left(1+i\right)^n} - \text{INV} \tag{9.4}$$

Copmin, Copmetal, are operating cost for mining and metallurgical processing in $/kg nickel, Ccapexmin represents capital cost for mining and transportation (converted to $/annual kg nickel based on POP), Ccapexmetal represents capital costs for processing in (converted to $/annual kg nickel based on POP). E_{Ni}, P_i, and R_i relate to the price of nickel, the price of other *i*th component considered and recovery ratio values of the considered component with respect to nickel, *T* rate is the prevailing tax rate, *I* is the required interest rate, *n* is the lifetime of the investment, INV is the total capital investment, NPV is the net present value. The net accruable revenues (profit) in terms of nickel equivalent is readily obtained by inserting values for the variables in the parenthesis of the right hand side of Eq. 9.3, which include annual nickel production rate (expressed as nickel equivalent), annual operating cost and prices of metals (Nickel and other metals). In our present application, operating and capital costs related to mining are excluded. Thus, the net profit for processing is estimated by considering the operating expenditure that includes depreciated processing-related capital expenditure in addition to direct costs including energy expenditure. As mentioned previously, the proportion of energy expenditure is directly related to energy demand for a process technology that is also related to nature of products being considered in the foreground process.

Nickel equivalent, energy expenditure, and returns Reduction of energy expenditure is related to choosing the specific process steps that entail high energy consumption and also considering the choice of the marketable manganese product nature, the process for preparation of which entails different energy consumption values. Energy expenditure would thus be affected not only by the process steps to obtain the metallic products, but also the steps for preparing the manganese-bearing product. We consider the choice of manganese-bearing product to be marketed and the possible relationship with process energy consumption. Manganese products include silicomanganese alloy, manganese compound such as carbonate, manganese metal or manganese-bearing slag that can be suitably used by a silicomanganese alloy producer. These products would not lead to the same nickel equivalent computed for a resource because of variable market prices for manganese products, assuming that the other products (Cu, Ni, and Co) are produced in metallic forms. Production of a manganese product such as ferroalloy in a polymetallic nodules venture is an energy-intensive operation as it entails high electrical energy consumption. Although ferroalloy production can enhance the revenue of a polymetallic nodules venture, lowering of energy consumption with production of a co-product of an enriched manganese-bearing slag will fetch a lower revenue. This will lower the nickel equivalent and also the return for a chosen plant capacity producing a ferroalloy; it may be necessary to enhance the capacity for attaining the desired return. It needs to be emphasized that a well-designed multi-metal operation like exploitation of polymetallic nodules resources needs to minimize energy demand, simultaneously maximizing profitability of operation by choosing an appropriate product mix in terms of nickel equivalent as well as plant capacity for an acceptable return.

A specific case is discussed below.

A hypothetical polymetallic nodules operation is considered that aims at production of a manganese-bearing product of appropriate grade along with the metals of nickel, copper, and cobalt. Assuming a plant capacity of 1.5 million ton per year of resource exploitation and considering a mining and processing operation with a capital cost of 1400 million dollars, operating cost of 770 million dollars, the choice of the manganese-bearing product is seen to bring out a direct correlation between nickel equivalent, profit, and internal rate of return using a simplified computation approach as outlined earlier (Biswas et al. 2009). Metal values and recovery values for nickel, cobalt, copper, and manganese were taken as 1.3% (92%), 0.15% (82%), 1.25% (86%), and 30% (70%) respectively. Prices for nickel, cobalt, copper were taken ($/kg) as 15, 30, and 4, respectively. For manganese product, two grades were considered: a lower grade product as manganese slag with lower price (0.6 $/kg of contained manganese) and lower energy consumption and a higher grade product (ferroalloy) with a higher price (1.0 $/kg) but higher energy consumption. For the lower grade of slag, the indicative profit and IRR values are respectively 5.2% and 2.1% for a nickel equivalent of 2.57 per 100 kg of nodules. For the higher price of product (ferroalloy), the profit and IRR values are estimated as 14.2% and 13.6% respectively for a nickel equivalent of 3.13 per 100 kg of nodules. Since producing a higher manganese value product as ferroalloy may entail higher energy consumption as well as nickel equivalent, reduction of energy consumption (operating cost) and nickel equivalent may necessitate enhancement of plant capacity because of lower returns. Although the nickel equivalent is directly related to the operation profitability, the relation between the operating cost and nickel equivalent is not clear from this computation as similar operating costs have been assumed in spite of energy reduction.

Even without changing product type, energy expenditure reduction may be effected with change of input energy of a process flow sheet at *same nickel equivalent*. The proportion of operating costs/energy consumed could be different for different operations, but this requires additional cost data. It is thus possible that energy expenditure could be different for different flow sheets at identical nickel equivalent, but returns as well could be different through variation of operating cost at identical gross revenues.

4.2.1 Comparison of Process Schemes Based on Identical Nickel Equivalent and Differing Energy Consumptions

The relationship of nickel equivalent with process energy requirement needs to be worked out for alternative technologies. Alternative technologies need to ensure *identical nickel equivalents* for comparison of energy requirement (identical products and process recoveries). Novel technology development efforts are required to reduce process energy requirement that is a major factor of resulting GHG emissions. Once this is achieved, energy expenditure (energy cost) for alternative processing paths becomes the deciding factor in ensuring returns (profitability) at identical nickel equivalents. No attempt is made in this chapter to establish profitability of alternative processing paths; rather, the *energy consumption* at *identical nickel equivalent* is analyzed so that estimates of greenhouse gas (GHG) emissions can be compared. Profitability and operation capacity can be worked out subsequently for an acceptable rate of return.

Table 9.3 Variation of emission with energy content of fuel

Gas	Energy (GJ/kNM^3)	T C/kNM^3	T CO_2/kNM^3	T CO_2/GJ	MWh/kNm^{3a}	TCO_2/MWh
Coal/oil	Energy (GJ/T)	T C/T	T CO_2/T		MWh/T[a]	
N.GAS	38.20	0.53	1.96	0.051	3.66	0.54
Coal1	19.20	0.40	1.47	0.076	1.84	0.80
Coal2	25.90	0.59	2.16	0.083	2.48	0.87
Coal3	16.94	0.47	1.72	0.102	1.62	1.06
Coal4	10.66	0.42	1.54	0.144	1.02	1.51
Coal5	13.15	0.48	1.75	0.133	1.26	1.39
Coking coal	29.39	0.77	2.81	0.096	2.81	1.00
Fuel oil	41.80	0.86	3.15	0.075	4.00	0.79

[a]Heat rate: 10.45 GJ/MWh

4.3 Role of Input Fuel Mix Used for Energy Supply: GHG Emissions

The energy requirements of a process are supplied by various types of input fuels. The individual fuels are characterized by fuel-specific GHG emissions. Table 9.3 lists out some computed values based on IPCC approach (IPCC (2000): Background papers, CO_2 emissions).

Table 9.3 provides a comparison of energy values of various fuels along with the specific emission per unit energy value of the fuel. Natural gas, various grades of coking and non-coking coal and fuel oil energy values are provided, based on actual values reported at plant sites. Default values are to be found in the IPCC document.

Thus, the fuel mix used in any process can be directly correlated to process emission value. It is apparent that use of natural gas in the input fuel mix leads to a lesser emission of the resultant process. If the fuels are also used also for power generation at site in addition to reduction of the ores, the additional associated emissions per unit of electrical energy generated for a given heat rate of the fuel used needs to be estimated (Last column, Table 9.3).

4.4 Role of Chemical Reagents Used in Estimating Process Energy Demand: Importance of Reagent Recycle

Several reagents have been used in processing of polymetallic nodules through hydrometallurgical/pyrometallurgical routes. The paragraphs above have attempted to outline the contribution of fuel energy used in the process flow sheet. GER estimates require input energy estimates for reagents that need to be separately added to the fuel energy inputs. Inputs that have predominantly featured include NH_3, HCl. Production of NH_3 from methane will require feed and fuel energy of 28.8 GJ/t

NH_3. The IKARUS database (Utrecht University, IKARUS database 1998) provides GER for HCl and Cl_2 as 17 and 18 GJ/t, respectively. The input energies lead to upstream CO_2 emissions ascribed to the processing route as discussed earlier under foreground and background processes, Fig. 9.1 (World Steel Association 2021).

For minimizing the net usage of these inputs, it is important to conceive of recycle processes. The recycling process described for solid stream recycle is also applicable to liquid stream recycles. Associated GHG emissions need to be obtained both for input stream and recycle streams. Generally, recycle stream-energy emissions are expected to be lower than input fresh stream. Thus, the energy required for a specific recycle process needs to be evaluated to obtain the net reduction of emissions as compared to a no recycle case. The Metallugie Hoboken-Overpelt process proposing to use HCl as the preferred input (Van Peteghem 1977) has proposed flow sheet design involving a pyrohydrolysis step for recycling HCl, thus attempting to arrive at a sustainable flow sheet.

Additionally, the use of non-carbon bearing reagents needs to be analyzed from the point of view of liquid/gaseous effluent disposal issues arising out of the use of the specific reagent combination used. For example, excess Cl_2 generated from use of HCl may be used by an adjoining industry and energy credit claims are possible. Also, excess ammonium sulfate produced in some processes needs to be bled out to an adjoining user industry.

5 Energy Sources and Consumption for Sea Nodule Processing Flow Sheet: Core Process Steps

Both hydrometallurgical and pyrometallurgical process-based flow sheets examined by different consortia members use diverse fuel-based energy sources (primary/secondary) for sustaining the energy changes for reduction of the constituent oxides including electrical energy inputs. The energy to be supplied can readily be computed based on initial and final states of the reactants and product streams and reactor/stream enthalpy losses. Chemical inputs for effecting reduction have often been used for several hydrometallurgical operation-based flow sheets. Additionally, steam derived from combustion of fuels is a major input for providing energy for hydrometallurgical system reactors.

Primary and secondary energy sources need to be analyzed for conducting an energy balance. It is noted that primary energy (PE) is an energy form found in nature contained in raw fuels, and other forms of energy received that has not been subjected to engineered conversion process. Primary energy can be non-renewable or renewable. Secondary energy sources refer to those obtained through conversion from a primary energy source including renewable energy sources such as wind, solar. to generate energy carriers such as electricity, fuel oil, enthalpy bearing process streams, hydrogen.

In terms of the above discussions, it may be necessary to generate energy input groups to a flow sheet that comprise of (a) primary energy sources, (b) secondary energy sources such as fuel oil, diesel oil, and syngas generated from coal/other primary sources, steam and (c) major energy carrier streams such as electricity delivered from central resource. Additionally, the upstream energy for fresh reactants used in a flow sheet needs to be accounted for computing net input stream energy, as discussed in Sect. 4.4. The discussions that follow will attempt to look at energy requirement of some core process steps of hydrometallurgical and pyrometallurgical flow sheet. The core steps considered are leaching and electro winning for a hydrometallurgical scheme and high temperature reduction and smelting processes of pyrometallurgical flow sheet. The energy requirements pertaining to the core steps are to be interpreted as minimum energy requirement pertaining to a flow sheet.

5.1 Approach for Estimating Energy Consumption: Hydrometallurgical and Pyrometallurgical Processes

As brought out in the preceding sections, both hydrometallurgical and pyrometallurgical treatment options are available for exploiting a sea nodule-like resource.

A detailed stream analysis approach for estimating energy requirements of a process flow sheet can be performed based on enthalpy balance when complete stream profile data are available. The following equation provides the required parameters for performing such an analysis.

$$\mathrm{SEC} = \mathrm{E}(\mathrm{I}) - \mathrm{E}(\mathrm{O}) - \mathrm{HL} \tag{9.5}$$

where SEC, E (I), E (O), and HL relate to specific energy consumption of a process block under consideration in the flow sheet per ton of ore source, input energy, output energy, and heat loss, respectively.

The energy related to exit product stream gases (EFGASES) and energy ascribed to liquid/solid products (E_PRODUCTS) exiting the flow sheet is related to individual process block specific energy consumption (SEC) and total input energy, E (I_TOT) through Eq. 9.6 as given below.

$$\Sigma\mathrm{EFGASES} + \Sigma E\_\mathrm{PRODUCTS} = \mathrm{E}(\mathrm{I\_TOT}) - \Sigma SEC - \Sigma HL \tag{9.6}$$

The relevance of these equations can be understood by noting that *for a given process step-only the important energy consumers contributing to SEC are considered. The approach thus is not to undertake detailed energy analysis for a flow sheet.*

While considering the input and output stream enthalpies, only the sensible heat component contributing to input enthalpy of an incoming leaching stream is considered and reaction enthalpies are neglected. All heat losses are neglected. For reagent recycle, reaction heat requirements are considered. For the total flow sheet, *upstream enthalpy of fresh input of reactants* are considered (as described in Sect. 4.4), in addition to other fossil fuel energy inputs. All processed energy (electricity) is converted to primary fuel energy.

The above simplified approach for energy estimation of core steps provides a good basis for comparison of minimum energy requirements of the different flow sheets based on core step analysis.

The approach details for energy computations are presented below. As the energy source used is directly related to emissions through a characteristic value presented in Table 9.3, total emissions can be estimated for a process.

5.2 Energy Requirements for Hydrometallurgical Operation: Leaching, Including Pressure Leaching and Electro Winning

Several hydrometallurgical flow schemes have leaching blocks embedded in the overall flow sheet. The slurry pulp density of the leach scheme is critical in estimating the energy requirements of the process step. Use of the following equation leads one to the estimation of solids throughput for a chosen slurry density:

$$d = 1/\left[\frac{1}{dl} - .01S\left(\frac{1}{dl} - \frac{1}{ds}\right)\right] \tag{9.7}$$

(d, dl, and ds represent slurry density, density of liquid, and density of solid in g/cc, S is the weight percentage of solid in the slurry).

Based on solid density of 3.8 g/cc, the heat requirement for heating the slurry to the desired leach temperature (e.g., by indirect steam heating) for a given percentage of solids in the slurry are computed in Table 9.4.

Table 9.4 Variation of energy requirement during leaching

% Solids	10	40
Slurry density (Eq. 9.4)	1.08	1.42
Heat requirement/solid throughput (mj/t of solid) heat load: 25 °c → 110 °c	3288	627
Heat requirement/solid throughput (MJ/T of solid) Heat load: 25 °C → 240 °C	8317	1582

Solids density assumed: 3.8 g/cc

It is observed from the above table that the leach energy requirement considering only sensible heat is substantially dependent on the leach pulp density as well as the leach operating temperature. Leach operating temperatures are higher for acid leaching operations under pressure, as discussed subsequently. Leach operating temperature can be substantially brought down if a reductant is employed such as use of ammonia and sulfur-dioxide together (Das et al. 1998). In this case, leach reactant recycle energy (ammonia) is to be additionally accounted for minimizing input reagent costs. Thus, in addition to the energy requirements estimated in Table 9.4 above, additional energy for reagent recycle for reagents such as ammonia are to be accounted for. For a steam stripping operation for ammonia using app 5–7 T steam/t ammonia, additional energy costs may work out to be 3000 MJ/T ore using a 20% pulp density of leach. In such a case, the total energy requirement for slurry heating (1500 MJ/T ore, 20% pulp density) and reagent recycle can well be around 4500 MJ/T ore depending on the actual conditions of leach.

Metal winning from leach solution is generally based on electro winning. Typical energy requirements for a sea nodule operation are around 70–75 kWh, which is about 900 MJ/T ore for fuel oil equivalent.

Hydrometallurgical operations generate manganese-bearing leach residue which requires additional processing for conversion to a useful co-product. This is because of the adverse Mn/Fe ratio of the leach residue which cannot be used directly by a silicomanganese alloy production unit without additional pretreatments. This residue contains significant amount of manganese: (Specific case, manganese 26%, iron 10%, and silica 16%). Thus, the leached residue cannot be directly employed for silicomanganese smelting due to lower Mn/Fe ratio (2–3) than generally required. Pyrometallurgical upgradation for upgrading Fe/Mn ratio may require 200 kWh/T ore (estimated). Thus, residue treatment for co-product may require 2400 MJ/T ore based on fuel oil equivalent of electricity generation.

The total energy requirement of an ammoniacal-based process may thus be around 7800 MJ/T of ore (polymetallic nodules) without considering upstream energy associated with fresh ammonia input. Considering an input energy of 30 GJ/T ammonia, an additional energy input on this count is estimated based on data on ammoniacal flow sheet as 6000 MJ/T ore.

It is of interest to analyze process energy requirements when the reagent is not subjected to energy intensive reagent recovery process. This variant is typically a sulfuric acid high pressure leaching operation without additional reductant used: this involves direct treatment of the feed in aqueous solution leading to different considerations of energy consumption. The practices followed for terrestrial laterite include Moa Bay/Amax flow sheet concepts as well as Australian flow sheet concepts of Murrin-Murrin, Bulong and Cawse plant operations (Mayze 1999). The nodules treatment flow sheets propose to utilize Bulong and Cawse flow sheet concepts of solvent extraction/electrowinning for Ni and Co as contrasted to hydrogen reduction of the pregnant solution at Murrin Murrin. The steam requirements for high pressure acid leaching are readily worked out: for a leach temperature of 250 °C and an L: S ratio of 2:1, the thermal requirement is 2100 MJ/t feed. This leads to 0.67 t steam/t ore using high pressure steam. For LCA concept implementation, a H_2SO_4 production plant from S is also integrated; this plant may generate about 20–30% of the steam requirement depending on the S input. The fuel oil requirement then works out to be 35 kg/t feed for steam generation (about 1.55 kg/t Ni of ore as 2.5%, 90% recovery). Considering fuel oil requirement for steam generation is about 70% of the fuel oil required for thermal heating, the oil requirement works out to be 50 kg/t feed. The steam requirement is dependent on the total heat load; for an L:S of 3:1, the estimated heat requirement is 3060 MJ/T ore and the steam requirement would accordingly increase as compared to the earlier case discussed.

The load of steam heating can be reduced if a lower leach temperature in acid leaching is preferred by using an additional reductant such as SO_2 (Khalafalla and Pahlman 1981), organic reagent. For a leach temperature of 110 °C, the heating load is estimated as 1500 MJ/T ore. By using additional reductant, the manganese in the feed reports substantially in the aqueous phase that allows us to examine a possibility of a different product of manganese other than a co-product that is suitable for sale to a ferroalloy manufacturer. An example of such a product is Electrolytic Manganese dioxide (EMD), used in the battery industry. This product requires around 2 kWh of energy consumption/kg of EMD, which translates to 650 kWh/T of nodule with a moderate input of manganese (23–25%) and 80% recovery. The energy requirements for a lower temperature acid leach system offers interesting possibilities for an optimal energy consumption, as discussed subsequently.

5.3 Energy Requirements for Pyrometallurgical Process of Nodule Treatment: High Temperature Reduction and Smelting

For laterite ores, detailed LCA inventory data have been provided (Wei et al. 2020) for production of NiO from the ore. The cited drying/calcination/pre-reduction steps have an energy consumption of 200 GJ/T alloy that forms the basis of an estimate of 5300 MJ/T ore for the estimated nickel input of 2.0%. The value is similar to earlier references on laterite ore drying/calcination operation (Roorda and Hermans 1981).

Pyrometallurgical operation leads to production of an alloy for further acid treatment electro winning of the dissolved metal sulfate solution and a slag for integrating with ferroalloy production. The alloy and the slag are produced after smelting of the reduced charge (Sridhar et al. 1976) after drying/calcination to complete the metal reduction process. Further treatment of the slag after the first smelt can be undertaken only if a final manganese bearing product is to be marketed. Else, a co-product is generated after the first smelt for integrating with a ferroalloy producer. In an optimal operation, the first stage smelt has been reported to consume 500 kWh/ton of slag produced (Abramowski and Marante 2018) which leads to about 200 kWh/T nodules. Metal electro winning from sulfate solution will consume around 70 kWh/ton nodules. Thus, the total energy requirement for alloy treatment to extract metals and co-product manganese-bearing slag formation including co-product generation is of the same magnitude (3300 MJ/T ore) as is in a hydrometallurgical operation ammoniacal based leach system. The minimum total energy requirement of a pyrometallurgical treatment route is estimated as 8600 MJ/T ore as compared to 7800 MJ/T ore, of an ammoniacal *without considering additional input energy of the reactant in the hydrometallurgical circuit.*

5.4 Observations on Energy Requirements and Possibilities of Reduction

The following observations can be drawn based on the above discussions.

(a) The added reactants in a hydrometallurgical process such as ammoniacal leaching would contribute to upstream energy that would be added to the process energy consumption of 7800 MJ/T nodules. Fresh ammonia added contributes to an upstream energy of 6000 MJ/T of feed. Alternative energy-efficient methods of ammonia generation from waste product streams and use of alternative renewable sources of steam generation other than fossil fuels would result in net energy reduction. Regarding sulfuric acid, it is assumed that this is generated within the plant from elemental sulfur. Sulfur added to generate sulfuric acid contributes (assumed consumption: 0.35 T acid/T ore) to an additional energy input of 1000 MJ/T ore. This energy is however not accounted for emission analysis.

(b) If a sulfuric acid leach system is carried out under similar temperatures of ammoniacal-SO_2 leaching system by using renewable organic reactants, the thermal energy requirement during leaching is similar (1500 MJ/T ore), but the additional energy requirements of the reductant would be reduced if the source is renewable. Processing parameters for low temperature reductive acid leaching have been generated (Aishvarya et al. 2013). However, this system leads to manganese dissolution and a different manganese-bearing product such as electrolytic manganese di-oxide (EMD) needs to be looked at. The energy required for EMD formation is estimated to be approximately identical to ferroalloy formation from leach residue/reduced ore feed (650 kWh/T feed), as discussed earlier. Depending on market conditions, sale of a product rather than a co-product from leach residue may be further studied as nickel equivalent will be enhanced along with operation profitability.

(c) For pyrometallurgical process involving drying, calcination and reduction roasting and related downstream operations including manganese-bearing co-product formation, the net energy requirement is 8600 MJ/T ore. This is based on energy requirement of front-end operations as 5300 MJ/T ore (Roorda and Hermans 1981) and downstream (3300 MJ/T ore). Under the conditions described in the text, this is higher than energy requirement of ammoniacal-sulfur dioxide leach including reagent recycle, and also higher than the energy for the high-pressure sulfuric acid leach circuit (6400 MJ/T feed). Thus, there is requirement to examine pyrometallurgical flow sheet options with respect to replacement of high carbon-bearing reductants used.

(d) **CO_2 emissions:** Emissions depend on the minimum total energy requirement of a process as well as the emission factors associated with each stage of processing. The energy requirements worked out earlier are indicative of the variation of equivalent fuel oil requirement for the spectrum of energy values for the different processes if the entire energy is based on fuel oil. The spectrum leads to fuel oil energy equivalent variations of 0.15–0.21 T/T ore with the assumption that no major variations in metal recoveries occur among the processes compared and also manganese is recovered in a co-product. This spectrum leads to emission variations from 0.47 T CO_2/T to 0.65 T CO_2/T. If manganese-bearing ferroalloy formation is considered in place of co-product formation, higher fuel oil equivalent (0.35 T/T ore) needs to be considered. For ferroalloy formation, CO_2 emissions may reach 1 T CO_2/T source. In terms of recovered metals reported as nickel equivalent, this may be as high as 40 T CO_2/T nickel equivalent with the possibility of lowering energy consumed as well as emission, if (a) manganese-bearing co-product (slag) is sold rather than manganese-bearing ferroalloy and (b) grid electricity emissions can be substantially lowered, for example, by use of hydroelectricity. It needs to be noted that the nickel equivalents computed depend on metal recoveries of individual process routes. For example, a lower cobalt recovery in a specific process may lead to a lower nickel equivalent, with attendant higher CO_2 emissions for the energy expended.

Pyrometallurgical processes requiring a total energy of 8600 MJ/T ore may lead to 0.2 T of fuel oil equivalent and 0.67 T CO_2/T ore. Both lowering of electricity grid emissions as well as reductant energy emissions (use of methane, hydrogen as reductant) may help lowering emissions. The flow sheet process options are discussed later.

Hydrometallurgical processes vary in steam energy requirements for slurry heating and reagent stripping (when applicable) between 1.5 GJ and 4.5 GJ per ton of nodule feed (ammoniacal, acid leaching) leading to emissions from 0.113 to 0.338 T CO_2/T feed. Electrical energy varies between 3.3 GJ (slag co-product and metals) and 9.3 GJ/T feed (ferroalloy and metals) leading to 0.25–0.7 T CO_2/T feed. The variation is also because in certain acid leaching processes, there is complete manganese dissolution and it is no longer a manganese-bearing slag that is produced. A higher value-added product such as electrolytic manganese di-oxide can be produced with approximately identical electrical energy requirement as ferroalloy production. This leads to higher emissions but enhances profitability of operation.

(e) Alternative pyrometallurgical processes, such as direct smelting of the source ore, have been reported (Sahu et al. 2013; Kojima 1997). Such processes may lead to higher electrical energy expenditure during smelting as the endothermic reaction heats are supplied by electrical energy used in place of direct fuel energy. From energy expenditure aspect, differences are foreseen with a standard pyrometallurgical route involving calcination, pre-reduction, and smelting as discussed previously. Energy consumption may be higher.

6 Use of Renewable Energy Options

One objective of the current chapter is to examine the scope of replacement of the fossil fuel energy used by renewable energy in the different process routes for reducing process emissions. Other areas requiring consideration are discussed in later sections. These include:

- Possibility of replacing the coal-based reductant used in high temperature processes by lower emission methane; methane leads to lower GHG emissions, as shown in Table 9.3. A renewable hydrogen source can be targeted after reduction using methane has been studied as a first step.
- Use of renewable electricity for smelting operations is to be further explored; as grid electricity source is a major contributor to emissions, hydrometallurgical options need to be carefully compared for estimating the net emissions.
- The scope of reducing electricity consumption during smelting by supplementing preheating operation prior to smelting may be looked into.
- For hydrometallurgical processes using ammonia, fresh ammonia input needs to be minimized. In this context, use of green ammonia is to be explored. For sulfuric acid leaching processes, as discussed earlier, use of a renewable reductant that could also simultaneously decrease the high temperature of the pressure acid leach operation will reduce energy consumption.
- Possibility of using a lower temperature leaching operation in hydrometallurgical processes generated using renewable reductant sources has earlier been discussed and needs to be considered further.

Other options that have been taken up at smaller scale, but may contribute to emission reduction for nodule processing flow sheets include:

- Possibility of electrolyzing CO_2 in electrolytic cells using renewable electricity to generate CO as reductant and lower the net emissions
- Novel use of fuel cells to generate heat and electricity (CHP mode)

Although the above possibilities may involve important process changes, the optimization of a given process flow sheet may well lead to improved performances and lower energy consumptions through structural/parameter optimization and/or utilization of lost thermal energy (Westerberg et al. 1979). Systematic studies on optimization of pilot scale flow sheets have been scarcely reported. These aspects will not be discussed further although they may lead to improvement of energy use.

6.1 Pyrometallurgical Flow Sheet Modifications for Lowering Emissions

As discussed previously, pyrometallurgical options for processing polymetallic nodules ores resemble laterite treatment processes that eventually produce ferronickel after an ore drying/calcination/pre-reduction step. One option for improving the energy efficiency of pretreatment process of the ore prior to smelting is to utilize renewable energy sources, such as waste heat emitted from a smelter or from the carbonization of coal. In this connection as a preliminary study of this innovative process, hydrogen gas was employed as the preferred reducing agent for the processing of nickel laterite ore (Lu et al. 2013). In addition, sodium sulfate has been used by the authors to promote sulfidization and energy economy with better reduction of NiO. The hydrogen-rich gas requirement is estimated maximum as 0.7 Nm^3/kg. Pure hydrogen (0.56 kmol/100 kg of limonitic laterite ore, 0.125 Nm^3/kg ore) has been used (Elliott and Pickles 2017) to study the reducibility of laterite, but the reducing agent requirement is likely to be different than an ore similar to polymetallic nodules because of different iron and manganese contents. This pretreatment/reduction step based on laterite ores has been estimated as discussed earlier (Roorda and Hermans 1981) to consume about 5300 MJ/T equivalent to around 0.5 Nm^3 hydrogen/kg ore. In any case, supply of this energy will be beneficial if hydrogen supplied is generated as green hydrogen that can well serve as a reducing agent. This would reduce upstream effects and this aspect is discussed later.

Natural gas, although not renewable, has a low emission coefficient. Laterite ores have been reduced by methane by a number of researchers, such as Pickles (Pickles and Anthony 2018) and Li (Li et al. 2018). Pickles (Elliott and Pickles 2017) indicated methane consumption of 0.03–0.1 Nm^3/kg of saprolitic laterite whereas the indicated consumption by Li et al. (2018) is 0.1 Nm^3/kg for low grade laterites. It is difficult to compare the consumption values of laterite because of different raw materials, but the values indicate the ranges of gas consumption for acceptable nickel recoveries.

Limited number of studies has been reported on using polymetallic nodules in a shaft reactor with methane as a reducing agent. A recent flow sheet developed in an Indian laboratory (Sanjay 2021) is schematically presented below (Fig. 9.2).

Methane use emissions Although use of methane can be experimentally tuned to the exact nodules grade, for a 1.5 Mill TPA and using 0.25 Nm^3/kg nodules of methane based on energy requirement of 5300 MJ/T ore for the drying/reduction roast/calcination step, around 1.05 MMSCM/day of gas requirement (average value) is foreseen. On a basis of this usage of methane (0.25 Nm^3/kg nodules), the emission of CO_2 is estimated as 0.49 T CO_2/T source (nodules). When fuel oil-generated electricity is also considered for the downstream operations generating a co-product (3300 MJ/T fuel equivalent electricity), 0.25 T CO_2/t needs to be additionally considered. The total emissions may then be about 0.73 T CO_2/T which indicates that more work needs to be undertaken on the use of methane gas as reductant.

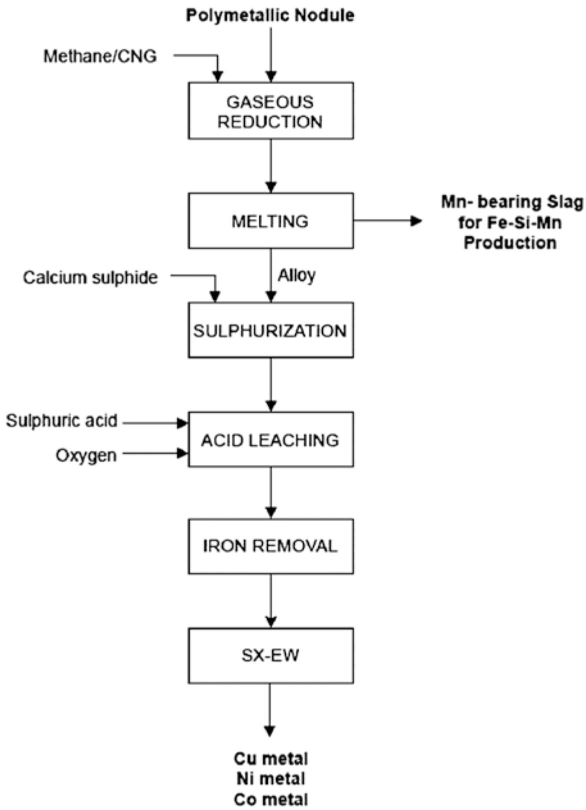

Fig. 9.2 Use of methane for reduction of polymetallic nodules: schematic representation

Hydrogen use emissions Hydrogen requirements, with similar energy consumption to laterite processing for drying/calcination/pre-reduction step, are estimated to be approximately 1.0 Nm^3/kg of nodules (@50% efficiency, with Fe, Mn reduction, energy requirement of 5300 MJ/T ore) and would lead to using 90 kg H_2/T source ore. If energy for drying is supplied in a different manner, the hydrogen requirement may almost be halved. If the H_2 is generated using steam methane refining, this would lead to 0.0.36 T CO_2/T source using the upstream emission value of CO_2 generation provided by Proost (2020). The total emissions including downstream operations is then estimated as 0.6 T CO_2/T feed based on upstream emissions incurred in steam methane reforming. It is possible that the hydrogen requirement during reduction thus estimated can be further reduced that would reduce the related upstream emissions. The associated energy consumption for steam methane refining (feed + fuel + credit steam) has been cited by Linde (Linde Engineering 2021) as 12.85 MJ/Nm^3.

Use of renewable hydrogen (green hydrogen) has currently been vigorously pursued (IEA 2019). A renewable hydrogen source if used for ore reduction will drastically reduce the emissions pertaining to the step being discussed. Although this is a preferred option for emission reduction, the current scale of renewable hydrogen generation may not be feasible for a total integration of this technology for a polymetallic nodules plant. This aspect will require additional discussions. Also, the renewable H_2 parity cost with fossil-based hydrogen current cost is an additional consideration for using renewable hydrogen for reduction.

6.2 Options for Using Renewable Hydrogen for Reduction: Production Requirements and Cost

With declining costs for renewable electricity, in particular from solar PV and wind (IRENA 2019a) and varying costs from 0.06 to 0.08 $/kWh, other than off shore wind and concentrating solar power, interest is growing in renewable electrolytic hydrogen with a number of demonstration projects in recent years. The electrolyser efficiency typically is around 70% depending on the technology being used for electrolysis. If all of today's dedicated hydrogen output (69 MtH_2) is generated from renewable electricity, this would result in an electricity demand of 3500 terawatt hours (TWh) that in any case is not presently feasible based on regional total production figures (IEA 2019).

In addition to costs of renewable electricity as discussed earlier (IRENA 2019a), the available capacities of renewable energy are important to permit integration with water electrolysis technology. Detailed renewable energy production capacities, globally and countrywise, have been reported by IRENA documentation (IRENA 2019b). Global availability of renewable energy capacity does not appear to be a problem when integration with water electrolysis technology for hydrogen production is considered. Preference for a preferred source of renewable electricity may need further analysis. For example, capacity for electricity production using concentrated Solar Thermal systems (CSP) is lesser as compared to other renewable resources. It needs to be noted that concentrated Solar Thermal systems (CSP) are not the same as Photovoltaic panels; CSP systems concentrate radiation of the sun to heat a liquid substance that is then used to drive a heat engine and drive an electric generator. This indirect method generates alternating current (AC) which can be easily distributed on the power network. Photovoltaic (PV) solar panels differ from solar thermal systems in that they do not use the sun's heat to generate power. Instead, they use sunlight through the "photovoltaic effect" to generate direct electric current (DC) in a direct electricity production process. The DC is then converted to AC, usually with the use of inverters, in order to be distributed on the power network. Thus, CSP systems are far more attractive for large-scale power generation as thermal energy storage technologies are far more efficient than electricity storage technologies; CSP systems can produce excess energy during the day and store it for usage over the night, thus energy storage capabilities cannot only improve financial performance but also dispatch ability of solar power and flexibility in the power network. Since currently CSP is limited globally, it would be useful to consider other sources such as wind and hydropower. Hydropower availability is helpful if a process plant can be located near the power source.

The electrolyzer capacities that are currently available do not appear to be limited by the cost/availability of renewable energy. Adequate electrolyzer capacities do not currently exist for full integration with a polymetallic nodules plant of 1.5 MTPA capacity. If renewable hydrogen is used for calcination/reduction step using a hydrogen input of 0.5 Nm^3/kg of source, the total electrolyzer capacity required is worked out as 370 MW for full load operation round the year, which is much larger than the present range of PEM-based electrolyzers commercially being currently tried out. Documentation by Siemens (2018) has indicated availability of Silyzer 300 and higher capacities (10–100 MW) during the period 2018–2023. The electrolyzing capacity will be reduced if the hydrogen input is differently estimated.

For an application to a specific plant design, it would also be important to foresee a possible cost of producing renewable hydrogen, as discussed by Proost (2020). The simplified H_2 cost (€/kg) is estimated by:

$$H_2\text{COST} = \left[\frac{\text{Renewcost}}{1000} + \frac{\text{CPX}}{10}\cdot\frac{1}{\text{Full load hrs}}\right].\varepsilon$$

"Renewcost" is the renewable cost (€/MWh), CPX (€/kW) is capital cost depreciated over 10 years, "Fullloadhrs" is full load hours of electrolyzer operation, ε is the electrolyzer power consumption in kWh/kg of hydrogen. For a renewable cost of 70 €/MWh (0.084 $/kWh), capital expenditure as 1000 €/kW and electrolyzer power consumption as 47 kWh/kg at electrolyzer efficiency of 70%, the hydrogen cost works out as approximately 4 €/kg of hydrogen for 6000 h of electrolyzer operation. To bring forward parity with current hydrogen cost from SMR (2 €/kg) (Proost 2020), reduction of capital cost and renewable energy prices to about 50% of the values assumed are necessary.

Thus, there is a necessity to integrate renewable hydrogen with hydrogen generated from fossil fuel resources. A venture solely dependent on use of renewable hydrogen will be limited both with respect to renewable hydrogen production capacity available as well as the envisaged hydrogen cost. Limited integration of hydrogen produced by electrolysis using renewable energy and hydrogen generated by fossil fuel resources and may still be possible if the project returns permit to allow profitable operation with higher renewable hydrogen costs.

Solar energy-based methane reforming Solar energy-based steam methane reforming has been currently modeled (Shagdar et al. 2020). In a typical case, the SRM process is carried out at 30.1 MW of heat input for processing 5.0 tons of methane and 20.0 tons of steam under 800 C of temperature and 1.02 bar of pressure. The results show that 2.14 tons of hydrogen can be produced from 5.0 tons of methane using 30.1 MW of solar power. Direct normal irradiation was an important factor. Hydrogen yield was 60% with around 50% hydrogen. Additional data have not been reported, but the research direction is interesting for possible future applications.

6.3 Smelting/Electro Winning Operations with Renewable Energy

Subsequent operations to drying/calcination/pre-reduction in a pyrometallurgical flow sheet comprise of melting/smelting of the reduced mass in electric arc furnaces to produce a manganese co-product followed by electro winning of remaining metals from metalized residue after leaching. The major energy inputs to this step consist of use of electricity. The emission factor for electricity is a characteristic feature of the supply grid. In European countries, the grid emission factor is lower than Asian countries such as India, principally because of a larger share of renewable electricity in the grid. The introduction of solar and wind energy has however steadily reduced the grid emission factor in the European Union to the current level of 0.42 t CO_2/MWh consumed (Moro and Lonza 2018). This is lower than the global GEI of fleet average 0.52 t CO_2/MWh produced (Energy Technology Perspectives 2017). Sweden, France, Finland, and Belgium have GEIs below the EU average; Sweden emits 0.04 t CO_2/MWh consumed and Belgium 0.26 t CO_2/MWh consumed (Moro and Lonza 2018).

The electrical energy required has been estimated as 500 kWh/t slag (Abramowski and Marante 2018), which translates to around 200 kWh/T nodules with assumed weight losses during pre-treatment step. This step may lead to additional 0.16 T CO_2/T nodules using a higher grid intensity factor.

If the electrical energy is supplied using hydropower only, the smelting related emission can be substantially reduced. This is a feasible option for polymetallic nodules plant if these are located close to water resources.

Another alternative is to use solar energy during a pre-smelting step. This is being currently looked at in ferroalloy industries. Hockaday (Hockaday et al. 2020) evaluates an alternative ferromanganese production flow sheet seeking to preheat manganese ores with concentrating solar thermal energy to 600 °C. A preheater energy demand, kWh/t feed 339.8, was estimated related to feeding a 30 MW high carbon ferromanganese furnace that requires a manganese ore feed of approximately 40 t/h. Emission reduction has been reported, but trial run data have not been reported.

Hydrometallurgical flow sheet options also utilize electricity for *pyrometallurgical residue treatment as well as metal winning.* If hydroelectricity is available, hydrometallurgical emissions may be under 0.34 T CO_2/T feed depending on the process used for an ammoniacal reduction leaching scheme.

6.4 Alternative Technologies for CO_2 Reduction Pyro Metallurgical Flow Sheets: Context of Sequestration

Reduction of CO_2 emissions is dependent on flow sheet design concepts in addition to energy intensity. It is relevant here to discuss about the relevance of CCU (carbon capture and utilization) and CCS (carbon capture and storage) concepts applicability for pyrometallurgical flow sheet. CCU as well as CCS involve pre-combustion capture of the emitted gases from a reduction furnace. A natural gas-based reduction system (0.25 Nm^3 natural gas/kg nodules) can be compared with a steam methane reforming system and exit gas volumes (CO, CO_2, H_2, H_2O) may be threefold (0.75 kNm^3/T nodules). Considering the total reduced mass of reduced slag and metal, the gas production can be estimated as 1000 Nm^3/T products. Similar values are observed in a steel-making industry for producing 1 ton of hot metal.

For both CCU and CCS, it is necessary to enrich the fuel gas similar to a pre-combustion process. Enrichment can be conventionally done by ammine scrubbing with steam stripping that places an additional demand on generation of steam. If waste heat is not sufficient, it would be necessary to consider steam generation using renewable sources of electricity so that additional emissions do not accrue. If methanol is considered as a product of interest, hydrogen generated from renewable resources would need to react with enriched CO_2 using compressors for the reactor. This would require additional electricity. Thus, implementation of CCU will require additional energy resources such as electricity and renewable hydrogen. CCS would however require additional steam generation using grid electricity beyond the plant waste heat available.

Steam generation options Steam generation needs to be foreseen using renewable energy options. Additionally, once renewable hydrogen is available, it is pertinent to note that fuel cells have been suggested to operate on CHP mode providing both electricity and heat (Dodds et al. 2015). The heat produced may be used to generate steam in the industrial context for both CCU and CCS operations with additional renewable electricity, but the scale of operation is small.

6.5 Reuse of CO_2 in Flow Sheet

Another interesting and promising development is to reuse the CO_2 generated after concentration for regeneration of CO in a reduction shaft using renewable electricity. In this way, the CO_2 that is thus recirculated will be in a continuous loop without contributing to plant emissions. Messers Haldor Topsoe (Mittal et al. 2017) has developed the electrolytic CO solution (eCOs) system, wherein CO is produced via the electrolysis of CO_2 at 700–850 °C using solid oxide electrolysis cell technology. On-site CO thus generated can be mixed with hydrogen gas generated from fuel/renewable resources for continuous recirculation. It may be noted that hydrogen reduction of several metal oxides such as wustite is endothermic and recirculation of CO may balance the endothermic reactions as reduction by CO is generally exothermic. Details on piloting plans have been indicated. A demonstration eCOs Plant has been supplied to Gas Innovations and is located in LaPorte, near Houston, Texas, USA. The unit produces CO at a capacity of 3–5 Nm^3/h and more than 99.95% purity (Küngas et al. 2017). A theoretical background has been presented by Küngas (2020). For a reversible cell voltage of 1.03 V at 800 °C, a CO flow rate of 5 m^3/h is indicated for a 12 kW unit. A 300 kW unit is being built for a CO supply rate of 96 Nm^3/h that is as per the thermodynamic analysis presented (Küngas 2020).

6.6 Hybrid Flow Sheet Options for Pyro Metallurgical Processing: Varied Reductants

Use of low emission reductants along with recycle of generated CO_2 leads one to consider varied options for reducing emissions for pyrometallurgical flow sheet. In a hypothetical scenario analysis where both methane and hydrogen are used as reductant, we assume that reduction by hydrogen is used for 50% of the feed stock along with CO as a mixed gas with hydrogen: CO ratio of 1:1. One needs to look into additional CO_2 sources, which can be used in a high temperature steam co-electrolysis process, under development (Wang et al. 2018). Hydrogen flow rates of about 22,000 Nm^3/h and an equal volume flow rate of CO will be necessary for 50% of the polymetallic nodules flow rate for the mixed gas stream reduction. The hydrogen electrolyzer module capacities required lie between 90 and 94 MW. Siemens have already projected a scale-up requirement to the envisaged capacities by 2025 for hydrogen production (Siemens 2018) using water electrolysis. These modules will effectively reduce the emissions. If CO_2 electrolysis technology of Haldor Topsoe (Mittal et al. 2017) is also scaled up so that additional CO is generated with recycled CO_2 and a hydrogen: CO ratio of 1:1 is produced in a mixed gas for reduction, further scale up of electrolysis technology will also be required. The technology differences between the development issues of CO_2 electrolysis and water electrolysis may not be major, other than the material and safety issues.

7 Hydrometallurgical Flow Sheet Options

Hydrometallurgical flowsheet options have been discussed where it was pointed out that energy is used for both recycling the active reagent and heating of the aqueous slurry for leach reactions to occur. These components of energy used would constitute a major part of net process energy requirement. Slurry heating thermal requirements are dependent on the leach temperature. Recycle of reagents such as ammonia may be energy-intensive and the requirement can be higher than only slurry heating requirements. For example, in ammonia-sulfur dioxide leaching system, the leach slurry thermal energy requirements are almost half the energy requirements of ammonia recycle, the total value being estimated as 4500 MJ/T feed.

The sensible heat requirements of hydrometallurgical circuits are met by steam; reagent recirculation (ammonia) is also done using steam. Steam is normally generated using fossil fuel resources and high steam usage leads to enhanced net process energy use as well as higher carbon dioxide emissions. Reduction of the process steam energy requirement can be achieved through better process design. The possibilities include using waste heat from the plant flue gases for additional steam generation and increasing the leach pulp density (solid: liquid ratio) to decrease steam requirement for recirculating the active reagent load (ammonia). Additionally, use of renewable sources such as renewable electricity for generating steam may be looked into. This aspect has been discussed earlier.

It has also been earlier remarked that low temperature sulfuric acid leaching processes in the presence of reductant is low in energy consumption, without taking into account the upstream reagent energy contribution. Re-design of flow sheet has been attempted in Indian laboratory (Sanjay, K., 2021) where an energy-intensive ammonia-SO_2 leaching route has been combined with a lower energy sulfuric acid-reductant leaching system with a view to reduce energy consumption of the total circuit (Fig. 9.3).

It may also be noted from the above treatment scheme that ammonia is being recovered in two stages, namely (a) through steam tripping and (b) through conversion of a reacted product in solution (ammonium sulfate) to ammonia through a salt

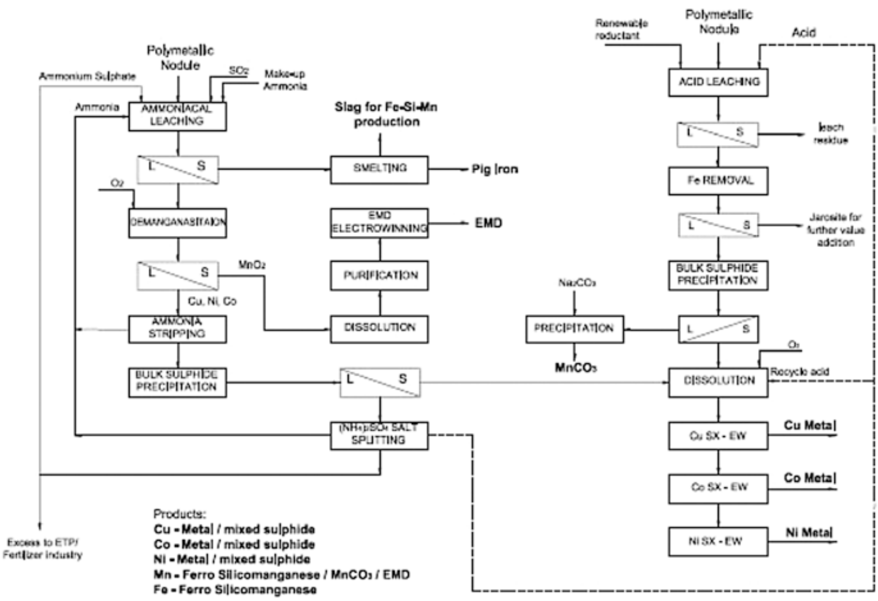

Fig. 9.3 Combined hydrometallurgical flow sheet for energy reduction

splitting process developed by the laboratory. Ideally the whole of the product may be converted to ammonia, thus reducing the input fresh ammonia additions to a minimum quantity. In practice, this decomposition process has been ascribed a stage efficiency so that excess ammonium sulfate is directed to an effluent treatment plant.

The objective of recovering ammonia to the fullest extent is guided by the observation that fresh input ammonia carries an energy penalty in terms of upstream energy. As different chemical inputs have been considered in various hydrometallurgical processes, it may be recollected that energy values associated with input chemicals have been tabulated, as mentioned before: the IKARUS database (Utrecht University, IKARUS database 1998) provides GER for NH_3, HCl, and Cl_2 as 30.1, 17, and 18 GJ/t, respectively. Because of the high energy content of upstream ammonia, the possibility of reducing the ammonia production energy by considering green ammonia production is reviewed in the next section.

7.1 Production of Green Chemicals: Case of Green Ammonia

In comparison to the conventional ammonia process, the sustainable future of the Haber–Bosch process (and the chemical industry in general) relies on the use of renewable energy as part of what is generally called electrification of the chemical industry. In this particular case, renewable energy has the potential to provide all the energy requirements, replacing methane as both feedstock and fuel. Hydrogen is produced by the electrolysis of water and is converted to ammonia using a Haber–Bosch reactor similar to the conventional process described above.

A modern, optimized, and highly efficient methane-fed HaberBosch process emits 1.5–1.6 tCO_2-eq/tNH_3 as emissions (Smith et al. 2019). An estimated 76%of the methane consumed in the process is associated with the production of hydrogen via the SMR reaction and yields a stoichiometric quantity of CO_2 of 1.22 tCO_2-eq/tNH_3. The remaining 24% of the methane is consumed as fuel to provide heat of reaction for the endothermic reforming reaction. Bicer et al. (2016) demonstrated that switching the hydrogen production method from methane to hydropower-electrolysis reduces the CO_2 emissions from 1.5 to 0.38 tCO_2-eq/tNH_3. On the other hand, the use of renewable energy for the electrically driven Haber Bosch process significantly decreases the associated CO_2 emissions. Assuming that the system requires a 38.2 GJ tNH_3 (35.5 GJ tNH_3 for hydrogen production assuming 60% efficient electrolyzer and approximately 2.7 GJ tNH_3 for the N_2 separation and compressors) a wind-powered ammonia process will have a carbon intensity of 0.12–0.53 tCO_2-eq/tNH_3 (Smith et al. 2019).

The techno economics of ammonia production using renewable resources has been earlier analyzed for 1202.55 MT/day anhydrous ammonia production (Matzen et al. 2015). Electrolytic hydrogen, however, will likely be practical for niche applications but it was pointed out that barriers need to be overcome due to high electricity costs, especially when electricity is generated by renewable energy sources.

Liu et al. (2020) have provided cradle-to-gate energy consumptions for conventional and renewable processes, varying from 40 to 2 GJ/T ammonia and corresponding emissions between 2.55 and 0.22 T GHG/T ammonia, which establishes the superiority of ammonia production technology both from the point of view of emissions and energy requirements. The higher values correspond to hydrogen generation using steam methane reforming.

It is evident that the energy use for ammonia production as well as emissions generated upstream of a polymetallic nodules extraction process using 0.2 T of ammonia/T polymetallic nodules will lead to an increase of CO_2 emissions of about 0.5 T/T nodules. It is from this angle that maximum effort should be devoted to development of energy-efficient ammonia recycle processes.

Upstream energy additions are also pertinent to sulfuric acid leaching processes. Around 9 GJ/T sulfur needs to be added as an energy contribution (equivalent sulfur present in sulfuric acid consumption/ton of nodules that is source for sulfuric acid used). For an acid consumption of 300 kg/T of nodules, around 1000 MJ/T of nodules energy increase is foreseen. However, unlike ammonia additions, this energy does not lead to greenhouse gas emissions.

8 Use of Renewable Energy at Various Stages of Metal Extraction Processes from Polymetallic Nodules: Drawing Industry Parallels

The processes of interest for extracting the metals of interest have been described in various sections of the manuscript. These have been classified under front end pyrometallurgical processes followed by hydrometallurgical operations and front-end hydrometallurgical processes followed by pyrometallurgical treatment. Energy requirements for different flow sheet options have been analyzed with implications on emissions. The primary source energy considered in this chapter is fuel-based from which secondary energy such as steam and electricity is generated. Attempts have been made to examine replacement of fuel-based energy such as coal/fuel oil with lower emission fuels such as natural gas. Typical energy replacement values of low energy alternative fuels (natural gas, hydrogen generated from natural gas) have been looked at. Emissions associated with the use of secondary energy (such as steam, electrical energy) are dependent on the primary energy source and scope of use of renewable energy in these applications has been discussed. A number of hydrometallurgical processes are also dependent on the use of chemicals such as ammonia that leads to associated emissions. Such chemicals may be made using a renewable energy source such as hydrogen generated using water electrolysis with a renewable electricity source.

Progress made in the application of renewable energy for various industrial applications of renewable energy is comprehensively reviewed by International

Energy Agency in an Insight series publication (IEA 2017) covering different industry sectors.

It is brought out in this publication that reducing long-term greenhouse gas (GHG) emissions of the industry sector is one of the toughest challenges of the energy transition. Combustion and process emissions from cement manufacturing, iron- and steelmaking, and chemical production are particularly problematic to control. These comments are equally applicable to a different source of metals containing various metals such as Cu, Ni, Co, and Mn. The specific energy requirements considering all the metals produced (including manganese) are not very different from metals extracted from a different source (similar metal content), say production of steel from iron ores using high temperature reduction processes. A total quantity of 300 kg metal extracted from a manganese bearing source as considered in the current chapter may consume around 8000–10,000 MJ/T of source, which is somewhat identical to specific energy consumption of producing steel from a ton of resource comprising of iron ore/sinter/pellets.

It would thus be useful to review possibilities of renewable resource integration with a polymetallic nodules plant, in line with efforts being undertaken in other industries. With an estimated consumption of 7.7 exajoules (EJ) in 2015, biomass is by far the largest renewable energy source in industry today (IEA 2017). Cement, iron, and steel industry and the chemical industry have been important users. The uptake of *direct renewable heat* in industry is often hampered by barriers that are hard to overcome, such as long distances to high-value resources (e.g., geothermal heat), lack of nearby land space (for solar heat) high costs (of appropriate biofuels), and seasonal imbalances. The solar industry is shifting attention and commercial efforts from its traditional markets—household-level space heating and water heating systems—to emerging markets such as district heating systems and industrial users. Various industries have teamed with academics and research centers to explore possible new uses of high-temperature solar heat, such as calcination of alumina for Alcoa. The uptake of *renewable power* by industry can be increased in two ways, and these methods can be employed separately or combined. One method is to substitute the direct use of fossil fuels with electricity, even from the grid, assuming that most power mixes already incorporate a continuously growing fraction of renewable power. The other is to substitute electricity from the grid with renewable electricity. Industrial heating is a sector that is dominated by low-cost fossil fuels with attendant high emissions. The most efficient way to reduce emissions from industrial heating processes, such as steam heating applications for leach slurry heating, is through direct electrification, *also using renewable electricity.* This is already possible in several processes, including forging, foundry, and drying in the food processing industry. Electrification of industrial processes, if based on renewable technologies, may offer greater potential for CO_2 emissions reductions. Renewables-based electrolysis of water can produce hydrogen-rich chemicals such as ammonia, termed *as green ammonia*. Polymetallic nodules hydrometallurgical plants have been proposed on ammonia leaching processes. Until the 1960s, most fertilizers sold in Europe came from hydropower-based water electrolysis and ammonia production until these were replaced by steam methane reforming plants operating on cheaper gas prices. Thus, polymetallic nodules processing plants if based on ammonia leaching may continue to be associated with upstream ammonia emissions in spite of the possibility of decreasing this in future. It is to be noted that a combination of low electricity costs and high load factors would allow renewables-based hydrogen generation to compete with SMR for ammonia production except in countries with especially low natural gas costs.

Iron and steel is the second-largest industry energy consumer, claiming 23% of total global industry final energy demand, but it is the largest industrial CO_2 emitter, with 28% of the sector's total direct CO_2 emissions in 2014 owing to more carbon-intensive fuel use (mostly coal) and considerable process emissions in the reduction of iron ore. Industrial trials have been conducted to use *hydrogen as the reducing agent.* Based on its solid experience of using the natural gas-based DR method, the Swedish iron and steelmaking industry (LKAB and SSAB), in association with Vattenfall and with strong support from the Swedish Energy Agency, has undertaken a feasibility study for reducing iron ore with pure hydrogen, a variant that has been termed hydrogen-DR (H-DR). The Indian electricity grid is currently at around 700 gCO_2/kWh, although this is expected to decrease rapidly over the time period, in line with ambitious renewable energy targets (Hall et al. 2020). Nonetheless, with today's emissions intensity of grid electricity, taking into account the efficiency penalty of electrolysis, hydrogen produced from the grid would have emissions intensity over 1000 gCO_2/kWh, higher even than coal-based hydrogen production. Emissions reductions are heavily dependent on the CO_2 intensity of the electricity being used in the production of hydrogen and for the EAF and are expected to show a sharp decrease by 2050 when grid source renewables content is higher.

Use of renewable hydrogen for pyro metallurgical reduction of polymetallic nodules is to be looked at in details since the reduction processes of iron ores and polymetallic nodules have similar thermal requirement and possibly similar reduction kinetics because of the constituents involved.

Policy perspectives for use of renewable hydrogen Although use of renewable energy resources for large industries has indeed received a thrust for decreasing process emissions, a polymetallic nodules plant design needs to compare all available alternatives drawing parallel from other industries. However, certain policy perspectives *for the use of hydrogen for pyrometallurgical ores processing* need to be outlined so that useful possibilities emerge. To deliver an accelerated transition of the industry sector from the wide-scale use of fossil fuels to the use of low carbon energy sources, such as hydrogen, a holistic policy framework that provides a "supply push" along with a "demand pull" is necessary. This would give participating companies for a new venture clear direction for future investments, reducing their risk of investing in low carbon production processes. Some desirable directions are outlined below.

(a) To facilitate a long-term goal of use of renewable hydrogen for ore reduction, access to natural gas at low prices is required that will facilitate production of reformed hydrogen/direct use of methane for newer applications. Gradually, scale-up parameters related to hydrogen-based reduction of polymetallic nodules will be made available.

(b) Medium- to large-scale demonstration plants using polymetallic nodules as the source and renewable hydrogen should be established to familiarize the industry sector with the renewable hydrogen energy technology, start scale-up of technology manufacture, and signal a serious intention for deep decarbonization for this source. This will involve tie up with electrolyzer companies producing low emission hydrogen for use.

(c) To provide a clear, sector-wide direction for deep decarbonization will require ambitious policy to limit CO_2 emissions. The most common method for doing so would be the implementation of an industry-wide carbon tax, so that high-polluting plants would pay more.

(d) Coal-based metal manufacturing plants are often very polluting, particularly if the production capacity is medium scale. They would also be better suited to switching from coal-based technologies, to hydrogen direct reduction, if applicable, to a given output product. Institutional and public support will be required to help transition of these smaller plants, helping to retain local employment and supply chains. Such re-engineered plants can serve as focal points of effecting larger scale changes in future technology plants using a different source ore such as polymetallic nodules.

9 Summary and Conclusions

1. The current thrust on locating metal resources for producing metals to be used for clean energy generation has led to renewed interest for considering deep-sea polymetallic nodules as a single ore resource for production of such metals.
2. Limited information on sustainability of polymetallic nodules resources for specific use based on life cycle analysis is available in literature. LCA studies for polymetallic nodules processing flow sheets are limited. These are largely based on similar pyro metallurgical processes as land-based nickel laterite ore treatment using conventional fuel resources. Similar studies on using alternative fuel resources are not available. Metal life cycle analysis data for land-based deposits are available based on which energy requirements and emissions can be compared to a proposed polymetallic nodules processing flow sheet. However, alternative technology paths of exploitation of polymetallic nodules resources have not been subjected to LCA analysis.
3. Environmental impact of metal production from polymetallic nodules is dependent on the gross energy consumption for metal extraction economic value of the deposit. The role of upstream operations to metal extraction such as mining is excluded from the energy requirements because of diverse transport destinations.

4. Minimum cumulative energy demand of process flow sheets is analyzed considering foreground and background systems and key process steps. Background systems include not only non-renewable energy resources, but also several chemicals with associated energy values.
5. To simplify resource comparisons based on maximum revenue and minimum energy consumption, the amounts of all metals to be produced may be converted into nickel equivalents. Reduction of energy expenditure is related to choosing the specific process steps that entail high energy consumption. A low nickel equivalent with reduced energy use may require an enhanced capacity of exploitation for desired internal rate of return using conventional technology. The relationship of nickel equivalent with process energy requirement needs to be worked out for alternative technologies. No work has been reported on polymetallic nodules using alternative energy sources.
6. Energy requirements of chosen process blocks of a hydrometallurgical/pyrometallurgical flow sheet based on simplified assumption (no heat loss, no chemical enthalpy of outgoing process gases) have been estimated. For hydrometallurgical flow sheets, leaching, reagent recycle blocks are considered. For pyro metallurgical route, drying/reduction step has been considered based on available LCA data. For both the process routes, Ni/Cu/Co metal recovery using electro winning and production of an upgraded manganese-bearing slag using electrical energy has been considered.
7. Leach energy requirement for slurry heating considering only sensible heat is substantially dependent on the leach pulp density as well as the leach operating temperature. Leach operating temperature can be substantially brought down if a reductant is employed such as use of ammonia and sulfur-dioxide together. The total energy requirement for slurry heating (1500 MJ/T ore, 20% pulp density) and reagent recycle can well be around 4500 MJ/T ore depending on the actual conditions of leach. Metal electro winning and generating an enriched manganese-bearing slag as co-product may consume additional 3300 MJ/T ore. High temperature acid leach (25% pulp density) is estimated to consume around 3060 MJ/T of ore for the leaching step. The load of steam heating in acid leaching can be reduced if a reductant is used as this would bring down the leaching temperature for acceptable recoveries of metals. However, high manganese dissolution may occur leading to another marketable product in place of manganese-bearing slag as electrolytic manganese di-oxide with higher energy requirement as compared to slag production.
8. The minimum total energy requirement of a pyro metallurgical treatment route based on key process steps is estimated as 8600 MJ/T ore as compared to 7800 MJ/T ore, of an ammoniacal reductive leaching circuit and key process, without considering additional input energy of the reactant in the hydrometallurgical circuit.
9. On the basis of converting the energy requirements to fuel oil equivalents for the different process routes, emission variations from 0..47 T CO_2/T to 0.65 T CO_2/T of ore are estimated. If manganese-bearing ferroalloy formation is considered in place of co-product formation, higher fuel oil equivalent (0.3 T/T

ore) needs to be considered. For ferroalloy formation, CO_2 emissions may reach 1 T CO_2/T source.

10. For using renewable energy as replacement of fossil fuel energy, possibilities exist to replace reductant used in high temperature processes by lower emission methane/renewable hydrogen source and also use renewable electricity for smelting. Electricity consumption during smelting may be reduced by supplementing preheating operation by renewable energy as is being attempted for ferroalloys industry.
11. Pyrometallurgical flow sheet development efforts toward reductant replacement are reported for laterites for hydrogen as well as methane. Such studies indicate the quantitative requirements of these alternative inputs. It is difficult to extrapolate the consumption values for laterite samples to polymetallic nodules reduction processes, although the raw materials bear similarities with respect to concentration of metals. Reported values indicate the ranges of gas consumption values for acceptable nickel recoveries for laterite samples. Limited studies have been reported on the use of methane as a reducing agent for polymetallic nodules using shaft reactors. There is hardly any information on hydrogen consumption for polymetallic nodules; one is guided by reported values for laterites and stoichiometric requirements using polymetallic nodules with partial manganese reduction in place of iron in laterites.

    (a) On a basis of reduced usage of methane 0.25 Nm^3/kg nodules, the emission of CO_2 is estimated as 0.49 T CO_2/T source (nodules). The total emissions may then be about 0.73 T CO_2/T that indicates that more work needs to be undertaken on the use of methane gas as reductant.
    (b) Hydrogen generated by steam methane reforming would lead to 0.36 T CO_2/T source using the upstream value of CO_2 generation provided in literature and hydrogen consumption based on stoichiometric requirements.
    (c) A renewable hydrogen source if used for ore reduction will drastically reduce the emissions pertaining to the step being discussed. Although this is a preferred option for emission reduction, the current scale of renewable hydrogen generation may not be feasible for a total integration of this technology for a polymetallic nodules plant. A venture solely dependent on use of renewable hydrogen using water electrolysis will be limited both with respect to renewable hydrogen production capacity available as well as the envisaged hydrogen cost. Thus, there is a necessity to integrate renewable hydrogen and methane-based reduction of polymetallic nodules as separate reducing gas inputs. As per other industry practices, a mixed gas stream of hydrogen and carbon monoxide can be conceived. Limited conceptual studies have been undertaken on solar energy-based methane reforming for generation of hydrogen, but the findings need to be justified with additional work. Other smaller scale options include recirculation of CO_2 generated in the process flow sheet using electrolysis and use of fuel cells on CHP mode for utilizing the heat generated to generate steam for flow sheet use.

12. Subsequent operations to drying/calcination/pre-reduction in a pyro metallurgical flow sheet comprises of melting/smelting of the reduced mass in electric arc furnaces. The grid intensity factor as discussed in the text is country-specific and, globally, there is a major thrust on reduction of this factor as discussed in the text. If the electrical energy is supplied using hydropower only, this smelting-related emission can be substantially reduced. Another alternative is to use solar energy during a pre-smelting step. This is being currently looked at in ferroalloy industries.

    The context of sequestration technologies (related to steam generation options) and reuse possibility of CO_2 generated has been discussed, although the present scope is limited by operation scale and steam generation requirements. Hybrid flow sheet options for pyrometallurgical processing involving use of methane, limited quantities of renewable hydrogen and carbon monoxide generated from recycled CO_2 need to be looked with background work on renewable resources being undertaken by commercial firms such as Siemens and Haldor Topsoe.
13. For hydrometallurgical processes using ammonia, use of fresh ammonia needs to be minimized. Green ammonia sources, if available, need to be explored. A renewable reductant during acid leaching may be looked into for reducing energy use during sulfuric acid leaching. Hydrometallurgical flow sheet options also utilize electricity for pyro metallurgical residue treatment as well as metal winning. If hydroelectricity is available, hydrometallurgical emissions may be under 0.34 T CO_2/T depending on the process used. Flow sheet redesign involving use of low temperature sulfuric acid leaching along with ammoniacal leaching for generating diverse product portfolio with higher nickel equivalent is an interesting option.
14. It is useful to draw industry parallels for efforts undertaken to reduce emissions in other similar industry sectors.

    These efforts can be classified under (a) uptake of renewable power by the industry, (b) uptake of direct renewable heat, (c) use of renewable energy resources for reduction, including renewable hydrogen. Various industries have teamed with academics and research centers to explore possible new uses of high-temperature solar heat, such as calcination of alumina for Alcoa. Industrial trials have been conducted in the iron and steel industry for using renewable hydrogen. Although use of renewable energy resources for large industries has indeed received a thrust for decreasing process emissions, a polymetallic nodules plant design needs to compare all available alternatives of energy resources drawing parallel from other industries.
15. Thus, although there is potential to consider the use of various renewable resources for a hypothetical design of a polymetallic nodules plant for emission curtailment, additional data by way of experimentation/extrapolation from other industry parallels need to be generated for detailing out a specific application.

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Chapter 10
Reductive Ammonia Leaching Process for Metal Recovery from Polymetallic Nodules: Can There be a Zero Waste Approach?

Navin Mittal and Shashi Anand

Abstract Polymetallic nodules (PMN) are considered to be a potential source of valuable metals such as copper, nickel, and cobalt. Over the last five decades, several processes have been developed to recover these metals with or without recovering manganese. Utilization of this resource has become more pertinent due to the large requirements of these metals for lithium-ion batteries used in electric vehicles besides other conventional requirements. Environmental agencies are enforcing strict regulations for metallurgical and chemical industries to minimize liquid, solid, and gaseous effluents. In fact, presently the emphasis is on zero waste processes. In this chapter, it is proposed to critically analyze the hydrometallurgical reductive ammonia leaching process for the recovery of metal values from nodules. This process comprises ammonia leaching with sulfur dioxide, demanganization of dissolved manganese, copper solvent extraction-electrowinning to obtain copper cathode, bulk sulfide precipitation followed by its dissolution and solvent extraction-electrowinning for cobalt, nickel separation to produce their respective cathodes. In this chapter, we look into the effluents generated in this process and critically analyze the utilization/minimization of the effluents for providing a cleaner environment.

Keywords Polymetallic nodules · Reductive leaching · Solid waste · Liquid effluents · Zero waste

1 Introduction

In the present world economic and environmental scenario, it has become an absolute necessity for the industries to put all-out efforts for waste reduction. The majority of the industrial waste generated is considered problematic due to the dangerous

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and/or heavy minerals it contains that may pollute the air, the soil, or nearby water sources, thereby posing a great risk to the environment and health of people. Industries are now moving toward a “Zero Waste” approach. Industrial waste that appears to be harmful, with effective techniques and greener technologies, can significantly reduce the volume of waste by using them as raw materials in other applications. There exist several options for reducing the generation of waste which may include reusing, recycling, or taking appropriate action to prevent waste generation (https://mediaroom.wm.com, 2018). In metallurgical industries, there are two ways to define the “Zero Waste.” The first approach is where no solid/liquid or gaseous wastes remain within the industrial complex meaning thereby that (1) the solids generated are sent for landfills or any other alternate utility without further processing, (2) the gaseous streams are captured in appropriate media, and (3) the liquid effluents generated are treated in such a way that these can be sent to the designated destination as approved by the environmental agencies. The second approach toward “Zero Waste” is where all solid/liquid and gaseous effluents are converted into saleable by-products. The second approach is usually very difficult to achieve in commercial metallurgical operations. However, efforts are undertaken by the industries to work toward the second approach as far as possible.

The demand for metals such as copper (Cu), nickel (Ni), cobalt (Co), and manganese (Mn) are on the rise due to their use in the production of lithium-ion cells used in electric vehicles (EV). Demand for certain EV battery metals is projected to increase by 11 times than the current level by 2050 according to the World Bank, and shortages in nickel, cobalt, and copper have been predicted to emerge in the very near future. The polymetallic nodules found in various ocean regions of the world are now being projected as a potential resource of these metals especially in view of their need for EVs (Abramowski and Stoyanova 2012; Hein et al. 2020; Bairstow 2020). Although R and D activities for process development to recover metals from polymetallic nodules had started more than 50 years back (Das and Anand 2017; Mittal and Anand 2019), till date no commercialization has taken place to extract metals from this vast resource despite the fact that several processes have been tested on pilot scale (ISBA 2008). The processes are based on pyro-hydrometallurgy or hydrometallurgy or in a combination of the two. Made up of 167 Member States, and the European Union, the International Seabed Authority (ISBA) is mandated under the UN Convention on the Law of the Sea to organize, regulate, and control all mineral-related activities in the international seabed area for the benefit of mankind as a whole (ISBA 2018). Looking at the utilization of this resource for EVs, the recovery of all the four metals is essential. The renewed interest in polymetallic nodules is clearly observed with various news items and research being carried out for the development of new processes, which have been projected to be environmental friendly (Friedmann et al. 2017a, b; Hein et al. 2020; https://www.prnewswire.com/, Bairstow 2020). They have reported the development of a sustainable, zero-waste(pyro) metallurgical process to treat polymetallic nodules obtained from Clarion Clipperton Fracture Zone (CCZ). The aim was to generate Mn-product as ferromanganese as well as a Ca-Si product, which was not reported in the past, while ensuring a complete recovery of the valuable constituents Ni, Cu, and Co along with Fe as an alloy. However,

Table 10.1 Effluents generated during reductive ammonia leaching

Solid effluents	Leach residues; impurity cakes (precipitated sulfides, gypsum containing precipitated impurity metal ions)
Liquid effluents	Wash liquors with dilute ammonia containing metal ions; bleed/raffinate solutions from SX-EW circuits; dilute ammonium sulfate/ammonium carbonate solutions
Gaseous effluents	Dilute ammonia gas in air; gaseous effluents of coal-based steam generators

the Cu-Ni-Co-Mo-Fe alloy so produced needs to be treated through acid pressure leaching to keep iron at a minimum level. Further, the purification, solvent extraction, and electrowinning (SX-EW) also have to be carried out to obtain respective cathodes of Cu, Ni, and Co. There will be a number of pH adjustments and solid-liquid separation steps. Finally, whether it will really be a "Zero Waste" process needs to be further evaluated (Keber et al. 2020). In view of the increasing demand for these base metals coupled with the concern for the environmental requirement of "Zero Waste," the researchers should put all efforts to achieve this goal.

Ammonia leaching processes have been widely commercialized for recovery of Cu, Ni, and Co both from oxides (laterites) as well as sulfides (Ni-Co sulfide ores) through pyro-hydrometallurgical or only hydrometallurgical process route. The reductive ammonia leaching process is required for the leaching of metals from oxides whereas the oxidative leaching process is essential for metal recovery from sulfides. It is well known that ammonia forms soluble stable complexes with metal ions, that is, Cu, Ni, Co, Zn, Cd, Ag, whereas Fe and Mn form unstable complexes which tend to precipitate and their dissolution can be controlled by choosing experimental conditions especially with respect to pH/Eh and ammonium salt concentrations (ammonium carbonate, ammonium sulfate, or ammonium chloride). The materials like silicates, calcium, and magnesium remain in the leach residue thereby saving the lixiviant consumption. Broadly the various effluents generated during ammonia leaching are illustrated in Table 10.1.

An ammonia sulfur dioxide (NH_3-SO_2) reductive leaching process has been tested on pilot scale in India (Das 2001; Mittal and Sen 2003) for processing of polymetallic nodules to recover desirable metals. The present chapter looks into the effluents generated in this process and critically analyzes utilization/minimization of these effluents with a view to approach toward "Zero Waste." The nodules were collected from specified areas of the Indian Ocean and provided by National Institute of Oceanography, Goa. In general, the nodules used for process development contained approximately 1.0–1.2% Ni, 1.0–1.3% Cu, 0.10–0.14% Co, 19–25% Mn, and 8–12% Fe.

2 The Reductive Ammonia Leaching Process

Various steps during reductive SO_2-NH_3-$(NH_4)_2SO_4$ process are given below:

1. Crushing, grinding, and sieving of nodules to obtain (−) 100 mesh BSS particle size

2. Ammonium sulfite solution preparation for leaching
3. Leaching of nodules in ammonia–ammonium sulfite–ammonium sulfate solution
4. Demanganization
5. Ammonia recovery from Mn-free leach solution
6. pH adjustment of ammonia-free leach solution
7. Copper solvent extraction followed by electrowinning to produce copper cathode
8. Precipitation of Ni-Co bulk sulfide from copper-free raffinate
9. High-pressure oxidative leaching of bulk sulfide in sulfuric acid in presence of oxygen
10. Cobalt solvent extraction followed by electrowinning to produce cobalt cathode
11. Nickel solvent extraction followed by electrowinning to produce nickel cathode
12. Sodium sulfate production through evaporation

Several papers have been presented/published covering different aspects of this process (Sanjay et al. 1999a, b; Das 2001; Mittal and Sen 2003; Sarangi et al. 2004; Anand and Das 2005; Ghosh et al. 2005; Rout et al. 2005; ISBA 2008, 2018; Panda et al. 2009). The detailed process flowsheet is illustrated in Fig. 10.1. For convenience, the various unit operations have been divided into three sections and section-wise effluent treatments strategies have been discussed.

The Sect. 2.1 includes ammonium sulfite preparation, leaching, solid-liquid separation, demanganization of leach liquor followed by solid/liquid separation and ammonia recovery. The unit operations being considered in Sect. 2.2 include pH adjustment of ammonia-free liquor, Cu SX-EW and Co-Ni bulk sulfide precipitation, solid-liquid separation to obtain sulfide cake, and a filtrate containing ammonium sulfate. In Sect. 2.3, bulk sulfide dissolution, Co SX-EW, Ni SX-EW, and Na_2SO_4 evaporation are included.

2.1 *Leaching, Demanganization and Ammonia Recovery*

This section deals with the preparation of feed to copper solvent extraction circuit. Leaching of ground polymetallic nodules of specific particle size is done using ammonium sulfite solution and recycled ammonium sulfate solution in an autoclave at specified process conditions. Metals present in nodules are in oxide form and during leaching, and they form their respective soluble ammonium complexes namely $Cu(NH_3)_4SO_4$, $Ni(NH_3)_6SO_4$, and $Co(NH_3)_4SO_4$ in the presence of free ammonia and ammonium sulfate. MnO_2 and FeOOH associated with the nodules undergo the following chemical reactions:

$$MnO_2 + (NH_4)_2 SO_3 = MnO + (NH_4)_2 SO_4 \quad (10.1)$$

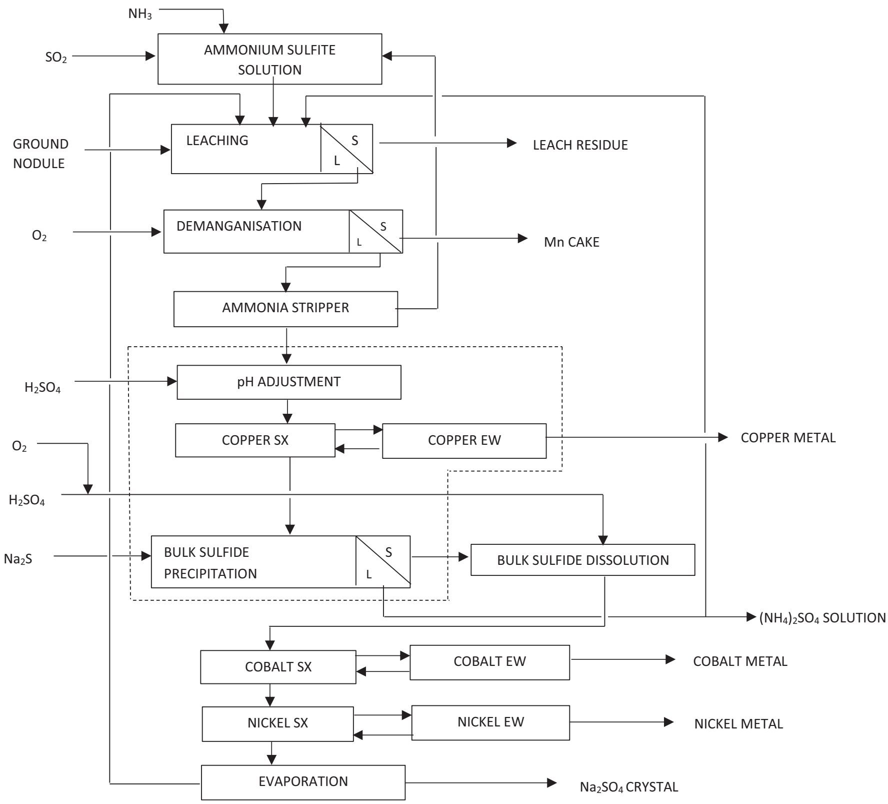

Fig. 10.1 Schematic flowsheet for recovery of valuable metals from nodules through NH_3-SO_2 process

$$MnO_2 + (NH4)_2 SO_3 + 2NH_3 = Mn(NH_3)_4 SO_4 + H_2O \tag{10.2}$$

$$2FeOOH + (NH_4)_2 SO_3 + H_2O = 2Fe(OH)_2 + (NH_4)_2 SO_4 \tag{10.3}$$

The leach slurry is filtered after completion of the reaction in a filter press and the leach residue is washed with the required quantity of water.

The leach solution is subjected to demanganization wherein the dissolved manganese is precipitated under oxidative conditions. Part of the manganese that dissolves in leach solution forms an unstable ammine which gets dissociated into $Mn(OH)_2$, MnO, Mn_2O_3, and MnO_2. Formation of MnO does not require oxidative conditions whereas formation of Mn_2O_3, MnO_2, and $Mn(OH)_2$ requires oxidative conditions as per equations given below:

$$Mn(NH_3)_4 SO_4 + H_2O + 1/2O_2 = MnO_2 + (NH_4)_2 SO_4 + 2NH_3 \tag{10.4}$$

$$Mn(NH_3)_4SO_4 + H_2O = MnO + (NH_4)_2SO_4 + 2NH_3 \quad (10.5)$$

$$Mn(NH_3)_4SO_4 + H_2O + 1/2O_2 = Mn(OH)_2 + (NH_4)_2SO_4 + 2NH_3 \quad (10.6)$$

$$2Mn(NH_3)_4SO_4 + 2H_2O + 1/2O_2 = Mn_2O_3 + 2(NH_4)_2SO_4 + 4NH_3 \quad (10.7)$$

The slurry containing precipitated manganese is filtered and the purified solution is fed to an ammonia stripper for recovery of free ammonia. The recovered ammonia is recycled back to process for the preparation of ammonium sulfite solution using SO_2 and makeup NH_3 as per below chemical reaction.

$$2NH_4OH + SO_2 = (NH_4)_2SO_3 + H_2O \quad (10.8)$$

In the process, there are two types of solid cakes which are generated (1) leach residue and (2) manganese cake. Water balance is to be effectively maintained during this process. In order to get the best metallurgical performance, the following steps should ideally be maintained.

1. Use of high pulp density during leaching. It helps in increasing the metal ion tenor in the leach solution for downstream processing and also increases the concentration of ammonium sulfate in the filtrate obtained after bulk sulfide precipitation of Co and Ni. Part of this solution is recycled to the leaching circuit while the rest remains as liquid effluent.
2. Optimization of wash ratios for both leach residue as well as manganese cake.
3. An efficient ammonia recovery system from demanganized leach liquor to obtain a high concentration of ammonia in solution. It will result in the lesser volume of ammonium sulfite solution, which in turn will result in providing leverage for the addition of more wash solution to the leach autoclave.
4. Filter press should be designed to avoid ammonia losses during solid/liquid separation of both leached and demanganized slurries.

Various options to treat the two solids namely leach residue and manganese cake generated are discussed below.

2.1.1 Treatment of Leach Residue

There are two approaches for the treatment of leach residue generated during leaching. The first one is the hydrometallurgical processing to recover manganese by mineral acid leaching in presence/absence of a reductant. The weight of dried leach residue is about 70% of the original weight of the polymetallic nodules. To leach more than 95% of manganese from leach residue reductant is to be added during leaching. All the iron present in leach residue will also come into solution mostly in a ferrous form which will need to be oxidized prior to its removal. Recovering

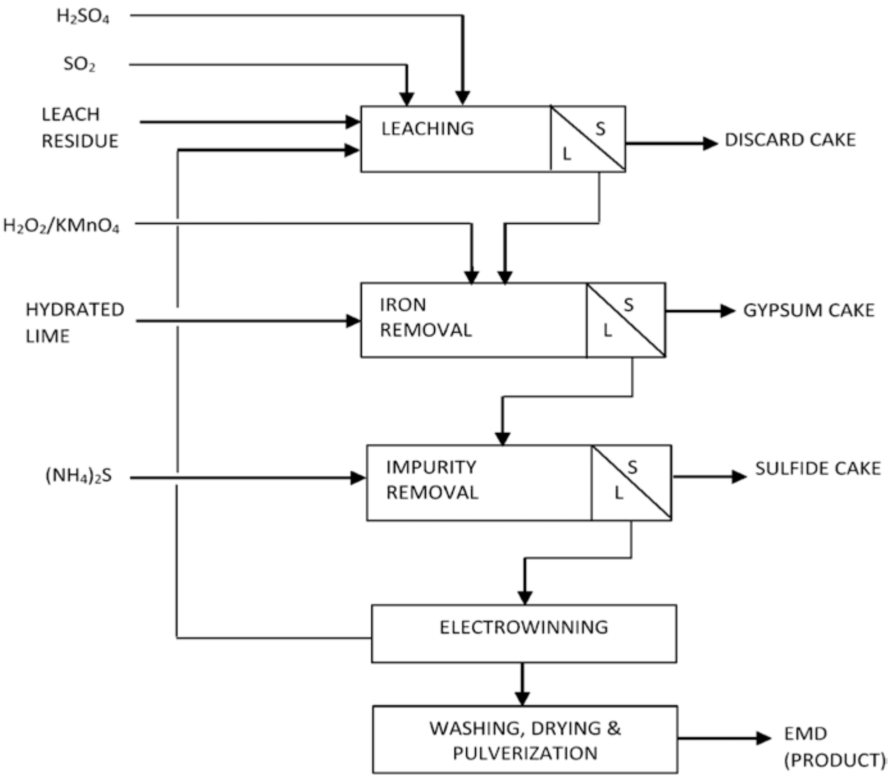

Fig. 10.2 Conceptual flowsheet for recovery of manganese from leach residue

manganese from the leach residue will consist of several unit operations including leaching, solid-liquid separation, washing, purification, and preparation of EMD. The conceptual flow sheet is illustrated in Fig. 10.2. The main problem associated with this scheme shall be the generation of another residue, which will require further treatment prior to its disposal as solid waste. In fact, it will be a parallel hydrometallurgical plant similar to the original ammonia leaching of polymetallic nodules with a difference of acid leaching instead of reductive ammoniacal leaching.

The other alternative to treat the leach residue is through a pyrometallurgical route. For this option, first the leach residue needs to be washed and dried followed by smelting. Ferromanganese and calcium silicate are produced through two pyrometallurgical operations (Friedmann et al. 2017a, b; Bairstow 2020). In the present case, the ferromanganese produced will also have certain amounts of Cu, Ni, and Co, which were not leached during the reductive ammoniacal leaching. The approach reported in recent years by Friedmann et al. (2017a, b) and Bairstow (2020) may be applicable with certain modifications. The advantage here will be an approach toward the minimization of solid waste. It is felt that the pyrometallurgical treatment of leach residue will provide a better option.

2.1.2 Recovery of Manganese from Manganese Cake

Manganese cake generated in this process can be regarded as a by-product as it is relatively pure with very small quantities of Cu, Ni, and Co present as impurities. Several studies have been carried out to recover manganese from the manganese cake. It contains Mn as MnO, Mn_2O_3, and MnO_2. Complete dissolution of Mn from this cake requires a reductant. The various options for dissolving Mn from the cake are (1) dissolving it in mineral acids in the presence/absence of reductant. (2) Dissolving in organic acids in the presence/absence of reductants.

Manganese can be effectively dissolved in sulfuric acid using carbon or SO_2 as the reductant. In case carbon is used as a reductant again a residue will be generated. The advantage of using SO_2 as a reductant along with H_2SO_4 is that complete dissolution of cake takes place. The leach solution so produced will have small quantities of Cu, Ni, and Co as impurities, which are removed through pH adjustment and precipitation using sodium/ammonium sulfide. The purified solution is treated through the electrolytic process to obtain EMD. A laboratory-scale study for the production of EMD has been reported (Sanjay et al. 1999a, b; Panda et al. 2009). In the laboratory scale, the EMD produced from manganese cake showed a high discharge capacity of 290 mAh/g.

The other option is to evaporate the purified manganese sulfate solution to obtain manganese sulfate monohydrate crystals. In this case, it is essential to keep the pulp density as high as possible (25–30%) during leaching so that the manganese concentration is increased in the purified solution thereby reducing the evaporation load. A conceptual flowsheet for the recovery of manganese from manganese cake is shown in Fig. 10.3.

2.2 Preparation of Copper Cathode and Bulk Sulfide Precipitation

The pH of the purified solution after removal of the free ammonia is adjusted using sulfuric acid. The ammines of Cu, Ni, and Co form their respective sulfates during this step. Ammonium sulfate is also generated as shown in Eqs. (10.9)–(10.11).

$$Cu(NH_3)_4SO_4 + 2H_2SO_4 = CuSO_4 + 2(NH_4)_2SO_4 \tag{10.9}$$

$$Ni(NH_3)_6SO_4 + 3H_2SO_4 = NiSO_4 + 3(NH_4)_2SO_4 \tag{10.10}$$

$$2Co(NH_3)_5SO_4 + 5H_2SO_4 = 2CoSO_4 + 5(NH_4)_2SO_4 \tag{10.11}$$

The solution is then subjected to Cu SX-EW to produce pure copper cathodes. The Co, Ni along with small amounts of dissolved manganese are precipitated as bulk sulfide cake using sodium sulfide. The slurry is filtered to get bulk sulfide cake

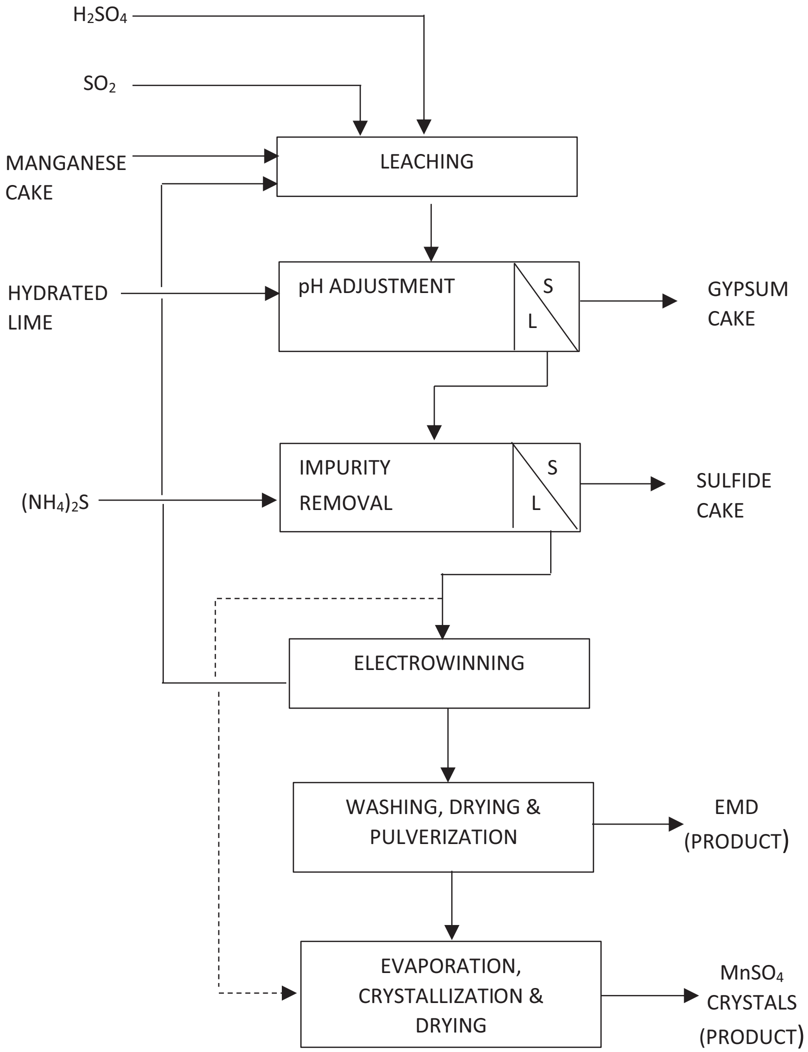

Fig. 10.3 Conceptual flowsheet for recovery of manganese from manganese cake

and ammonium sulfate solution as liquid effluent. It is suggested that ammonium sulfide may be used, which produces ammonium sulfate rather than sodium sulfate so that the filtrate contains only ammonium sulfate and not a mixture of ammonium and sodium sulfates. The sodium sulfate may later be built up and can cause difficulty both in the process as well as in the treatment of the effluent. The liquid effluent generated during this process contains about 110 g/L ammonium sulfate. As mentioned above about 1/3rd of this solution is recycled to the leaching.

2.2.1 Treatment of Ammonium Sulfate Effluent

The liquid effluent containing 110 g/L of ammonium sulfate is generated, which needs to be treated. There can be several approaches to treat this effluent. Besides this, there will be some extra wash solutions containing low concentrations of ammonium sulfate 3–8 g/L. A detailed study on various possible ways to treat this effluent for either ammonia recovery or for enriching it to a maximum possible concentration has been done by Sarangi et al. (2004). The studies were carried out using a synthetic solution of ammonium sulfate.

Electro-Dialysis

During this study, it was concluded that ammonium sulfate could be concentrated from 110 to 268 g/L. It was observed that due to the transport of ~30% water molecules, input and output concentrations of ammonium sulfate became almost constant at ~270 g/L, hence further enrichment was difficult. The energy consumed for concentrating $(NH_4)_2SO_4$ was calculated to be ~0.4 kWh/kg of $(NH_4)_2SO_4$. Further, it had to be evaporated to obtain ammonium sulfate in solid form. The overall process seems technically feasible.

Electro-Decomposition

Electrodecomposition or electrochemical splitting is a process that generates ammonium hydroxide and dilute sulfuric acid as shown by the following equation:

$$\left(NH_4\right)_2 SO_4 + 2H_2O = 2NH_4OH + H_2SO_4 \quad (10.12)$$

The studies indicated that the electrochemical splitting technique is a viable process to simultaneously generate ammonium hydroxide and sulfuric acid. The presence of small quantities of metal ions such as Cu(II), Ni(II), and Co(II) appeared to decrease the current efficiency. The authors compared the energy required for the production of ammonia from the effluent streams containing ammonium sulfate with other processes for ammonia production. Such a comparison is made in Table 10.2 (Kirk-Othmer 1978). It can be inferred that ammonia produced through electrodecomposition would require minimum energy. A combination of electrodialysis and electrodecomposition may seem to be a good proposition so that the ammonium hydroxide generated can be recycled. Here one needs to ascertain the concentration of ammonium hydroxide generated. Dilute sulfuric acid produced in the electrodecomposition process may be used in bulk sulfide precipitation. However, the economics remains to be an important issue.

Table 10.2 Comparative energy requirements for ammonia production

Sr. no.	Process	Energy requirements, KWh/kg
1	Natural gas reforming	10.34
2	Naphtha reforming	10.98
3	Fuel oil partial oxidation	11.31
4	Coal gasification	
	Lurgi	14.54
	Koppers-Totzek	16.18
5	Natural gas reforming	10.34
6	Electrochemical splitting method	
	Sarangi	8.00

Lime Boil Method

Recovery of ammonia through lime boil could provide another option for the treatment of ammonium sulfate-containing effluent. In this process, ammonia is generated and the sulfate is rejected as calcium sulfate. Several studies have been reported to regenerate ammonia through this technique (Johnson and Zhaung 1999; Reagan 1999; Johnson et al. 2000; Harrison 2008). The decomposition reaction is given below:

$$(NH_4)_2SO_4 + CaO = CaSO_4 + 2NH_3 + H_2O \quad (10.13)$$

The studies (Sarangi et al. 2004) carried out on the decomposition of ammonium sulfate by lime boil showed it to be efficient as 93% decomposition could take place and ammonia could be regenerated for recycling. To achieve such high efficiency, the requirement of lime was reported to be 2.5 times stoichiometric. About 10 tons gypsum (dry basis)/ton ammonia will be produced. The plus point here is that the gypsum produced will be of very high purity. Generally, the high requirement of lime is due to the formation of the protective layer of gypsum on unreacted lime. Van Den Berg et al. (2009) have suggested improvements in equipment design for efficient ammonia recovery from ammonium sulfate by lime boil method whereby the lime utilization is up to 91% hence drastically reducing the consumption of lime to just a little above the stoichiometric requirement during this process. This makes the lime boil process attractive.

In view of the above discussions on the treatment of ammonium sulfate-containing effluent, a conceptual flowsheet is presented in Fig. 10.4. Here it is suggested that the ammonium sulfate containing liquid effluent can be treated through the lime boil, followed by electrodialysis of the filtrate for the enrichment of ammonium sulfate. Part of this solution can be evaporated to get ammonium sulfate crystals. The other part may go through electrodecomposition generating ammonium hydroxide for recycling to the leaching. In this step, dilute sulfuric acid is generated which in turn is enriched by electrodialysis. The enriched acid so obtained will be

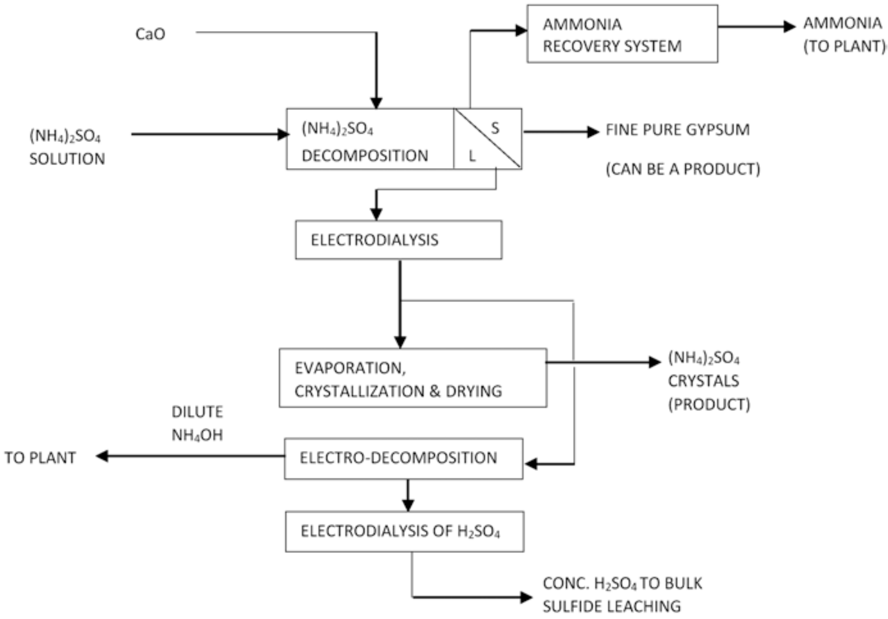

Fig. 10.4 Conceptual flowsheet for treatment of ammonium sulfate containing liquid effluent

used for Ni-Co sulfide leaching. The gypsum generated in the lime boil is of high quality and should be saleable.

2.3 Cobalt and Nickel SX-EW

Here bulk sulfide cake is leached with sulfuric acid in the presence of oxygen overpressure in an autoclave. There is negligible residue and the solution undergoes fine filtration prior to solvent extraction. Both Co SX-EW and Ni SX-EW are closed-loop processes. After nickel separation raffinate generated will contain sodium sulfate which can be evaporated to get sodium sulfate crystals as illustrated in Fig. 10.1 which will be a by-product of the process.

3 Conclusions

In this chapter, the ammonia-sulfur dioxide process has been discussed with an objective to assess whether this process can adopt an approach toward minimization of wastes to achieve a Zero Waste goal. The process flowsheet shows two main effluents namely (1) ammoniacal leach residue and (2) a liquid effluent containing ammonium sulfate. There is also a manganese cake, though it can be considered as a by-product but it is advisable to treat it through hydrometallurgical route for the production of electrolytic manganese dioxide or manganese sulfate monohydrate crystals. The ammoniacal leach residue needs to be treated through a pyrometallurgical route for producing ferromanganese and calcium silicate. The liquid effluent containing ammonium sulfate can be treated through a combination of various techniques including lime boil, electrodialysis, and electrodecomposition. Almost pure fine gypsum is produced through the lime boil. The electrodialysis coupled with electrodecomposition steps can generate ammonia and sulfuric acid for their utility in plant. Sodium sulfate crystals are another byproduct. The main products remain to be copper, nickel, cobalt cathodes, and EMD/manganese sulfate monohydrate crystals. The success of hydrometallurgical plant is pivoted on an excellent water balance; hence, it is suggested (1) to optimize for higher pulp density during leaching, (2) efficient ammonia recovery system, and (3) optimized wash liquors.

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Navin Mittal is the founder and CEO of Hydromet Technology Solutions Pvt Ltd. He has led numerous research programs in the area of extractive metallurgy including the design of 500 kg/day polymetallic manganese nodules pilot plant in India. He has led the team of scientists in developing flowsheet for the extraction of metals from spent lithium-ion batteries. He has to his credit the design of several solvent extraction plants for copper, nickel, and cobalt. He is currently working on projects for the extraction of manganese as battery grade electrolytic manganese metal and high purity manganese sulfate monohydrate crystals from low-grade manganese ores.

Shashi Anand obtained her M.Sc. and Ph.D. degrees in chemistry from Indian Institute of Technology, Delhi. She worked in the hydro-electrometallurgy Department of Institute of Mineral and Materials Technology, IMMT (earlier RRL) for almost 32 years. Dr. Anand was associated on processing of Indian Ocean polymetallic nodules for three decades. She along with her co-workers published several papers and obtained a number of patents related to processing of Manganese nodules. Dr. Anand successfully led a team of researchers from IMMT side, who operated India's first 500 kg/day nodule processing plant. Currently, she provides consultancy for hydrometallurgical processes for the recovery of metal values from secondary sources. Her other interests include the synthesis of nanomaterial and remediation of toxic ions from aqueous solutions. Several researchers obtained doctorate degrees under her guidance.

Part III
Ecosystem Studies, Environmental Monitoring and Management

Chapter 11
Natural Variability Versus Anthropogenic Impacts on Deep-Sea Ecosystems of Importance for Deep-Sea Mining

Teresa Radziejewska, Kamila Mianowicz, and Tomasz Abramowski

Abstract Deep-sea ecosystems (DSE) undergo changes which result from natural variability and from human activities, with frequent feedbacks between these two dimensions. Given the seriousness and costs of future deep-sea mining (DSM), a substantial human intervention into the natural environment of the deep-sea, this intervention should be successful (providing the benefits intended), sustainable (providing the benefits in a long term) and responsible (causing the least possible disruption of the deep-sea environment and its communities). The success, sustainability and responsibility of DSM require knowledge of conditions under which the intervention will be carried out as well as the ability to predict the severity of mining effects. The present knowledge on the status and natural variability of ecosystems to be impacted by future mining operations, particularly polymetallic nodule fields on abyssal plains and polymetallic sulphides in hydrothermal vent fields on mid-ocean ridges, is severely limited, as is knowledge on possible consequences of the impacts caused by DSM and rates of recovery from it. We present a brief overview of time-series studies carried out to date in the parts of DSE targeted for future mining operations and discuss the two major dimensions of DSE changes, natural and anthropogenic. We conclude by reiterating the need for intensified, high-resolution observation system(s) of DSE and the necessity of having appropriately resolved time-series of data.

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1 Introduction

Marine ecosystems, including the deep-sea, are anything but static; they have been, and are, changing. The changes can be linear, non-linear (including cyclic), oscillation-like, appear as a sudden change of state, or be visible as structural shifts (Cloern et al. 2016; Chaparro-Pedraza 2021). Ecosystem changes can result from natural variability driven by a multitude of processes operating on various spatial and temporal scales, from local to regional to global and from intra-annual (seasonal) to inter-annual, decadal, secular and longer. Evidence for variously scaled natural variability in the Earth's past has been provided by palaeoceanographic studies involving microfossils (foraminifera, ostracods, diatoms) serving as proxies of change in environmental conditions (e.g. Gooday 2003; Yasuhara et al. 2012; Witkowski et al. 2020). In the words of Glover et al. (2010) 'The deep sea is one of the best-studied palaeoenvironments, and a repository of long-term sedimentary records that contain microfaunal and isotopic proxies of past climate'.

Deep-sea ecosystems (DSE) undergo changes on the historical time scale as well. In addition to natural drivers, there is a powerful force in action, namely human activities. Motivated by the need to expand and exploit, humans have been, and are, adding materials and energy, in the form of, e.g. litter, artificial constructions, radioactive substances, to the marine environment (Ramirez-Llodra et al. 2011). Humans also have been, and are, removing (extracting) a lot from the marine environment in the form of living resources, minerals and energy (oil and gas) (Ramirez-Llodra et al. 2011).

Deep-seafloor areas are known as repositories of important minerals (Petersen et al. 2016; Zawadzki et al. 2020), including those which are indispensable for high-tech applications and/or facilitate the switch to a green economy (Cuyvers et al. 2018). Some of those minerals are rare on land, or hardly accessible there (because of, e.g. political tensions), and their removal leaves visible damage (Cuyvers et al. 2018). From this point of view, extraction of minerals from the deep seafloor via deep-sea mining (DSM) appears as an attractive alternative (Sparenberg 2019; Childs 2019). However, it has been increasingly frequently pointed out that DSM will hardly be environmentally inconsequential (Weaver et al. 2018), even though the consequences, including environmental changes, may not be immediately evident.

Environmental changes in marine ecosystems are assessed based on measurements of a range of physical and chemical variables as well as on metrics and indices derived directly or indirectly from the analysis of biological communities (Borja et al. 2016). The biological metrics include, inter alia, individual population/species characteristics such as abundance and biomass as well as community structure attributes such as taxonomic richness and biodiversity.

A sufficiently long time series of data produced by the analysis of those metrics allows to detect signals of change, to infer its magnitude and significance, and—in combination with environmental data—to look for the underlying cause(s) of the change. However, to allow for reliable detection of such signals, the data series should be—in addition to covering an appropriately long period of time—of a sufficient temporal resolution, in other words it should ensure continuity of information acquisition. This is very difficult to achieve in marine situations, particularly where the deep-sea is concerned, because of a multitude of technological, logistic and financial constraints (Glover et al. 2010; Danovaro et al. 2020).

For this reason, the deep-sea part of the world's ocean still remains poorly known, the knowledge being far too insufficient, particularly in view of the uses planned for the deep sea.

Given the paucity of more or less continuous, long-term data series on the deep-sea biological communities (see below) on the one hand, and the need to find ways for assessing potential impacts which might be brought about by anthropogenic activities on the other, relatively common has been a short-cut type of approach whereby data collection events (cruises, expeditions, campaigns) were separated by long time intervals. For example, follow-up studies at the experimentally disturbed deep seabed sites were conducted variously from about 2 (Radziejewska 2002) to 20 (Radziejewska et al. submitted) to 26 and more years post-disturbance (Khripounoff et al. 2006; Miljutin et al. 2011; Stratmann et al. 2018a, b; Simon-Lledó et al. 2019; de Jonge et al. 2020). Although no data were collected during the intervening years, claims have often been made regarding causes of the changes observed in the faunal communities and community structure parameters identified during a visit to the formerly disturbed site, and regarding the recovery—or otherwise—of the previously disturbed benthic community. The changes were primarily reported for the megafauna (e.g. Simon-Lledó et al. 2019) and the meiobenthos (Miljutin et al. 2011; Radziejewska 2002, 2014; Radziejewska et al. submitted). Most often, the differences observed relative to the initial states (the ones at the beginning of the observation series) have been attributed to a lingering effect of the former disturbance (e.g. Miljutin et al. 2011; Gausepohl et al. 2020), although recovery from the disturbance has been inferred as well (e.g. Khripounoff et al. 2006; Radziejewska 2014; Stratmann et al. 2018a). However, a question arises whether such claims are substantiated, given the lack of information on what was happening in the area of study in-between the sampling campaigns. This question touches on a broader issue, namely that of disentangling anthropogenic changes from those resulting from natural drivers. The issue is challenging, and has featured strongly at the focus of attention of both scientists and practitioners concerned with environmental monitoring and assessments (Tasser et al. 2010).

A possibility to disentangle anthropogenic changes in DSE from those resulting from natural drivers is also of importance for the environmental management of deep-sea areas subject to exploration—and the future exploitation—activities by the International Seabed Authority (ISA) contractors, including preparation of the environmental impact assessment and the environment impact statement (Billett et al. 2019; Clark et al. 2019). From a contractor's standpoint, the ability to assess the degree of natural variability and stability of the contract area's environment will be important for, inter alia, appropriate designation of impact and preservation reference zones (Jones et al. 2020). In addition, knowledge of natural changes will facilitate understanding the post-mining recovery (Jones et al. 2017). Although the contractor cannot be expected to have long-term time-series data from before the start of their activities, the range of environmental conditions in the reference area, collected over some period of time (rather than just one-time observations), should be taken into consideration while evaluating the impact.

In this chapter, we present a brief overview of time-series studies carried out to date in those parts of the DSE which are of immediate and/or tangential importance for ISA contractors' exploration activities, i.e. abyssal plains and hydrothermal vent fields. We then discuss the two major dimensions of DSE changes, separated here more for clarity of the narrative than because of a sharp and unambiguous distinction between them. We focus first on the natural dimension of DSE changes and invoke non-human drivers of change. We then move on to tackle the human dimension of change and discuss available data and inferences on effects of human intervention in the DSE. We close the chapter by reiterating the need, raised by several authors (e.g. Levin et al. 2019; Danovaro et al. 2020; Ingels et al. 2021) for intensified, high-resolution observation system(s) of DSE and the necessity of having appropriately resolved time-series of data to be able to make informed inferences on drivers and mechanisms of changes observed.

2 Background: Setting the Scenes

As already pointed out, we focus on two deep-sea realms that are of concern from the standpoint of DSM, as they host mineral resource deposits most interesting and important for future use: the abyssal plain, with a particular reference to the NE subequatorial Pacific and its polymetallic nodule resources in the Clarion-Clipperton Fracture Zone (CCFZ), and hydrothermal vent fields on mid-ocean ridges, of commercial importance because of their polymetallic sulphide deposits. We disregard other habitats which feature prominently in the deep-sea, such as canyons, seamounts, trenches, submarine plateaus, cold seeps and cold-water coral reefs. Although important because of ecosystem services they provide (Ramirez-Llodra et al. 2010; Le et al. 2017), they are of no immediate commercial interest (except for deep-sea fisheries on and around the seamounts; Clark 2009; Clark et al. 2016).

Abyssal plains cover about 75% of the deep seafloor (Ramirez-Llodra et al. 2010; Watling et al. 2013). They are mostly sedimented systems (in the sense of Glover et al. 2010) and, although far from uniformly flat, their topographic relief is much reduced, compared to other areas of the deep seafloor (e.g. Durden et al. 2020a) (Fig. 11.1).

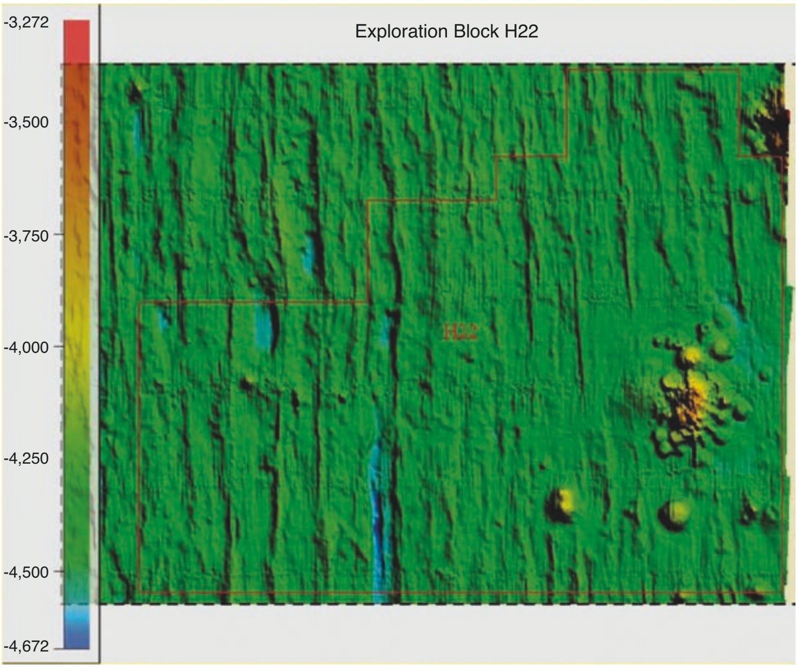

Fig. 11.1 An example of relative topographic complexity at the CCFZ seafloor: a fragment of seafloor topography at the IOM contract area in CCFZ (block H22 4151 km^2 in size) (Credit: IOM)

The abyssal seafloor, particularly in areas underlying oligotrophic oceanic regions, features characteristic mineral deposits—polymetallic nodules (Kuhn et al. 2017) (Fig. 11.2).

Although polymetallic nodules are known to occur in numerous places throughout the world's ocean (Ingole and Koslow 2005; Riehl et al. 2020; Belkin et al. 2021), by far the world's largest accumulation of nodules is to be found in the NE subequatorial Pacific in the so-called Clarion-Clipperton Fracture Zone (CCFZ) (Kuhn et al. 2017). In addition to containing an array of minerals and metals of interest to DSM (Kuhn et al. 2017; Zawadzki et al. 2020), nodules provide a discontinuous hard-substratum habitat on an otherwise soft-sediment bottom. Their presence imparts a particular type of habitat heterogeneity to the seafloor (Vanreusel et al. 2010), and they are known to be used individually as permanent settlement sites for a number of specific organisms (e.g. Veillette et al. 2007) (Fig. 11.3), including, e.g. the recently described nodule-specific sponge *Plenaster craigi* (Lim et al. 2017). Evidence accumulated so far shows the nodule field fauna, in all the size categories studied by benthologists, to be highly diverse, although the full extent of this diversity has not been yet appreciated (Vanreusel et al. 2016; Gooday et al. 2021).

Hydrothermal vents on mid-oceanic ridges are of economic interest because of their deposits of polymetallic sulphides (PMS) (Rogers 2015; Cherkashov 2017).

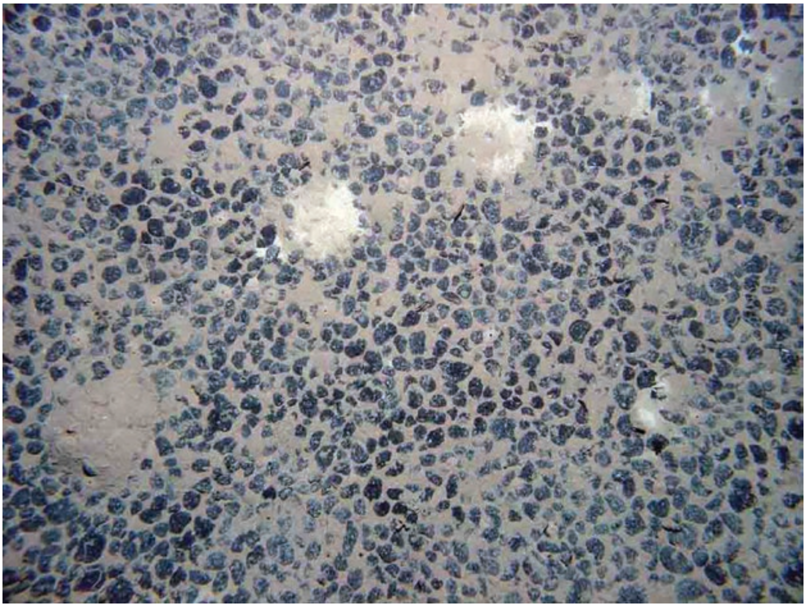

Fig. 11.2 A nodule-covered swath of the CCFZ seafloor (Credit: IOM)

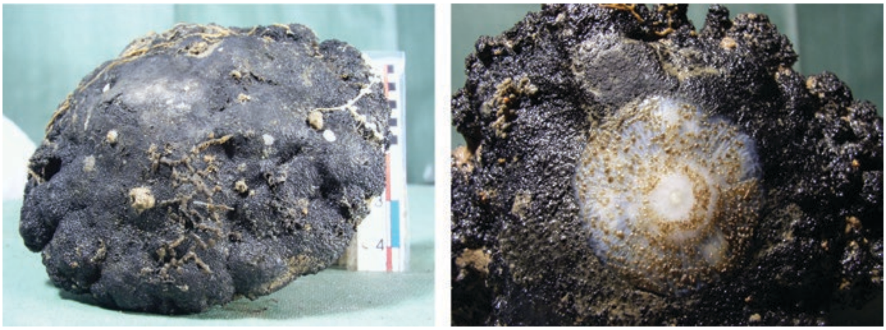

Fig. 11.3 Nodules with sessile organisms attached; note the sponge *Plenaster craigi* in the lower photo (Credit: IOM)

On the other hand, they are of enormous scientific interest because of the characteristic faunal communities they support (Fig. 11.4) and unique biogeochemical processes operating in those communities allowing their persistence (Van Dover 2000). These ecosystems are thought to be controlled primarily by geological processes, as they depend on the supply of sub-bottom fluids, highly chemically enriched. Therefore, any change in the fluid flow will result in alteration of the composition, distribution and dynamics of a vent community (Tunnicliffe 1991). Geological controls on the fluid flow may involve eruptive or intrusive catastrophic events which bring about temporal variability (Glover et al. 2010; see below). Vent field

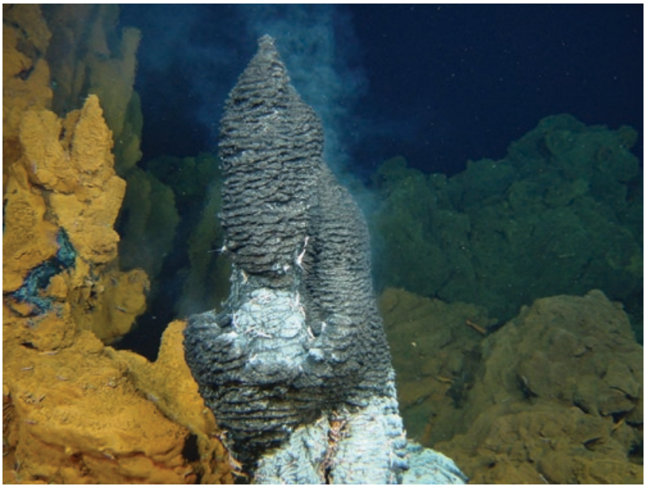

Fig. 11.4 An example of a hydrothermal vent community [Credit: IFREMER; IFREMER (2005). Fumeur actif du site hydrothermal Rainbow. Ifremer. https://image.ifremer.fr/data/00569/68072/]

ecosystems support communities adapted to the fluid flow variability and unique in terms of their composition (they show a high level of endemism), biomass (much higher than the deep-sea average because of no apparent food limitation) and functioning (reliance on chemosynthetic primary production, prevalent symbioses) (Van Dover 2000). The vent field ecosystems are, broadly speaking, ocean-specific, with conspicuous differences in faunal composition between, e.g. the Atlantic and Pacific vent fauna. On a smaller (regional) spatial scale, there are differences between individual vent fields within a region (e.g. between vent fields of the Mid-Atlantic Ridge; Gebruk and Mironov 2006) and even within individual fields (Galkin 2016; Spedicato et al. 2020), apparently stemming from habitat complexity. This complexity imparts another challenge associated with gathering data, namely deciding whether findings from a spatially constrained area will be amenable to extrapolation onto a wider expanse of the ridge (e.g. a contract area) (Billett et al. 2019). Much attention has been recently drawn to the distinction, still incompletely resolved, between active and inactive vent fields and their communities (Van Dover 2019), as it is most likely the inactive vents that will be mined for polymetallic sulphides in the first place.

3 Time-Series Studies in Abyssal and Vent Ecosystems: Some Examples

Information on long-term changes in the DSE of concern for this chapter is generally limited. The most comprehensive review of long-term data time-series originating from studies predating the beginning of the present century is that of Glover et al. (2010). They identified 11 deep-sea sites in the sedimented systems (including 2 on the abyssal plains) and 12 hydrothermal vent sites for which multi-year to multi-decadal data series had been published. They also brought together information produced by temporally resolved studies still in progress at the time their review was being written.

With respect to the abyssal plains, there were two sites for which long-term benthic data were available for Glover et al. (2010), and which still supply data to science: the Porcupine Abyssal Plain (PAP) site in the NE Atlantic (4850 m depth), with observations starting in 1977, and Station M in the NE Pacific (4100 m depth), with observations starting in 1989.

By 2010, observations at the PAP site, concerning primarily invertebrate megafauna, brought some quite extraordinary findings, the most spectacular of these being the so-called *Amperima* event (Billett et al. 2001, 2010). It involved a 'boom-and-bust' sequence of holothurian (primarily *Amperima rosea*) abundance dynamics, with a rapid and large increase in 1996/1997, followed by a decline; the second such sequence was observed in 2002–2005. The abundance increase ('boom') was correlated with sedimentation of copious amounts of phytodetritus from the euphotic zone (Thiel et al. 1989). There were also changes in shallow-infaunal foraminifera and surface deposit-feeding polychaetes, more or less synchronous with changes in the holothurian abundance.

The PAP observatory is still in use and serves as a multidisciplinary open-ocean time series site (Hartman et al. 2021). The data are collected in studies focusing on connections between the surface and deep ocean. The in situ measurements of climatically and environmentally relevant variables, conducted for more than 30 years, have substantially contributed to our present understanding of temporal variation in the deep sea and effects of surface phenomena on the seabed.

Observations from Station M (e.g. Ruhl and Smith 2004) documented, between 1997 and 1999, a major change in the community structure of the dominant epibenthic megafauna. The change was synchronous with a large El Niño Southern Oscillation (ENSO) event in those years (see below). Responses to phytodetritus pulses were reported in protozoans (agglutinating foraminifera in particular) as well as major macrobenthic metazoans (Drazen et al. 1998) and also in the benthic community metabolism, determined as the sediment community oxygen consumption (SCOC). That proved directly correlated with the particulate organic carbon (POC) flux with no time lag (Ruhl et al. 2016). The 29-year-long observation series at Station M allowed Smith et al. (2018) to identify episodes of phytodetritus input to the seafloor and thus assess the magnitude and frequency of POC fluxes, i.e. the food supply to the abyssal benthos.

Recently, Durden et al. (2020b) analysed subsets (30 and 18 months at PAP and Station M, respectively) of long-term data from the two abyssal observatories and compared effects of phytodetritus sedimentation onto the seafloor on mobile megafauna in both locations. While the magnitude of the POC flux was similar at the two stations, PAP was characterized by a pronounced seasonality. The responses of various megafaunal taxa to phytodetritus inputs were not consistent, and appeared to be taxon-specific.

Although the hydrothermal vent ecosystems are widespread in the deep-sea (Beaulieu et al. 2013, 2015), only a handful of them have been studied regularly. The pace of studies in some areas (notably in the Indian Ocean and South Atlantic) accelerated somewhat after a number of contracts for exploration of polymetallic sulphides have been recently signed by the ISA (Van Dover et al. 2020) and new discoveries have been made (Connelly et al. 2012; Rogers et al. 2012). Nevertheless, as highlighted by Glover et al. (2010), temporal patterns can be inferred from a relatively few sites: in the East Pacific, primarily on the East Pacific Rise (EPR) and in the North Atlantic's Mid-Atlantic Ridge (MAR).

The former supports a few fields that had been visited several times, albeit at irregular time intervals. A characteristic example of community changes occurring at active vents in the fast-spreading area of the EPR is provided by the site named the Rose Garden. It was visited in 1979, 1985, 1988, 1990 and 2002 and showed a temporal succession of dominant species. The succession, as observed, started with the initial luxuriant presence of the tubeworms *Riftia pachyptila* in 1979, replaced as a dominant by the mussels *Bathymodiolus thermophilus* in 1985 and by the clams *Calyptogena magnifica* in 1988. Further changes were recorded later on, with the peripheral fauna (notably the whelks *Phymorhynchus* sp. and squat lobsters *Munidopsis* sp.) moving into the active area in 1990. Observations made in 2002 (Shank et al. 2003) showed a collapse of the community due to burial by a fresh basaltic flow, and a new vent (called the Rosebud) with an assemblage of young colonizers was found to have been opened some 300 m north-west of the Rose Garden.

More temporal stability has been reported from another EPR vent site (21ºN), visited in 1979, 1982 and 1990 and presumed to have been active for at least 300 years. Desbruyères (1998) regarded the vent communities there as temporally stable, at least on a decadal scale. At the EPR site 13°N, visited in 1982, 1984, 1987, 1991, 1992, 1996 and 2002, signals of change in the wake of a collapse of some vent site fragments were detected. A faunal succession due to subsequent warm-water venting and diffuse emissions was described following the collapse, but no major change during the last decade of observations was visible, with *R. pachyptila* and the polychaete *Alvinella pompejana* dominating the vent communities (Desbruyères 1998).

A long-term monitoring transect (the BioGeoTransect) was established (Shank et al. 1998) at still another EPR site (9°N) following the eruption and lava flow there in April 1991. The event annihilated a large part of the vent communities and the monitoring cruises documented very fast rates of colonization and temporal succession (Shank et al. 1998, 2003; Desbruyères 1998).

Recently, Mullineaux et al. (2020) summarized investigations of ecological succession after the catastrophic 2006 eruption on the EPR which eradicated the entire vent community. They were able to continue observations for more than a decade and showed the succession (and thus community changes) to proceed continuously. With respect to the post-disturbance recovery of vent communities, they likened it to that following a mining disturbance and concluded that 'the vent communities, in general, may be less resilient to mining disturbance than originally expected', the eradication of the community by the eruption being equalled to the annihilation due to resource removal.

Hydrothermal ecosystems in the NE Pacific (primarily on the Juan de Fuca Ridge) have featured in some studies involving temporal variability and faunal succession assessments, mostly in the wake of eruptions (the first identified in 1986) (e.g. Baker et al. 1989; Sarrazin and Juniper 1999; Tsurumi and Tunnicliffe 2001).

In contrast to the fast-spreading ridges of the NE Pacific, the MAR belongs to slow-spreading ones (Cherkashov 2017), with spatial frequency of venting much lower than in the Pacific and apparently less frequent stochastic disturbance (tectonic and volcanic events). Therefore, the MAR vent fields are expected to display larger temporal stability and activity. Nevertheless, a 2-year monitoring for seismic events at the northern part of MAR (Smith et al. 2003) did provide evidence of some variability in this respect.

The MAR hydrothermal vent fields are classified as belonging to two biogeographic provinces (Van Dover et al. 2002; Gebruk and Mironov 2006), one including shallower sites (Lucky Strike, Menez Gwen and Rainbow) south of the Azores and the other featuring deeper fields (TAG, Broken Spur) further south. In general, the two provinces differ in the community dominant, the mussels *Bathymodiolus azoricus* and the shrimps *Rimicaris exoculata* being dominant in the northern and southern part, respectively. The longest-studied MAR vent community is that at the TAG site, the studies having been initiated there already in the 1980s (Rona et al. 1986; Copley et al. 2007). The observations allowed to conclude on a relative stability of the TAG communities, notwithstanding certain within-site differences (Galkin 2016; Spedicato et al. 2020).

Cuvelier et al. (2011) followed vent community dynamics at the Lucky Strike site, based on 14 years of observations (starting in 1992). They found the overall faunal coverage (primarily by mussels) to have been stable on a decadal scale, but a finer resolution, temporal and spatial, showed differences in coverage and distribution. They proposed a community succession model for shallower MAR fields whereby the bare substratum is first colonized by *B. azoricus*. Under continuous venting, the observations suggested the presence of two micro-environments, one close to fluid exit and the other further away from it. Compared to that on the EPR, the rate of community change proved significantly lower (55–60 versus 68–88%). It has been suggested that the MAR vent ecosystems, persisting under more stable conditions and experiencing much less frequent stochastic events, are more susceptible to biological control mechanisms such as competition and predation, compared to the more physically structured vent ecosystems of the EPR (Glover et al. 2010).

Glover et al. (2010) wrote their review with four hypotheses in mind which stem from observations of the presumed natural variability at the sites selected, and are based on analyses of benthic community records. After more than a decade since Glover et al. (2010) published their review, it seems that at least three of their hypotheses are still valid and merit consideration. The first hypothesis stated that biologically driven forcing events induced by climate change or climate variability in recent decades affect deep-sea sedimented ecosystems. The review allowed

Glover et al. (2010) to generally support this hypothesis, with a caveat that naturally occurring climatic changes are at present reinforced by anthropogenic influence, with still unknown effects in the deep sea, mostly due to insufficiently long periods of observation. The second hypothesis posited that stochastic geological forcing events are of primary importance for chemosynthetic ecosystems (including hydrothermal vent ones). The available evidence suggests that this may be the case on fast-spreading ridges, with frequent catastrophic events and prolonged recovery. The slow-spreading areas, on the other hand, support more stable communities the post-disturbance recovery rate of which is not known; it is not known, either, whether any changes in vent ecosystems are climate-related. The third hypothesis states that, despite different drivers, the ecosystems present in the contrasting settings of abyssal and vent ecosystems show certain responses to be similar. There is a contradiction in the hypothesis itself, and the different drivers (as well as the apparent insulation from the climate change impact in vent ecosystems) will lead to differing responses. And finally, the fourth hypothesis of Glover et al. (2010) that effects of climatic changes that have occurred over evolutionary (geological) and ecological (historical) time scales are best observed in the deep-sea benthos needs further consideration. This is because, on the one hand, it has not been completely resolved how the processes operating in the water column are translated to the deep seabed communities (but see below), while on the other, some effects may be more easily detectable in those communities than in other compartments of the DSE.

4 The Natural Dimension

Current interest in the global climate change (Bindoff et al. 2019) has resulted also in drawing attention to possible effects and impacts on the deep-sea (e.g. Smith et al. 2008, 2013; Levin and Le Bris 2015). In addition to expecting such effects in the historical (ecological) time, large-scale climatic regime changes in Earth's history, as already pointed out, have been deciphered in the palaeoceanographic record. For example, based on the description of fluctuations in the Late Quaternary ostracod species diversity in the equatorial Atlantic (with about 5000-year resolution), Yasuhara et al. (2008) inferred climatic (temperature) changes as the principal cause. Having observed abrupt shifts in ostracod diversity on millennial and shorter time scales during the last 20,000 years, Yasuhara and Cronin (2008) found the shifts to coincide with climatic oscillations and made inferences on associated changes in surface productivity.

Another group of organisms abundantly preserved as fossils in the deep-sea sediment are the Foraminifera. The extensive literature on foraminifera-based palaeorecord (e.g. Gooday 2003) shows trends interpreted as reflecting changes in productivity and temperature.

In this context, Doi et al. (2021) have recently pointed out that the discussion on drivers of change in deep-sea biodiversity, as inferred from the palaeorecords, revolves around effects of temperature versus surface productivity and the associated POC export. Based on the ostracod record in their sediment cores, Doi et al. (2021) themselves argue for changes in productivity to have driven long-term changes in the deep-sea biodiversity.

On a still different note, Rogers (2015) pointed out that, over millennial time scales, changes from cold (well-oxygenated) to warm (associated with oxygen deficiency and hydrogen sulphide prevalence) ocean states might have been associated with extinctions or might have created conditions for radiation of species into the deep sea.

With regard to historical changes, Karl et al. (2021) have recently reviewed data produced by 30 years of observations and measurements of primary production and particulate carbon (PC) export at Station ALOHA located within the North Pacific Oligotrophic Gyre. They found the PC export to range sixfold, with sub-decadal variability, over extended periods of relatively low flux (1991–1996, 2010–2011, 2013–2014). They also observed seasonal variability, with the maximum PC export in May–August and the minimum between September and January. The environmental forcings discussed by the authors included important and complex climate oscillations (the North Pacific Gyre Oscillation, ENSO and Pacific Decadal Oscillation). In this context, it is particularly interesting to mention the ENSO. During the 30 years of study covered by the data discussed by Karl et al. (2021), there were three strong or very strong El Niño periods: 1991–1992, 1997–1998, and 2015–2016. For the period 1997–1998, a 50% increase in the euphotic zone depth-integrated primary production (relative to a multiyear average) was recorded. Interestingly, in 1997, there was evidence of a strong phytodetritus sedimentation to the abyssal seafloor in the eastern part of the Clarion-Clipperton Fracture Zone which apparently elicited responses in the meiobenthic community (an increased abundance of opportunistic nematode taxa; Radziejewska 2002, 2014). Previous observations (referred to by Rogers 2015; see above) showed the rapid phytodetritus sedimentation to trigger responses in the deep-sea community (e.g. the *Amperima* event) and to modulate the abyssal benthic ecosystem structure and function. Moreover, a link has been found between climate variability represented by the Multivariate ENSO index (MEI) and ocean productivity inferred from the surface chlorophyll concentrations (Behrenfeld et al. 2006; Smith Jr. et al. 2006). Changes in ocean productivity, in turn, have been connected to changes in the POC flux and the quality of organic material arriving at the deep seabed (Smith et al. 2006, 2009).

Interestingly, Karl et al. (2021) observed a significant increasing trend in primary production over the 30-year observation period. They analysed mechanisms that might explain this trend and considered changes in: (1) the phytoplankton structure, (2) the total photon flux to the lower part of the euphotic zone, (3) the net-to-gross photosynthesis ratio, (4) the mesozooplankton abundance with associated top-down responses and (5) an increased flux of new nutrients. Their data allowed them to dismiss the first four mechanisms. As to the new nutrient supply, they invoked a significant increase in the atmospheric deposition of anthropogenic fixed N from north-eastern Asia (Duce et al. 2008; Kim et al. 2014) and concluded that 'this allochthonous supply of fixed N is more than sufficient to support the significant increasing trend of euphotic zone (0–125 m) ^{14}C-based primary production at

Station ALOHA since 1989'. They found the particulate organic matter export (at the base of the euphotic zone) to correlate with primary production on monthly to seasonal scales; however, on annual to decadal scales, the primary production and POC export seem to be decoupled, hence potentially other changes in the pelagic ecosystem structure could have been important.

As shown by data from PAP, variations in the POC export from the euphotic zone (i.e. the export flux) and hence to the seafloor in the Atlantic Ocean, as well as the quality (biochemistry) of the material that reaches the seafloor (Lampitt et al. 2010), appear to be associated with the North Atlantic Oscillation (NAO) (Henson et al. 2012). This is a climatic phenomenon resulting from pressure differences between the northern and tropical parts of the Atlantic (Hurrell et al. 2001; Hurrell and Desel 2009) which has a bearing on precipitation, storm intensity and frequency, and winter conditions on both sides of the Atlantic Ocean. The changes in the quantity and quality of food that reaches the seafloor via phytodetritus sedimentation and resulting indirectly from NAO effects are thought to underpin, inter alia, the 'boom-and-bust' events on the seabed, such as the *Amperima* event (Glover et al. 2010).

The long-term data series have been used to formulate predictions as to DSE responses to climate change. Both direct and indirect effects are expected (Rogers 2015). Projections of future impacts of processes associated with climate change on the DSE for the next ~84 years have been recently presented by Sweetman et al. (2017). When characterizing the present and predicted future conditions of the deep seafloor, they took into account the near-bottom water layer temperature, oxygenation, pH and POC flux (or food supply to the seafloor). Under a future climate change scenario, Sweetman et al. (2017) envisaged, for the abyssal zone, a major change in the POC flux resulting from intensified thermal stratification in the upper ocean and a reduced primary production. This will be coupled with lowered export efficiency of the primary production-derived phytodetritus on account of a change in the primary producer structure (a shift toward phytoplankton being dominated by picoplanktonic forms). Sweetman et al. (2017) predict most drastic reductions in the POC flux to the seafloor to take place in the oceanic gyres and equatorial upwelling zones. The POC flux decline will impact the abyssal seafloor fauna, already stressed by limited food supply, and result in reduced size of organisms, biomass and diversity as well as in major shifts in community composition. Such changes in marine benthos, resulting from increased temperature, have already been and are taking place (Poloczanska et al. 2013; Birchenough et al. 2015). Shifts in community composition are predicted to be associated, inter alia, with shoaling of the carbonate compensation depth (CCD) due to increased CO_2 levels and the resultant acidification (lowered pH levels) and suppression of calcifying taxa, which in turn has a bearing on the community functioning, as, e.g. non-calcareous foraminifera (already dominant in the abyssal settings) are thought to be less active in carbon processing than calcareous forms (Gooday et al. 2008).

Among expected impacts of increasing acidification on the deep seafloor biota (Orr et al. 2005), Rogers (2015) mentions those on cold-water corals, which are major deep-seafloor calcifiers, including reduction of habitat available to coral-associated species. However, as most of the abyssal plain areas of interest for DSM are already situated below the CCD, the direct effects in this respect may not be acute.

Regarding changes in oceanic oxygenation, it has to be remembered that the amount of oxygen in seawater depends on both biological processes (photosynthesis and respiration) and physical ones (circulation, mixing) (Rogers 2015). Nevertheless, the net result of predictions formulated by Sweetman et al. (2017) is a general deoxygenation of the ocean, with concomitant expansion of oxygen minimum zones (OMZ) in the water column. Although abyssal depths are generally well-oxygenated, time series observations in the Atlantic, Pacific and Indian Oceans did show declining oxygen levels (Rogers 2015). OMZ expansion is expected to impact benthic communities where OMZs come in contact with the seafloor; it seems that the abyssal depths of economically important nodule deposits will be spared, at least for some time.

The discussion of natural drivers of variability in the DSE should also touch upon hydrodynamic processes which are manifested as sudden, stochastic events, e.g. catastrophic gravity-driven sediment mass movements (slumps, slides, gravity flows); these, however, are more typical of bathyal than abyssal environments (Glover et al. 2010). Volcanic ash falls have been also invoked as catastrophically affecting the DSE (Glover et al. 2010). A particular example was the Mt Pinatubo eruption in 1991, with ash layers covering large areas of the South China Sea floor. Recolonization of the affected seabed by foraminifera was followed at a few-year time intervals (1996 and 1998) (Hess and Kuhnt 1996; Hess et al. 2001), providing data on the role of foraminifera in recovery from disturbance.

Stochastic physical events at hydrothermal vents, as referred to above, seem to be more frequent on fast-spreading ridges than on slow-spreading ones, but evidently more observations are needed to conclude on the relative roles of environmental drivers (Glover et al. 2010).

Thus far, apart from the POC flux resulting from the surface primary production, the narrative in this chapter has hardly touched upon biological processes in DSE, such as interspecific interactions (competition, predation, mechanisms of species co-occurrence, biodiversity maintenance mechanisms) and intraspecific (e.g. density-dependent) effects, which might play a role in shaping long-term changes. Although there have been efforts to look into the contribution of biological processes to natural variability in the DSE, the empirical basis is still too scant and hypotheses as to the functioning of DSE, advanced in the past, have not become outdated yet (McClain and Schlacher 2015).

5 The Human Dimension

The human footprint in the deep sea can take on multiple forms (Ramirez-Llodra et al. 2011; Rogers 2015), from the introduction of hard substrata to soft-sediment areas to organic enrichment, chemical pollution from chemicals used in oil and gas production and chemical weapons, radiochemical, light and acoustic pollution to

Fig. 11.5 An example of a direct anthropogenic effect on the deep seabed: plastic litter on the CCFZ seafloor (Credit: GEOMAR)

biomass removal and mechanical disturbance. These footprint forms can be visible through direct and indirect effects (Fig. 11.5).

Direct effects, such as the presence of litter on the deep seafloor, including the largest ocean depths in seafloor trenches (Shimanaga and Yanagi 2016) or mechanical damage to the seafloor and its communities (including cold-water corals) by demersal trawling (Clark 2009; Clark et al. 2016) can be quite spectacular and attract a lot of media and public attention. In contrast, the processes resulting in indirect effects are more surreptitious and may be discernible after a (sometimes considerable) time lag (e.g. CO_2 build-up in the seawater and the resultant anthropogenic acidification; Orr et al. 2005). As they may be overlain on the natural variability of the DSE, or vice versa—natural variability may be overlapping with anthropogenic impacts on the DSE, it is challenging to prise the two groups of processes apart (see above).

The human dimension of interest to this contribution involves deep-sea mining (DSM) and its impact on the DSE. Although no mining activities have been undertaken in the deep-sea areas managed internationally (by the ISA) so far, the ISA contractors are working on technological systems to be used for resource extraction (Atmanand and Ramadass 2017) and prototype mining equipment is being tested (e.g. Patania II of GSR; Voosen 2019). The preparations to commence mining are carried out with realization that the challenges involved are considerable, as mining operations will have to proceed under extreme environmental conditions, using remote technology (Atmanand and Ramadass 2017; Cuyvers et al. 2018).

As outlined by Cuyvers et al. (2018), deep seabed mineral deposits—depending on their nature—will be scraped from the seafloor surface, excavated and disaggregated on the seafloor, collected (sucked in) from the seafloor surface or directly drilled into. The ores extracted will then have to be transferred onto a transporting vessel on the sea surface.

Fig. 11.6 The altered sedimentary cover structure (tracks of a disturbing device) persisting 20 years after experimental disturbance at the IOM Benthic Impact Experiment (BIE) (Radziejewska 2002); top: as viewed by ROV Kiel6000; bottom: as photographed by AUV, with an imprint of a box corer (Credit: GEOMAR)

Each of those operations carries a potential to produce environmental impact. To date, there have been a number of reviews dealing with purported consequences of extracting deep-sea minerals.

As early as in the beginning of the 1980s, Jumars (1982) identified the major impacts on nodule benthic community to arise from future mining operations. He listed a direct mechanical damage to the fauna as the nodules are collected and crushed, the sedimentary cover structure is altered (Fig. 11.6) and the sediment is compacted by the mining gear, resedimentation of the sediment plume resulting in burial of the seabed surface and fauna as well as changes in food resources and in sediment biogeochemistry resulting from the removal of the top sediment layer.

Most likely, the major impact will result from the direct loss of habitat (both the nodules and the sulphide cover at a mined vent site) and the organisms directly depending on it (Vanreusel et al. 2016; Gollner et al. 2017; Cuyvers et al. 2018). While benthic mobile species have the ability to return after habitat destruction or disturbance, sessile species will hardly recover (Bluhm 2001; Thiel et al. 2001). In this context, Ardron et al. (2019) presented a simulation of impacts resulting from polymetallic nodule extraction on the megafauna. They took into consideration the purported magnitude of exploitation producing lethal effects and stressed the need for the contractors to be able to recognize when the impacts produce 'serious harm' (Fig. 11.7). The question of 'serious harm' (a legal term used in the United Nations Convention on the Law of the Sea and in official ISA documents; e.g. ISA 2013) has been taken up by Levin et al. (2016) who proposed actions aimed at understanding impacts leading to 'serious harm'. With respect to nodule mining, such actions should include detailed baseline studies, realistic and large-scale mining disturbance studies as well as determination of recovery rates in the sedimentary and pelagic communities.

The expected effects of mining the polymetallic sulphides in hydrothermal vent ecosystems have been summarized (Van Dover 2014; Levin et al. 2016; Miller et al. 2018) as those affecting the habitat which in turn are predicted to elicit community responses. The first category includes habitat destruction (likened to the open-pit mining on land) and loss, degradation of habitat quality, alteration of the local vent circulation, sediment plume sedimentation, light and noise pollution. The second category, community (biological) responses, includes extirpation of vent communities as the most dramatic effect, but also loss of planktonic larvae (responsible for ensuring connectivity), extinctions of rare species, altered seafloor primary production, altered trophic interactions, reduced diversity, ecotoxicological effects and altered behaviours of fauna.

The proposed actions aimed at understanding impacts leading to 'serious harm' with respect to polymetallic sulphide mining in hydrothermal vent settings, whether active or inactive (Levin et al. 2016), include acquiring adequate knowledge on the distribution of hydrothermal sites and their communities, connectivity of populations, their biological traits, endemicity and natural variability (including succession patterns) as well as ecotoxicology of plumes generated by mining and related operations.

Among the secondary impacts in mined areas, there will be turbidity plumes (Aleynik et al. 2017) produced by deposit (e.g. nodule) extraction and discharge plumes formed during the ore lift-up and dewatering. The consequences of plume formation in the near-bottom, mid- and surface waters include increased turbidity of water (impacting filter-feeding, Mestre et al. 2017 and bioluminescent organisms and decreasing the light propagation), increased metal/nutrient concentrations in the water column (Hyun et al. 1998; Koschinsky et al. 2003; Hauton et al. 2017), particle resedimentation (and blanketing of the benthic fauna) (Cuyvers et al. 2018). Desprez (2000) argues that the sediment plumes and resedimentation in the neighbouring sites can be as significant as direct impact due to sediment removal.

Fig. 11.7 Serious harm to the deep-sea environment in the eyes of a 10-year-old Polish schoolkid (Credit: Marcel Czernik; Arch&Art Grażyna Czernik)

Numerical modeling is commonly used in order to assess the spreading of the extraction plume (Jankowski et al. 1996; Sharma et al. 2001; Abramowski et al. 2016; Kulkarni et al. 2018). Results of numerical modelling in general are corroborated by in situ observations (Kulkarni et al. 2018), but in some cases plume dispersion wider than observed in situ has been computed (Jankowski et al. 1996; Oebius et al. 2001). Abramowski et al. (2016) note that there is a necessity for defining the criteria of clean (sediment-free) water in order to be able to unambiguously assess the spatial scale of plume dispersal.

Due to technical issues, most of the experimental studies on plume propagation focus on the shallower water (e.g. Kulkarni et al. 2018; Kaikkonen et al. 2018), where environmental factors such as water column stratification and near-bottom current differ significantly from the conditions at the deep-sea bottom. Nevertheless, general conclusions regarding the scale of the projected impact can be considered as relevant also for the abyssal plains: the ability to predict the spatial and temporal plume dispersal and resedimentation is critical for the environmental impact assessment. The sediment plume impact is predicted to potentially extend far beyond the mining area (Rolinski et al. 2001; Kaikkonen et al. 2018).

There will also be other secondary impacts, with consequences difficult to predict, such as noise and light pollution, electromagnetic disturbance and potential leaks and spills of fuel (Cuyvers et al. 2018).

It is also necessary to consider cumulative impacts, i.e. simultaneous effects of more than one stressor (e.g. Halpern and Fujita 2013; Stephenson et al. 2019). They may be additive, antagonistic, or synergistic, and be produced at many levels (Levin et al. 2016), for instance, by parallel mining operations, by other activities, also from non-mining sectors (fisheries, tourism); the stressors may originate on land. Cumulative impacts may be important also when the natural stressors overlap with anthropogenic activities.

In order to adequately assess all the impacts, long time-series of environmental baseline data of good quality will be particularly needed so that contractors are able to make a good case for their exploitation plans, including the mitigation actions. Adequate sampling methodology, following the Best Available Techniques and Good Industrial Practice and appropriate temporal and spatial representation are of key importance here. Environmental data are submitted by the individual contractors to the ISA and fed into the DeepData environmental database managed by the ISA. The standardized methodologies of sample acquisition, data processing and storage will allow for regional syntheses of environmental conditions and development and adjustment of regional environmental management plans. The baseline data collections in the Area are regulated by ISA (2020a) and the contractors are obliged to follow the recommendations. Currently, the ISA is in the process of drafting the legal framework for exploitation of mineral resources in the Area (and polymetallic nodules in the first place), including a set of guidelines and standards, also for the expected scope and standards of baseline environmental data collection.

As mining activities are being planned, so are remediation measures, required by the Environmental Impact Statement (EIS), Environmental Management and Monitoring Plan (EMMP) and Closure Plan (CP) which will be parts of the Application for the exploitation of mineral resources in the Area (ISA 2020b). The measures to mitigate damage inflicted by mining operations follow a general hierarchical framework of environmental mitigation, with avoidance, minimization, restoration and offsets as the key steps (Van Dover 2014; Gollner et al. 2017; Cuvelier et al. 2018; FFI 2020). While avoidance (for example, of collecting sulphide structures) has been advocated with respect to research at hydrothermal vent sites, it is out of the question as far as DSM in general is concerned, unless a total ban on the industry is enforced. However, establishment of protected areas (e.g. Areas of Particular Ecological Importance, or APEIs and Preservation Reference Zones, or PRZ in the CCFZ) is a form of avoidance. Minimization of impact requires measures to be taken to ensure that a minimum of damage is inflicted. This is proposed to be achieved by, e.g. controlling the extent of particle plumes as well as imposing spatio-temporal restrictions on mining operations (Cuvelier et al. 2018). Restoration measures imply creating and deploying habitat patches similar in properties to those that have been removed. There have already been experimental deployments of artificial substrata at hydrothermal vent sites, but no general conclusions as to their success could be drawn yet (Cuvelier et al. 2018; Mullineaux et al. 2020). Deployment of artificial substrata in nodule fields has been proposed (Cuvelier et al. 2018), but not put to effect yet, also because of numerous problems associated with the choice of a deployment mode as well as because of the sheer magnitude of an area that would have to be 'reseeded' with artificial nodules. Niner et al. (2017) argue that no restoration techniques for the deep seabed would be possible in the mining project's lifetime (including post-closure monitoring) and that offsets in the case of DSM would lead to a net loss of biodiversity; therefore, the priority should be given to the first two steps of mitigation hierarchy (i.e. avoidance and minimization).

6 Final Remarks

Natural and human-induced variability are often confounded and their understanding is complicated by frequent feedbacks. There is, however, a need for distinction between the natural and human-induced variability. It is commonly agreed that such distinction would be greatly facilitated by acquisition and availability of long-term time-series data collected in a consistent manner. In the words of Cloern et al. (2016), 'Time series of environmental measurements are essential for detecting, measuring and understanding changes in the Earth system and its biological communities'. Despite technological advances in deep-sea observations, including deployment of stationary cabled observatories such as Neptune Canada (Aguzzi et al. 2020), there are still inherent difficulties in obtaining satisfactory data sets of appropriate temporal and spatial resolution to inform both science and management decisions. The DSE are commonly regarded as undersampled (e.g. Gooday et al. 2021), and Rogers (2015) in his review of changes in the deep sea also complained of the 'recurrent lack of reliable data'.

Such data can be provided by environmental monitoring of the DSE (Levin et al. 2019; Howell et al. 2020). They will facilitate development of an Environmental Impact Assessment (Clark et al. 2019) and will make it possible to identify areas to be set aside (not-to-be-mined) with the purpose of monitoring the natural variability as well as to facilitate recolonization of the mined areas. Monitoring programmes are necessary for the regulatory authorities such as the ISA and the contractors alike. A plea for the establishment of a global observation system for the deep-sea has been recently put forth by Danovaro et al. (2020) and Ingels et al. (2021).

The ISA contractors are obliged to conduct environmental monitoring in the contract areas in accordance with the prescribed regulations and recommendations (ISA 2020a, b). The Environmental Management and Monitoring Plan (EMMP) will have to be prepared and submitted to the ISA by an applicant as a part of the application for exploitation activities in the Area. The EMMP 'sets out commitments and procedures on how mitigation measures will be implemented, how the effectiveness of such measures will be monitored, what the management responses will be to the monitoring results and what reporting systems will be adopted and followed' (Regulation 48(1) of ISBA/25/C/WP.1). Monitoring will have to be performed during all phases of exploitation and must continue after completion of operations (post-closure monitoring, required also by the Closure Plan). Guidance for monitoring actions is currently under stakeholder consultations.

In shallow areas, including marginal seas, sustained observations allowed to draw a number of conclusions regarding the ecosystem changes (Cloern et al. 2016), including the rate of changes. The changes there occur faster than anticipated a decade earlier, take on many forms and their nature is systemic. Evidently much more work remains to be done to conclude on the nature of changes in the deep-sea ecosystems.

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Chapter 12
Comprehensive Understanding of Seafloor Disturbance and Environmental Impact Scenarios

Tomohiko Fukushima, Akira Tsune, and Hideki Sugishima

Abstract The International Seabed Authority (ISA) is developing a regulation for seabed mining beyond areas of national jurisdiction. On the other hand, there are calls against seabed mining due to concerns about various environmental impacts. One of the key causes for environmental impact is the plume that would be generated by the operation of the mining collector. The potential impact of plume was recognized four decades ago, and about 30 years have passed since four impact assessment experiments were conducted, followed by two long-term monitoring studies. Considering the knowledge accumulated on monitoring the environmental conditions over 25 years, the authors have summarized the findings so far and converted them into a scenario that shows the causal relationship that would lead to the impact of seabed mining.

Keywords Deep-sea mining · Meiobenthos · Nematodes · Species diversity · Competitive exclusion · Allee effect · Jansen · Connell effect · Priority effect · Clarion · Clipperton fracture zone

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1 Introduction

The International Seabed Authority (ISA) is developing a regulation that describes obligations for contractors and procedures of contract for seabed mining beyond national jurisdiction (hereafter referred to as the regulation[1]). In response to this effort, there are a lot of voices calling for rigorous environmental impact assessment (EIA) for mining of seafloor mineral resources and a moratorium on its development (Mining watch Canada 2020; Rosane 2021; SEAS AT RISK 2021; Reuters 2021, etc.). Given those, ISA is proceeding with the preparation of guidelines for environmental conservation or management,[2] referring to the opinions of neutral experts, in parallel with the preparation of the regulation, and is currently conducting public consultation[3] (May 2021).

EIA is a process for predicting the likely impact on the environment before the actual mining is carried out. Therefore, impact assessment experiments have been conducted in order to understand the likely impacts and to improve the accuracy of prediction. However, the impact assessment experiment is not always conducted under the same conditions as the actual development in terms of scale, location and the machinery used. Consequently, there is no guarantee that the result of the experiment and that of the actual development will be the same. Predicting the impact in advance means taking such risks and so it is dangerous to apply the fragmentary results provided by the impact experiment for impact prediction at the time of actual development. For example, it is a logical leap to conclude that the impact is not serious in actual development because of the smaller impact in the impact assessment experiment (and vice versa).

The purpose of the impact assessment experiment is not to apply the obtained results to the impact prediction as it is, but to understand the process of impact and the causal relationships through the experiment. Hence, the authors believe that converting fragmentary information into scenarios that show causality will lead to highly accurate and applicable predictions. On the other hand, if this scenario is used to decide whether a development will take place in the near future, enough

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[1] ISA has already published a draft version of the rules in 2019 (draft regulations on exploitation of mineral resources in the Area; ISBA/25/C/WP.1).

[2] The following documents are being prepared; Guidelines for the preparation of environmental management and monitoring plans, Guidelines for the establishment of baseline environmental data, standard and guidelines for the preparation and implementation of emergency response and contingency plans, Guidelines for the preparation of an environmental impact statement, Standard and Guidelines for environmental impact assessment process, Standard and Guidelines for the safe management and operation of mining vessels and installations, Guidelines on tools and techniques for hazard identification and risk assessments.

[3] Stakeholder Consultations on draft standards and guidelines to support the implementation of the Draft Regulations for Exploitation of mineral resources in the Area: https://www.isa.org.jm/stakeholder-consultations-draft-standards-and-guidelines-support-implementation-draft-regulations (Accessed 31 May 2021).

time has not been given. Thus, the approach is to present the optimal solution under given constraints while focusing on the search for truth.

The subject of this chapter is a deep-sea impact experiment conducted to assess the impacts of plume. Plume[4] is suspended water containing fine sediment particles generated by the operation of polymetallic nodules collector, that has been recognized as a potential factor that could impact the seafloor environment during development of seafloor mineral resources since 1980 (NOAA 1981; NOAA 1982). In the 1990s, four impact assessment experiments were conducted: NOAA-Benthic Impact Experiment (NOAA-BIE), Japan Deep Sea Impact Experiment (JET), InterOceanMetal's Benthic Impact Experiment (IOM-BIE), Indian Deep-Sea Environment Experiment (INDEX) (Trueblood 1993; Fukushima 1995; Kotlinski 1995; Sharma 1999). All the four experiments have shown decreased abundance of benthic organisms, at least temporarily (Trueblood et al. 1997; Fukushima 2004; Radziejewska 2014; Sharma et al. 2000). However, since the first monitoring study was completed 1 year after NOAA-BIE, 2 years after JET, 5 years after IOM-BIE, and 3.66 years after INDEX (44 months), the length of the impact of seafloor disturbance remains unknown. Among them, JPI oceans conducted a long-term monitoring survey 20 years later at IOM-BIE site in 2015 (JPI oceans 2016), and Japan has conducted a long-term monitoring surveys 17–18 years later in 2011–2012 (Shirayama et al. 2017) and also 25 years later at JET site in 2019. The long-term monitoring survey at the JET site revealed the fact that the number of benthic organisms and the chemical composition of sediments are at almost the same levels as those before the experiment, whereas, the species diversity of nematodes is different from the state before (Fukushima and Tsune 2018).

In this chapter, we will summarize the results of the monitoring 25 years after JET was conducted. It should be noted that being extension of the previous study, contents of this manuscript may overlap with Long-Term Monitoring of Environmental Conditions of Benthic Impact Experiment (Fukushima and Tsune 2019).

[4] Plume was defined in ISBA/25/LTC/6/Rev.1; A dispersion of seawater that contains dense sediment particles. Seabed-disturbance plume is a stream of water containing suspended particles of sea-floor sediment, abraded minerals and macerated benthic biota that emanates from the mining collector as a result of collector disturbance of the sea floor and spreads in a zone close to the sea floor. The far-field component of the seabed-disturbance plume is termed the "rain of fines". Discharge plume is a stream of water containing suspended particles of sea floor sediment, abraded minerals and macerated benthic biota resulting from the separation, on board the mining ship, of the nodules from the water carrier, and spreads in a zone closer than seabed-disturbance plume to the ocean surface.

2 Summary of Research Results So Far

2.1 Experiment Site and Procedure

JET was carried out on the west side of the Clarion-Clipperton Fracture Zone (CCZ), the area which is currently in the exclusive exploration area for the Deep Ocean Resources Development Co., Ltd (DORD) (Fig. 12.1). At the site, the water depth is about 5200 m, located in a north-south valley, and the polymetallic nodules are relatively few. The experiment consisted of baseline survey, benthic disturbance and monitoring surveys, and the magnitude of impact was evaluated by comparison between the results of baseline and monitoring survey. Benthic disturbance included sucking up of seafloor sediments and discharging them from 4 m chimney using a benthic disturber. The area where the discharged sediment was redeposited is called the disturbance area. For convenience, the baseline survey is called JET1, the monitoring survey immediately after the disturbance is JET2, after 1 year is JET3, after 2 years is JET4, after 17–18 years is JET5 and after 25 years is JET6 (Table 12.1).

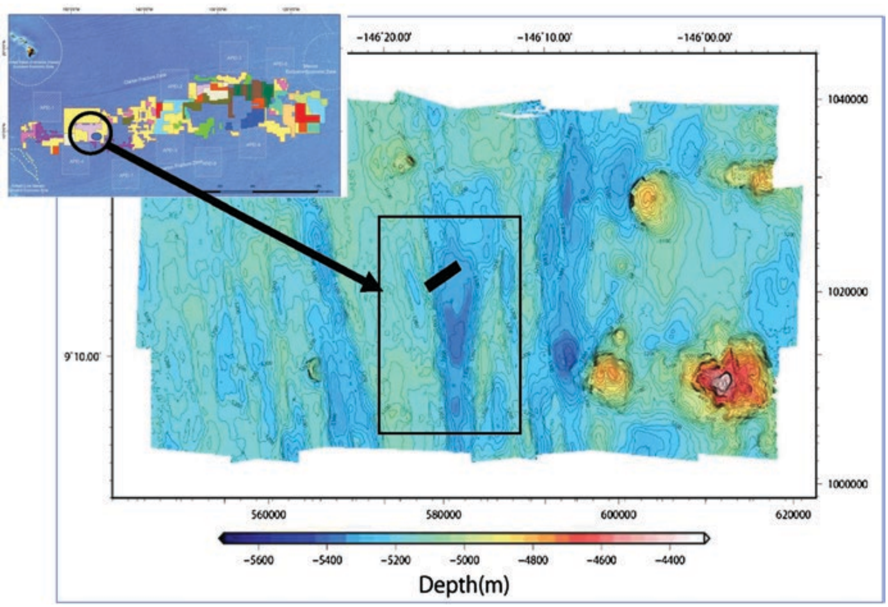

Fig. 12.1 Location and topography of the experiment site

Table 12.1 Durations of the baseline survey, the benthic disturbance and monitoring surveys

Event	Duration
Baseline survey (JET1)	August 10–15, 1994
Benthic disturbance	August 27–September 11, 1994
Monitoring survey	
First monitoring (immediately after: JET2)	September 15–21, 1994
Second monitoring (1 year after: JET3)	September 12–October 23, 1995
Third monitoring (2 years after: JET4)	September 11–October 22, 1996
Fourth monitoring (17–18 years after: JET5)[a]	November 6–17, 2011
ditto	August 28–September 5, 2012
Fifth monitoring (25 years after: JET6)	August 8–26, 2019

[a]JET5 was conducted in two parts, 2011 and 2012, due to the time required for the survey

2.2 Benthic Disturbance and Area Classification

Benthic disturbance refers to the act of sucking up and discharging sediments using the Deep Sea Sediment Re-suspension System (DSSRS, hereafter referred to as benthic disturber) developed for a series of experiments. It uses a fluidizing pump to loosen the sediment, a lift-up pump to suck up slurry deposits, and discharge them from 4 m high chimney (Tsurusaki 1997).

The benthic disturber was towed on parallel courses from northeast to southwest for 2000 m, i.e., the southern track (track#1; 150 m in width) and the northern track (track#2; 110 m) (Fig. 12.2 (2.1)). They were separated by 100 m. Towing duration is 20 h and 27 min for 16 days from August 27th to September 11th. Barnett and Yamauchi (1995) estimated total amounts of sediment to be 352 t (dry weight equivalent) based on the pump performance, towing times, and samples taken with a rosette sampler attached to the tip of the chimney (see below).

Total mass dried sediment discharge = ALPD(L/S) × TTT × ACS (g/L) = 352 t
ALPD: Average Lift Pump Discharge (125 L/s)
TTT: Total Towing Time (20 h and 27 min)
ACS: Average Concentration of Sample (38.3 g/L)

The quantity of sediment flux during the experiment was much heavier than that of natural one. In the station where the heaviest sedimentation was observed was observed, setting particle was estimated to be equivalent to 1105 days of natural flux

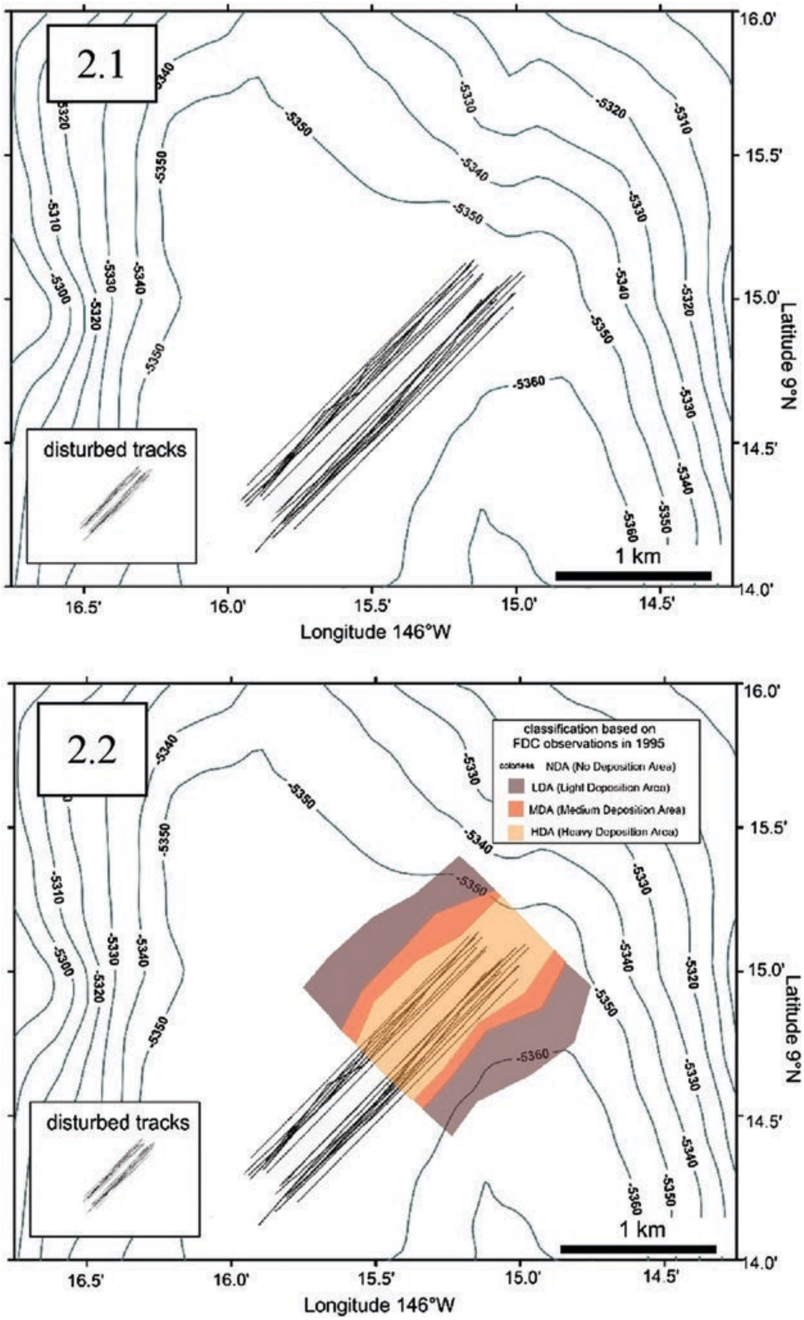

Fig. 12.2 Location of the disturber tow tracks (2.1) and area classification (2.2)

Table 12.2 Chemical composition of surface sediment and suspended particles during natural and artificial setting

	Organic carbon (%)	Organic nitrogen (%)	Calcium carbonate (%)	Remarks
Surface sediment[a]	0.50–0.75	0.07–0.10	0.27–0.54	Harada et al. (1995)
Artificial deposit[b]	0.60–1.03	0.00–0.11	0.00–0.62	Fukushima et al. (2002)
Natural deposit[c]	5.46	0.76	43.50	Harada et al. (1995)

[a]Data was obtained from the sediment (0–0.5 cm layer) collected in July 1994
[b]Data was obtained from sediment trap deployed around disturber tow tracks
[c]Data was obtained from sediment trap deployed away from disturber tow tracks

(average rain rate within a year). On the other hand, quality of sediment, chemical composition was almost the same as the sediment on the sea floor, but completely different from the settling particles in natural condition (Fukushima et al. 2002) (Table 12.2).

In addition, Yamazaki et al. (1997) analyzed stereophotographs of the seafloor obtained in a Finder mounted Deep Sea Camera (FDC) survey conducted 2 years after the seafloor disturbance to measure the depth of the formed groove, and estimated that the release was a mixture of sediments up to 0–7 cm thickness.

The extent of re-deposition was also confirmed by the FDC observation during JET4, and then the disturbance area was classified into heavy deposition area (HAD), medium deposition area (MDA), light deposition area (LDA), and no deposition area (NDA) (Fukushima et al. 2000) (Fig. 12.2 (2.2)). Besides, the diffusion range of the plume is estimated from the kriging method using sediment trap data (Barnett and Suzuki 1997), the particle diffusion model using current direction/velocity data and particle size distribution as parameters (Nakata et al. 1997; Doi et al. 1999) as well as color intensity analysis and seafloor photographs (Yamazaki et al. 1997). Although there are differences in details, the general trends are the same, such as the plume subsided within a range of 500 m from the disturber tow tracks.

2.3 Sampling Points and Sample Processing

In order to understand the impacts of the benthic disturbance on benthic organisms and its habitats, sediment samples were collected by multiple corer (MC) and box corer (BC), and seafloor observations were performed by FDC. Sampling points and observation lines are shown in Fig. 12.3. MC samples were subsampled with a 28 mm diameter syringe, and then sliced into 0–0.25, 0.25–0.5, 0.5–0.75, 0.75–1.0, 1.0–1.5, 1.5–2.0, 2.0–2.5, 2.5–3.0 cm layers, and those were analyzed for meiobenthos and chemical components such as total organic carbon (TOC), total nitrogen

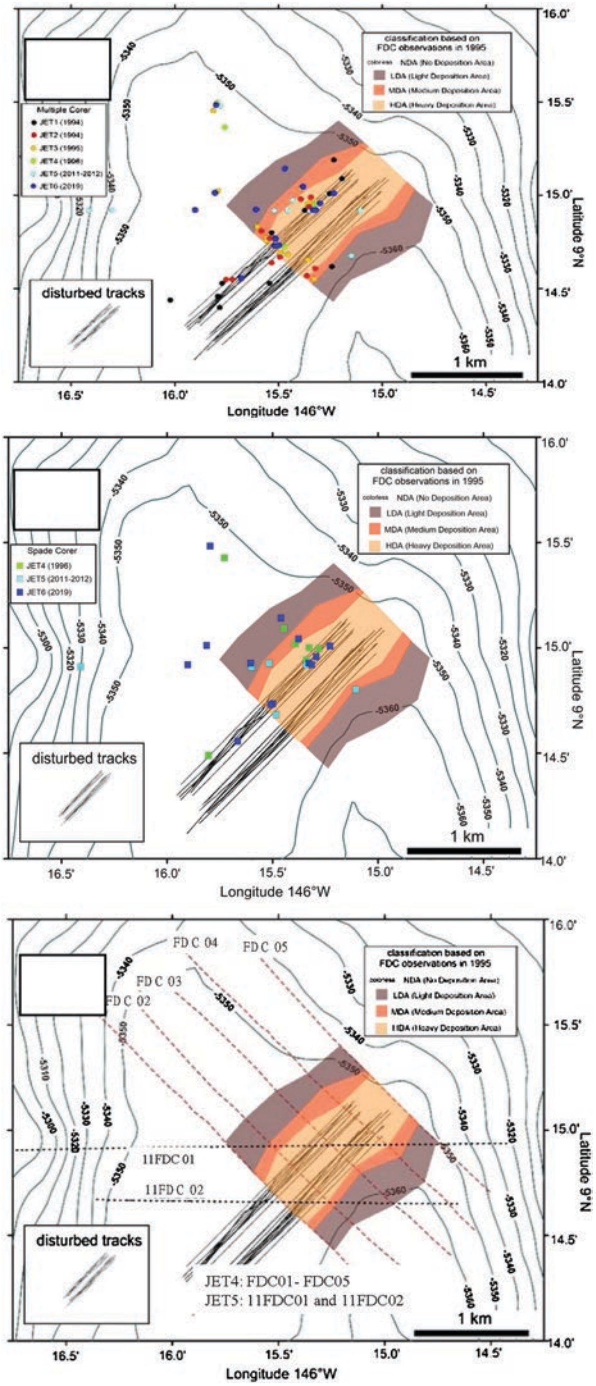

Fig. 12.3 Sampling position of Multiple Corer (3.1), Box Corer (3.2), and observation lines of FDC (3.3)

(TN), calcium carbonate ($CaCO_3$) and Opal.[5] TOC and TN were measured with CHN analyzer (Yanagimoto Model MT5) and $CaCO_3$ with a CO_2 coulometer. Opal was extracted over a 5 h period using 2 M Na_2CO_3 and analyzed with the molybdenum-yellow absorption spectrometric method.

Meiobenthos are defined as organisms larger than 32 μm and smaller than 250 μm, and identified into lower taxa as much as possible. For quantitative analysis, these were compiled into these categories; Nematoda, Crustacea, and others. Foraminifera is one of the most abundant taxa, however, it is excluded from the quantitative data because is it difficult to count.[6] Therefore, the meiobenthos dealt with in this chapter is metazoan meiobenthos. Efforts were also made to identify species level for Nematoda, but due to expert restrictions, data was limited.

The BC sample was sliced into 0–1, 1–2, 2–3, 3–5 cm for macrobenthos.[7] For macrobenthos, total abundance was compared by area, and dominant faunal groups such as Polychaeta and Crustacea were also compared by area. However, for JET5 and JET6, the number of samplings was small, so LDA and MDA were treated together (M/LDA).

The FDC photo/video was used for megabenthos.[8] The observed organisms were divided into suspension feeders, deposit feeders and others, and sessile fauna and motile fauna, and each group was subdivided into major taxonomic groups.

The obtained data was analyzed for spatiotemporal variation using statistics. For vertical changes in chemical composition in sediments, significant differences were tested by analysis of variance (ANOVA) for each parameter. Similarly, for the horizontal distribution of chemical components, the first principal component (PZ1) of the principal component analysis (PCA) was used as a comprehensive index, and the value and distance from the tow-tracks of the disturber were plotted and regression analysis was performed. The abundance of meiobenthos was confirmed to change over time by *t*-test. Regarding the species diversity of nematodes, the expected species number (Es (n)) was calculated and the changes over time were compared.

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[5] In addition to these, water contents, particle size, cone penetration strength, shear strength, etc. are measured, but since they are not mentioned directly, the explanation is omitted in this paper.

[6] Foraminifera are generally included as a main component of meiobenthos, but this site is below the carbonate compensation depth (CCD); therefore, species that were difficult to count have been excluded from the quantitative data.

[7] In this paper, macrobenthos is synonymous with macrofauna by ISA; Animals retained on a 250- or 300-μm mesh, typically sorted and identified with a microscope, that include taxa such as polychaetes, bivalves, isopods and tanaids (ISBA/25/LTC/6/Rev.1.).

[8] In this paper, megabenthos is synonymous with megafauna by ISA; Animals large enough (larger than 2 cm) to be determined in photographs, proposed as key taxon (see taxonomy) for environmental impact assessment in deep-sea mining (ISBA/25/LTC/6/Rev.1.).

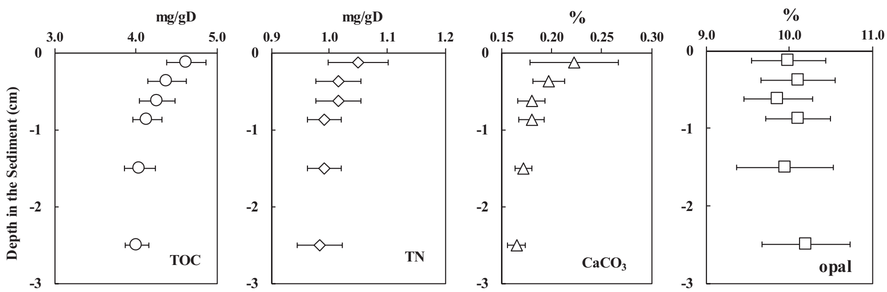

Fig. 12.4 Vertical profiles of chemical components (TOC, TN, $CaCO_3$ and Opal) in the predisturbance condition (JET1). Statistically significant decrease were found in TOC, TN and $CaCO_3$

2.4 Chemical Components in the Sediment

2.4.1 Vertical Profile

In JET1, concentration of TOC, TN, and $CaCO_3$ were found to decrease exponentially from the surface to 3 cm depth in the sediment, while no decrease in concentration dependent on depth was observed for opal (Fig. 12.4). Therefore, opal was excluded from the monitoring items after JET2. In the HDA of JET2, the concentrations of TOC, TN, and $CaCO_3$ varied widely, and no vertical decrease was observed. However, after that, the variation gradually decreased, and significant vertical structures of $CaCO_3$ were observed in JET3 and JET4, and TOC and $CaCO_3$ were observed in JET5 and JET6 (Fig. 12.5, Table 12.3).

2.4.2 Horizontal Environmental Decline

In order to compare the environment in the areas of the benthic disturbance with the surrounding environment, the horizontal environmental gradient was investigated using PZ1, the first principal component of PCA, as a comprehensive index. When the relationship between PZ1 and the distance from the tow tracks was plotted by sediment depth layers, there was no environmental gradient in any depth layer in JET1, but there was a statistically significant gradient in JET2 and JET3, i.e., 0–0.25 cm and 0.25–0.5 cm layers in JET2, and 0–0.25 cm layer in JET3. However, when it came to JET4, JET5 and JET6, there was no horizontal decline in any depth layer (Fig. 12.6).

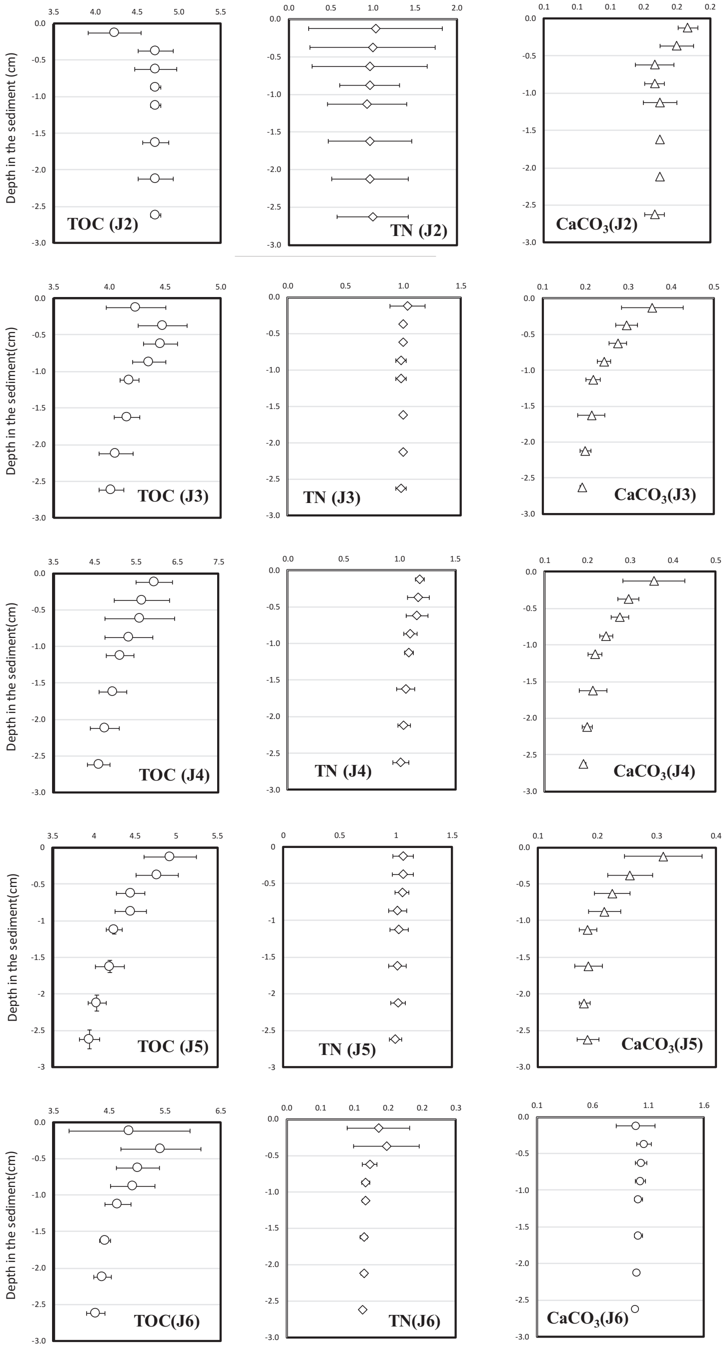

Fig. 12.5 Vertical profiles of chemical components (TOC, TN and $CaCO_3$) in the heavy deposition area (HDA) during post-disturbance condition (JET2–JET6)

Table 12.3 Probabilities of vertical reduction in chemical component parameters were tested by analysis of variance (ANOVA)

		df	*F* value	*P* value	Results
J1	TOC	11	10.47	2.55E – 05	**
(1994)	$CaCO_3$	11	7.66	3.16E – 04	**
	TN	11	4.17	11.0E – 3	*
	Opal	11	0.81	550.0E – 3	ns
J2	TOC	9	0.26	0.85	ns
(1994)	$CaCO_3$	9	0.46	0.71	ns
	TN	9	0.05	0.98	ns
J3	TOC	9	1.18	3.30E – 01	ns
(1995)	$CaCO_3$	9	12.25	1.12E – 05	**
	TN	9	1.23	0.31	ns
J4	TOC	7	1.08	3.78E – 01	ns
(1996)	$CaCO_3$	7	7.61	7.15E – 04	**
	TN	7	2.64	6.92E – 02	ns
J5	TOC	8	12.10	2.70E – 09	**
(2011–2012)	$CaCO_3$	8	34.21	5.21E – 18	**
	TN	8	0.92	0.50	ns
J6	TOC	7	5.64	2.58E – 05	**
(2019)	$CaCO_3$	7	3.37	3.4E – 3	**
	TN	7	1.73	0.11	ns

NS Not significant, *: $p<0.05$, **: $p<0.01$

2.5 Benthic Organisms

2.5.1 Abundance

Benthic organisms were studied separately as meiobenthos, macrobenthos and megabenthos. Meiobenthos were collected during all surveys, but macrobenthos collections were limited to JET 1, 4, 5, and 6, and megabentho observations were limited to JET 4 and 5.

Among meiobenthos, *Nematoda* and *Crustacea* dominated, and other species such as *Gastrotricha*, *Tardigrada,* and *Loricifera* were less abundant. Comparing the total number of meiobenthos between JET1 and JET2 in HDA, it was significantly smaller in JET2 (*t*-test: $p < 0.01$), but there was no statistically significant difference with JET3 and JET4, and that almost the same with JET5 and JET6 (Fig. 12.7). Comparing *Nematoda* and *Crustacea*, a statistically significant decrease was observed only in nematodes in JET2.

In macrobenthos, *Polychaeta* and *Harpacticoida* dominated, and other species such as *Nemertea*, *Isopoda*, *Ostracoda*, *Tanaidacea*, *Bivalves*, *Gastrotricha,* and *Ophiuroidea* appeared in less numbers. Looking at the total number of abundances in JET4, there was no significant difference between the abundances observed during JET1 in HDA, MDA, LDA and NDA. On the other hand, to see separately,

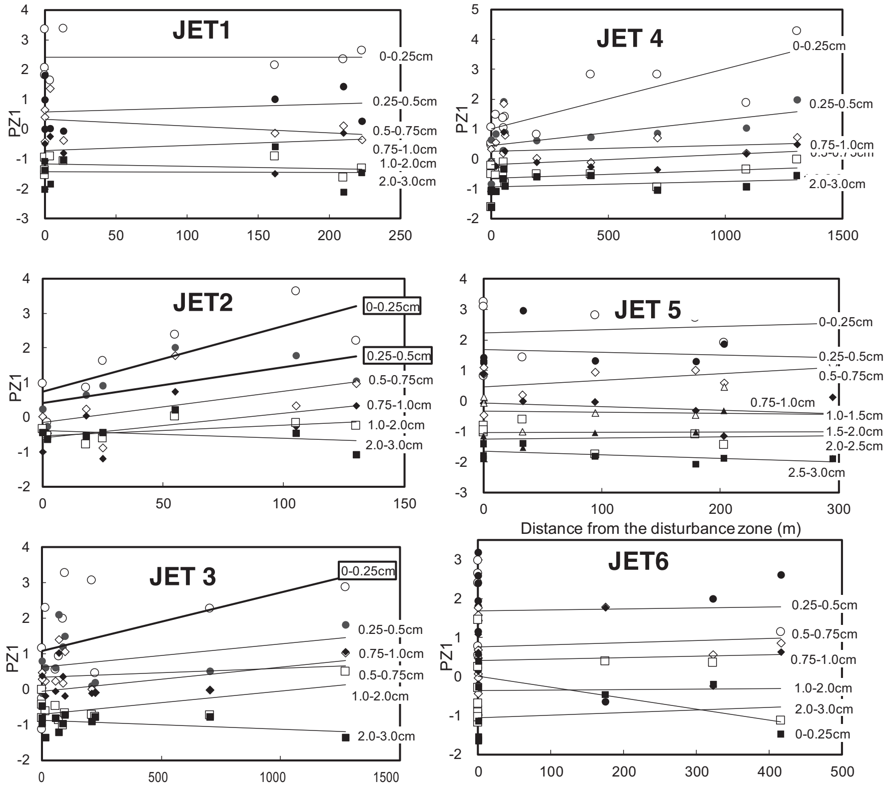

Fig. 12.6 The relationship between the first principle component (PZ1) and the distance from the edge of the disturber tow track. Statistically significant declines were observed in 0–0.25 cm layer and 0.25–0.5 cm layer in JET2, and 0–0.25 cm layer in JET3

Polychaeta was the most abundant in NDA and was significantly different from other areas, i.e., LDA, MDA, and HDA. In case of *Crustacea*, conversely, it was the most abundant in HDA, but there was no significant difference between areas. In JET5, HDA is two samples and NDA is one sample, which is limited data, but in NDA, it was only 1/5 of HDA. In JET6, seven samples were HDA and three samples were NDA, both of which had almost the same number of abundances (Fig. 12.8).

In megabenthos, *Porifera*, *Actiniaria*, *Pennatulida*, *Crinoidea*, *Holothuroidea*, *Ophiuroidea*, *Asteroidea*, *Lophenteropneusta* appeared. The suspension feeders defined in this study were Porifera, Actinaria, Crinoidea and *Pennatulida*, while the deposit feeders were *Holothuroidea* and *Lophenteropneusta* (Table 12.4). As a result, in JET4, total number of megabenthos, motile fauna, deposit feeders and holothurian were significantly lower as compared to DA than that of NDA. In JET5, though statistical analysis has not been done as there is only two lines data, the total number, predominant population, motility type, and feeding type were almost the same on both observation lines (Fig. 12.9).

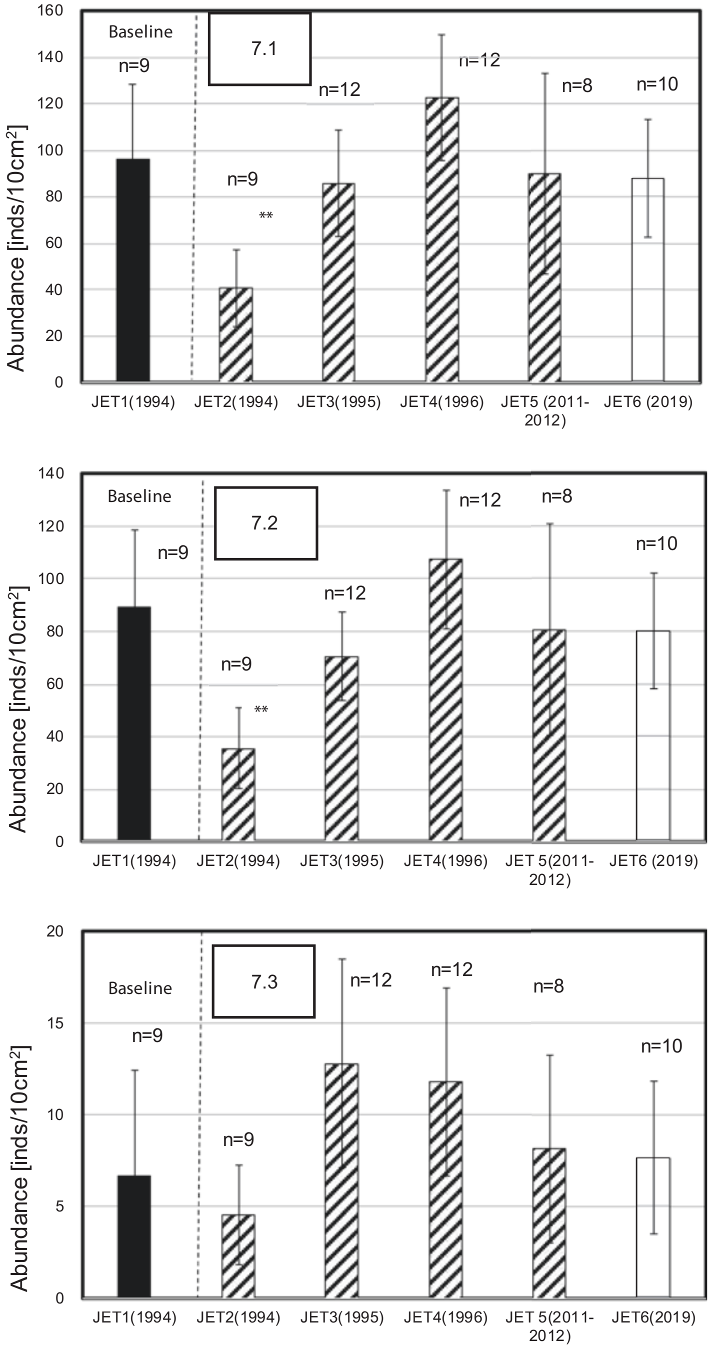

Fig. 12.7 Abundances of total metazoan meiobenthos (7.1), Nematoda (7.2) and Crustacea (7.3). Statistically significant difference compared to baseline (JET) were found in total metazoan meiobenthos and Nematoda

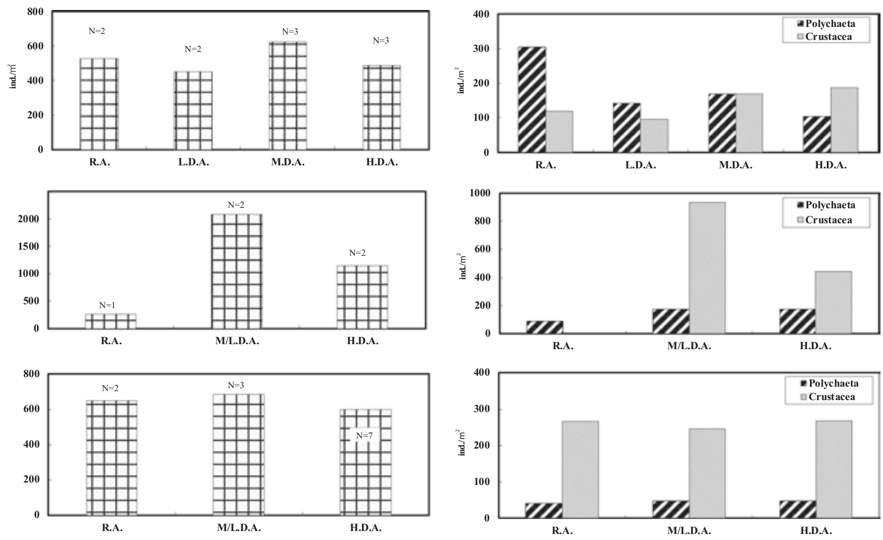

Fig. 12.8 Abundances of macrobenthos and dominant faunae (Polychaeta and Crustacea) in each deposition area in the JET4 (upper), JET 5 (middle) and JET (lower)

Table 12.4 Identified taxa, motility types and feeding types

Phylum	Taxa	Motility type	Feeding type
Protozoa	Xenophyophorea	SE	SU
[a]Porifera		SE	SU
Cnidaria	[a]Pennatularia	SE	SU
	[a]Actiniaria	SE	SU
Arthropoda	Crustacea	MO	OT
Echinodermata	[a]Crinoidea	SE	SU
	[a]Comatulida	SE	SU
	[a]Holothuroidea	MO	DE
	[a]Ophiuroidea	MO	OT
	[a]Asteroidea	MO	OT
Hemichordata	[a]Lophenteropneusta	MO	DE
Vertebrata	Osteichthyes	MO	OT

Life habitat: *SE* sessile fauna, *MO* motile fauna
Feeding habitat: *SU* suspension feeder, *DE* deposit feeder, *OT* others
[a]Megabenthos taxa apply to quantitative abundance data

2.5.2 Species Diversity

The species diversity of nematodes (Es (n)) was calculated. Although the data is limited, the number of species was the least in JET1 and the highest in JET6. Also, the dominant species was different for each observation: *Pseudolla* sp.1 (55%) for JET1, *Linhystera* sp.1 (31%) for JET4, *Halalaimus* sp.1 (43%) for JET5, and

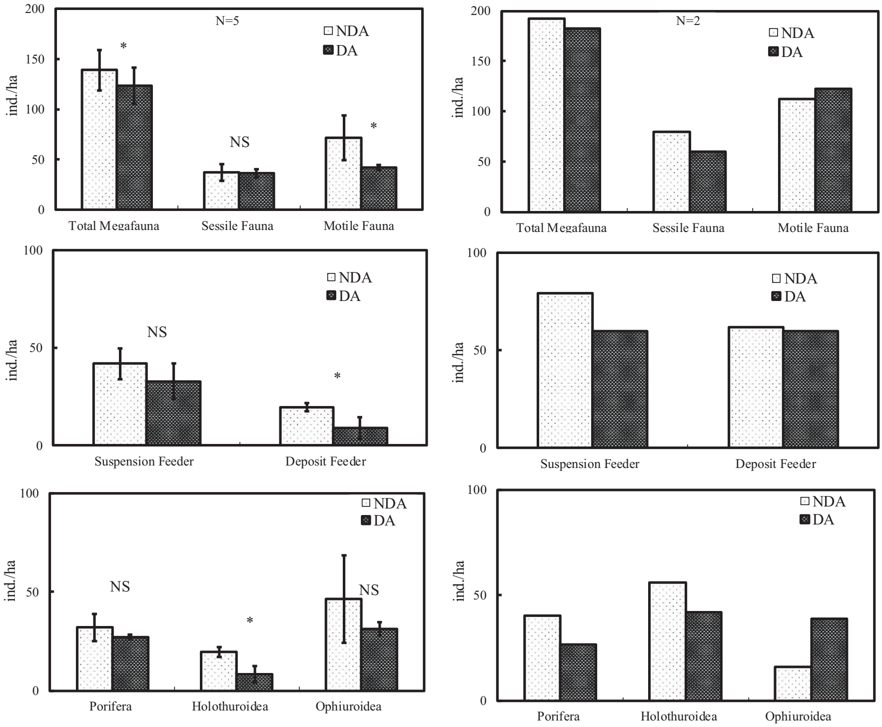

Fig. 12.9 Abundances of macrobenthos in each deposition area in the JET4 (left) and JET 5 (right). Observed areas were divided into deposition area (DA) and no deposition area (NDA)

Table 12.5 Dominant species and dominance rate of Nematoda

	JET1	JET4	JET5	JET6
Number of species	10	17	14	16
Dominant species	*Pseudolla* sp. 1	*Linhystera* sp. 1	*Halalaimus* sp. 1	*Diplopeltidae* sp. 1[a]
Dominant rate (%)	55	31	43	34

[a]This could not be identified down to the genus level

Diplopeltidae sp.1 (34%) for JET6 (Table 12.5). Comparing Es (n) value, JET1 was the lowest and JET4 was the highest. When it comes to JET5, it is lower than JET4 but higher than JET1, and in JET6 it is lower than JET5 but higher than JET1 (Fig. 12.10).

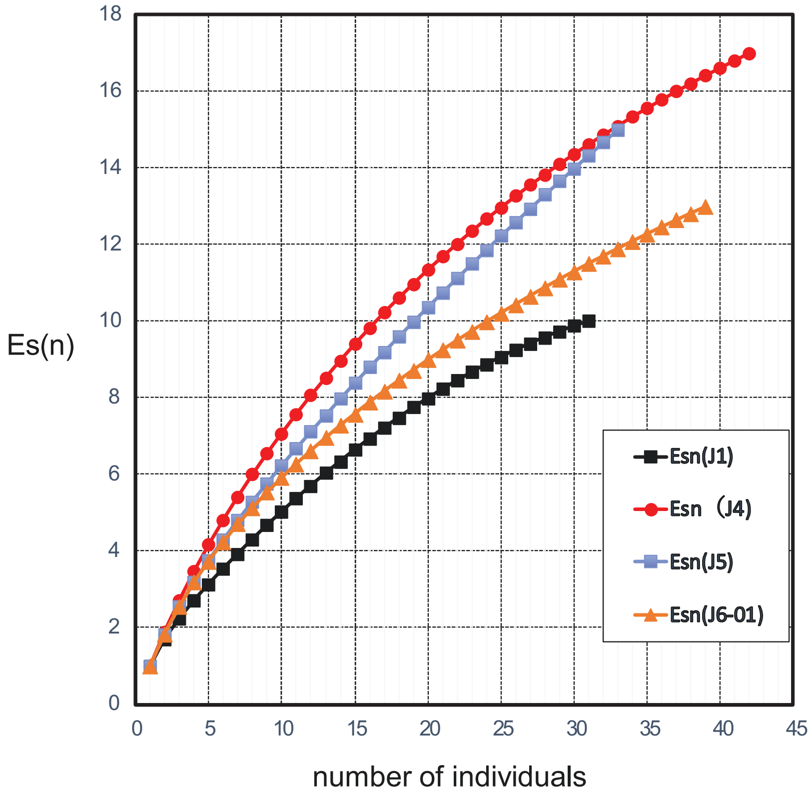

Fig. 12.10 Species diversity of Nematoda by expected species number (ES(n)). Esn (J1), Esn (J4), Esn (J5), Esn (J6): expected species number of nematodes from a population before the disturbance, 2 years after the disturbance, 17–18 years and 25 years after the disturbance respectively

3 Scenario of the Impact on Benthic Organisms and Its Habitats

3.1 Natural Condition

The experiment area is in abyssal plain in the oligotrophic waters of the Central Pacific Ocean with a depth of approximately 5200 m. Concentration of organic material in the sediment is extremely low, and categorized as pelagic clay. Benthic animals are supported mainly by the small rain of organic material arriving from productive surface water more than five thousand meters above. Among them, the abundance of epifauna and suspension feeders is controlled by the supply of organic material from the surface layers, on the other hand, abundance of infauna and deposit feeders is controlled by the organic matter in the sediment. In this area, benthic organisms are concentrated near the top surface of the sediment in JET 1 (Fig. 12.11 (11.1)).

3.2 Short-Term Monitoring Results

Benthic disturbance resulted in more than 1000 times of sediment flux than normal condition in less than a month. Since the suspended particles were mainly composed of inorganic substances that were redeposited and the concentration of organic material was low even under natural conditions, the organic matter concentration was further diluted as a result of the experiment. This is supported by the findings that there was a change in the vertical profiles of the chemical components in the sediment immediately after the benthic disturbance (JET2: Fig. 12.11 (11.2)). It can be estimated that situation of insufficiency of organic materials continued for at least 1 year because research results indicated that the horizontal environmental gradient continued until 1 year later. This suggests that a severe reduction of food source for infauna and deposit feeders cause a portion of them to either die or lose the energy needed to reproduce, resulting in lower abundance. While it can be speculated that epifauna, which depends on fresh organic material immediately after reaching the seabed, or suspension feeders, which depend on organic material before reaching the seabed, were also negatively affected. However, in the case of epifauna and suspension feeders, some individuals might die because they could not tolerate the rapid redeposition event, but if they could withstand the worse condition for less than a month, the conditions will return to the normal feeding environment. This speculation and the following research results were consistent, i.e., *Nematoda* were affected more and for longer period than *Harpacticoida* in meiobenthos, *Polychaeta* were affected more than *Crustacea* in macrobenthos, and deposit feeders were affected more than suspension feeders, and *Holothuroidea* were affected more than *Porifera* in megabenthos (JET 3, 4; Fig. 12.11 (11.3)).

3.3 Long-Term Monitoring Results

After the disturbance, the vertical profiles of TOC, TN, and $CaCO_3$ in the sediment also changed significantly immediately and 1 year after the experiment, and it is considered that an unusual condition was developed horizontally on the seafloor. However, with the passage of time, it approached its original state both vertically and horizontally, and its carrying capacity returned to its original state, as the infauna and deposit feeders were also found to have reached their original levels (JET 5, 6: Fig. 12.11 (11.4)).

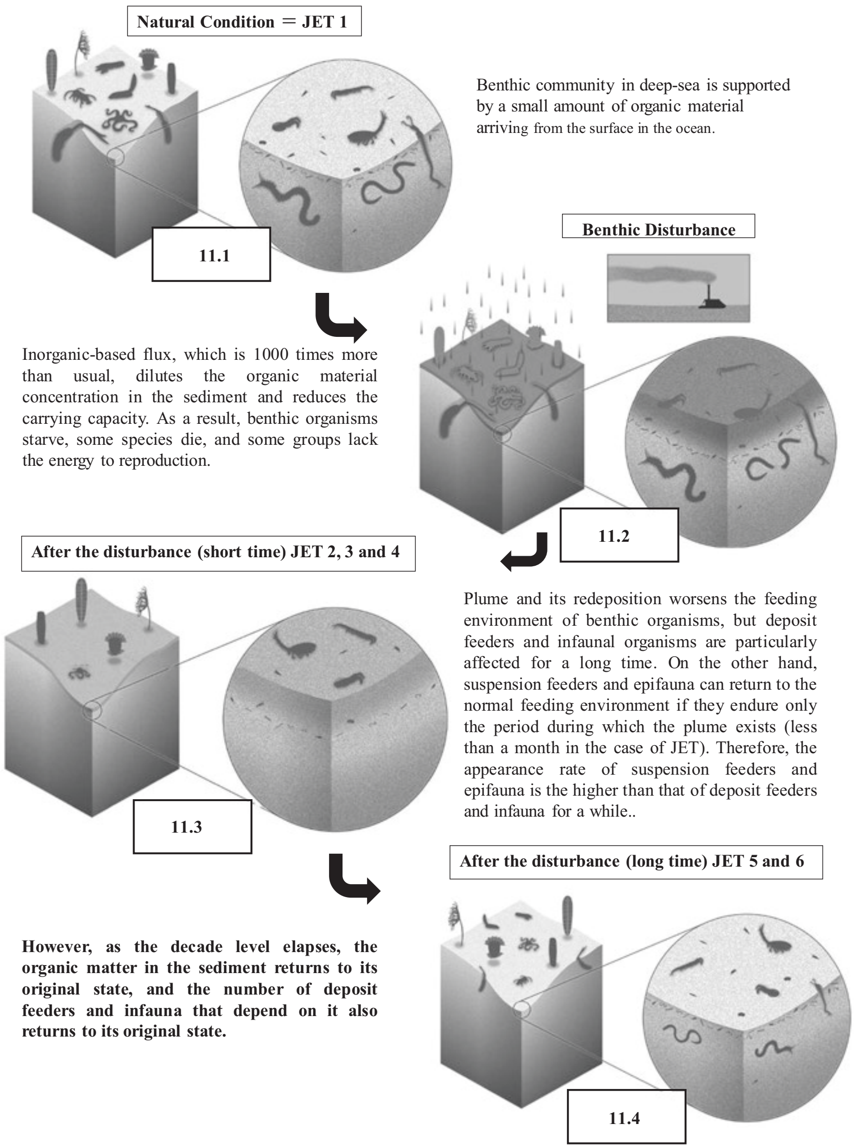

Fig. 12.11 Mechanism of effects of plume and its redeposition on the abundance of benthic communities

4 Scenarios of Impact on Species Diversity of Nematodes

During the observations, the species diversity of *Nematoda* was low under natural condition, while it became higher 2 years after the disturbance, and then it reduced after 17–18 years, and then further decreased 25 years later but was higher than the pre-disturbance level. Generally, the mechanism of species diversity formation is explained by the fact that environmental heterogeneity promotes niche differentiation, resulting in multi-species coexistence (niche differentiation theory) (Silvertown 2004). But there are other factors such as interspecific competitions and dispersal abilities (MacArthur 1972). In the case of organisms without a planktonic larval stage, such as Nematoda, dispersal ability is low, and similar to plants, the principle of dispersal limitation works. Therefore, the offspring are more prosperous around their parents, and if generations are repeated without serious disturbance, patches of communities consisting of the same species are established. In this case, country to the Janzen–Connell effect[9] (Jansen 1970; Connell 1971; Turner 2001), the low species diversity of Nematoda in JET1 is explained by what the offspring formed patches around their parents (Fig. 12.12 (12.1)).

Generation of sediment plume and its redeposition reduced the carrying capacity, resulting in reduced density of benthic organisms. In other words, the seafloor disturbance resets the patches-like community with low species diversity, and creates a virgin area. Temporary settlements (van Steenis 1972) by some species such as opportunistic species can occur if there is an intrudable condition such as these virgin areas. If various species invade into the virgin area created by the effects of redeposition, the species diversity at the spot will increase. That is considered to be the state of JET4.

However, in the above scenario, it is questionable why nematodes with low dispersion ability could be invaded. Assuming that the experimental disturbance created a virgin area, which allowed the invasion of new species, the new species attempted to invade under natural conditions, but the lack of a virgin area can be speculated to prevent settlement. In case of this experimental site, where the density of organisms is extremely low, it is unlikely that there is enough space for intruders to invade.

Another question is why once species diversity increased in JET4, but it has declined in JET5. The authors speculate that the reason for the decline in diversity from JET4 to JET5 was the competitive exclusion[10] over time (Fukushima and Tsune 2018). However, if competitive exclusion is considered as one of the effects on diversity, the effect of competitive exclusion should not be large in low-density communities. Given those questions, the authors would like to reconsider the question about changes in the species diversity of *Nematoda*.

Firstly, the reason as to why *Nematoda* with low dispersion ability could invade new areas after the disturbance could be because the sediments from the surface to a depth of 7 cm were mixed and discharged from 4 m chimney, which became a

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[9] The Janzen–Connell hypothesis is a theory to explain the maintenance of tree species diversity in tropical rainforests. According to the theory, there are host-specific herbivores, pathogens or other natural enemies for the child tree, so the environment around the parent tree is difficult to live in. As a result, the seeds grow a place far from the parent tree, and then the high diversity is maintained.

[10] When two species with the same niche exist in the same place, one is always excluded by competition, so it will not coexist stably in the absence of other environmental factors (Gause's Law of competitive exclusion).

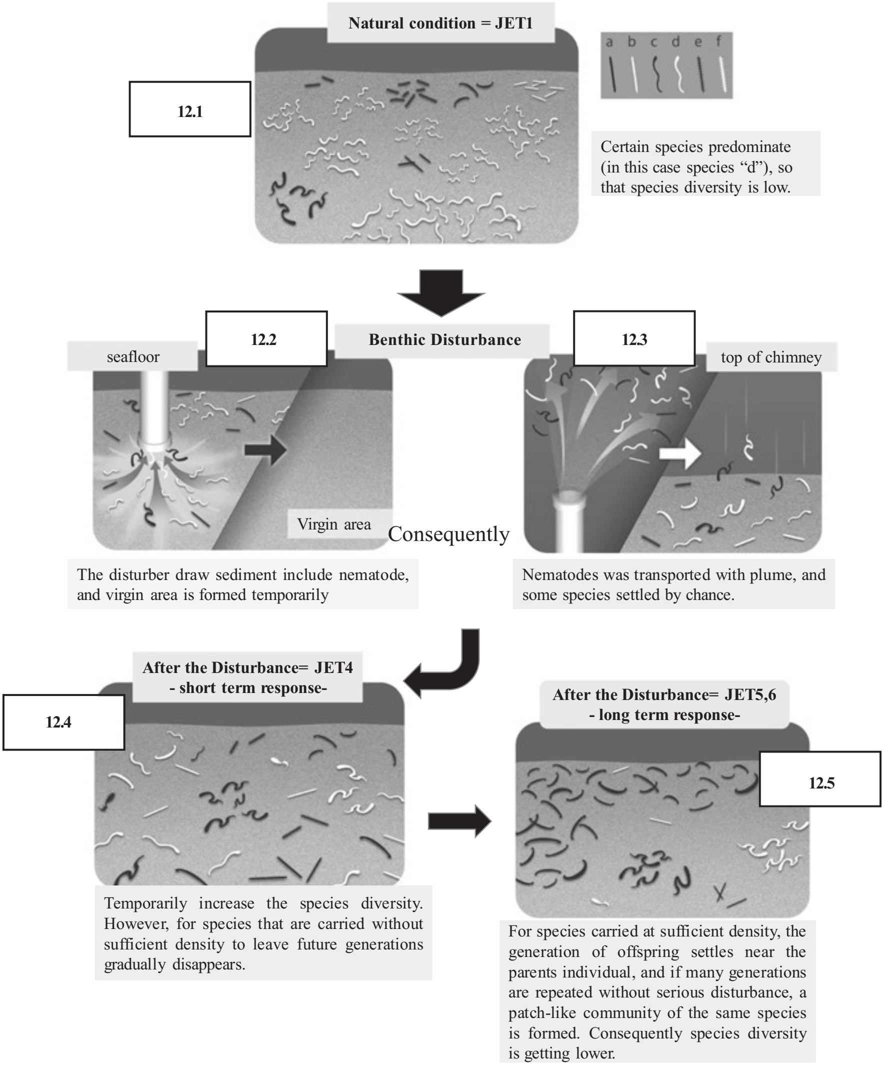

Fig. 12.12 Mechanism of effects of plume and its redeposition on the species diversity of Nematoda

plume and redeposited over a distance of about 500 m around the disturbance area. If so, it is no wonder that the nematodes were carried with the plume at that time.

However, for species carried without sufficient density to leave future generations, the Allee effect,[11] does not work and they gradually disappear. In particular, in

[11] A phenomenon in which the fitness of individuals belonging to a population increases as the population density increases. When the population density decreases, it becomes difficult to find a

the case of *Nematoda*, since they are hermaphroditic, they are a group of organisms that require a certain density for encounters between males and females, so it is possible that they are susceptible to negative effects of low density. On the other hand, it is considered that the species transported at sufficient density formed patches that consists of the same species and gradually formed a state of low diversity. In this way, seeds that are accidentally dispersed and obtain a certain density form a patch. Once the patch is made, the priority-effect (MacArthur 1972; Gilpin and Case 1976; Tilman 1988) works and prevents the increase of the population that invades later (Fig. 12.12 (12.5)). In this way, accidental settlement determines the distribution of species, not environmental conditions, so multiple patches of different species are formed in the virgin area. Therefore, it is not unreasonable that the dominant species differs for each sampling after disturbance. In addition, although α diversity in these patches is low, the diversity of meta-ecosystems (β diversity) that includes multiple patches is not necessarily low. The above is a scenario of changes in species diversity and replacement of dominant species, albeit with limited data.

5 Conclusion

A scientific hypotheses derived by observation and analysis can be a reliable hypotheses only if they withstand the falsification test. In that sense, the aforementioned hypothesis on species diversity formation may not yet be robust. In other words, it can be said that the discussion is about to begin. However, since the experiment started in 1994, it took 25 years to reach the current hypothesis. Of course, in the case of scientific discussions, long-term deliberations and more data and observations are needed to ensure the hypothesis. However, it should also be recognized that there is a time constraint to conclude such as hypothesis when it is carried out as a part of EIA of deep-sea mineral resource development like this one.

In this chapter, we have discussed the diversity of hermaphroditic Nematoda, which have no planktonic larval stages, but there are other scenarios for organisms with different ecological characteristics. In that case, the items to be considered become enormous, and it is not realistic to understand them in the duration of an EIA study. In other words, in discussing the environmental impact of deep-sea mineral resource development, a practical scientific approach is important to enable future prediction, and it must also be considered to lead to realistic countermeasures. It is not easy, but it is necessary to devise ways to pursue two approaches.

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mating partner, and even if mating is possible, inbreeding may occur and the reproductive rate may decrease. Therefore, there is a threshold of density to maintain the population.

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Chapter 13
Adaptive Management as a Tool for Effective Environmental Management of Deep-Sea Mining

Malcolm R. Clark, Richard Johnson, and Jayden Hyman

Abstract Adaptive management is widely referenced as a way to manage uncertainty about environmental impacts of an operation. However, it is often perceived as a 'trial and error' approach—rather than a structured process that works from a known state and integrates information, learning and management responses to support flexible decision making. Applied in this latter way adaptive management enables operations to be adjusted on a clear pathway to effective environmental management driven by science, or stopped if unacceptable harm is likely.

The chapter is divided into three core sections: the first describes the main concepts of adaptive management and aspects the approach needs to include to be effective; the second presents ideas of how to make the concepts more operational through a participatory systems modelling approach; and the third covers practical managerial and regulatory experience from mining proposals in New Zealand, and lessons learnt about what contractors need to consider in their management plans to help their uptake. Combining these three components can provide important insights for both contractors and managers in helping design and implement plans for adaptive management in deep-sea environments.

Keywords Deep-sea mining · Adaptive management · Decision-making · Systems modelling · Participatory approach

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1 Introduction

Interest in mining deep-sea minerals continues to grow, driven by the use of a number of metals in green technology such as electric vehicles and wind-driven power generation (e.g. Hein et al. 2013, 2020; Sharma 2017). The industry is still in the exploration phase, and whether in national waters or in the High Seas (the ‘Area’ under the jurisdiction of the International Seabed Authority), efforts have largely been focused on establishing the geological characteristics of the resources, and collection of baseline environmental data. No deep-sea mining operations have yet started, and there are many environmental concerns associated with assessing adequately the risks and impacts associated with moving to mining (e.g. Durden et al. 2017; Miller et al. 2018; Jones et al. 2020; Clark et al. 2020; Howard et al. 2020). A key factor in progressing from exploration to mining is how to cope with the uncertainty that exists in scientific knowledge of baseline ecological characteristics, the nature and extent of potential impacts, and how these could affect ecosystem structure and function (e.g. Levin et al. 2016; Miller et al. 2018; Niner et al. 2018; Smith et al. 2020).

It is recognised that uncertainty is unavoidable to an extent in any environmental impact assessment (e.g. Tenney et al. 2006; Retief et al. 2013) but this uncertainty has to be accounted for in any comprehensive scientific assessment (e.g. Clark et al. 2017). It further needs to be incorporated into management through adoption of a precautionary approach to prevent actions that could lead to harmful effects (e.g. Levin et al. 2016; Jones et al. 2018) and/or employing an adaptive management strategy whereby operations can be flexible and change as mining develops and more is learnt about impacts on the ecosystem (Jaeckel 2016; ISA 2017a, b; Craik 2020; Hyman et al. 2021a) as well as taking into account the specific statutory framework applying to the jurisdiction within which the operation is undertaken (Jaeckel 2016; Craik 2020).

In this chapter we outline some of the main scientific and regulatory features of a robust adaptive management process (Sect. 2), propose a participatory systems modelling approach to make adaptive management more operational in the context of deep-sea mining (DSM) (Sect. 3), and set out some lessons learnt about governance application from proposals to apply it to management of offshore mining in New Zealand (Sect. 4).

2 Adaptive Management for Deep-Sea Mining

2.1 *The What*

Adaptive management is an approach for simultaneously managing and learning about natural resources and the impacts of human activities (Williams 2011a). It involves flexible decision-making bounded by the terms and conditions of

Fig. 13.1 Schematic diagram of the Adaptive Management Process, showing the iterative approach with multiple stages associated with decision-making and learning (from Clark et al. 2017)

regulatory authorities, that can be adjusted in the face of uncertainties as outcomes from management actions and other events become better understood (National Research Council 2004). It has been an evolving concept and approach since initially being developed in the context of fisheries management (e.g. Holling 1978; Walters 1986). Early on it seems to have often been interpreted as a trial-and-error process but this fosters an aspect of a 'surprise result' and the risk of unforeseen consequences resulting from management actions (Allen et al. 2011). That interpretation of adaptive management has been firmly replaced by its recognition as a structured learning process where there are clear goals to improve understanding over time (e.g. Allen et al. 2011), and adaptation whereby there is adjustment of management through time based on improved information about the system and reduced uncertainty (Walters 2007; Williams 2011a, b) (Fig. 13.1).

An important distinction within the definition of adaptive management is 'passive' versus 'active' (e.g. Schreiber et al. 2004; Williams 2011b). Both benefit from a growing knowledge base as operations proceed, but as implied by the wording, passive adaptive management focuses on resource objectives with learning a useful, but potentially unintended, by-product. The objectives here will explicitly account for the effect of management actions on resources, but not the influence of management on uncertainty. Active adaptive management, on the other hand, incorporates the reduction of uncertainty through management interventions, as well as their effects on resources (Williams 2011a).

In a review of adaptive management literature, Rist et al. (2012) found that few authors defined the term explicitly or described how it offered a means to improve management outcomes in their specific management context. This becomes an important element with a developing industry, as specific definitions, a clear and certain statutory framework, and clear expectations, will be key to coping with the uncertainty in many environmental components of deep-sea mineral ecosystems.

2.2 The Why

Natural resource systems are dynamic and change through time, and deep-sea ecosystems are no different (Tyler 2003; Ramirez-Llodra et al. 2010). However, environmental characteristics and their variability are generally poorly known and understood in the deep sea. The rapidly increasing literature on deep-sea environments associated with mineral resources is impressive, but recent review papers consistently identify a lack of knowledge about the structure and function of deep-sea ecosystems, and hence a poor understanding of the nature and extent of potential impacts of a mining operation (e.g. Levin et al. 2016; Gollner et al. 2017; Miller et al. 2018; Jones et al. 2018; Weaver and Billett 2019). This uncertainty about resource processes (and the effects of management actions) can be a critical impediment to effective management. Hence, the development of deep-sea mining from exploration to exploitation is at a cross roads, with contradictory viewpoints and options to either do nothing until more is known about the environment and likely impacts (as per calls for a moratorium on deep seabed mining [e.g. European Parliament 2018, WWF 2021]), or allow controlled development whereby management can be improved by learning and by reducing uncertainty during the management timeframe (i.e. adaptive management).

A number of sources of uncertainty may limit a manager's ability to make informed decisions (after Williams 2011a):

- Environmental variation in the deep sea is one of the most prominent issues facing DSM but this is largely uncontrollable, often unrecognised, and often appears to be random.
- Partial observability relates to uncertain resource status. For DSM and other marine resources this can include selecting inappropriate measures, taking inaccurate measurements and sampling variation.
- Partial controllability is the difference between intended and actual management actions (or their effects). It can be difficult to confidently attribute a change to a management action rather than an associated indirect effect of the action, or natural processes. This is complicated by the operational uncertainty facing deep-sea mining with no mining operations yet developed to learn from.
- Structural or process uncertainty involves a lack of understanding about the structure of biological and ecological relationships that drive resource dynamics. In the deep sea this is a major constraint.
- Statutory uncertainty in the absence of case law.

Understanding what types of uncertainty might exist, and what can be addressed by certain mining or management actions is an important aspect of designing an adaptive management regime.

2.3 The When

Adaptive management is one option in the manager's toolbox, however, it is important to acknowledge when it is appropriate in the context of natural resource management. Whether it is an appropriate approach compared to other options depends on relative levels of uncertainty in the knowledge/resource information, and in controllability of the management actions (Allen et al. 2011). Adaptive management is an approach that can work when there is high uncertainty but also high controllability of management actions; otherwise other approaches may be appropriate. An adaptive management approach is particularly well-suited to project- and ecosystem-scale management and is less appropriate for regional-scale management where controllability is generally much lower (see Birgé et al. 2016). There have been a number of studies documenting the 'failures' of adaptive management (e.g. Allan and Curtis 2005; Walters 2007; Allen and Gunderson 2011; McFadden et al. 2011; Rist et al. 2013). However, often this seems related to a lack of careful consideration of whether the approach will be useful before starting.

A number of questions can be asked ('a problem-scoping-key') to evaluate if adaptive management will be a suitable approach (after Williams et al. 2009):

1. Is a management decision to be made?
2. Can stakeholders be engaged?
3. Can management objectives be stated explicitly?
4. Is decision-making confounded by uncertainty about management impacts?
5. Can resource relationships and management impacts be represented in models?
6. Can monitoring be designed to inform decision making?
7. Can progress be measured in achieving management objectives?
8. Can management actions be adjusted in response to what has been learnt?
9. Does the whole process fit within the appropriate legal framework?

If the answers to most of these questions is 'Yes', then adaptive management can be a useful tool. If not, it is necessary to reconsider what the issues are and how effective such a strategy, if incomplete, will be.

Rist et al. (2013) proposed a decision-tree approach, with three stages:

- Stage 1 relates to the goal of reducing ecological uncertainty and the appropriateness of using adaptive management.
- Stage 2 emphasises the need to consider resource constraints as well as the social, political and institutional context of management.
- Stage 3 involves evaluating the success of adaptive management.

A number of the decisions and feedback loops involved in this approach link closely with the steps described by Williams et al. (2009).

Hence in Table 13.1 we combine elements of these questions and decision-trees within the context of determining whether adaptive management could be suitable for deep-sea mining.

It is also important to consider the wider application of adaptive management, and the governance structures that ultimately integrate the mixture of scientific, societal and economic pressures. The three closely allied concepts of adaptive management, adaptive co-management and adaptive governance (see Rist et al. 2013) emphasise that what might seem primarily a science-oriented technique needs ultimately to account for the societal, cultural and political nature of decision-making which influence management (see Sect. 4 of this chapter).

2.4 The How

There are excellent descriptions and detail of the adaptive management process provided by Williams et al. (2009) and Williams (2011a), where typically two phases to an adaptive management system are identified:

1. The Set-up Phase: this involves identifying stakeholders, defining objectives, examining alternatives, designing and running models, and establishing a monitoring plan.
2. The Iterative Phase: this involves components of decision-making, monitoring and assessment which then feeds back into decision making.

2.4.1 Set-Up Phase

The initial set-up phase puts in place key components of adaptive management.

There is a framing of the resource problem that takes into account the views and information provided by multiple stakeholders. Stakeholder involvement is critical for DSM as there are broader societal goals and objectives to consider beyond that of just scientific uncertainty, or objectives of the company or contractor. The 'handshake approach' can be important to develop a clear understanding and mutual respect between researchers and decision-makers without endangering scientific credibility (Bormann et al. 2007). This stakeholder engagement provides a broad view of the problem from different perspectives and can hopefully result in a general consensus or agreement about its scope, objectives and potential management actions within a broader management process (Reed 2008).

The resource status and state of current knowledge of the environment and ecological systems influence the definition of objectives, as well as the choice of management interventions that might be appropriate for adaptive management. If operations haven't commenced, and baseline knowledge of the structure and

Table 13.1 Problem-scoping key and sequence for adaptive management of DSM, with some issues to consider and the types of solutions required (based on Williams et al. 2009; Rist et al. 2013)

Question/step	Considerations relevant to deep-sea mining	Answer/Solution/Output
1. What management decisions need to be made	There are generally legal requirements to avoid excessive impacts to the environment: 'harmful effects', 'significant adverse impacts', 'serious harm', etc. depending upon the legal regime. This means for seabed mining that a management decision to stop or proceed will definitely be applicable	Yes Information in subsequent steps will be needed to support management options based on decisions to: 1. Stop the activity 2. Continue the activity as planned 3. Modify the nature and extent of the activity or how it is carried out
2. Can stakeholders be engaged?	Deep-sea mining as a new industry needs to consider societal and political requirements and expectations as well as environmental aspects in decision-making. Under the United Nations Convention on the Law of the Sea (UNCLOS), as well as most national environmental or seabed mining legislation, consultation and engagement with relevant stakeholders is required A wide range of stakeholders may need to be included: scientists, regulatory authorities, managers, policy makers, non-governmental organisations, public, etc. These need to cover environmental, societal and cultural disciplines Engagement and consultation need to be done in a meaningful way, not just telling stakeholders what is planned but incorporating adequate discussion and feedback. Remote communities without internet also need to be considered (e.g. Nautilus Cares Solwara 1 consultation) The aim is to ensure that the concerns, interests, and knowledge of stakeholders are considered and acknowledged during the definition and preparation of an adaptive management plan	Yes A consultation plan, describing what needs to be done and by whom should be developed early on. Activities should include provision of written material and facilitation of written feedback, webinars, face to face meetings and workshops, telephone discussions Adequate time needs to be given to those consulted to read, understand and respond to consultation material This should be linked to consultation with stakeholders as part of the environmental impact assessment (EIA) Process (especially scoping where stakeholder engagement is usually undertaken)

(continued)

Table 13.1 (continued)

Question/step	Considerations relevant to deep-sea mining	Answer/Solution/Output
3. Can management objectives be stated explicitly?	Decision-making will need to occur in the context of multiple management objectives, dynamic resources, and uncertain responses to management actions. Objectives will vary with stakeholder perceptions and expectations, so this is a key consideration with stakeholder engagement The sort of objectives covered by elements of the ISA Draft Exploitation Regulations (ISA 2019) relevant to minimising harmful effects include: • Prevent significant loss of biological and genetic diversity • Minimise loss of habitat • Minimise loss of community types • Minimise loss of ecosystem-level components, including food webs, ecosystem function and structural complexity • Minimise significant loss of connectivity between populations at an appropriate scale • Minimise contamination of the marine environment Each of these 'higher level' objectives will have a series of indicators, or metrics, and the key here is to focus on elements of management that are most directly connected to the objectives, and are critical to ecosystem well-being or most uncertain in effect	Yes, but at several levels Clear definition of management objectives will be a cornerstone of the adaptive management plan. These will vary in their level, some being relatively general (e.g. to prevent loss of biodiversity), whereas others may be specific (e.g. to maintain abundance of coral species above 50% of baseline)
4. Is decision-making confounded by uncertainty about potential management impacts?	This is linked to the main reason for considering adaptive management whereby ecological uncertainty is seen as a key obstacle to decision-making and achieving management goals But this also covers uncertainty about the consequences of a management action	Yes

Question/step	Considerations relevant to deep-sea mining	Answer/Solution/Output
5. Can resource relationships and management impacts be represented in models?	Models are an important component of structured decision-making. Different model types, and/or different representations of the structure and function of components can help understand why measured changes occur, and which 'view' of how the system works is more appropriate (see Sect. 3) Management Strategy Evaluation techniques can be a useful part of active adaptive management (see Bunnefeld et al. 2011) and are well developed for a number of marine resources, especially fisheries Preliminary cumulative (qualitative) modelling work has been carried out at several ISA workshops for polymetallic sulphide and cobalt-rich crust systems (e.g. ISA 2020). Defining various 'scenarios' of ecosystem structure and relative mining impacts was done in a workshop setting (e.g. vent connectivity, processing water discharge depth, spatial extent and composition of plume)	Yes These models may need to be developed for a specific area, specific resource, and the differing environmental characteristics that occur over a range of spatial and temporal scales An expert workshop is an appropriate format to develop scenarios, establish model structure, and identify information gaps and sources of uncertainty
6. Can ecological 'experiments' and monitoring plans be designed to inform decision making?	This step needs to be based on establishing the impacts from the activity that are most uncertain, or most likely to result in management objectives not being met An environmental risk assessment is an important part of this process. For example, it might indicate that sediment plume effects could be serious for smothering of sessile fauna or clogging suspension feeders. Yet plume modelling based solely on the small disturbance caused by exploration activities or component testing may be uncertain with low confidence in dispersal distances of various sized particles. Hence data will be needed to map the actual distribution and density of the plume, and its effects on faunal communities. This may need an extensive network of moorings, benthic landers or autonomous underwater vehicles (AUV) deployments. Are resources sufficient to undertake such experiments and monitoring in order to learn and reduce the uncertainty? There may need to be consideration given to a combination of field and laboratory experiments: the former to determine changes in a natural setting, but the latter to control certain variables and help untangle cause-effect relationships Monitoring design needs to incorporate gaining information on responses to management actions	Yes However, these may need to be complex, extensive, and expensive. They may require considerable resources over the lifecycle of the mining operation

(continued)

Table 13.1 (continued)

Question/step	Considerations relevant to deep-sea mining	Answer/Solution/Output
7. Can progress be measured in achieving management objectives?	The monitoring plan is not just about assessing the state of the system but should reflect the learning aspect of adaptive management. There should be increased confidence in understanding how the system is responding to impact The detectability of change should be an important consideration when selecting indicators (Table 13.2) for monitoring in the adaptive management plan. If change cannot be detected using a certain indicator within a reasonable timeframe, it may not be useful for management and learning Management objectives are multi-dimensional and there may be trade-offs between outcomes associated with different objectives. This should not be unexpected, but also not seen as a failing if all objectives are not met at the same rate or to the same extent	Yes A nested structure in management objectives can enable progress at a higher more generic level to be assessed given more specific (and hence more quantifiable) objectives (or 'sub-objectives') that may vary in how quickly or completely they are met
8. Can management actions be adjusted in response to what has been learnt?	Management regimes often take time to change, and the level of 'proof' required can lead to lack of resolution and delays in implementing change. Hence the flexibility to change management rapidly is needed. This should be built into any consent conditions The interim results of the monitoring programme may not be conclusive, with faunal groups and other components of the ecosystem responding in different ways or at different rates to impact. The precautionary approach needs to be considered here, whereby uncertain information does not prevent management action. There can be a tendency to 'wait and see' and hence delay a management response The environmental management and monitoring plan (EMMP) and Adaptive Management Plan need to be very clear when they are proposed regarding details of the monitoring regime, frequency of measurements, review, and key trigger points for management action	Yes Adjusting the management response needs to be part of an EMMP. The adaptive management plan envisaged as part of the EMMP needs to include agreed conditions (between a contractor and the regulatory authority) that would result in a management response, as well as the nature and extent of that response

Question/step	Considerations relevant to deep-sea mining	Answer/Solution/Output
9. Does the whole process fit within the appropriate legal framework?	The flexibility that an adaptive management approach provides for resource management can be inconsistent with the level of certainty often required under legislation or regulation. The developing Exploitation Regulations of the ISA include reference to adaptive management as potentially part of the EMMP, but there needs to be further consideration of developing and relevant ISA rules, regulations and procedures, standards and guidelines, and the relevant regional environmental management plan National laws vary in their explicit references to adaptive management (see Sect. 4 for a New Zealand case study), and commentary by Craik (2020) There is a balance in adaptive management between allowing a project to proceed and reducing uncertainty, and restricting or preventing a project because of precaution	Possibly, depending on the specific international or national setting

function of the deep-sea ecosystems is poor, then the objectives may be higher level and less specific than a situation where considerable knowledge about the nature and extent of impacts exists. However, 'broad-brush' statements are often directed at the purpose of the management, rather than objectives that can help to guide decision-making (Williams et al. 2009). Such objectives should be 'SMART':

- Specific: unambiguous, with specific metrics and targets.
- Measurable: elements of the objectives need to be measured with field data, and be appropriate for evaluating the actions of management.
- Achievable: objectives need to be realistic in the context of the resource and ecosystems being managed. This also links to social and regulatory systems.
- Results-oriented: there need to be conditions or status-points that indicate progress or achievement of management. These will reflect the value of learning over time.
- Time-fixed: a timeframe for achievement is required, which is consistent with the duration of the operation as well as the management and monitoring plan.

It is very likely there will be multiple objectives for deep-sea mining, reflecting environmental, societal, economic and cultural interests. This might necessitate weighing up the relative importance of objectives to facilitate the comparison and prioritisation of management alternatives.

There is also the consideration of the practicality of the objectives. Uncertainty reduction is dictated by two key factors: the resources available for management, and management flexibility with respect to problem conception (Rist et al. 2013). Resource availability includes logistical support, the scientific expertise and funding available to support conduct of the monitoring plan (the experimental design) and analysis of the data. This may then set a limit on the type or number of uncertainties that can be addressed within a given time period or spatial extent.

Adaptive management involves the selection of certain management actions at each decision point. This requires the development of alternative 'views of the world' in that when monitoring might show deviations from what was expected, it is important to know what could be causing them. These alternatives cover both scientific models of the system, and management options. A suite of models can better capture key uncertainties, but this is a challenging task and should not be underestimated in the resources that it might take to develop and populate different scenarios.

The development of a monitoring plan is the last stage in the set-up phase. For DSM, adaptive management is most likely to sit within an environmental management and monitoring plan (EMMP). However, it is important that it is not simply referred to in general terms as something that will utilise the data from the monitoring part of the EMMP. Adaptive management should have its own plan, and monitoring must be clearly and unambiguously aligned with the objectives of adaptive management. It will ideally result in (1) an evaluation of progress towards achieving objectives, (2) determination of resource status in order to identify appropriate management actions, (3) an improved understanding of resource system dynamics by comparing observed and expected and (4) enhancement and development of better models of the resource system. Together these will promote learning for science, resource use and management.

2.4.2 Iterative Phase

The iterative phase of adaptive management uses the elements developed during set-up to support a feedback loop of management actions, monitoring, assessment, and then further management action, etc.

Decision-making is a task carried out at each decision point in the timeframe of an adaptive management plan. It selects an action from a set of management alternatives, based on the management objectives, the state of the system, and the level of understanding when the selection is made. Appropriate actions may change as more information is gathered, and hence management reacts to both changing resource status and learning. It ideally can use agreed indicators, targets-thresholds and trigger points to inform the nature or extent of the change to be made by management action (Table 13.2).

Monitoring is key to this process, and is an ongoing activity required to evaluate management interventions, update model parameters where appropriate, and prioritise management options. The current state of knowledge of deep-sea ecosystems is a constraint, but baseline data collection during exploration activities is continuing to grow environmental databases associated with deep seabed minerals (Lodge and Verlaan 2018), regulations (national or developing international) generally specify monitoring for the life of the project and potentially beyond the time of the closure plan (ISA 2019), and existing (e.g. ISA 2011) or developing Regional Environmental Management Plans can provide a larger spatial scale to link with individual projects.

Assessment is the third aspect of the Iterative Phase. This generally involves comparison of model predictions against measurements of actual change. Coincidence between predicted and observed measures is an important part of evaluating model adequacy, as well as guiding the appropriate management response.

Finally, there needs to be ongoing evaluation of the appropriateness, efficacy and success of the Adaptive Management plan. Principal amongst the range of considerations is the reduction of uncertainty and the building of a good understanding of the system through the iterative experiences of the management plan (Gerber et al. 2007), but the process by which this is achieved is still continuing to evolve (McFadden et al. 2011).

2.5 The Who

Adaptive management is an interdisciplinary process that requires input from a diverse range of stakeholders including mining contractors, environmental resource managers, regulatory authorities, sponsoring state representatives, scientists and non-government representatives (see Table 13.3). The roles of these stakeholders

Table 13.2 Illustration of a hierarchy of objectives, indicators, metrics and potential management action (if a target is not being met and threshold of change is recorded)

Objective	Operational indicator	Metrics and parameters	Management action examples
Prevent significant loss of biological and genetic diversity	Alteration of community structure	Abundance, species richness, density, species evenness, size structure, biomass, areal and depth distribution	e.g. prior development of a network of protected areas that contain representative communities and rare species. There would be no mining in these areas. Size of protected areas to be adequate for sustaining populations, or connectivity is maintained through corridors/proximity (e.g. Clarion Clipperton Zone Areas of Particular Environmental Interest (APEIs)) e.g. new protected areas established if areas of high faunal abundance or biodiversity are located e.g. reducing the mining area, leaving areas between vehicle transects, increasing distance between mined area and sensitive habitat e.g. technical modification of equipment (such as hoods to reduce sediment plume) or operation (such as depth of seabed penetration, depth of processing water discharge)
Minimise loss of habitat	Change in nature and extent of habitat type (both physical and biogenic)	Areal extent of habitat type Spatial patterns and patchiness of habitat Condition ('health') of habitat Structural complexity of habitat types	e.g. closed areas for protection of vulnerable habitat, restriction of mining activity on certain substrate or at certain depths e.g. reduction of sediment plume that impacts biogenic coral/sponge habitat e.g. stopping mining gear or lifting over certain habitat types
Minimise loss of ecosystem function	Energy flow in the food web (production/consumption/export)	Primary productivity levels Secondary productivity levels Flux to the seafloor Mean transfer efficiency between trophic level (e.g. ingestion, absorption, respiration, defecation, growth, reproduction)	Management options are more complex depending on which components are being affected e.g. prior development of a network of protected areas that contain representative communities and rare species and sufficiently large to maintain core ecosystem structure and function over large spatial areas e.g. new protected areas established if areas of high faunal abundance or biodiversity are located, or source populations determined e.g. stop surface discharge if primary productivity affected e.g. design of riser system if leaking or repelling fauna

Table 13.3 Key stakeholder groups associated with DSM projects and some of their roles in the adaptive management process

Key stakeholder groups	Role in the adaptive management process
Mining contractors	Develop natural resources. Advise on flexibility of mining operations and equipment. Inform feasibility of contractor-driven monitoring programmes. Economic input. Support collection and analysis of necessary scientific samples and data
Environmental (resource) managers	Evaluate potential environmental impacts, assess environmental risks, ensure adequate mitigation measures and monitoring of environmental changes. Environmental objective-setting. Evaluate levels of uncertainty
Regulatory authorities and decision-makers	Organise, regulate and control seabed mining activities (with the duty to ensure the effective protection of the marine environment). Determine decision rules and decision-points (timing and frequency), acceptable level of uncertainty. Monitor compliance with terms of permits and licences
Sponsoring state representatives (High Seas)	Supervise seabed mining activities and ensure regulatory compliance
Scientists (including expert groups)	Conduct scientific research to advance knowledge and aid decision-making. Support analysis of risk, impacts, environmental thresholds, indicators and metrics in monitoring programmes. Advise modelling approaches and methods
Society at large and non-government organisation (NGO) representatives	Represent the common values and concerns of society. Provide cultural and societal input to conservation and management objectives

are not all equal but are complimentary (not mutually exclusive) and within the overarching regulatory context influence each stage of the adaptive management process.

Stakeholder engagement works across all groups and disciplines, but each group is likely to have a particular set of skills and experience that can inform a balanced and integrated approach to resource management and conservation. This participatory approach is further developed in the next section.

3 A Way Forward: A Participatory Systems Modelling Approach

3.1 Systems Thinking

Ecosystems behave as unpredictable complex systems that are inherently difficult to manage (DeFries and Nagendra 2017). Deep-sea mining (DSM) projects must deal with this complexity in order to effectively manage environmental impacts from mining activities. Systems thinking can reduce this complexity by conceptualising the system (Arnold and Wade 2015). Systems thinking is a foundational framework for seeing the world as an interconnected complex system, and is a precursor to understanding system dynamics (Sterman 2001) and implementing adaptive management. Arnold and Wade (2015) identify eight key elements that define systems thinking:

1. Recognising interconnections;
2. Identifying and understanding feedback;
3. Understanding system structure;
4. Differentiating types of stocks, flows, variables;
5. Identifying and understanding non-linear relationships;
6. Understanding dynamic behaviour;
7. Reducing complexity by modelling systems conceptually; and,
8. Understanding systems at different scales.

Applying systems thinking to DSM projects can foster iterative learning, allowing for greater flexibility in the face of uncertainty (Senge 2014), and is increasingly recognised as a foundation for adaptive management to avoid trial and error (Hyman et al. 2021a) and pursue a more holistic approach to understanding and managing complex systems (Atkins et al. 2011; Cundill et al. 2012).

Systems thinking can help stakeholders understand potential causal relationships from mining pressures and how management actions may lead to unintended consequences over time (Dyball and Newell 2014). Complex systems should be examined as a whole since they have emergent behaviour owing to synergistic or antagonistic effects and non-linear dynamics (Sterman 2000). Adaptive management that is based on individual system components may overlook this emergent behaviour, potentially leading to surprises that often lead to implementation failures (Allen and Gunderson 2011). System approaches can also help environmental scientists and managers of DSM projects proactively identify system connections that could lead to undesirable or unintended consequences. For example, both pressures from mining activities and climate change should be considered in system models in order to understand the combined pressures acting on deep-sea ecosystem structures, functions and services (Levin et al. 2020). System archetypes are a diagnostic tool to analyse system structure to identify issues based on common patterns of emergent behaviour of complex systems (Wolstenholme 2003; Senge 2014). Considering potential emergent behaviours of complex systems (e.g. using system archetypes) is a critical first step to ensure that adaptive management is, in fact, appropriate for the resource problem and will not lead to unintended consequences.

3.2 Participatory Modelling

Models are central to the adaptive management of DSM projects to represent the current knowledge base, understand reality (i.e. via systems thinking), identify key uncertainties, synthesise evidence to inform management and support participatory

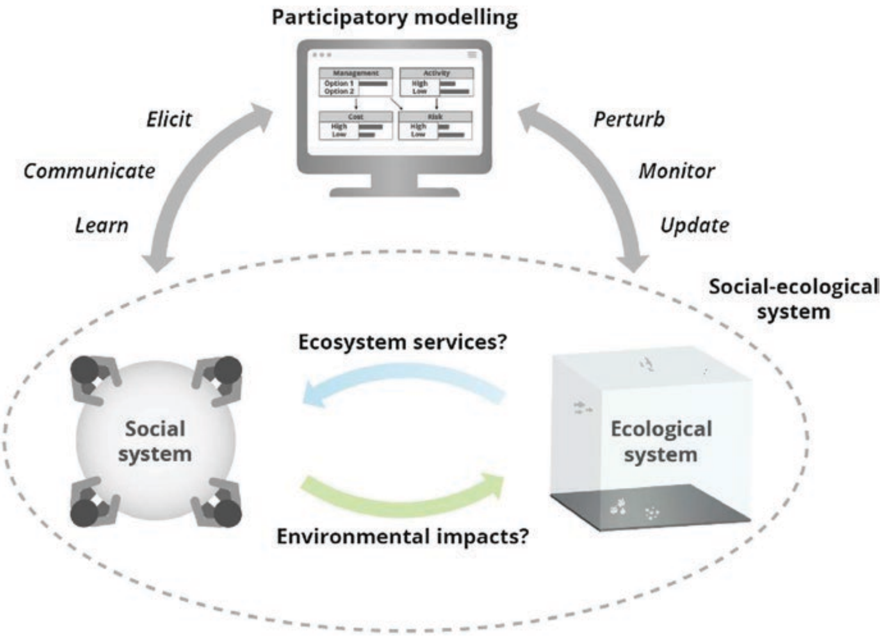

Fig. 13.2 Participatory systems modelling approach to operationalise adaptive management of deep-seabed mining projects (adapted from Hyman et al. 2021a)

decision-making. Conceptual models are a key step in the setup phase of adaptive management (see Sect. 2) since they can integrate multiple lines of evidence in a common framework for evidence-based planning (Williams et al. 2009). Existing literature, expert opinion and ongoing research efforts should be linked to an underlying conceptual model, providing a more complete, even if less precise, representation of the system (Maier et al. 2016).

An environmental management framework for DSM projects was detailed by Durden et al. (2017), which suggests using a conceptual model to capture the complexity of DSM project-related data. However, it is important to support an ecosystem approach to management, i.e. conceptual models should not simply be a collection of unstructured data. As highlighted by Dickey-Collas (2014), we cannot simply 'data-collect' our way to an ecosystem approach. Rather we need system models to utilise data to identify the key interactions between social and ecological systems, including how deep-sea ecosystem services benefit human-wellbeing, and the potential environmental impacts from mining activities to underlying ecosystem structures and functions (Fig. 13.2).

Adaptive management can be used to minimise residual environmental impacts from mining that risk shifting the ecological system into an undesirable state, thereby maintaining the flow of ecosystem services to society (Birgé et al. 2016). Integrating adaptive management and ecosystem services is now recognised as a key opportunity to improve the way we manage natural resources (Epanchin-Niell et al. 2018). Adaptive management recognises that not all uncertainties are equally important to resolve or relevant to decision-making (Runge et al. 2011). In order to implement active adaptive management in DSM projects whereby learning is a key objective (see Sect. 2), managers and decision makers need to evaluate the extent to which adaptive management will actually reduce uncertainty and improve the environmental management of DSM projects (see Sect. 4).

Models supported by expert judgements can be used to determine how informative each adaptive management strategy will be and how best to prioritise management actions and monitoring plans (Runge et al. 2011). Hence estimating the expected value of information from monitoring should be central to any adaptive management strategy for DSM (Runge et al. 2011; Williams et al. 2011). Unfocused monitoring can be expensive, especially in deep-sea environments, and can simply lead to declarations of a need for 'more research' instead of providing the information that is critically needed by environmental managers (Nichols and Williams 2006). Herein lies the value of models for the adaptive management of DSM projects—as a planning tool to represent the current knowledge about the system, and subsequently identify the uncertainties that are most important to resolve for effective environmental management.

Embedding both participatory modelling and adaptive management concepts in the EIA-EMMP process can improve the way uncertainty is managed in practice (Bond et al. 2015). Participatory modelling can be used to engage stakeholders to build system models and support decision-making throughout adaptive management. Hyman et al. (2021a) recently proposed a conceptual framework for adaptive management that employs a participatory systems modelling approach to operationalise adaptive management in deep-seabed mining projects (Fig. 13.2). For the social system, two-way communication is needed to: (1) elicit information from experts to build conceptual models; and (2) communicate these models to stakeholders to facilitate social learning (Reed et al. 2018). For the ecological system, two-way intervention is needed to: (1) perturb the ecological system with planned management experiments; and (2) monitor the dynamic behaviour of the ecological system to update models and support decision making (Lyons et al. 2008).

Participatory modelling enables social learning by updating the collective-knowledge base in light of new information from management experiments. Therefore, a focus on building models with input from key stakeholders, then updating these models as the knowledge-base improves over time, could provide a formal method for 'learning' about deep-sea ecosystems, and improving risk management in EIA and EMMP for DSM projects. Test mining was envisaged by the ISA (ISA 2013) and will be a critical learning phase for mining contractors to validate model predictions and perform the initial iterations of adaptive management. However, to date this has not extended beyond component testing of various equipment under exploration licenses.

Argent et al. (2016) highlight eight fundamental 'best practice actions' for participatory modelling to support stakeholder participation and lay the basis for adaptive management:

1. Use an open and transparent model development process;
2. Encapsulate and communicate concepts effectively;
3. Establish and maintain conceptual models;
4. Create robust and adaptable models;
5. Use a formal approach to model representation;
6. Test and re-test the models;
7. Explore model behaviour through scenarios; and
8. Ensure the model can be converted into an operational form.

The approach presented in Fig. 13.2 is based on the idea that participatory modelling and adaptive management can proceed independently but are synergistic for the management of social-ecological systems (Crevier and Parrott 2019). Participatory modelling applied in a structured framework (e.g. Williams et al. 2009; Williams 2011a, b; Hyman et al. 2021a) could facilitate the implementation of adaptive management in an operational setting for the effective environmental management of deep-seabed mining projects.

3.3 Bayesian Networks

Building on the approach presented in Fig. 13.2, we suggest Bayesian networks (BN) as one participatory modelling technique that could underpin an operational adaptive management strategy for DSM. BNs are well-suited to the adaptive management of natural resources and are particularly useful for decision-making under uncertainty (Howes et al. 2010; Nyberg et al. 2006; Pollino and Henderson 2010)—a key barrier to the effective environmental management of DSM projects (Hyman et al. in review). BN models can be easily updated with new data from monitoring, forming an iterative process to improve risk assessments and management decisions over time. BNs explicitly treat uncertainty using a probabilistic graphical interface, providing a clear picture of system relationships and greater transparency when presenting to decision-makers (Grêt-Regamey et al. 2013). In a recent review, Kaikkonen et al. (2020) found that BNs are increasingly used for environmental risk assessments. Hence BNs can also incorporate risk into adaptive management plans for DSM projects using international standards for risk assessment (Cormier and Londsdale 2020; ISO 2018). This could help address issues around levels of environmental risk associated with conditions for adaptive management, and the extent to which adaptive management could reduce this risk (as detailed in Sect. 4).

Most BN software is interactive and can be used for both predictive and diagnostic inference in environmental risk assessments (Moe et al. 2020). Predictions can be used to test different management options and the corresponding changes to model endpoints, and diagnoses can be used to determine which combination of management decisions would lead to the most desirable model endpoints (e.g. if there is a low probability of exceeding an environmental threshold for a certain management scenario). Thus, BNs could be interrogated to design precautionary measures under uncertainty and to test mitigation measures to minimise risks from DSM activities. Moreover, BNs can be applied in an integrated ecosystem assessment framework (see Levin et al. 2009) to initiate ecosystem-based management. For example, Fletcher et al. (2014) explore the value of using the integrated ecosystem assessment framework in a coastal ecosystem to build consensus among stakeholders and transfer ecosystem-based information to decision-makers and the public.

Furthermore, BNs can be used to model the links between ecosystem structures, functions, services, and the effect of management alternatives on the delivery of ecosystem services (Haines-Young and Potschin 2010; Landuyt et al. 2013). BNs can be structured based on the Common International Classification of Ecosystem Services (CICES) framework or the Drivers-Activities-Pressure-State changes-Impacts(on Welfare)-Response(as Measures) framework (DAPSI(W)R(M)) (Elliott et al. 2017; Kaikkonen et al. 2018). A key limitation of BNs is their general lack of support for feedback loops (Uusitalo 2007). If this limitation is found to be problematic during initial conceptual modelling, BNs are increasingly being integrated with alternative modelling techniques to overcome such limitations (Kelly et al. 2013; Marcot and Penman 2019). Such models link biophysical Structures (description of ecosystem characteristics), Function (quality or quantity of ecosystem functions), Service (quality or quantity of ecosystem services) to result in Benefit (economic value of ecosystem services) (Landuyt et al. 2013).

In summary, a participatory systems modelling approach could be used as a mechanism to develop the basis for adaptive management of DSM projects. Participatory modelling facilitates both the active involvement of stakeholders during the modelling process which is critical during the setup phase, as well as a shared understanding of the social-ecological system to support decision-making in the context of environmental management (Sect. 2). In addition, conceptual models can be used as an evidential foundation to address issues of insufficient data during regulatory review, and to develop robust plans for adaptive management to reduce uncertainty and improve environmental management over time.

4 Decision-Making Under Adaptive Management: Drawing on the New Zealand Experience

Adaptive management at the level of an individual project (the responsibility of the contractor) operates within the broader legal and management regimes of UNCLOS and the ISA (Jaeckel 2016; Craik 2020), and is therefore relevant to regulatory authorities and decision-makers. Decisions about both the suitability of adaptive management, and decisions about options within its framework, need to consider the social, political, institutional context and governance processes (Rist et al. 2013). In this section, we focus on specific experience from New Zealand to illustrate some of the issues that arose with applications from companies to utilise seabed resources and incorporate adaptive management into their plans of work.

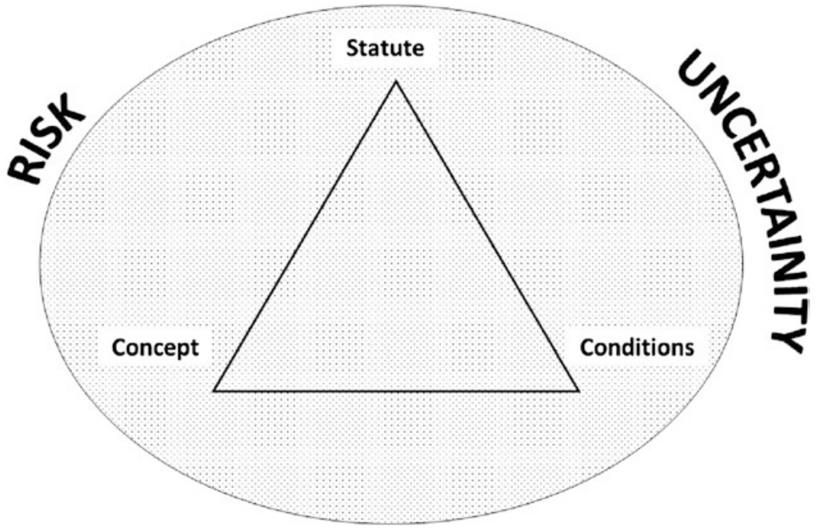

Fig. 13.3 Elements of DSM decision-making

Decision-makers for DSM applications work in a complex space often dominated by various levels of uncertainty. The management of environmental risks arising from uncertainty that decision-makers face adds significant pressure to making decisions that are robust, well-founded on science, and defendable both in a legal sense and in the court of public opinion. Decision-makers face additional challenges if they choose to use adaptive management as a part of their evaluation of permits, authorisations or consents (the term 'consents' has been used from this point to cover various authorisation types).

There are three elements that are common to all statutory decision-making involving adaptive management: the concept of adaptive management, the statutory regime, and any conditions of consent (Fig. 13.3). Each element can have its own degree of uncertainty which alone, or in combination, drives overarching risks that impact decision-making.

In this section we build on more generic accounts of the international legal context by Jaeckel (2016) and a mix of ISA and national issues by Craik (2020), and draw on New Zealand applications for resource use by King Salmon Ltd (an offshore salmon farming licence) and two applications in 2014 and 2016 by Trans-Tasman Resources Ltd (an offshore iron sand mining licence). The concept of adaptive management in terms of resource management is not settled. As explained in Sect. 2 of this chapter, adaptive management is often misinterpreted as a 'trial and error' approach, rather than a science-based process with distinct setup and iterative phases to promote caution and careful deliberation in the face of uncertainty about impacts to deep-sea ecosystems.

Decision-making for activities associated with DSM will be based on a statutory regime whether in the Area under the ISA or in national waters. This regime may define adaptive management for the specific purposes of that legislation; these tend to include bespoke definitions reflecting the scope and context of the legislation. For example, New Zealand's Exclusive Economic Zone and Continental Shelf (Environmental Effects) Act 2012 (New Zealand Government 2012) at section 64 defines adaptive management as including:

(a) Allowing an activity to commence on a small scale or for a short period so that its effects on the environment and existing interests can be monitored:
(b) Any other approach that allows an activity to be undertaken so that its effects can be assessed and the activity discontinued, or continued with or without amendment, on the basis of those effects.

In New Zealand the concept has been set out by the Supreme Court in the King Salmon case[1] where four characteristics of adaptive management were identified:

(a) There will be good baseline information about the receiving environment;
(b) The conditions provide for effective monitoring of adverse effects using appropriate indicators;
(c) Thresholds are set to trigger remedial action before the effects become overly damaging; and
(d) Effects that might arise can be remedied before they become irreversible.

If a decision-maker grants a consent then it is common practice for the scope and nature of such decisions to be shaped significantly by conditions of approval or consent. Adaptive management can only be given effect by conditions which should meet the Newbury tests[2]: being for the statutory/resource management purpose (and not any ulterior purpose), fairly and reasonably relate to the activity authorised by the consent; and not be unreasonable. In addition, other principles of enforcement and effective condition drafting include: being certain (specificity), being enforceable (vires or lawful), and not involving the future exercise of a discretionary power on the merits of an adaptive management response.[4]

All three elements of decision-making shown in Fig. 13.4 include their own degrees of uncertainty. They combine to set up a cloak of overall uncertainty, and associated risks, over the decision-making process as a whole. These issues include how well do decision-makers (and their advisers) understand the concept of adaptive management and how will they apply it; what is the legal risk of not complying with the legislation and is there case law or precedent to assist and guide decision-makers; and finally are the conditions capable of being given effect to, and not frustrate the exercise of a consent by being imprecise or uncertain in themselves.

Those overall uncertainties create risk around the basis of any decision and in the implementation of any decision through conditions. How they influence a decision is materially influenced by human factors such as the experience and background of

[1] *Sustain Our Sounds Inc v New Zealand King Salmon Co Ltd*.

[2] http://www.rmla.org.nz/wpcontent/uploads/2016/09/conditions_of_consent_judge_lj_newhook_final.pdf

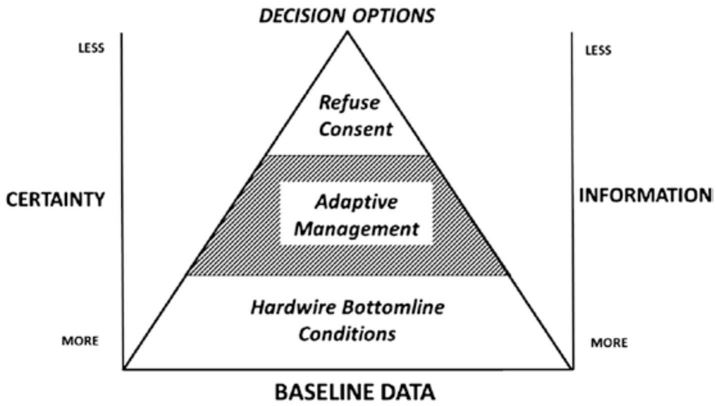

Fig. 13.4 Information certainty and decision options

the decision-making panel and those experts or lay people who advise it or provide evidence or submissions in hearings held by a panel. There is no standard or recipe for how individual members or panels use the information, advice and expert testimony presented to them to weigh up and resolve uncertainties and risks. First and foremost the decision is based on individual values, technical judgment through the testing of evidence, and any statutory and non-statutory policy guidance that may exist. It is then based on the collective experience, values and wisdom of the decision-makers.

All uncertainties and associated risks accepted by decision-makers have the potential to create adverse consequences to the marine environment. Having good baseline information on the marine environment within which activities are planned to occur is vital as it will enable decision-makers to consider the significance of those consequences, a critical requirement for robust and enforceable decisions. There is an interplay between how much information is available to a decision-making body and the attributes of that information. Both the volume of information and the 'quality' of that information affect the nature and degree of uncertainty, which in turn will lead a decision-maker to one of three decision options:

1. Refusing consent if there is too much uncertainty or too much risk.
2. Grant consent with conditions that provide for adaptive management in response to new information (if this then that, adapt and respond).
3. Grant consent with hard-coded (hardwired) performance based on environmental indicator conditions (environmental bottom line or indicator conditions).

The adequacy of baseline information, its degree of certainty and decision pathways are conceptualised in Fig. 13.4:

This interplay of management options based on the level of baseline data, information and certainty has important implications for how decision-makers interpret situations where adaptive management may, or may not, be appropriate. Several lessons can be learnt from New Zealand experience in marine consents for seabed mining under the EEZ Act. The Trans-Tasman Resources Limited (TTRL) applications to mine iron sands are illustrative of how these elements of information, uncertainty and risk can be decided. Some essential elements of decision-making relevant to other applications can be drawn from the second Decision-making Committee decision,[3] the subsequent High Court appeal[4] and the more recent Court of Appeal decision.[5]

4.1 Refusal of Consent

A fundamental proposition is that adaptive management cannot be used to make up for deficiencies in information in an application. Adaptive management as an approach to management of environmental risks requires a robust level of certainty and knowledge in order to test the effects of an activity against anticipated environmental effects. It is not of itself an information-gathering exercise in order to formulate a management response. It is rather an information-led process of testing propositions against targeted new information. An adaptive management response can only be implemented if the baseline information or the qualities and attributes of that information enable that as an approach as covered in Sect. 2 of this chapter.

A key point for decision-making bodies is to understand that the Courts in New Zealand have accepted that '*…there will always be more evidence that could be called on for every application or appeal. Decision-making bodies in this area have to make decisions based on incomplete data*'.

In its refusal to grant consent to TTRL's first application in 2014, the DMC made two highly pertinent observations about information. First, that 'best available information' does not mean all available information, and second, that the information deficiencies were on such a broad front that the 'application was premature'.

Refusal of consent could be based on inadequate baseline or other information presented during the hearing process, or on factors relevant to the particular marine environment where the proposed activities will take place. As an example, the Alternative View on the 2016 DMC decision focused on the consequences of an absence of baseline information:

> *The lack of adequate baseline information results in an inability to both adequately describe the potentially affected environment and to assess the sensitivity of the receiving environment. It follows that the formulation of robust consent conditions setting appropriate standards and limits that are linked to environmental protection is not possible. We consider that*

[3] TTRL Decision-making Committee Decision. https://www.epa.govt.nz/assets/FileAPI/proposal/EEZ000011/Boards-Decision/TTRL_Marine_Consent_Decision_EEZ000011_FINAL_version.pdf

[4] *Taranaki-Whanganui Conservation Board v Environmental Protection Authority* [2018] NZHC 2217.

[5] Court of Appeal Decision. https://www.epa.govt.nz/assets/FileAPI/proposal/EEZ000011/Objections-and-appeals/TTRL_Court_of_appeal_decision_3_April_2020.pdf

> *granting consent to the application before the collection of sufficient baseline data on the existing environment is unwise and untenable, and inconsistent with recognised best practice for environmental impact assessment.*

The weight to be given to any evidence and the reliability of the evidence can also include considerations such as whether it: is science-based; is independent or biased; is verified or unreliable; is relevant or unhelpful; is expert or lay evidence. A further specific comment made in the alternative view was that '*the impact assessment relies heavily on modelling based on inputs from other modelling, and this results in compounding levels of uncertainty (that could result in significantly greater adverse effects than predicted)…This level of uncertainty is largely due to the lack of good baseline information and the complexity of the marine environment*'.

4.2 Consenting with Adaptive Management

A decision-maker has to be satisfied that the attributes and qualities of the information in front of it enables it to either proceed to a decision to grant consent, or to formulate an adaptive management response. For the latter it has to be able to identify the marine environment indicators of most concern, the thresholds of when adverse effects are likely, the parameters to be measured to assess effects of an activity against those factors, and to specify a management response where harm is likely. Inadequate baseline information, or poor-quality information, will not allow for these components of an adaptive management approach to be taken.

The Court of Appeal in the TTRL case drew on the King Salmon Supreme Court decision to identify the pre-conditions for employing adaptive management:

The goal of an adaptive management approach is to enable an activity to proceed despite a measure of uncertainty about its effects, in a manner that is consistent with a precautionary approach, by sufficiently reducing uncertainty and adequately managing any remaining risk. Such an approach can be adopted only if there is an adequate evidential foundation to have reasonable assurance that the adaptive management approach will achieve those goals. If there is an adequate evidential foundation that provides that level of assurance, then the question whether the precautionary approach requires an activity to be prohibited until further information is available, rather than adopting an adaptive management approach, will depend on an assessment of a combination of factors:

(a) *The extent of the environmental risk (including the gravity of the consequences if the risk is realised);*
(b) *The importance of the activity (which could in some circumstances be an activity it is hoped will protect the environment);*
(c) *The degree of uncertainty; and*
(d) *The extent to which an adaptive management approach will sufficiently diminish the risk and the uncertainty.*

That decision sets out the responsibility of a decision-maker to understand the activity to be consented, and the attributes and qualities of the baseline and other information so they can determine conditions of consent that include appropriate environmental thresholds, monitoring and reporting requirements, timeframes and operational responses.

The specific statutory context of adaptive management in the EEZ Act and the limitations on adaptive management are traversed in the TTRL Court of Appeal decision including the role of management plans. This has a wide application beyond the EEZ Act.

The decision provides guidance as to what types of conditions are not adaptive in nature, such as:

1. Assessment of effects of an activity and the activity may be continued with or without amendment, i.e. operational responses to monitoring to ensure the activity stays within a consent envelope.
2. Requirements in conditions that correspond to statutory provisions applicable to all consents
   (a) Record keeping
   (b) Requiring monitoring of compliance with the conditions of a consent
   (c) Reporting.
3. Requiring activities to cease if their effects are outside the consented parameters.
4. Review of conditions in the event of unanticipated adverse effects or the breaching of a specified environmental threshold.

4.3 Granting Consent

The third decision-making option is to grant consent, usually with hard-coded (hardwired) performance based or environmental indicator conditions (environmental bottom line or indicator conditions). Here there will be no need to use an adaptive management approach. To grant consent a decision-making panel has to satisfy itself that it has the best and sufficient information available, that it is satisfied with the attributes, qualities and coverage of that information (its adequacy), and that it understands the residual uncertainties and risks within that information. This level of knowledge and understanding enables the decision-making panel to identify and specify the scope of the consent in terms of the operational boundaries of an activity, as well as the relevant parameters of consent so that a robust, science-based decision supported by certain and enforceable conditions can be made. At this point the decision has brought to bear sufficient, sound baseline and other information, minimised risk and minimised potential harm to the marine environment arising from consenting activities to mine the seabed.

5 Conclusions

Adaptive management is one of numerous tools available to mining contractors and environmental resource managers, but one that could be very important in the development of the deep-sea mining industry at large to overcome limitations of high uncertainty around ecosystem structure and function, and an incomplete understanding of impacts on environmental sustainability.

The conflict we have seen in this chapter, between the lack of knowledge and level of uncertainty that is able to be handled by an adaptive management approach, and emphasised by Sect. 4 and the New Zealand examples, highlights the potential paradox of adaptive management. This paradox is where it is arguably essential for deep-sea mining, but very difficult to achieve under legal frameworks (Ruhl 2008; Craik 2020). There is, however, a clear take-home message that adaptive management needs to be a scientifically robust approach, and also compatible with legal and regulatory requirements.

Key elements of a successful adaptive management approach include:

- It is not trial and error, but a structured learning process. Hence, it needs to be an active, not passive, approach, and include different model structures to better interpret changes during the monitoring phase.
- Participation: involvement of a wide range of stakeholders is important. A systems approach can help develop a more holistic representation of complex social-ecological systems using participatory modelling techniques such as Bayesian networks.
- The needs of managers and decision-makers must be considered in assessing and implementing the approach. Environmental as well as management conditions must be evaluated beforehand to assess whether the approach is appropriate.

Adaptive management is a well-accepted concept, but its success in practice has been mixed. The combination of a new industry with uncertain impacts, as well as limited understanding of the structure and function of deep-sea ecosystems means there is no easy formula for developing an adaptive management plan. The complexity of environmental characteristics, societal expectations and legal and regulatory requirements present a considerable challenge for the deep-sea mining industry, but one where adaptive management can play a potentially vital role.

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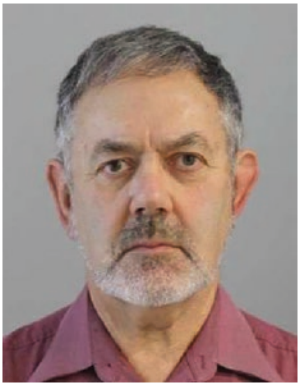

Richard Johnson was the foundation Manager for the New Zealand EPA Exclusive Economic Zone Applications team in 2013. He led the teams assisting Decision-making Committees on seabed mining marine consent applications, and a range of oil and gas exploration and production marine consents before his retirement in 2020. He has presented widely, including to international forums, on New Zealand's statutory regime for marine consents, and the lessons learnt from implementing that regime. He is assisting the Cook Islands Seabed Minerals Authority to set up its regulatory regime for seabed mining. Richard is a retired member of the New Zealand Planning Institute.

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Chapter 14
Integrated Environmental Management of the Ecological Impacts from Seafloor Massive Sulphide Mining: Perspectives from the Kermadec Volcanic Arc, New Zealand

Rachel E. Boschen-Rose, Malcolm R. Clark, Ashley A. Rowden, and Jonathan P. A. Gardner

Abstract Conducting comprehensive environmental baseline studies is a prerequisite for determining effective environmental management strategies for deep-sea mining. Studies conducted along the Kermadec Volcanic Arc have described biological assemblage structure at multiple spatial scales, connectivity of assemblages at different sites, and functional sensitivity of assemblages to Seafloor Massive Sulphide (SMS) mining. Integrating information from these studies highlights the importance of having a highly connected network of protected seabed areas to help mitigate the impacts of SMS mining activities. Using the Kermadec Volcanic Arc as a case study, the additional knowledge required to conduct a full ecological risk assessment is discussed.

Keywords Seafloor massive sulphide · Deep-sea mining · Ecological impacts · Integrated environmental management · Systematic conservation planning · New Zealand

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1 Background

1.1 Deep-Sea Mining and Seafloor Massive Sulphides

Seafloor Massive Sulphide (SMS) deposits (also known as Polymetallic Sulphides) are typically areas of hard substratum or sediment with high base metal and sulphide content that form through hydrothermal circulation. The high base metal content of some SMS deposits, along with commercially exploitable concentrations of gold and silver, has interested mining companies since the 1980s (Boschen et al. 2013), although the first licence for commercial exploitation of an SMS deposit was only issued as recently as 2011 to Nautilus Minerals Inc. offshore of Papua New Guinea. Interest in SMS mining also extends beyond national jurisdiction, with seven contracts for exploration awarded to date by the International Seabed Authority (ISA) in the North Atlantic (Mid-Atlantic Ridge) and Indian Ocean (Southwest and Central Indian Ridges)[1].

SMS deposits can be either inactive or active, with continued hydrothermal activity required to build on existing deposits. The distinction between hydrothermally active and inactive locations is not always clear (Jamieson and Gartman 2020), with some deposits switching between active and inactive on millennial timescales (Cherkashov 2017) and some within-deposit habitats rapidly switching in activity over months and years (Coffey Natural Systems 2008). Different biological communities colonise hydrothermally active and inactive SMS habitats, deposits and vent fields (Boschen et al. 2016b; Gerdes et al. 2019; reviewed by Van Dover 2019), with these different biological communities anticipated to display different sensitivities to mining activities (Boschen-Rose et al. 2021).

The potential impacts of SMS mining have been extensively discussed and reviewed (e.g. Van Dover 2011, 2014; Boschen et al. 2013; Gollner et al. 2017; Miller et al. 2018); however, until test mining or commercial exploitation occurs for SMS deposits, the spatial and temporal extents of disturbance and the ability of seafloor communities to recover from mining activities remains to be seen. This uncertainty in turn affects how seabed mining could be managed.

1.2 Environmental Management Frameworks for Deep-Sea Mining

Environmental management frameworks that could be applied to manage deep-sea mining activities would ideally include management strategies to conserve the special biological communities and habitats of SMS deposits, whilst enabling economically viable extraction of their mineral resources (ISA 2011a; Van Dover et al. 2012). Such resource management requires a robust legislative framework,

[1] https://www.isa.org.jm/index.php/exploration-contracts/polymetallic-sulphides

clear management objectives, comprehensive information on the SMS deposits themselve and, their wider environment, and the biological communities they support. These objectives will drive the subsequent science and management measures necessary to avoid harmful effects on (UNCLOS art. 145) or serious harm to (UNCLOS art. 162, 165; Levin et al. 2016) the marine environment.

The management of SMS mining is controlled by different regulatory regimes according to the jurisdiction under which the proposed mining project falls. Within an Exclusive Economic Zone (EEZ) or legal continental shelf of a country, all mining regulation and management falls under national jurisdiction. All seabed that does not fall within the EEZ or legal continental shelf of a country is termed 'the Area' (UNCLOS art. 1) and is managed by the ISA as determined by the 1982 United Nations Convention on the Law of the Sea (UNCLOS) and the 1994 Agreement relating to the Implementation of Part XI of the United Nations Convention on the Law of the Sea (1994 Agreement). All States party to UNCLOS and the 1994 Agreement must apply to the ISA for contracts to prospect, explore and exploit mineral resources in the Area. The ISA has issued regulations governing prospecting and exploration for SMS deposits, which were adopted in May 2010 (ISA 2010). These existing ISA environmental management measures include the requirements for contractors to establish environmental baselines against which changes from mining activities can be evaluated. Under developing regulations to govern exploitation (ISA 2019a), mining companies will need to conduct environmental impact assessments to determine the nature and extent of harmful effects, to develop and carry out environmental management and monitoring programmes, and to take measures to prevent, reduce and control pollution and other hazards to the marine environment.

Before developing strategies to mitigate the effects of anthropogenic disturbance, environmental managers must decide which aspects of biodiversity they are aiming to conserve as part of their management objectives. In the broadest sense, biodiversity is 'the variability among living organisms from all sources including, *inter alia*, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems' (Glowka et al. 1994). In the case of SMS mining, this means developing strategies that conserve all components of the community, from bacteria to megafaunal taxa, and not just at a species level, but to include genetic diversity within and amongst populations. This approach is consistent with both the precautionary principle and the ecosystem approach required by the ISA, as well as national legislation (e.g. New Zealand, Canada, Cook Islands). However, documenting this level of biodiversity and designing appropriate conservation measures for the full biodiversity spectrum is challenging, especially when there are so many ecological unknowns regarding SMS deposits and the habitats they may provide.

Conservation measures typically strive for efficiency, with the aim of protecting the largest number of conservation targets in the fewest sites or at the lowest cost (Possingham and Wilson 2005). The main management strategy currently proposed for deep-sea mining is the designation of protected areas (also known as 'set-aside' sites, 'reference' sites or 'preservation reference zones') to preserve all aspects of biodiversity that could otherwise be lost from the region through mining. These areas should have similar physical and biological characteristics to the mine site and should be located so as not to be impacted by mining activities (Coffey Natural Systems 2008; Collins et al. 2013).

Protected areas also need to be connected to be effective. Connectivity between SMS sites for seafloor organisms is typically maintained by larval dispersal (Hilário et al. 2015; Boschen et al. 2016a; Mullineaux et al. 2018). Maintaining connectivity amongst sites is necessary to facilitate genetic exchange and for the maintenance of healthy populations (ISA 2011a; Van Dover et al. 2012; Boschen et al. 2016a). However, using connectivity data to design a network of protected areas requires detailed information on larval dispersal and development, local current regimes, and the genetic structure of populations, much of which remains unknown in the deep sea (Hilário et al. 2015). It is often the case that networks of marine protected areas are implemented without knowledge of connectivity, and where networks of protected areas have been designated, the connectivity of these networks has not been assessed (Gaston et al. 2008; Joppa and Pfaff 2009).

The ISA is currently pursuing a strategy of no-mining areas whereby regionally representative 'coarse-filter' areas can be complemented by smaller 'fine-filter' areas in a two-tier spatial-scale management planning scheme (ISA 2019b). Such options have been explored for application to SMS deposits on the Mid-Atlantic Ridge (Dunn et al. 2018; ISA 2019c). Networks of Chemosynthetic Ecosystem Reserves have also been proposed to protect the diversity, structure, function and resilience of ecosystems in hydrothermally active areas (such as those occurring at SMS sites) alongside managing the use of the ecosystem's mineral resources (ISA 2011a; Van Dover et al. 2012). An example of this type of protected area network within an EEZ is the 'Endeavour Hydrothermal Vents Marine Protected Area', off the west coast of Canada, which contains five vent fields split between four management areas catering for observational (non-destructive) research, education and outreach and more intrusive research (such as biological sampling), demonstrating that it is possible to integrate multiple seabed uses and graded levels of protection into hydrothermal vent management (Fisheries and Oceans Canada 2009).

1.3 Mineral Deposits and Licensing on the Kermadec Volcanic Arc

In the EEZ of New Zealand, the potential for the existence of deep-sea hydrothermal deposits was first assessed more than 30 years ago (Glasby and Wright 1990). SMS deposits rich in silver and gold occur along the Kermadec Volcanic Arc (de Ronde et al. 2011) and on back-arc seamounts that lie between the Kermadec and Colville Ridges (see Fig. 14.1). These deposits occur at exploitable depths (Wright 1994; Wright et al. 1998; Wright and Gamble 1999), with prospecting licences to investigate these resources issued to Neptune Minerals Inc. in 2002[2] (Fig. 14.2).

[2] https://permits.nzpam.govt.nz/aca/

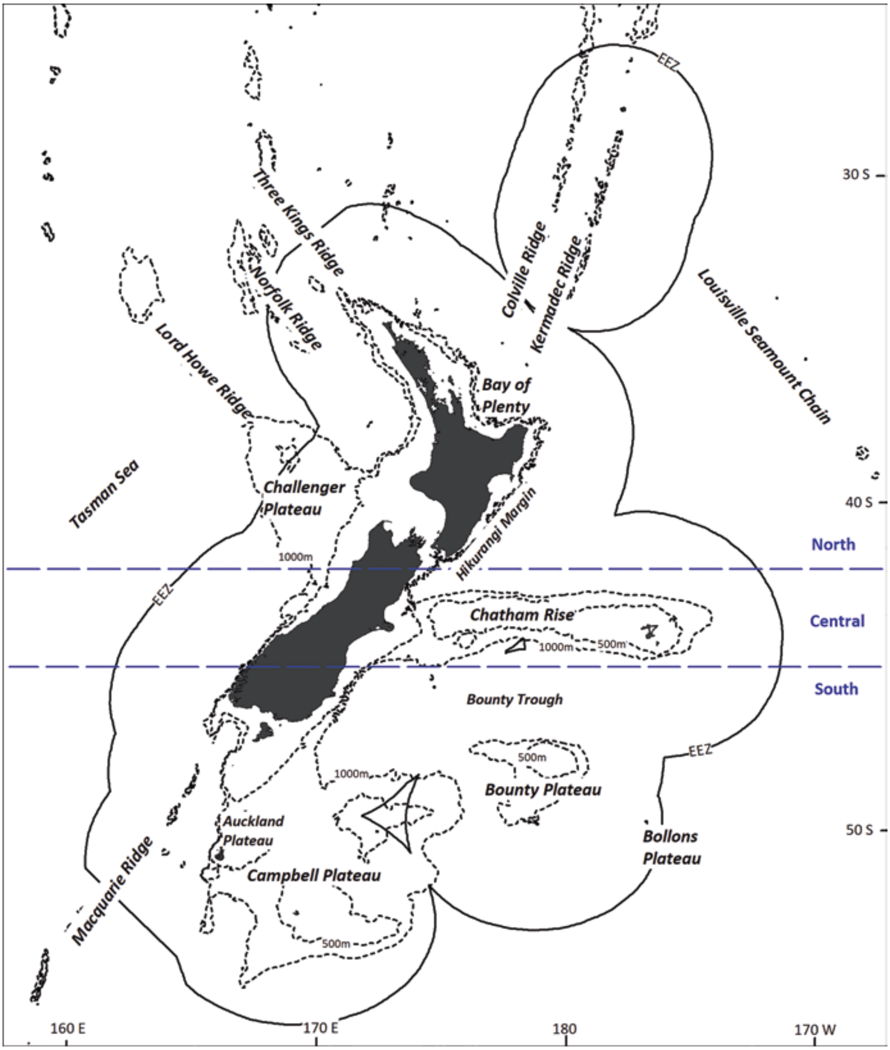

Fig. 14.1 The New Zealand region, showing the location of features mentioned in the text, as well as the regional boundaries at 42°S and 45°S that denote separation of north, central and south areas (see Sect. 3)

SMS deposits along the Kermadec Volcanic Arc that have been explored for their mining potential include those existing at shallow depths of 150–200 m in the Bay of Plenty (Stoffers et al. 1999), 870–930 m at Clark Seamount (Malahoff 2008) and as deep as 1150–1800 m at Brothers Seamount (Wright et al. 1998). Deposits at Brothers Seamount are rich in base (Wright et al. 1998) and precious (de Ronde et al. 2011) metals with high concentrations of copper, zinc, iron and gold (up to 15.3% weight, 18.8% weight, 19.1% weight and 9.1% weight respectively). In total,

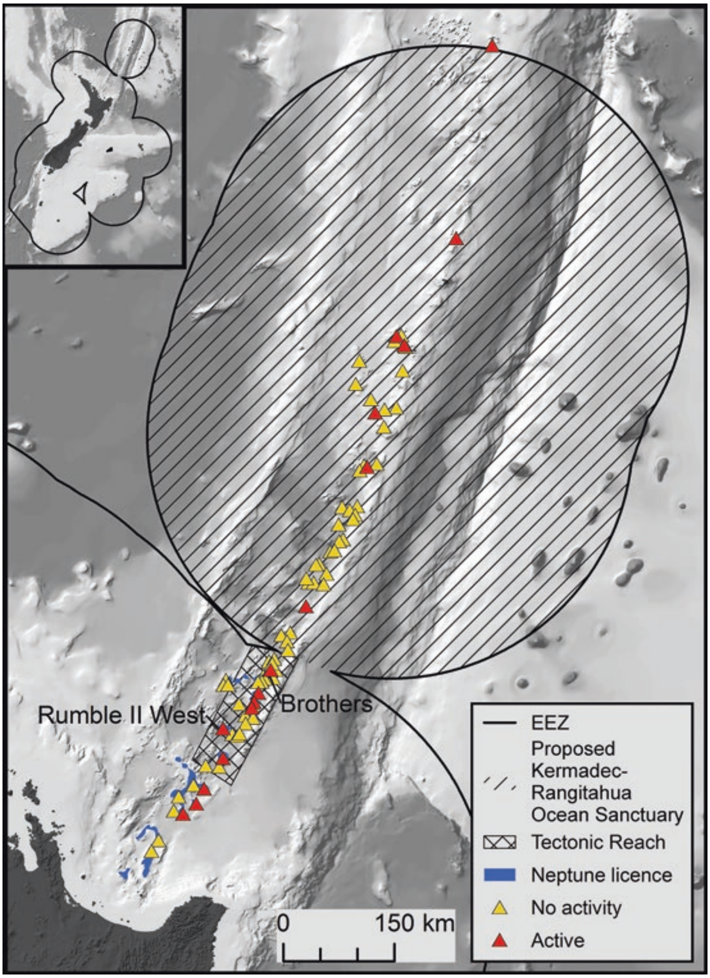

Fig. 14.2 The location of marine boundaries, protected areas, SMS prospecting licenses and seamounts along the Kermadec Volcanic Arc, relative to New Zealand. Main figure: The New Zealand Exclusive Economic Zone (EEZ: black line); the Kermadec Benthic Protection Area (BPA) and the proposed Kermadec-Rangitahua Ocean Sanctuary (black diagonal lines); Tectonic Reach BPA (black hash); Neptune Minerals Inc. prospecting licence areas (blue); and seamounts coded by hydrothermal activity—no hydrothermal activity detected (yellow triangles) and active (red triangles). Inset: New Zealand mainland and EEZ (black line). Modified from Boschen-Rose et al. (2021)

of the 78 seamounts on the Kermadec Volcanic Arc within the New Zealand EEZ, at least 16 are known to be hydrothermally active (Rowden et al. 2005, 2008; de Ronde et al. 2007; NIWA unpublished data) (Fig. 14.2), thus possessing the potential for SMS deposit formation.

The initial prospecting licences issued to Neptune Minerals Inc. have expired and these locations are currently part of a Mineral Reservation Area with no exploration permitted until at least 2024[3]. The Kermadec region also includes Benthic Protection Areas (BPAs) where bottom trawling is banned, and the proposed Kermadec-Rangitahua Ocean Sanctuary (Ministry for the Environment 2021) being considered by the New Zealand Government. Although deep-sea mining for SMS along the Kermadec Volcanic Arc may be unlikely to occur in the near future, the existence of commercially viable SMS deposits at exploitable depths means the region remains a potential target for mining.

1.4 Kermadec Volcanic Arc Baseline Studies and Environmental Management

At the time of prior interest in exploiting Kermadec SMS deposits, multiple studies were conducted to determine the potential ecological risk from SMS mining and to establish robust environmental baselines prior to any mining activities. Comprehensive environmental baseline studies are needed before any mining operation begins to measure the subsequent impacts of mining at a site. Such studies need to assess the marine environment at, and in the vicinity of, the proposed mine site, potential sites for observing mining impacts as part of a monitoring programme, and locations acting as protected areas to mitigate mining impacts.

Despite hydrothermal communities first being recorded from the Kermadec Volcanic Arc in 1998 (Wright et al. 1998), prior to prospecting licences being issued to Neptune Minerals Inc. there was little published on the distribution and structure of these communities (but see Clark and O'Shea 2001; Rowden et al. 2003) and no published research on the communities inhabiting the hydrothermally inactive and non-hydrothermal hard substrata in close proximity to active vents.

The environmental baseline studies discussed in this chapter were designed to provide some of the information needed to support environmental management for SMS mining. Section 2 provides an overview of two studies designed to investigate the influence of hydrothermal activity on assemblage structure at sites licenced for the prospecting phase of SMS mining, accommodating the complex spatial heterogeneity at seamount-hosted SMS deposits. Section 3 provides an overview of population genetics studies that have included species found on the Kermadec Volcanic Arc, thereby providing insight into the connectivity patterns amongst areas licenced for prospecting along the Arc. Section 4 discusses the findings of a study to develop a functional traits assessment framework to determine the relative sensitivity of seafloor organisms, assemblages, and locations to different SMS mining disturbances.

[3] https://gazette.govt.nz/notice/id/2021-go2612

The findings from all these studies are integrated in Sect 5, where they are discussed in the context of systematic conservation planning on the Kermadec Volcanic Arc, and perspectives are shared on how these findings may be applied to environmental management of deep-sea mining on seamounts or tectonic boundaries in other ocean regions.

2 Kermadec Volcanic Arc Seafloor Community Structure

2.1 Assessing Seafloor Community Structure at Multiple Spatial Scales

SMS sites can contain a mixture of seafloor communities distributed across hydrothermally active, hydrothermally inactive and non-hydrothermal seafloor habitats. Hydrothermally active areas are colonised by a chemosynthetic assemblage of hydrothermal vent specialists (reviewed by Van Dover 2000, 2014), typified by high biomass and low species diversity (Grassle 1985) and rapid growth rates (Lutz et al. 1994). Where hydrothermal activity has ceased, inactive (relict) deposits can be colonised by 'background' fauna typical of hard substrata on seamounts, such as sponges, hydroids, corals, anemones, squat lobsters, ophiuroids and holothurians (Galkin 1997; Collins et al. 2012; Gerdes et al. 2019), although not all inactive areas support such diverse assemblages (reviewed by Van Dover 2019). Over a scale of 10 s to 100 s of meters, chemosynthetic and background faunal assemblages can exhibit zonation based on proximity to hydrothermal flow, with chemosynthetic assemblages in close proximity to hydrothermal flow, and background assemblages at the vent periphery (Arquit 1990; Sudarikov and Galkin 1995). It has also been hypothesised that a third assemblage may exist at SMS deposit sites, one specific to the unique chemical environment of weathering inactive SMS deposits (Van Dover 2007, 2011, 2019).

SMS seafloor communities are potentially vulnerable to mining disturbance, with mining activities expected to remove all large organisms and their habitat in the immediate area to be mined, along with downstream effects from turbidity plumes caused by the mining activity (Van Dover 2011, 2014). Before suitable mitigation strategies for seabed mining can be designed, there needs to be a thorough understanding of the seafloor communities that could be affected in the area where mining is proposed.

To provide initial environmental baselines for prospective SMS mining, two surveys were undertaken on seamounts on the southern Kermadec Volcanic Arc to assess the structure of benthic communities potentially at risk from mining activities (Fig. 14.3). Video footage and environmental data were obtained to investigate the patterns of benthic megafauna distribution, community structure and association with environmental variables, both within and amongst three seamounts (Fig. 14.4; Boschen et al. 2015a, 2016b). Each seamount has different levels of hydrothermal activity: Rumble II East has no history of hydrothermal activity, Brothers is hydrothermally active, and Rumble II West is predominantly inactive. The degree of

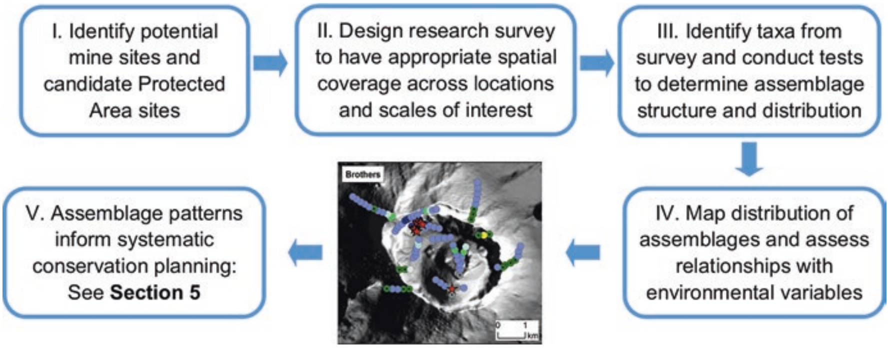

Fig. 14.3 Flowchart summarising general methodology for assessing seafloor assemblage structure as a prerequisite for systematic conservation planning of deep-sea mining activities. The research survey could consist of video transects, still imagery, biological sample collection or a combination of survey methods

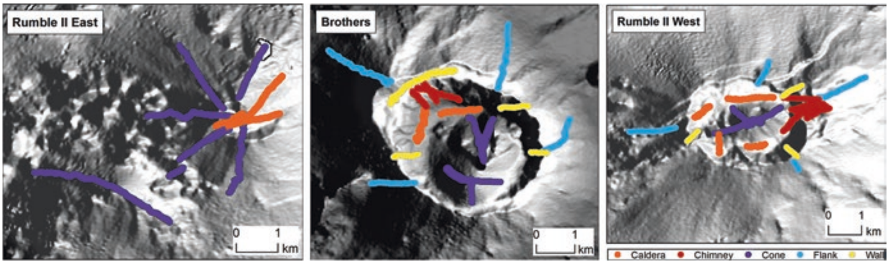

Fig. 14.4 Transect lines for the seamount survey conducted at Rumble II East (left), Brothers (centre), and Rumble II West (right) seamounts. Transects were distributed amongst a priori habitat types including caldera (orange), chimney (red), cone (purple), flank (blue), and wall (yellow). Modified from Boschen et al. (2015a)

hydrothermal activity at each seamount was hypothesised to have a structuring effect on the benthic assemblages present across the three seamounts.

In the first study, towed video transects were distributed randomly amongst broad-scale habitat strata (caldera floor, caldera wall, seamount cone, seamount flank and chimney fields) defined a priori based on general topography from a previous multibeam survey (Fig. 14.4; Boschen et al. 2015a). Megafaunal organisms and substratum type were identified from the video, which was split into 200 m sections for analysis. Seafloor magnetivity data across the three seamounts, as a proxy indicator of hydrothermal activity (Caratori Tontini et al. 2012), were also collected. In the second study, patterns of benthic megafauna distribution and community structure were examined using video data from an industry survey with a Remotely Operated Vehicle (ROV). Two sites were surveyed, a proposed mine site (Proteus 1) and a proposed Reference Site, close together on the northeast flank of Rumble II West (Boschen et al. 2016b). During the site-scale survey, previously unknown areas of hydrothermal activity on Rumble II West were identified at Proteus 1; the

Reference Site was not hydrothermally active but had similar depth and topography to the proposed mine site. Megafaunal organisms and substratum type were identified from the video, which was split into 15 m segments for analysis. For both studies, additional environmental parameters (depth, backscatter, rugosity, aspect, slope and three measures of curvature) were extracted from multibeam echosounder data. The relationship between the faunal distribution data and environmental variables was assessed using multivariate statistical routines.

2.2 Seafloor Community Results and Interpretation

The seafloor community structure assessments discussed in this section determined three key sets of information:

1. The structure of seabed assemblages varies within and amongst seamounts and sites. Mapping the spatial distribution of seabed assemblages enables the identification of seabed locations colonised by unique assemblages, as well as more common assemblages. This information could inform decisions on the location of suitable protected areas aiming to conserve rare or endemic assemblages and representative habitats.
2. There are significant relationships between assemblage structure and environmental variables, which provides an important step towards future habitat modelling to predict the location of similar assemblages in un-surveyed locations.
3. Preliminary evidence supports the existence of unique assemblages in association with hydrothermally inactive habitat.

The complex spatial distribution of habitats and assemblages within and amongst Kermadec Volcanic Arc seamounts poses a substantial challenge for developing an effective network of protected areas in the region. In the three-seamount study, 20 assemblage types were characterised (Boschen et al. 2015a). Of these assemblages, only six were shared amongst seamounts and could be included within protected areas designed to conserve representative habitats across seamounts (Fig. 14.5). The other 14 assemblages were unique to one of the three seamounts and could be included within protected areas with the aim of conserving rare or endemic assemblages.

In the smaller-scale two-site study located on Rumble II West seamount, 11 assemblage types were identified (Boschen et al. 2016b). Despite being only 200 m distant, the two sites had significantly different assemblage structures, with only a subset of the total assemblages being present at the proposed Reference Site (Fig. 14.5). Only five assemblages occurred at both sites, with six assemblages being unique to the proposed mine site. These results suggested that, on its own, the proposed Reference Site would not be representative of Proteus 1 and therefore insufficient as a protected area.

The relationship between assemblage structure and environmental variables sheds some light on the environmental drivers of assemblage structure in this region. For the three-seamount study, magnetivity (a proxy for hydrothermal activity)

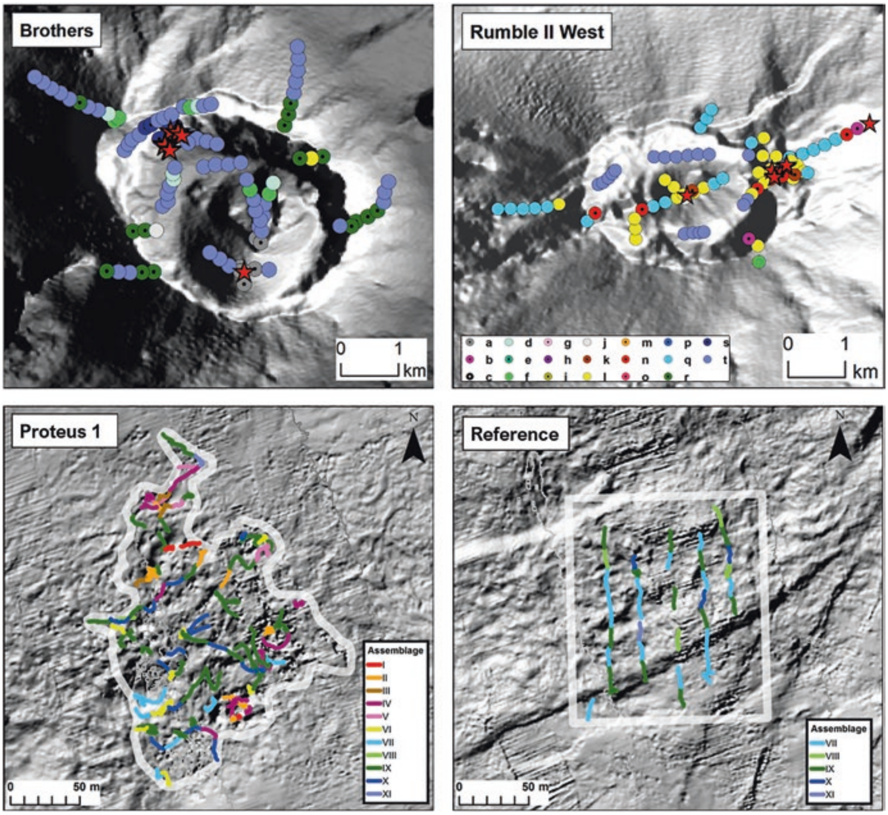

Fig. 14.5 Assemblage distribution at two seamounts (top left: Brothers; top right: Rumble II West) and two sites within Rumble II West (bottom left: proposed mine site Proteus 1; bottom right: proposed Reference Site). Different coloured dots (top) and lines (bottom) indicate different assemblage types. Red stars in the top two images indicate the location of hydrothermal vent chimney structures (hydrothermally active at Brothers; hydrothermally inactive at Rumble II West). Top images modified from Boschen et al. (2015a); bottom images modified from Boschen et al. (2016b)

explained most of the variation in assemblage structure amongst seamounts, with depth, topography, substratum (and magnetivity for Brothers) explaining most of the variation in assemblage structure within seamounts. The most important environmental descriptors in the analysis for the two-site study were also those related to hydrothermal activity (active and inactive chimneys; dead vent mussel shells; altered sediment and oxide deposits). Thus, in a move towards habitat suitability modelling over larger unsampled areas, evidence of hydrothermal activity (current or previous) seems to be the best predictor for the distribution of different seafloor assemblages across sites and seamounts.

Notably, the spatial location of five of the six unique assemblages at Brothers and Rumble II West seamounts coincided with records of hydrothermal vent chimney structures; chimneys were generally hydrothermally active on Brothers and inactive on Rumble II West (Boschen et al. 2015a). The assemblages that were unique to the proposed mine site Proteus 1 also occurred in locations associated with hydrothermal activity, including inactive chimney structures, providing further evidence for the existence of specialised assemblages in association with hydrothermally inactive sulphide habitat. Although assemblages colonising hydrothermally inactive sulphide habitat may be comprised of individual taxa that are widely distributed, such as the urchin *Dermechinus horridus*, it is the way these taxa are grouped in assemblages that appears to be unique (see Fig. 14.6 for examples of Kermadec Volcanic Arc taxa and assemblages).

Taken together, the three-seamount and two-site studies provide support for including both hydrothermally active and inactive habitat within protected areas. Ultimately, the high variability in seamount assemblages described by Boschen et al. (2015a, 2016b) implies that protecting one seamount to enable mining at an adjacent seamount may not be a suitable strategy. Instead, to conserve the suite of assemblages present, it may be necessary to protect multiple seamounts or a network of sites.

2.3 Perspectives on Seafloor Community Structure

The seafloor community assessments presented by Boschen et al. (2015a, 2016b) offer detailed insights into assemblage structure at a range of spatial scales, and the relationships between assemblage structure and environmental variables. These types of surveys help to establish biological baselines to inform environmental management decisions for deep-sea mining at seamounts. For similar surveys to be conducted in other locations or for other mineral resources, several key points will need to be considered:

1. The underlying survey design will determine the spatial resolution possible for assemblage characterisation, which has consequences for the resolution of information available to support decisions on spatial management.
2. A suite of sampling methods would be needed to fully characterise the communities colonising mineral resources, in particular to address the size spectra of organisms.
3. A wide range of environmental variable measurements need to be taken across multiple spatial scales to act as a basis for predictive habitat suitability modelling.

The studies discussed in this section demonstrate strong differences in assemblage structure at a range of spatial scales, with considerable variability in habitat and biodiversity within and amongst seamounts. These results illustrate the importance of surveys conducted at multiple spatial scales. The appropriate spatial scale of seafloor survey will ultimately depend on the spatial scale of environmental management considered. Combining information from site-scale and large-scale regional studies enables more robust recommendations to be made that not only inform site-level decisions made by SMS mining companies and environmental regulators, but also support the establishment of regional environmental management plans for SMS mining.

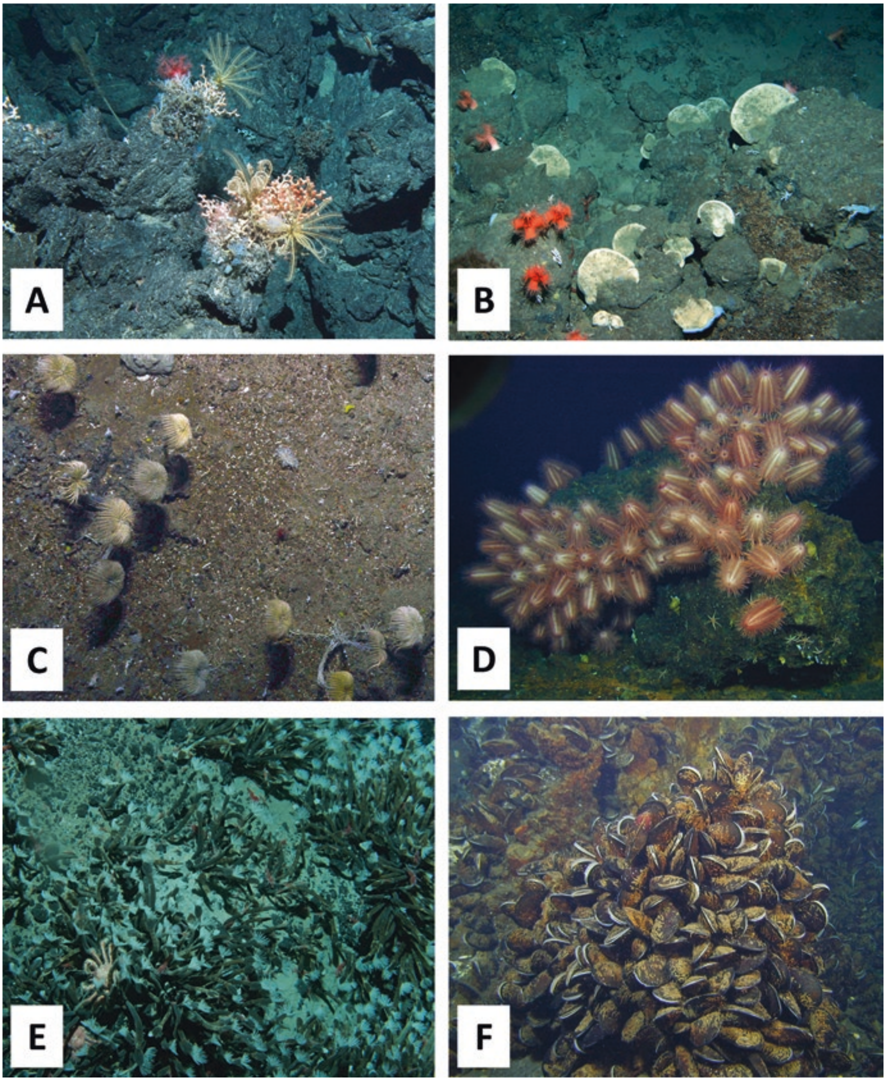

Fig. 14.6 Images of seafloor taxa and assemblages from the Kermadec Volcanic Arc. (**a**) mixed corals and comatulid crinoid assemblage; (**b**) anemones and sponges; (**c**) stalked crinoids; (**d**) aggregation of sea urchin, *Dermechinus horridus*; (**e**) vent stalked barnacles, *Vulcanolepas osheai*; and (**f**) vent mussels, *Bathymodiolus manusensis.* Image credits: (**a**, **b**, **c** and **e**) NIWA; (**d** and **f**) NOAA-NIWA-GNS

The three-seamount survey analysed a total of 49.8 km of seabed transects over an approximate total area of 120 km^2 (40 km^2 for each seamount), with seamounts separated by 13 km (between Rumble II West and Rumble II East) or 100 km (distance from Brothers to Rumble II West and Rumble II East). The mine and

Reference Site comparison analysed 2.3 km of transect across the two sites, with each site having an approximate area of 0.02 km^2, and sites being separated by 0.2 km. However, whilst the survey tracks in the three-seamount study were distributed in a similar manner across the three seamounts, the survey pattern for the two-site comparison was quite different between Proteus 1 and the Reference Site, as these sites were part of Industry surveys with differing objectives. As a result, whilst the survey tracks at the Reference Site were distributed as linear, equally spaced transects, those at Proteus 1 were meandering and overlapping, concentrated around the areas of hydrothermal activity of interest for mineral formation. Such a haphazard survey design increases the risk of introducing bias, potentially undermining the results of mine site and reference area comparisons. For robust recommendations to be made on protected area suitability, there needs to be a dedicated survey of multiple mine and reference sites that uses the same methods across all sites.

Both the three-seamount and two-site studies were constrained by an absence of replication. Without replication, it is difficult to know if survey results are representative or the result of a rare event that depends on space and time. Replication, in terms of multiple survey sites and re-visiting the same sites on multiple occasions, is essential to address the natural spatial and temporal environmental variability at SMS sites. To conduct robust monitoring programmes to assess mining impacts, and to ensure protected areas collectively encompass all the biodiversity that could be lost from the mine site, future survey designs should encompass multiple unimpacted (control or set aside) and impacted (mined) sites (Collins et al. 2013), sensu Beyond Before-After-Control-Impact (BACI: Green 1979; Underwood 1992, 1994), re-visited on multiple occasions to assess temporal variability. The issue of replication also applies at the regional scale: Rumble II East, Brothers and Rumble II West are just three of the 78 seamounts that occur along the Kermadec Volcanic Arc, many of which fall within areas previously licenced for the prospecting phase of SMS mining. Adequate baseline data on other seamounts and sites along the Kermadec Volcanic Arc would ideally utilise the survey techniques employed by Boschen et al. (2015a, 2016b).

One of the biggest limitations of the studies conducted by Boschen et al. (2015a, 2016b) is that they were only able to assess the structure of benthic megafaunal assemblages observed from video data and not able to consider any of the other size fractions of fauna. The term ‘community’ in an ecological sense refers to ‘the individuals of all species that potentially interact within a single patch or local area of a habitat’ (Holyoak et al. 2005); thus, to fully assess benthic community structure at SMS deposits, there needs to be additional surveys focussed on biological sampling (such as sleds, grabs, cores or suction) to collect and assess the macrofaunal, meiofaunal and microbial assemblage structure. Only by combining information across the size fractions of the benthic biota would it be possible to establish a true community perspective on SMS deposit ecology.

Overall, environmental proxies were able to explain 26–47% of the variation in assemblage structure within and amongst seamounts (Boschen et al. 2015a, 2016b). Whilst this is an important first step towards predictive habitat suitability modelling, this still leaves a large fraction of variation in assemblage structure unexplained by environmental characteristics for which there were no available data. For predictive modelling to be effective, there needs to be further work that includes additional environmental variables across a greater range of spatial scales to determine the best combination of environmental variables at the appropriate spatial scale to act as a basis for predictive habitat suitability modelling. Such modelling work has subsequently been conducted for the Kermadec Volcanic Arc area using biological data compiled from various surveys that have taken place across the region over the last few decades (Rowden et al. unpublished). However, whilst predictive habitat modelling approaches could help to identify candidate sites for protected areas, the suitability of these sites would need to be subsequently determined by ground-truthing model results.

3 Connectivity of Kermadec Volcanic Arc Seafloor Populations

3.1 Assessing Connectivity of Seafloor Populations

Populations are maintained by a balance between births and immigration that add individuals and by deaths and emigration which remove individuals from the population. Not all populations contribute equally to the number of larvae that recruit to any given site and knowing where new recruits come from (source populations) is critically important to our understanding of population maintenance and long-term viability. However, there are still many challenges for identifying source populations in the deep sea (Ramirez-Llodra et al. 2010, 2011; Hilário et al. 2015).

Traditional views of marine population connectivity assumed all adults at any given site were immigrants (e.g. Tracey et al. 1975), but this view has recently been challenged by increasing evidence for moderately high levels (e.g. 20–60%) of self-recruitment across a range of different marine species. Self-recruitment occurs when larvae born at one site recruit back to that same site to settle as adults, rather than dispersing to another site (Kingsford et al. 2002; Sponaugle et al. 2002; Almany et al. 2007; Silva et al. 2019). From a management perspective, understanding the balance between self-recruitment and immigration/emigration at any site is critically important for the management and protection of populations from anthropogenic activities.

One of the biggest problems facing deep-sea researchers is access to specimens, both in terms of spatial coverage and ‘freshness’, meaning how old the specimens are and how they have been stored (e.g. Boschen et al. 2015b; Zeng et al. 2017, 2019; Holland et al. 2020; Yan et al. 2020). Ideally, studies are based on the assessment of genetic variation within newly collected samples. However, given the cost of sample collection from the deep sea, many studies are reliant on previously collected archived material. The limitations in the use of archived material have been discussed for museum specimens more generally (Wandeler et al. 2007), and specifically for deep-sea specimens (Miller et al. 2010; Boschen et al. 2015b; Zeng et al. 2017, 2019; Holland et al. 2020; Yan et al. 2020). Despite the challenges of working with archived material, such material may be all that is available from a given location and can also represent an important historical record.

Multiple studies have been conducted to describe spatially explicit species-specific genetic diversity and population connectivity of taxa that have included those colonising the seafloor of the Kermadec Volcanic Arc and the wider Kermadec Ridge region. The spatial extent of these studies has been regional (Miller et al. 2010; Boschen et al. 2015b), restricted to the New Zealand EEZ (Zeng et al. 2017), has extended beyond national jurisdiction (Holland et al. 2020) or has involved the acquisition of samples from another country's EEZ (Miller et al. 2010, 2011; Yan et al. 2020). Using an array of genetic markers, collectively these studies have identified or made estimates of: the location(s) and spatial extent(s) of genetic differentiation; genetic diversity hotspots; the locations of source and sink populations; effective population sizes; genetic bottleneck (contraction) and population expansion events; the locations of putative barriers to gene flow and described the form or type of barrier; and factor(s) promoting gene flow between regions.

Table 14.1 summarises the data for samples collected across 16 taxa from four phyla as they relate to the Kermadec Volcanic Arc and the wider Kermadec Ridge region, and how Kermadec populations are connected to those elsewhere. Not all species or taxa that were included in each study are included in this table, instead the focus is on those taxa for which there are collections from the Kermadec Volcanic Arc and Ridge region. The general workflow for conducting these connectivity assessments is summarised in Fig. 14.7. Typically, these connectivity studies have taken a standard hierarchical approach to testing for the existence of spatial genetic

Table 14.1 Summary table of studies in which genetic connectivity has been assessed for taxa in the Kermadec Ridge area (which here includes the Kermadec Volcanic Arc). Refer to Fig. 14.1 for the main sampling locations, and Fig. 14.8 for images of some of these taxa

Phylum	Genus and species	Seamounts/locations sampled	Genetic marker(s) used	Source
Mollusca	*Bathymodiolus* new species NZ-1 (now *Bathymodiolus manusensis*)	Kermadec Ridge sites only: Rumble III Seamount; Rumble V Seamount	Allozymes (11 loci)	Smith et al. (2004)
	Gigantidas gladius	Kermadec Ridge sites only: Macauley volcano; Rumble V Seamount; Tangaroa Seamount; Clark Seamount; Calypso Vents (Bay of Plenty)	*COI* sequencing	Boschen et al. (2015b)

(continued)

Table 14.1 (continued)

Phylum	Genus and species	Seamounts/locations sampled	Genetic marker(s) used	Source
Cnidaria	*Solenosmilia variabilis*	Kermadec Ridge; Chatham Rise; Macquarie Ridge; sites in Australia	*16S*, *ITS* and *D-loop* sequencing	Miller et al. (2010)
	Stichopathes filiformis	Kermadec Ridge sites only: Otara Knoll; Rangatira Knoll; Tumokemoke Knoll; Mahina Knoll; Tuatoru Knoll; White Island (all Bay of Plenty)	*16S*, *ITS* and *D-loop* sequencing	Miller et al. (2010)
	Stichopathes variabilis	Kermadec Ridge; NW continental shelf; Norfolk Ridge; sites in Australia	*16S*, *ITS* and *D-loop* sequencing	Miller et al. (2010)
	Desmophyllum dianthus	Kermadec Ridge; Chatham Rise; Campbell Plateau; Macquarie Ridge; sites in Australia; sites in Chile	*16S*, *ITS* and *D-loop* sequencing	Miller et al. (2011)
	Goniocorella dumosa	Kermadec Ridge; Auckland Plateau; Campbell Plateau; Challenger Plateau; Chatham Rise; Hikurangi Margin; Macquarie Ridge	Microsatellites (27 loci)	Zeng et al. (2017)
	Madrepora oculata	Kermadec Ridge; Campbell Plateau; Challenger Plateau; Chatham Rise	Microsatellites (11 loci)	Zeng et al. (2017)
	Solenosmilia variabilis	Kermadec Ridge; Bollons Plateau; Bounty Plateau; Bounty Trough; Campbell Plateau; Chatham Rise; Hikurangi Margin; Louisville Seamount Chain; Macquarie Ridge; Tasman Sea	Microsatellites (27 loci)	Zeng et al. (2017)
	Desmophyllum dianthus	Kermadec Ridge; Campbell Plateau; Chatham Rise; Louisville Seamount Chain; Macquarie Ridge	*ITS* sequencing and microsatellites (9 loci)	Holland et al. (2020)
	Enallopsammia rostrata	Kermadec Ridge; Campbell Plateau; Challenger Plateau; Chatham Rise; Norfolk Ridge	*ITS* sequencing	Holland et al. (2020)

(continued)

Table 14.1 (continued)

Phylum	Genus and species	Seamounts/locations sampled	Genetic marker(s) used	Source
Porifera	*Neoaulaxinia persicum*	Kermadec Ridge; Three Kings Ridge; NE continental slope; Hikurangi Margin; Chatham Rise; Challenger Plateau	*COI* and *12S* sequencing	Zeng et al. (2019)
	Penares sp. (now *Penares turmericolor*)	Kermadec Ridge; Hikurangi Margin; Challenger Plateau; Chatham Rise; Macquarie Ridge	*COI* sequencing	Zeng et al. (2019)
	Pleroma menoui	Kermadec Ridge; Norfolk Ridge; NE continental slope; NW continental slope	*COI* sequencing	Zeng et al. (2019)
	Poecillastra laminaris	Kermadec Ridge; NE continental slope; NW continental slope; Challenger Plateau; Hikurangi Margin; Chatham Rise; Campbell Plateau; Macquarie Ridge	*COI* and *CytB* sequencing and microsatellites (10 loci)	Zeng et al. (2019)
Arthropoda	*Munida endeavourae*	Kermadec Ridge; Louisville Seamount Chain; Tasmanian slope	*COI* sequencing and microsatellites (11 loci)	Yan et al. (2020)
	Munida gracilis	Kermadec Ridge; Chatham Rise; Challenger Plateau	*COI* sequencing and microsatellites (9 loci)	Yan et al. (2020)
	Munida isos	Kermadec Ridge; Louisville Seamount Chain; Hikurangi Margin; Chatham Rise; Macquarie Ridge; Tasmanian slope	*COI* sequencing and microsatellites (17 loci)	Yan et al. (2020)

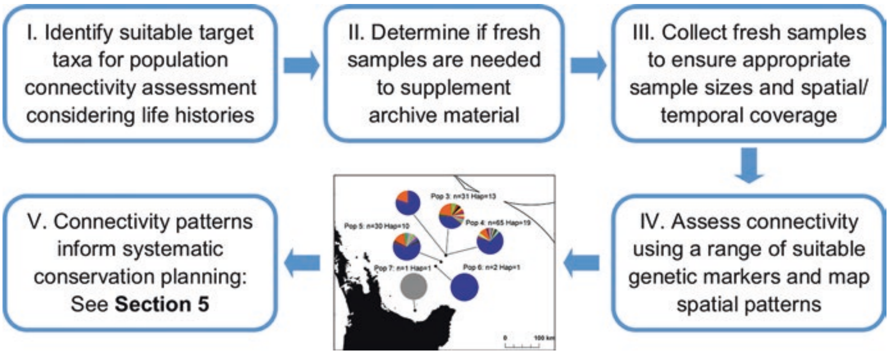

Fig. 14.7 Flow chart summarising general methodology for assessing seafloor population connectivity as a prerequisite for systematic conservation planning of deep-sea mining activities

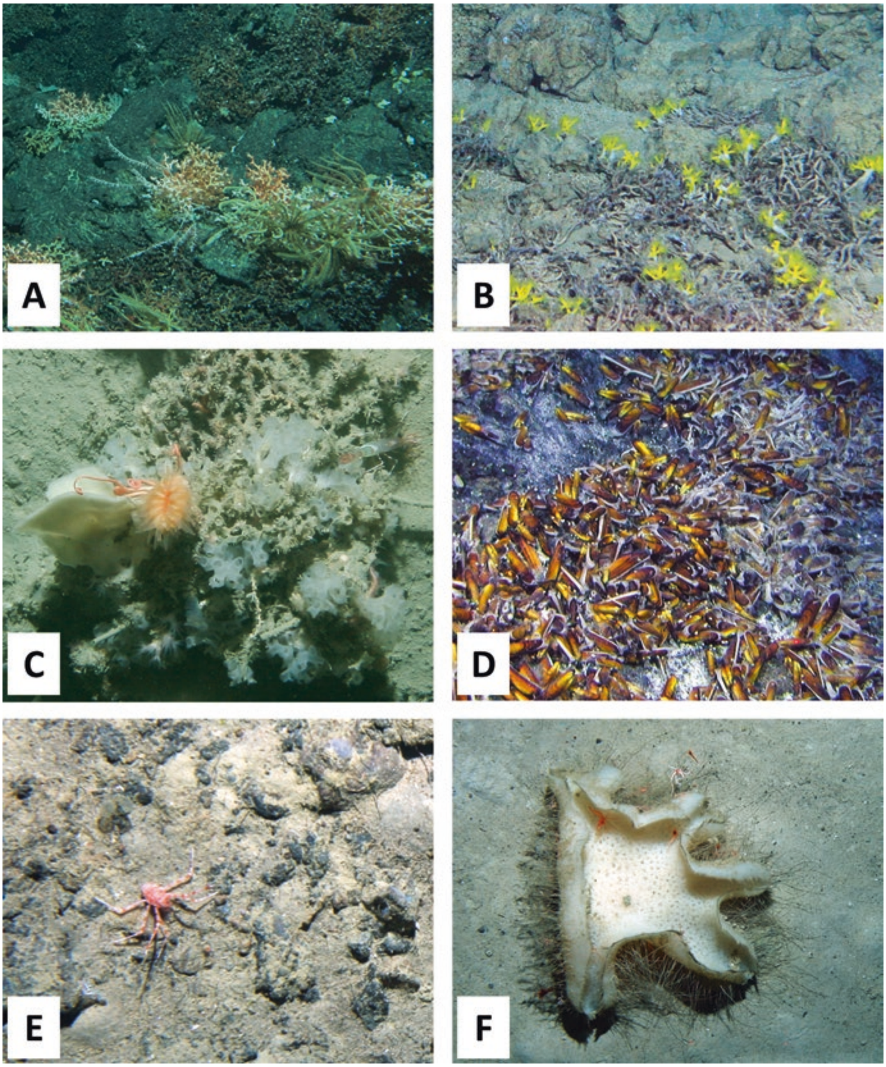

Fig. 14.8 Images of seafloor taxa used in population connectivity analyses for the Kermadec Volcanic Arc. (**a**) branching stony coral *Solenosmilia variabilis*; (**b**) branching stony coral *Enallopsammia rostrata*; (**c**) cup coral *Dendrophyllum dianthus*; (**d**) vent mussel *Gigantidas gladius*; (**e**) squat lobster of the family Galatheidoidea; and (**f**) sponge *Poecillastra laminaris.* Image credit: NIWA

variation, including comparing amongst regions (i.e. the north, central and south regions on Fig. 14.1) and comparing amongst major geomorphic features such as the Kermadec Volcanic Arc and Ridge.

3.2 Seafloor Population Connectivity Results and Interpretation

The seafloor population connectivity assessments (studies summarised in Table 14.1) identified three key sets of information:

1. The population genetic connectivity patterns of multiple species are species-specific and genetic marker dependent. This information can be used to determine the potential connectivity of different locations for different species.
2. The role that any one region (such as the Kermadec Ridge) plays in terms of source-sink dynamics may be variable, depending on the taxon under consideration.
3. The effective population size (the number of individuals within a population that contribute to subsequent generations) for different species is highly variable within and between phyla. Effective population sizes are often small (<50 individuals) suggesting high taxon-specific sensitivity to disturbances, such as mining.

In the context of deep-sea research, the studies listed in Table 14.1 represent a large body of detailed information for any one region, but nonetheless cover a fraction of the taxa that could be impacted by the commencement of deep-sea mining. Management decisions—where mining may occur, the extent of mining activity, the placement and number of protected areas—are based on the best available knowledge, but the state of this knowledge will change over time as new studies are conducted. Below, we summarise the major findings of the studies as they pertain to the Kermadec Ridge (including the Kermadec Volcanic Arc) area and note that a common theme is the lack of consistent patterns in the results across the different studies.

Several connectivity studies including the Kermadec Ridge area have reported an absence of spatial genetic differentiation at different scales. Such patterns are usually attributed to high levels of gene flow that act to homogenise population genetic composition. The Kermadec Volcanic Arc-endemic vent mussel *Gigantidas gladius* (Fig. 14.9) showed limited spatial genetic differentiation (Boschen et al. 2015b), and there was an absence of regional genetic differentiation for three of four deep-sea sponges (*Neoaulaxinia persicum*, *Pleroma menoui* and *Penares tumericolor*) within the New Zealand EEZ (Zeng et al. 2019). Most recently, Yan et al. (2020) reported no significant spatial population genetic differentiation based on analyses of *COI* (*mtDNA*) variation for three squat lobsters (*Munida endeavourae, Munida gracilis, Munida isos*) but did report spatial differentiation of the same individuals when analysed for microsatellite (*nDNA*) variation.

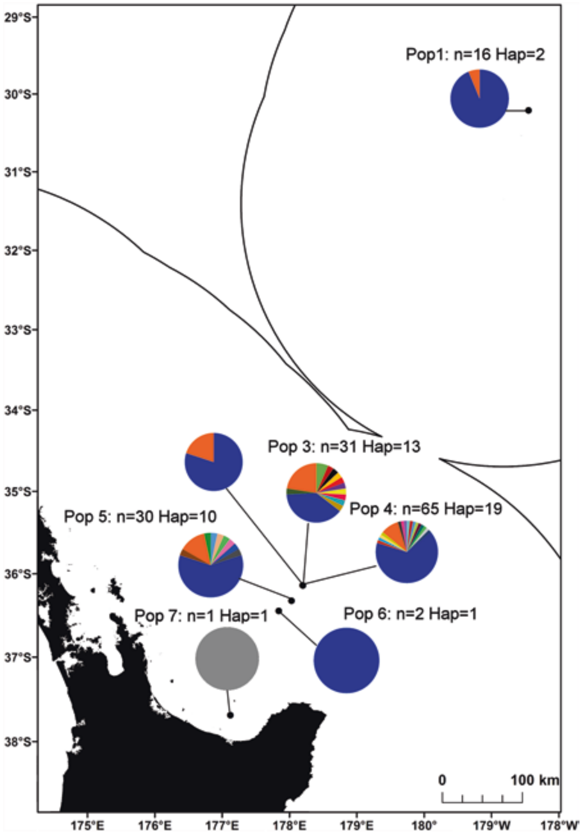

Fig. 14.9 Map illustrating low level of spatially explicit genetic diversity for the vent mussel *Gigantidas gladius* from the Kermadec Volcanic Arc. Each site-specific circle represents all the mussels analysed from that site. The different colours within each circle represent *COI* haplotypes observed at each site, with the pie size slice proportional to the frequency of occurrence of that haplotype. Modified from Boschen et al. (2015b)

Conversely, other connectivity studies featuring the Kermadec Ridge area have reported genetic differentiation both at relatively small spatial scales and oceanic basin scales. Genetic differentiation was detected between samples of the mussel *Bathymodiolus manusensis* (originally published as '*Bathymodiolus* new species NZ-1') collected from two seamounts only 50 km apart (Smith et al. 2004), which was attributed to localised current regimes promoting isolation of these populations. Contrasting patterns of gene flow were reported for nine deep-sea coral taxa with evidence of genetic subdivision across ocean expanses for three species (*Desmophyllum dianthus*, *Antipathes robillardi*, *Stichopathes variabilis*) but low levels of genetic variation for the remaining six species (Miller et al. 2010). For two species (*Stephanocyathus spiniger*, *Stichopathes filiformis*), there was no evidence of genetic subdivision amongst sites within regions, suggesting sufficient gene flow occurs to maintain genetic homogeneity at scales of tens to hundreds of kilometres (Miller et al. 2010). These contrasting results suggest that for some coral species ocean expanses of 500–1000 km are effective barriers to gene flow whereas for other species this is not the case. At the oceanic basin scale, population genetic differentiation has been reported for the solitary deep-sea cup coral *Desmophyllum*

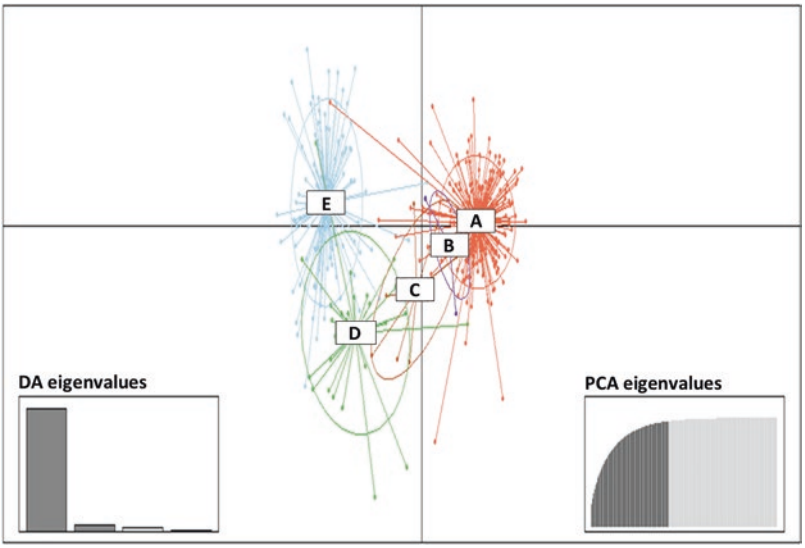

Fig. 14.10 Discriminant Analysis of Principal Components (DAPC) of multi-locus microsatellite variation amongst samples of the hard coral *Desmophyllum dianthus* collected from five geomorphic features. Clockwise from top: (A) Chatham Rise in brick red; (B) Macquarie Ridge in purple; (C) Campbell Plateau in brown; (D) Kermadec Ridge in green; (E) Louisville Seamount Chain in light blue. Individual colour-coded points represent individual corals, and the points are joined by a line to the centroid of the sample (geomorphic feature). Clusters that are close together (overlap) are genetically similar whereas clusters that are far apart (do not overlap) are genetically distinct. The green Kermadec Ridge cluster is distinct from the brick red Chatham Rise cluster. Modified from Holland et al. (2020)

dianthus between New Zealand, Australia, and Chile (Miller et al. 2011) suggesting that larval dispersal rarely occurs across oceanic basins (i.e. distance is a barrier to gene flow).

More recently, contrasting patterns of genetic differentiation were described for three coral species (*Goniocorella dumosa*, *Madrepora oculata*, *Solenosmilia variabilis*); although estimates of genetic differentiation were all low, there was no clear pattern to the results (Zeng et al. 2017). For *S. variabilis*, genetic differentiation was observed between bioprovinces (based on Watling et al. 2013), amongst regions (north-central-south, see Fig. 14.1), and amongst some geomorphic features, such as large topographic features including the Kermadec Ridge (Zeng et al. 2017). For *G. dumosa*, genetic differentiation existed amongst regions and geomorphic features, but not between provinces, whilst for *M. oculata*, only regional structure was observed.

In another recent study of deep-sea corals, *Desmophyllum dianthus* samples in all three studied regions were significantly different from each other based on microsatellite F_{ST} values (Holland et al. 2020). At the geomorphic features level, the Kermadec Ridge population of *D. dianthus* had the highest value of allelic richness and was differentiated from the population on the Chatham Rise to the south but no other population using multiple genetic markers (Fig. 14.10). For *Enallopsammia* *rostrata*, population structuring was less pronounced than for *D. dianthus*, although statistically significant differences between populations did exist. Genetic diversity of *E. rostrata* was highest overall in the Kermadec Ridge area, although the Kermadec Ridge sample was genetically indistinguishable from all other samples. Patterns of genetic connectivity for both *D. dianthus* and *E. rostrata* were generally consistent with directional predictions of where larvae with different pelagic larval durations could be carried by ocean currents. However, dispersal models did not always predict the extent of connectivity between distant sites, and the models suggest that connectivity between distant sites was more likely to occur via shallow than deep water currents.

The Kermadec Ridge also appears to have an important role in connectivity patterns for deep-sea sponge species (Zeng et al. 2019). Significant genetic differences were observed between bioprovinces, amongst regions, and amongst geomorphic features between bioprovinces for *Poecillastra laminaris*. The population of *P. laminaris* associated with the Kermadec Ridge had the highest degree of genetic variation, whilst the *Neoaulaxinia persicum* Kermadec Ridge population had the highest genetic diversity. Amongst the geomorphic features studied, the Kermadec Ridge population of *Pleroma menoui* was significantly differentiated from populations of two other major topographic features to the south (Campbell Plateau and Chatham Rise). For *Penares tumericolor*, although there was no significant population structure, the north region had the highest nucleotide diversity in *12S*, which was closely related to high diversity associated with populations from the Kermadec Ridge.

Subtle regional differences and high levels of gene flow across the sampled SW Pacific region were observed for three squat lobster species using microsatellite-derived F_{ST} values (Yan et al. 2020). The Kermadec Ridge population of *Munida isos* was differentiated from the Macquarie Ridge and Tasmanian Slope populations to the far south and the Kermadec Ridge population of *Munida endeavourae* was differentiated from the Louisville Seamount Chain population; however, the Kermadec Ridge population of *Munida gracilis* was not significantly differentiated from any other population. In contrast, *COI*-derived Φ_{ST} values for all three species from population pairwise tests involving the Kermadec Ridge population were not statistically significant.

Where self-recruitment has been estimated for species found in the Kermadec Ridge area, it has been reported as being moderate to very high. Medium to high levels of self-recruitment were reported for four coral species at the geomorphic feature level (Zeng et al. 2017). High historical and contemporary levels of self-recruitment were reported for a solitary cup coral (Fig. 14.11; Holland et al. 2020) and estimates of contemporary self-recruitment for three species of squat lobsters were reported to be high to very high (60–90%: Yan et al. 2020). These three studies all included samples from the Kermadec Ridge area, indicating that for multiple species, self-recruitment is critically important in maintaining the viability of populations in the New Zealand EEZ, including those of the Kermadec Ridge area.

Based on the connectivity studies conducted in and around the Kermadec Ridge area, depth may be a bigger barrier to gene flow than geographic (linear) distance. Populations of the coral *D. dianthus* at different depths are isolated and have begun

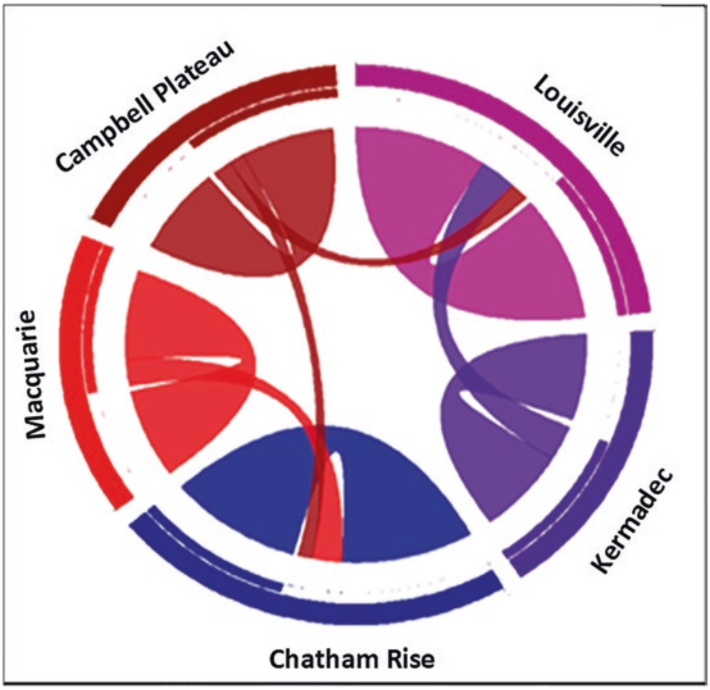

Fig. 14.11 Comparative gene flow diagram for the stony coral *Desmophyllum dianthus* based on allelic variation of microsatellite loci. The colours represent different geomorphic features (i.e. populations). In this diagram a pathway that moves away from its colour of origin indicates source to sink movement (e.g. the Kermadec Ridge population sends larvae to the Louisville Seamount Chain population), whereas a 'hill' represents self-recruitment (e.g. all populations, including the Kermadec Ridge population, exhibit high levels of self-recruitment). Modified from Holland et al. (2020)

to diverge from each other (Miller et al. 2011), with shallow water *D. dianthus* populations being distinct from those in deep water. These results indicate that there is no vertical exchange of larvae even across as little as several hundreds of metres of depth on the same or neighbouring seamounts. A significant isolation-by-depth pattern was reported for the corals *G. dumosa* and *M. oculata*, with an isolation-by-distance pattern for *S. variabilis* (Zeng et al. 2017). A significant isolation-by-depth relationship was also reported for the sponge *N. persicum* using *COI*, although nine other separate species-by-marker tests for isolation-by-distance and isolation-by-depth were not significant (Zeng et al. 2019). Whilst these isolation-by-distance and isolation-by-depth tests and their results reflect analyses that are conducted by including data from all sites (populations) and are not therefore specific to the Kermadec Ridge area, these findings nonetheless highlight how both geographic distance and depth need to be considered as key factors when considering the connectivity of a particular site. The connectivity results discussed in this sections suggest that a shallow mine site in the Kermadec Ridge area will, on average, be isolated (not receive recruits) from deeper source populations, just as a geographically remote mine site will be isolated from less remote populations.

Different locations in the Kermadec Ridge area could act as source populations for different species. For the vent mussel *G. gladius*, the Rumble V Seamount sample had the highest genetic diversity and may be acting as a source population in the region (Boschen et al. 2015b). For the coral *S. variabilis*, populations on all geomorphic features were to some extent source populations for other populations, but those from the Kermadec Ridge area, the adjacent Louisville Seamount Chain and another feature in the south (Bounty Trough) seem to be particularly important (Zeng et al. 2017). The *G. dumosa* populations of the Kermadec Ridge and another area in the northern region were also important for genetic connectivity. For the sponge *P. laminaris*, the Kermadec Ridge was the only source of migrants for the population of the Hikurangi Margin to the south (Zeng et al. 2019). For the coral *D. dianthus*, contemporary migration pathways indicate that populations of the Kermadec Ridge area act as a larval source for the Louisville Seamount Chain (Fig. 14.11; Holland et al. 2020). The Kermadec Ridge area was also an important sink population for three squat lobster species of the genus *Munida* (Yan et al. 2020).

Understanding the effective population size (how many individuals in a population contribute offspring to subsequent generations) is critical to good management because if the effective population size is low then a population, regardless of the number of individuals present at any given time, is expected to be more vulnerable to disturbance and ultimately at greater risk of extinction. The estimated effective population size values at bioprovince, region and geomorphic feature scales for three habitat-forming corals (*G. dumosa*, *M. oculata*, *S. variabilis*) were very small, and in the range of ~20–60 individuals (Zeng et al. 2017). Conversely, high values of contemporary effective population size values were reported for almost all populations of *D. dianthus* in a New Zealand-focussed study, including populations in the Kermadec Ridge area (Holland et al. 2020). Very high effective population size values were also reported for Australian samples of *D. dianthus* (Miller and Gunasekera 2017). It is unclear why different species of corals seem to have such profoundly different values of effective population size, although this may be a function of different reproductive life-history characteristics. Regardless, this considerable variability in effective population size estimates and the fact that several species have very low values, highlights the vulnerability of such species to anthropogenic disturbances, including future deep-sea mining.

3.3 Perspectives on Seafloor Population Connectivity

An increasing appreciation of the importance of genetic connectivity in management decision making and planning, coupled with an increasing number of genetic studies, suggests that in the future the use of genetic (connectivity) data will be more frequent. Based on the body of work discussed in this section, if connectivity assessments are to be used to inform environmental management of deep-sea mining, several key points need to be considered:

1. Archived material alone may be insufficient to conduct robust connectivity assessments, resulting in the need to supplement archived material with targeted fresh sample collections.
2. Sampling design for connectivity assessments, including spatial and temporal coverage and sample size, should reflect the management objectives that the study is aiming to inform.
3. The identification of genetic diversity hotspots is important to enable suitable protection to be afforded to these locations to conserve regional population connectivity.
4. The identification of suitable protected areas based on genetic connectivity characteristics will be influenced by the choice of species and genetic marker(s) for assessment.
5. Estimates of population genetic connectivity (gene flow) should be supported by physical oceanographic modelling, to confirm patterns of connectivity and identify previously uncharacterised routes of larval movement.

It is unusual for managers to explicitly consider patterns of genetic diversity in the conservation of marine resources (Beger et al. 2014; Boschen et al. 2016a; Zeng et al. 2019), even though the value of such information for spatial planning and conservation prioritisation has long been appreciated (Palumbi 2003). Integrating genetic data into protected area network designs, especially for marine invertebrates, is rare (McInerney et al. 2012; Laikre et al. 2016). It is, however, recognised that management of vulnerable marine ecosystem indicator taxa would benefit from increased consideration of genetic connectivity data for such taxa (Clark et al. 2012; Baco et al. 2016; Boschen et al. 2016a), especially data derived from multiple species with overlapping ranges (e.g. Zeng et al. 2017, 2019; Holland et al. 2020; Yan et al. 2020).

Obtaining sufficient fresh samples can be challenging in the deep sea, potentially restricting the spatial and temporal coverage of connectivity assessments (Miller et al. 2010; Ramirez-Llodra et al. 2010; Boschen et al. 2015b; Baco et al. 2016; Taylor and Roterman 2017). Mining companies would be expected to cover the cost of studies at prospective mine sites; however, regional-scale studies are essential for understanding the connectivity of organisms at meaningful spatial scales. Utilising archived material could enable large-scale studies to be conducted in resource-limited situations. However, archived material alone may be insufficient to conduct robust connectivity assessments, and environmental managers should be aware of the possible loss of information content as a consequence of having to employ low-definition genetic markers on what may be small sample sizes.

The sampling design for connectivity assessments should reflect the management objectives that the study is aiming to inform. If an aim of environmental management is to conserve population genetic connectivity amongst sites across a region, it is important to assess genetic connectivity not just over the 100 s or 1000 s of km that may encompass a species' range as discussed in this section, but also at smaller spatial scales appropriate to mining disturbance. Such a nested design was used in a study of the vent snail *Ifremeria nautilei* in the Manus Basin to determine connectivity characteristics across multiple spatial scales, including amongst patches within an SMS deposit-mound, amongst SMS mounds within a site, and amongst sites within a vent field (Thaler et al. 2011). The influence of depth, as well as linear distance, also needs to be considered, particularly to understand how isolation by distance and/or depth may act as barriers to gene flow (i.e. the supply of larval recruits). This information is needed to support management decisions about the placement of a mine site in the context of other comparable sites that may contribute new recruits post-mining disturbance.

The identification of genetic diversity hotspots is important to enable regional population connectivity to be determined and conserved. However, as detailed in this section, different species have different patterns of connectivity, and even the same species can display different connectivity patterns according to the genetic markers used. Thus, the identification of suitable protected areas based on genetic connectivity characteristics will be influenced by the choice of target species and genetic marker(s) used for assessment. Different locations may be important source populations for different species, thus conserving regional population connectivity for multiple species may require protecting several connected sites and their associated populations.

Patterns of regional genetic diversity are likely to be influenced by taxon-specific life history trait differences, including mode of reproduction, pelagic larval duration and larval behaviour. For most taxa that are associated with potential deep-sea mining areas we do not have a good understanding of key life history traits, which hinders our understanding of patterns of connectivity. Although estimates of population connectivity can be generated from population genetic analyses, the physical routes of connectivity amongst populations for most deep-sea species are unknown. Confirming patterns of connectivity and identifying previously uncharacterised routes of larval movement will require additional information on ocean currents, for example, through physical oceanographic modelling.

4 Functional Sensitivity of Kermadec Volcanic Arc Seafloor Communities

4.1 A Framework for Assessing Functional Sensitivity to Deep-Sea Mining

Incorporating functional sensitivity into ecological risk assessment (ERA) for deep-sea mining enables mining impacts to be considered at a community or assemblage level, thus supporting an ecosystem approach to environmental management (Boschen-Rose et al. 2021). A functional traits approach shifts the focus from individual taxonomic species to the ecological characteristics of each taxon, which can

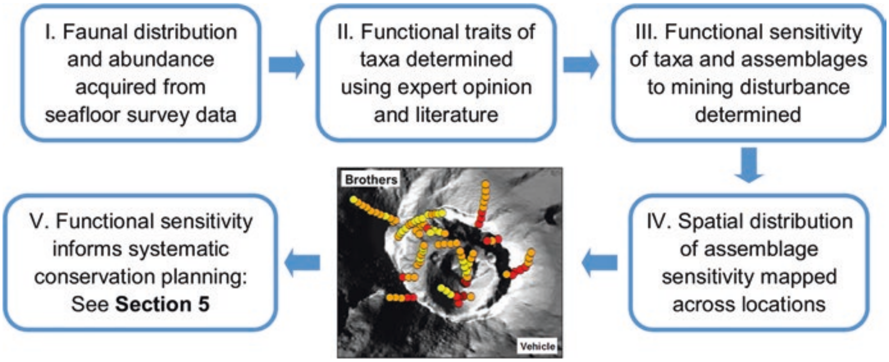

Fig. 14.12 Flow chart summarising general methodology for assessing seafloor assemblage functional sensitivity as a prerequisite for systematic conservation planning of deep-sea mining activities

be combined for different sites to gain a community or assemblage-level appreciation of functional sensitivity. Utilising functional traits thus enables risk assessment to be conducted across a wide range of sites and habitats with different species compositions (Hewitt et al. 2008), or in situations where detailed species-specific knowledge is limited (Tyler-Walters et al. 2009).

Traits-based approaches have been used in multiple settings to assess sensitivity of communities to disturbance and to inform conservation strategies (Miatta et al. 2021). The focus is typically on 'response traits' that influence the abilities of species to persist in the face of environmental change (Díaz et al. 2013; Nock et al. 2016). The functional traits approach has been incorporated into frameworks determining the sensitivity of benthic communities to fishing and other forms of anthropogenic disturbance for more than 10 years (Tyler-Walters et al. 2009; Hewitt et al. 2011, 2019; Baird et al. 2015; Clark et al. 2016). Existing risk assessment approaches for deep-sea fisheries using functional traits provided the basis for developing a novel framework to assess functional sensitivity of Kermadec Volcanic Arc benthic fauna to deep-sea mining impacts (Boschen-Rose et al. 2021).

The general methodology employed by Boschen-Rose et al. (2021) is summarised in Fig. 14.12. This framework utilised six functional traits: adult size, environmental position (at seafloor/in sediment), living habit, feeding habit, mobility and structural fragility. Each of the attributes for these traits was assigned a sensitivity score based on its perceived sensitivity (the likelihood of impairment to, or death of, an individual) to three types of mining disturbance: the passage of large mining vehicles ('vehicle impact'); sediment plumes generated by mining activity ('plume'); and extraction of minerals from the seafloor ('extraction').

Values of functional trait attributes were assigned for individual taxa using the available literature and expert knowledge from a group of scientists familiar with the regional benthic fauna. For each taxon at each mining disturbance, sensitivity was calculated by multiplying the taxon's trait assignment scores by the sensitivity of that trait to each mining disturbance and summing all trait-sensitivity values for that taxon to give an overall score per taxon for each of the three mining disturbances. Scores were ranked to give an overall sensitivity for each taxon (1–5: very low to very high sensitivity).

The overall sensitivity of an assemblage to each of the three mining disturbances was calculated in two steps. Firstly, the raw sensitivity value of each taxon was multiplied by its log(n + 1) transformed abundance in each given sample so that assemblages with larger numbers of sensitive individuals could be determined as more sensitive overall than assemblages with lower abundances of sensitive individuals. Secondly, these abundance-weighted sensitivity values per taxon were summed across all taxa within an assemblage, and the final sensitivity scores ranked to give a value between 1 (very low sensitivity) and 5 (very high sensitivity) for each assemblage.

The data used to develop this framework, and to test its utility, consisted of distribution and abundance data for benthic megafaunal taxa visible on the surface of the seafloor along video segments conducted during two studies along the Kermadec Volcanic Arc (Boschen et al. 2015a, 2016b: see Sect. 2). Survey data from two seamounts (Brothers and Rumble II West) and two sites (the proposed mine site Proteus 1 and proposed Reference Site) were used as the basis for the sensitivity analysis because of the potential these locations have for SMS mining. The video segments from the seamount and site surveys were used as samples, with the megafaunal 'assemblage' consisting of the relative abundance of megafaunal taxa within each segment.

4.2 Functional Sensitivity Results and Interpretation

The functional sensitivity framework made it possible to determine two key sets of sensitivity information:

1. Different taxa have different relative sensitivities to the three mining disturbances, with particularly sensitive taxa potentially able to act as indicator taxa for monitoring mining impacts. The functional traits sensitivity approach could inform decisions on management or conservation priorities based on the occurrence of highly sensitive taxa.
2. Different assemblages have different relative sensitivities to the three mining disturbances, whilst mapping assemblages by sensitivity illustrates the spatial distribution of sensitivity within seamounts and sites. This approach enables the identification of seabed locations that are particularly sensitive to different mining disturbances, which could inform decisions on the location of suitable protected areas or siting mining activities to avoid or minimise environmental impacts.

Regarding the relative sensitivity to the different mining disturbances, taxa were most sensitive to extraction, followed by plume and then vehicle impacts (Fig. 14.13). Different phyla displayed different sensitivity profiles across the three impacts.

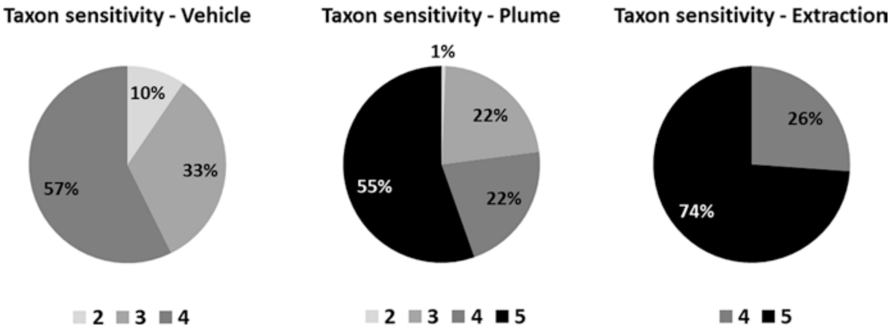

Fig. 14.13 The proportion of Kermadec Volcanic Arc megafaunal taxa (*n* = 157) at each sensitivity level for the three mining disturbances: heavy vehicle movement over the seafloor (Vehicle—left), plume generation (Plume—middle) and mineral extraction (Extraction—right). Sensitivity is ranked as very low (1), low (2), intermediate (3), high (4) or very high (5). Data from Boschen-Rose et al. (2021)

Brachiopoda, Bryozoa and Mollusca had the highest sensitivity to all three mining impacts, whilst Annelida (tubed polychaetes and spoon worms) were also very highly or highly sensitive to all mining impacts. Porifera (sponges) and Cnidaria (corals, anemones and hydroids) also exhibited high sensitivity, scoring as very highly or highly sensitive to extraction and plume impacts, and intermediate or highly sensitive to vehicle impacts. The greatest within-phylum variation in sensitivity profiles was observed for individuals of the Arthropoda (crabs, squat lobsters, shrimp, pycnogonids and isopods) and Echinodermata (asteroids, ophiuroids, echinoids and holothurians).

The three taxa endemic to hydrothermally active habitat were some of the most sensitive to mining impacts. The stalked barnacle *Vulcanolepas osheai* and vent mussel *Bathymodiolus manusensis* were very highly sensitive to extraction and plume impacts, and highly sensitive to vehicle impacts. The vent shrimp taxon Alvinocarididae/Hippolytidae was also very highly sensitive to extraction impacts and intermediately sensitive to plume and vehicle impacts.

Assemblage sensitivity was a product of the sensitivity of the different taxa that made up each assemblage and the relative abundance of each taxon. As such, locations with high abundances of particularly sensitive taxa tended to be the most sensitive to the three mining disturbances (Fig. 14.14). As for individual taxa, assemblages were the most sensitive to extraction, followed by plume and then vehicle impacts. Assemblages with very high sensitivity to all three mining impacts only occurred at Brothers Seamount and the Proteus 1 site, in locations colonised by hydrothermal vent taxa such as *V. osheai* and *B. manusensis* (Boschen et al. 2015a, 2016b; Boschen-Rose et al. 2021). Additional highly sensitive assemblages at Proteus 1 overlapped spatially with records of hydrothermally active mounds and chimneys. Sessile vent-endemic invertebrates are expected to be severely affected by mining disturbance that could alter hydrothermal flow and remove hydrothermal habitat (Van Dover 2011, 2014; Boschen et al. 2013), with the suspension/

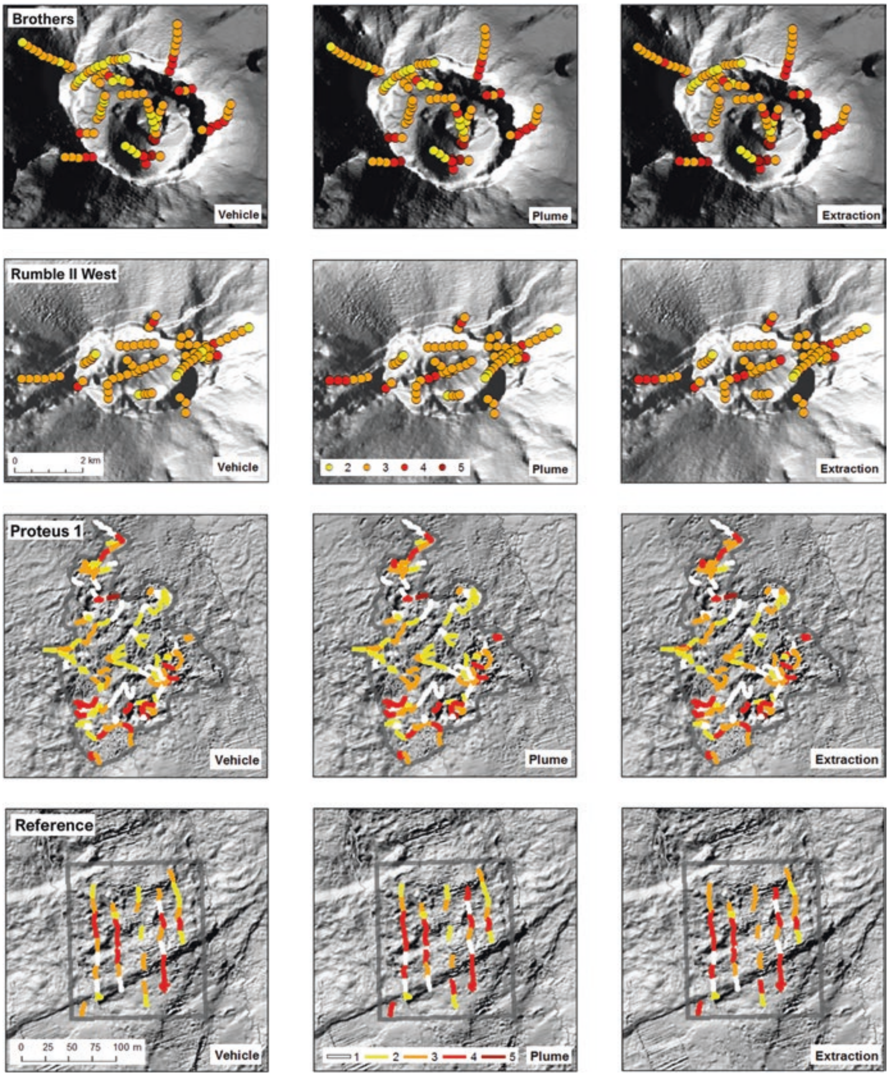

Fig. 14.14 Maps of sensitivity showing the spatial distribution of assemblages at Brothers Seamount (Brothers: top row), Rumble II West Seamount (second row from top), Proteus 1 Site (third row from top), and the Reference Site (bottom row) at each sensitivity level for the three mining disturbances: heavy vehicle movement over the seafloor (left), plume generation (middle), and mineral extraction (right). Sensitivity is ranked as very low (1), low (2), intermediate (3), high (4) or very high (5). Modified from Boschen-Rose et al. (2021)

filter-feeding *V. osheai* and *B. manusensis* being particularly sensitive to plume impacts (Boschen-Rose et al. 2021).

Some assemblages that were highly sensitive to mining impacts at the Proteus 1 site and on Rumble II West Seamount overlapped spatially with records of hydrothermally inactive chimneys. These assemblages were typically dominated by a very highly sensitive branching scleractinian coral (probably *Solenosmilia variabilis*). Scleractinian corals are very fragile, sedentary and erect, and are highly susceptible to physical disturbance caused by deep-sea fishing (Williams et al. 2010; Clark and Rowden 2009), with their suspension/filter feeding habits making them particularly sensitive to plume impacts.

Additional highly sensitive assemblages occurred on non-hydrothermal elevated sections of Rumble II West and in some parts of the Reference Site, where there was no record of hydrothermal activity. These assemblages were dominated by comatulid crinoids, branching scleractinian corals, schizopathid corals and primnoid/isidid corals, all of which are fragile and erect suspension feeders that are either sedentary or have limited movement (Boschen et al. 2015a, 2016b; Boschen-Rose et al. 2021).

Overall, the functional sensitivity analyses conducted at the site- and seamount-scales identify hydrothermal vent-endemic taxa and vulnerable marine ecosystem indicator taxa (such as corals and sponges) as being the most sensitive to SMS mining activities. These results provide support for environmental management strategies that include these groups in conservation measures, such as protected areas. Mapping assemblages according to their sensitivity also enables mining activities to be planned to avoid disturbing particularly sensitive locations, for example by routing seafloor crawlers away from locations with diverse coral and sponge assemblages or planning mineral exploitation activities so that high concentrations of suspended sediment do not drift over beds of *G. gladius* mussels or *V. osheai* stalked barnacles.

4.3 Perspectives on Functional Sensitivity Frameworks

Functional traits-based sensitivity frameworks offer an approach to determining spatial patterns of sensitivity of benthic organisms to deep-sea mining at seamounts and within sites, providing an important first step towards a more comprehensive ERA. However, for this approach to be utilised beyond the Kermadec Volcanic Arc or for mineral resources other than SMS, several key points would need to be considered:

1. Different traits can be used to assess sensitivity versus vulnerability, thus trait selection needs to consider the management objectives that functional assessments are aiming to inform.
2. Characterising the functional sensitivity of taxa to mining disturbances needs to consider the specific mining technology to be employed, which may differ between mining companies or change over time.
3. Abundance and diversity transformations should be carefully selected because they can impact sensitivity scoring with the potential to influence the identification of highly sensitive assemblages and locations.

4. The spatial resolution of sensitivity mapping determines the resolution of sensitivity information available for making decisions on spatial management measures, such as protected areas.

The functional traits used in an ERA framework should be selected based on the purpose of the framework, with different traits needed to provide information on sensitivity versus vulnerability. Whilst the terms 'sensitivity' and 'vulnerability' are sometimes used interchangeably, they are not synonymous: 'vulnerability' is a combination of three factors, including exposure to a disturbance, the sensitivity of the organism to disturbance, and the adaptive capacity an organism may have to cope with or recover from the disturbance (Weißhuhn et al. 2018). Thus, to determine vulnerability, additional traits are needed to capture the adaptive capacity or potential for recovery of an organism. Examples of such traits are the reproductive and life history traits used by Tyler-Walters et al. (2009). It is not always possible to determine vulnerability to mining disturbances, particularly where there is insufficient information available to score reproductive and life history traits (Boschen-Rose et al. 2021). Incorporating recovery into an ERA will only be possible once more information is available on the functional traits associated with recovery, and on the nature of the mining disturbance itself. Obtaining such additional functional trait information will require detailed studies on the reproduction and life history of taxa, alongside in situ observations of organismal response to mining disturbances.

The sensitivity of organisms will depend upon the nature and extent of mining impacts, which will vary amongst sites and as a function of mining methods (Boschen et al. 2013). Thus, scoring different modalities of traits for their sensitivity to mining disturbance needs to take careful account of mining methods. Current mining technology consists of either multiple Seafloor Production Tools (SPTs) with different functions, such as designed by SMD for Nautilus Minerals, or a single SPT with exchangeable heads, as used in scaled prototype testing in the EEZ of Japan (Okamoto et al. 2019). Different mining technologies, such as the trench cutter being developed by Bauer (Spagnoli et al. 2016), will have different impacts, resulting in different sensitivities of the benthic megafaunal taxa.

However, commercial exploitation of SMS deposits has not yet started, and the exact nature of mining disturbance is not yet known. In the absence of commercial mining, community or assemblage recovery could be investigated through controlled disturbance experiments. Suitable monitoring programmes would need to be established with multiple disturbance and control sites to assess recovery and successional dynamics against a background of natural spatial heterogeneity. Given the slow growth rate of many deep-sea taxa (e.g. Clark et al. 2016), monitoring programmes may need to be implemented over multiple decades to adequately assess recovery.

In the absence of controlled disturbance experiments to determine the effects of SMS mining, much of the available information on recovery of hydrothermally active communities comes from large-scale natural disturbances, such as those resulting from volcanic and tectonic activity (Lutz et al. 1994; Shank et al. 1998; Tunnicliffe et al. 1997; Gollner et al. 2020; Mullineaux et al. 2020; Dykman et al.

2021). However, because the mechanisms of these disturbances differ from those involved in SMS mining and communities may have adapted to such periodic seismic disturbances, the impacts they have on benthic communities could also be different. Recovery dynamics from disturbance studies in one ocean region may not be applicable to other ocean regions, as local controls and disturbance regimes may be different.

For functional traits sensitivity frameworks to be used in different ocean regions, the functional sensitivity of the taxa to mining disturbances will need to be determined, which requires sufficient information on the taxonomic distributions and the functional characteristics of those taxa. Standardised global datasets, such as the FDiv database developed by Chapman et al. (2019), enable functional trait analyses to be conducted amongst regions for a subset of fauna for which traits are comprehensively scored. However, global datasets may not provide sufficient regional or local taxonomic coverage to support functional analyses at scales that are relevant to assessing sensitivity to anthropogenic activities, such as deep-sea mining (Boschen-Rose et al. 2021).

The choice of numerical transformation used for generating assemblage sensitivity scores influences the sensitivity rank given to different assemblages, which may impact choices about which seabed locations to protect from mining activities (Boschen-Rose et al. 2021). Thus, sound ecological reasoning needs to be used to determine which transformation is the most suitable for use in sensitivity analyses. Potential SMS mine sites can encompass a range of habitats, including hydrothermally active areas colonised by hydrothermal vent fauna and hydrothermally inactive areas colonised by corals, sponges, urchins and other invertebrates (Boschen et al. 2016b). For a single functional sensitivity framework to be used at such sites, there needs to be a means to accommodate differences in abundance and diversity amongst assemblages that could otherwise inadvertently influence their sensitivity scoring (Boschen-Rose et al. 2021). For example, if untransformed abundance data were used the typically high abundance of vent taxa (Grassle 1985) would inflate the sensitivity scores for samples where hydrothermally active vent fauna occur, with samples characterised by less abundant larger organisms, such as corals and sponges, scoring as less sensitive. Utilising biomass instead of abundance data could help to address this issue but would require sufficient information for all taxa to create a reliable abundance-biomass conversion (Boschen-Rose et al. 2021).

Some ecological risk assessment frameworks take assemblage diversity into account in their calculations for sensitivity (e.g. Hewitt et al. 2011); such an approach would make samples with higher diversity of sensitive taxa, for example diverse coral and sponge assemblages, appear less sensitive than those with lower diversity of sensitive taxa, such as hydrothermal vent assemblages. Unless there is a clear reason why assemblages with lower diversity should be considered more sensitive to mining disturbance than assemblages with higher diversity, proceeding without diversity weighting makes fewer assumptions about the potential outcomes (Boschen-Rose et al. 2021).

The size of sample used to determine assemblage sensitivity will determine the spatial resolution at which sensitivity can be mapped. Different resolutions are required to address different environmental management objectives; thus, it is important to design the underlying seafloor survey with these objectives in mind. The two different transect sample sizes (200 m and 15 m) used by Boschen-Rose et al. (2021) could be used to support different types and scales of spatial management measures. The 200 m video sample size enables a broad spatial scale to be assessed, identifying portions of the different seamounts with greater sensitivity to mining impacts, such as relationships with seamount aspect, topography (e.g. seamount cone, flank, caldera) or depth range. Such broad scale resolution can inform mine site location to avoid mining impacts in specific locations that are highly sensitive, or the location of suitable preservation reference zones (PRZs) and impact reference zones (IRZs) envisioned as part of the exploration programme beyond national jurisdiction (ISA 2020). The smaller 15 m transect sample size enables higher spatial resolution of sensitivity analysis but with reduced spatial coverage. High spatial-resolution sensitivity information may be helpful to understand whether potential protected areas, PRZs or IRZs, have similar functional sensitivity compared to the proposed mine site/s. Greater spatial resolution can also help to inform decisions about the location of specific mining activities within a site to reduce impacts.

Ultimately, the information requirements to move from the 'level 2' semi-quantitative assessment reported by Boschen-Rose et al. (2021) to a more quantitative 'level 3' ecological risk assessment (see Hobday et al. 2011) are considerable. Such additional information may be unavailable for all but the best characterised SMS deposits. In the absence of more detailed, quantitative information, the framework presented by Boschen-Rose et al. (2021) enables mining companies and environmental managers to assess which taxa and locations are most sensitive to disturbance and hence what mitigation measures could be most effective.

5 Integrated Environmental Management for Mining Seafloor Massive Sulphides

5.1 Systematic Conservation Planning for Deep-Sea Mining

To ensure biodiversity at SMS deposits is suitably protected, there needs to be a systematic approach to conservation planning, as more typically used in terrestrial, freshwater and shallow marine environments (Margules and Pressey 2000). Conservation planning is the process of deciding how best to utilise conservation resources to minimise the loss of biodiversity, amongst other valued natural elements (Pressey and Botrill 2009). Doing this in a systematic way has the advantage that site connectivity can be integrated with the planning to determine protected area configurations that would best support persistence of populations amongst sites (Kininmonth et al. 2011).

Pressey and Logan (1997) outlined a basic six-step process for systematic conservation planning that could be adapted for environmental management of deep-sea mining:

1. Compile biodiversity data in the region of interest for mining—includes seafloor community structure and distribution.
2. Identify conservation objectives—includes preserving biodiversity (within species, between species and of ecosystems) that could otherwise be lost through mining activities.
3. Review current achievement of conservation objectives—includes existing protected areas, such as fisheries closures and other protected sites.
4. Select additional sites as necessary to create a coherent network—includes previously unprotected areas.
5. Apply conservation actions—includes formal designation of new protected areas.
6. Manage selected areas to maintain their conservation value.

This six-step process was later expanded by Pressey and Botrill (2009) to include five prior steps, acknowledging the placement of conservation planning within an often complex socio-economic and political environment. These stages include: (1) Costing the planning process; (2) Engaging with stakeholders; (3) Describing the regional context; (4) Identifying conservation goals; and (5) Collecting data on socio-economic considerations (Pressey and Botrill 2009). These additional aspects are important elements of conservation planning, particularly where there is a need to consider multiple uses of marine space, acknowledging that sites with conservation value may also be of interest for economic development (see Fig. 14.15).

As noted in Sect. 1.2, socio-economic aspects have been considered in the context of Chemosynthetic Ecosystem Reserves (CERs), which offer a general approach for systematic conservation planning of hydrothermally active areas (ISA 2011a; Van Dover et al. 2012). Systematic conservation planning has also been used to design a network of protected areas ('Areas of Particular Environmental Interest'—APEIs) for polymetallic nodule habitats at the Clarion–Clipperton Fracture Zone (CCZ) in the abyssal Pacific Ocean (Wedding et al. 2013, 2015). A network of nine large APEIs covering an area of 144,000 km^2 was established across the CCZ based on evaluating patterns of representativity, connectivity and productivity gradients, although there was a compromise in the optimal scientific arrangement of APEIs to accommodate the location of existing exploration areas (Wedding et al. 2013, 2015). A systematic conservation planning exercise was also undertaken for the management of SMS mining on the northern Mid-Atlantic Ridge (Dunn et al. 2018). However, in this case the use of large, regularly shaped APEI protected areas (coarse-filter approach) meant it was not possible to arrange APEIs in a way that avoided overlap with existing contract areas whilst meeting network criteria. Designating a greater number of smaller, irregularly shaped protected areas (fine-filter approach) distributed at suitable locations to enable connectivity amongst sites may be an alternative approach to balance conservation and socio-economic considerations on mid-ocean ridges and volcanic arcs where hydrothermal vent communities are spatially restricted (ISA 2019c). However, such an approach requires

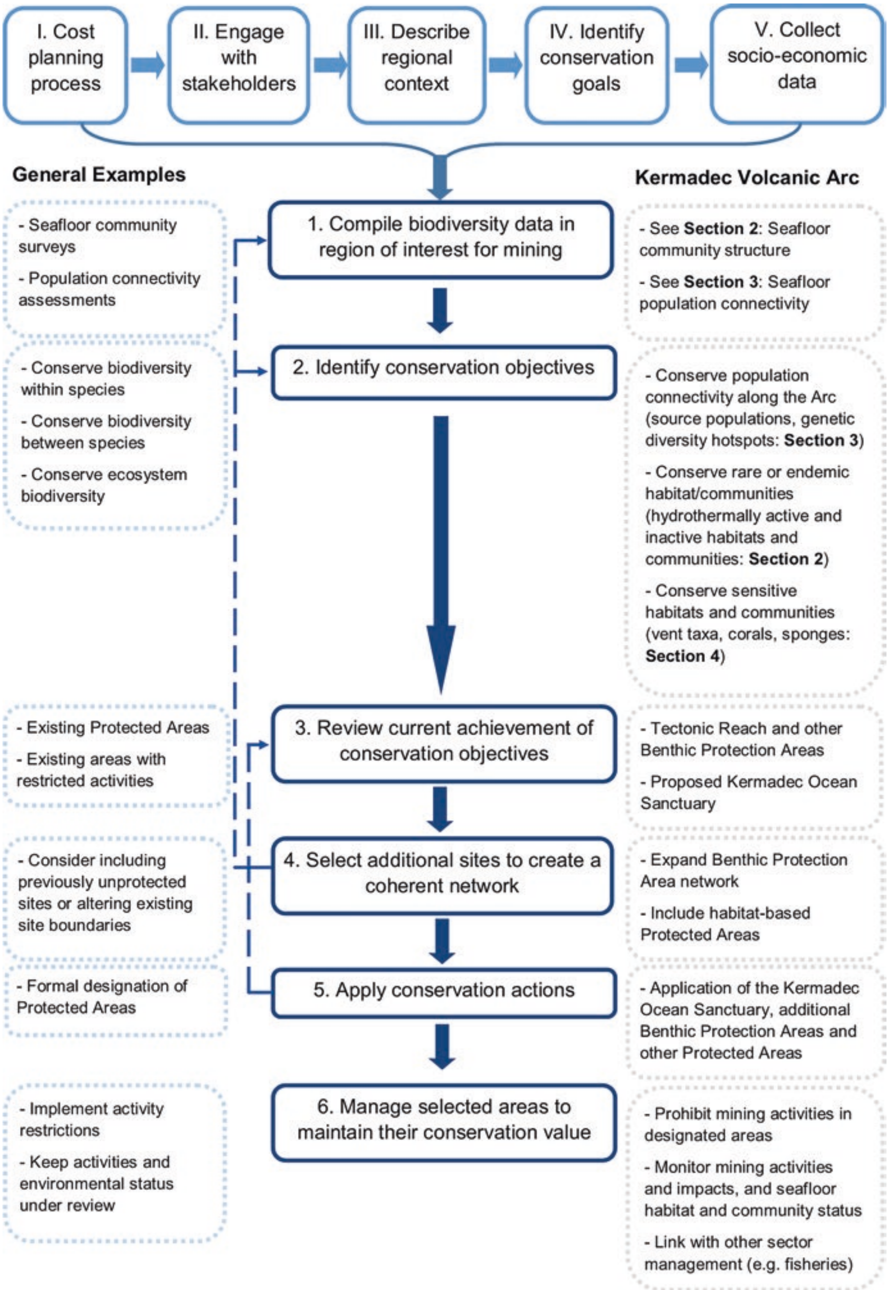

Fig. 14.15 Flow chart summarising how systematic conservation planning methodology (Pressey and Logan 1997; Pressey and Botrill 2009) could be applied to achieve integrated environmental management of deep-sea mining activities, including examples for how this process could be applied along the Kermadec Volcanic Arc. The steps illustrated are not independent, with the process including review and feedback loops

detailed environmental information across the region of interest, or the identification of suitable proxies.

5.2 An Approach to Systematic Conservation Planning on the Kermadec Volcanic Arc

Since the completion of many of the environmental baseline studies discussed in this chapter, the New Zealand Government has announced a proposal to establish the Kermadec-Rangitahua Ocean Sanctuary (Ministry for the Environment 2021) and established a Mineral Reservation Area with no exploration permitted until at least 2024. The proposed Kermadec-Rangitahua Ocean Sanctuary encompasses 620,000 km^2 of seabed and would provide protection from mining for all the assemblages at SMS deposits in the far north of the EEZ. However, many of the benthic assemblages at seamounts south of the proposed Sanctuary are not afforded the same protection. Brothers, Rumble II East and Rumble II West seamounts (the focus of seafloor community distribution surveys) are within the Tectonic Reach Benthic Protection Area (BPA), which protects them from bottom trawling, but does not provide any protection from mining. There are also seamounts south of the Tectonic Reach BPA that are not currently afforded any form of protection, including Rumble V Seamount, which is thought to host source populations of the vent mussel *G. gladius* and is thus important for population connectivity of this species (Boschen et al. 2015b). There is also evidence from population connectivity studies that protected area networks spanning national and international jurisdiction may provide better protection for some Kermadec Volcanic Arc taxa (Zeng et al. 2017; Holland et al. 2020).

If deep-sea mining is to be a potential industry in New Zealand, it would be necessary to negotiate multiple seabed uses in the region, with some SMS deposits protected from mining and others available for exploitation. Undertaking these negotiations prior to additional licence areas being granted is essential, to ensure there is the opportunity to establish protected areas in ecologically optimal locations. Such decisions could be made more transparently and inclusively using a systematic conservation planning approach that actively engages with multiple stakeholders.

As well as site or deposit-scale mitigation and protection measures there is also a need for larger scale regional measures as part of spatial management. It is important to identify spatial management goals for SMS communities at various levels, including site, deposit, region and even biogeographic province level. Spatial management of SMS sites through a series of open and closed sites (i.e. protected areas) would ensure the retention of undisturbed examples of the benthic habitats and communities targeted by SMS mining, and would ideally be part of a larger network of protected areas to enable ecosystem level conservation.

The findings of the studies discussed in this chapter highlight the need for a coherent network of protected seabed areas along the Kermadec Volcanic Arc and adjacent areas to help mitigate the impacts of any future SMS mining activities. Such a protected area network, if appropriately designed, could provide comprehensive protection for the diversity of habitats, and associated benthic communities on Kermadec Volcanic Arc seamounts. Protected areas would need high connectivity within and amongst seamounts to facilitate genetic exchange and the maintenance of healthy populations (ISA 2011a; Van Dover et al. 2012; Boschen et al. 2016a). This network should include both hydrothermally active and inactive areas to conserve (1) the endemic vent fauna in active areas and (2) the unique assemblages found in both environments. Including both hydrothermally active and inactive sites within protected area networks would align with calls from the scientific community to consider the special properties and environmental management needs of these locations (Van Dover et al. 2018, 2020).

The occurrence of hydrothermally active and inactive structures in proximity suggests that, from a management perspective, protected areas that encompass both habitat types may be more feasible than protecting separate smaller examples of each habitat. Capturing temporal and spatial fluctuations in hydrothermal activity and associated shifts in community dynamics (e.g. Sarrazin et al. 1997; Sen et al. 2014) would be easier to accomplish if whole SMS deposits were encompassed within a protected area network. To adequately protect the variability in seafloor habitat and communities within and amongst seamounts, it may be necessary to include entire seamounts within protected areas. However, if impacts of SMS mining are as localised as some have suggested (e.g. most sedimentation impacts should occur within 1 km of the mining site: Coffey Natural Systems (2008)), a network of smaller protected areas distributed within and amongst neighbouring seamounts may also be a suitable strategy.

The steps that could be taken to apply a systematic approach to conservation planning and protected area network development on the Kermadec Volcanic Arc are detailed in Fig. 14.15. In this figure, the biodiversity data described in Sects. 2 and 3 of this chapter underpin subsequent evaluation of specific conservation objectives, how well these conservation objectives are currently met through mechanisms such as BPAs, and whether additional conservation actions may be needed to meet the objectives of seabed mining alongside objectives of other users of the marine space.

5.3 Perspectives on Integrated Environmental Management and Systematic Conservation Planning for Deep-Sea Mining

Whilst it is possible, using currently available information from the studies described in this chapter, to design and implement protection measures for benthic communities on the Kermadec Volcanic Arc to mitigate the impact of future mining for SMS deposits, the full application of a systematic approach for conservation planning remains a daunting prospect. For example, there are still large gaps in our understanding of SMS ecology (see Sects. 2, 3 and 4) that constrain designing suitable management strategies. Furthermore, without a precedent for SMS mining, it is hard to predict the specific impacts mining may have on benthic and pelagic assemblages and develop appropriate mitigation strategies. Hence, such management plans are uncertain, potentially until a mining operation proceeds and its impacts and mitigation measures can be evaluated and incorporated.

Managing the impacts of SMS mining in the face of such uncertainty may benefit from a less static approach, such as active adaptive management (Walters and Holling 1990; Craik 2020; Clark et al. 2022) whereby effective management strategies are developed through a flexible learning and decision-making process. However, such an approach requires detailed and continued monitoring of communities colonising hydrothermally active, inactive, and non-hydrothermal substrata, and would be a substantial commitment and undertaking for environmental managers.

Alternative mitigation methods, such as organism relocation and the provision of artificial substrata to help restore mined areas also remain to be tested (Van Dover et al. 2014). Although restoration programmes are common in terrestrial, freshwater and coastal marine environments to facilitate recovery, their use in deep-sea mineral environments is challenging (Cuvelier et al. 2018), and preliminary studies have indicated the cost of restoring areas mined for SMS may be prohibitive (Van Dover et al. 2014). With the general uncertainty around the recovery and restoration of mined areas, designating a coherent network of protected areas appears to be the most pragmatic mitigation strategy currently available. Such a strategy would be in line with the Precautionary Approach, as defined in Principle 15 of the Rio Declaration and adopted as a guiding principle of the ISA Strategic Plan 2019–2023 (ISA 2018).

International conservation measures for shallow marine environments are moving towards coherent networks of protected areas (IUCN 2008). Creating a network of protected areas across a region, instead of one single large protected area, has the advantage of covering multiple major habitat gradients or centres of diversity (Simberloff and Abele 1976, 1982). Protecting a network of smaller sites also has the advantage of spreading protection across multiple populations of a species, rather than concentrating it in a single reserve (Cox 1993); for communities at risk from catastrophic conditions, a subdivision of reserves provides the best guarantee that species will survive somewhere within the set of preserves (Quinn and Hastings

1987; although see Gilpin and Diamond 1980; Quinn and Hastings 1988). Because SMS habitats and communities are patchily distributed and can be at risk from natural disturbances during volcanic eruption (Lutz et al. 1994; Tunnicliffe et al. 1997; Shank et al. 1998), a network of multiple smaller protected areas would be more prudent than a single large reserve. Regulations for the commercial exploitation phase of SMS mining have yet to be finalised by the ISA, but current thinking within ISA environmental policy reflects the widely accepted need for networks of protected areas in the deep sea (ISA 2011a, b, 2017; Van Dover et al. 2012).

Based on the information in this chapter, several general recommendations can be made for placement of a network of protected areas to conserve seafloor communities that are potentially vulnerable to seabed mining:

1. Sites that are particularly functionally sensitive to mining disturbance should be included in protected areas, based on the location of highly sensitive assemblages.
2. Protected areas should encompass important source populations to conserve population connectivity within the region.
3. Sites within the protected area network should be suitably distributed to maintain connectivity amongst sites, taking into consideration local and regional patterns in oceanography and current flow.
4. Multiple protected areas may be needed to capture the biological diversity and environmental characteristics with each individual mine site.
5. In the case of SMS deposits, protected areas should include hydrothermally active and inactive areas, to capture the unique assemblage structure and environmental conditions occurring at both these habitats.
6. Where the mineral resource is seamount-hosted, whole seamounts should be protected to capture the complex natural within-seamount spatial heterogeneity of habitats, populations and communities.

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Part IV
Techno-Economic Models, Risk Assessment and Payment Regimes

Chapter 15
Analysis of Different Models for Improving the Feasibility of Deep-Sea Mining

Tetsuo Yamazaki

Abstract Though metal contents of deep-sea mineral resources are ten times or more than on-land ones, deep-sea mining has not been realized in the last 50 years since their first recognition as the potential source of metals in future. Not only some technical issues but also less economic benefits of deep-sea mining are the reasons for non-realization. Assuming metal contents, distribution characteristics, metal prices, and mining methods, some fundamental economic analyses of deep-sea mining have been conducted by the author for all the four types of deep-sea minerals, viz. polymetallic nodules, cobalt-rich ferromanganese crusts, seafloor massive sulfides and rare-earth element-rich mud. These results are discussed in this article. How to improve the economies to realize deep-sea mining by applying new technical approaches is proposed. The approaches include mechanical lifting, ore selection on the seafloor, self-standing riser, combined excavation, pulp-lifting, and reuse of wastes.

Keywords Cobalt-rich ferromanganese crusts · Polymetallic nodules · Phosphorous ores · Rare-earth element-rich mud · Seafloor massive sulfides · Economic analyses · Deep-sea mining

1 Introduction

Many scientific, technical, and economical publications have been available on polymetallic nodules (PMN), mostly because they were considered as the primary commercial mining target in deep-sea mineral resources for the last 50 years (Mero

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1965; Cronan 1980). The geological distribution features have been studied by numerous researchers (Craig and Andrews 1978; Andrews and Friedrich 1979; Friedrich et al. 1983; von Stackelberg and Beiersdorf 1991; Morgan et al. 1993). Based on the information, the first mining target areas were focused in the Clarion-Clipperton Fracture Zone (CCZ) in the north-east Pacific. Since then, some of the international consortia had initiated their activities at the sites authorized under US domestic law (Padan 1990), whereas the State Parties who were initially called the Pioneer Investors were subsequently recognized as contractors by the International Seabed Authority (ISA) (ISA 1998). The first stage of research and development (R&D) activities for PMN mining was conducted by the international consortia in the 1960s and 1970s (Welling 1981; Kaufman et al. 1985; Bath 1989). Though some of the consortia's technological results were reported (Heine and Suh 1978; Clauss 1978; Burns and Suh 1979; Grote and Burns 1981; Chung et al. 1981; Kollwentz 1990), most of the important data and results remain secret.

The second stage of R&D was followed by several national projects (Herrouin et al. 1989; Kotlinski 1995; Yang and Wang 1997; Yamada and Yamazaki 1998; Hong and Kim 1999; Muthunayagam and Das 1999). Many publications were available from the national projects and other studies regarding seafloor PMN miner design (Li and Zhang 1997; Yasukawa et al. 1999; Hong et al. 1999; Yamazaki et al. 1999; Deepak et al. 2001), the hydraulic lifting characteristics of PMN in the pipeline (Bernard et al. 1987; Saito et al. 1989; Xia et al. 1997; Yoon et al. 2000; Chung et al. 2001), and the hydrodynamics of the riser pipe (Aso et al. 1994; Chung et al. 1994; Cheng and Chung 1997; Ohta and Morikawa 1997; Handschuh et al. 2001). Based on these technical R&D in the earlier stage, some economic feasibility studies on the development (Andrews et al. 1983; Hillman and Gosling 1985; Charles et al. 1990) were carried out. An economic feasibility study on cobalt-rich PMN deposits inside the Cook Islands exclusive economic zone (EEZ) (Søreide et al. 2001) was a unique one, because the high cobalt content in PMN, smaller production rate, and mechanical lifting were assumed in the mining model. Among the national projects, ones conducted by China, India, Korea, and InterOceanMetals are still active.

Seafloor massive sulfides (SMS) in the western Pacific have received much attention as resources for gold, silver, copper, zinc, and lead (Lenoble 2000). Since the end of the 1980s, SMSs have been found in the back-arc basin and on oceanic island-arc areas in the western Pacific, such as the Okinawa Trough (Halbach et al. 1989), the Izu-Ogasawara Arc (Iizasa et al. 1999), the Lau Basin (Fouquet et al. 1991), the North Fiji Basin (Bendel et al. 1993), and the East Manus Basin (Kia and Lasark 1999). Because the same smelting plants with on-land sulfides can accept SMS ores, it is considered that to start SMS mining is easier and cheaper than the other deep-sea minerals. Because of the higher metal contents and favorable social and geophysical conditions, a commercial mining project in Papua New Guinea (PNG) was expected to start from 2019 by a private company (Nautilus Minerals 2018). Although the project failed in 2019, some of the contract details and constructions of mining machineries and a mining vessel which had progressed under the project as well as the economic and technical data that were open to public are quite useful for this study.

In 2008 at Chennai, India, ISA conducted a workshop to evaluate technical and economic possibility of PMN mining. The specifications of mining 5000 t/day (1.5 Mt/year) in wet condition, the transportation and the metallurgical processing subsystems, and the capital and operation expenditures (CAPEX and OPEX) of PMN mining were discussed in the workshop. About 50 specialists in PMN mining technology, metallurgical processing, economics, and international law of the sea attended. Mining and metallurgical processing methods and cost analysis models for PMN were presented at first, then three working groups related to the mining technology, the metallurgical processing, and the economic model were created and the working groups reviewed the past published R&D results and models. At the end of the workshop, CAPEX, OPEX, and methods for mining, transportation, metallurgical processing, and model selection in the working groups were reported. Four mining methods with different collectors and risers and one processing method with hydrometallurgy were included in the report. The four mining methods involved using (a) a passive collector, (b) a tracked collector, (c) a Chinese collector with a steel riser pipe, and (d) Indian small tracked collectors with flexible risers. The draft summary of the workshop was open to the public in 2008 (ISA 2008) and the proceeding including the presentation papers and the economic evaluation results applying all the results of the workshop were open in 2012 (ISA 2012). Because no other opportunity is there to have this kind of extensive review and discussions, the results obtained from the workshop still have high technical and economic values and are useful for this study.

Cobalt-rich ferromanganese crusts (CRC) on the Pacific seamounts received attention as potential sources for strategic metals due to their vast distribution and higher cobalt content than PMN (Cronan 1980; Halbach 1982; Manheim 1986). However, because of the distribution aspect on seamount slope and few geotechnical information available (Yamazaki et al. 1990b), only a few studies were conducted for the mining technologies (Hawaii DPED 1987; DOMA 1995), though the same metallurgical processing methods for PMN are considered to be applied for CRC.

Deep-sea rare-earth element-rich mud (REE-rich mud) on the Pacific seafloor with high contents of rare-earth elements was reported by Kato et al. (2011). The authors also suggested their potential as a rare-earth element resource in the paper. A feasibility study of the REE-rich mud mining reported in economic constraints and proposed an in-situ chemical concentration for improving their economy (Bashir et al. 2012).

2 Economic Feasibility Analyses for Polymetallic Nodules

2.1 Previous Researches

Many publications on scientific, technical, and economic issues are available on PMN, because they were considered as the primary commercial target in deep-sea mineral resources (Mero 1965; Cronan 1980). The geological distribution characteristics have been studied in detail by numerous researchers (Craig and Andrews 1978; Andrews and Friedrich 1979; Friedrich et al. 1983; Von Stackelberg and Beiersdorf 1991; Morgan et al. 1993). However, very little detailed information on the first mining target areas in CCZ was available even in the 1990s (ISA 1999). Assuming basic geological and geophysical factors, some economic feasibility studies on PMN mining were conducted by applying the models (Andrews et al. 1983; Hillman and Gosling 1985; Charles et al. 1990). An economic feasibility study on cobalt-rich PMN inside the Cook Islands EEZ (Søreide et al. 2001) was a unique one, because the smaller production scale and a mechanical lift were assumed in the mining model. The results of these four feasibility studies are summarized and compared in Table 15.1. Because the market demand for manganese in the 1980s and 1990s was only 40% of that in 2019 (Honkawa Data Tribune 2020), the manganese recovery from PMN mining was not considered in some economic analyses (Hillman and Gosling 1985; Søreide et al. 2001). The price reduction in the market due to the large amount of manganese supplied by multiple PMN mining projects; it was considered not to incur the additional metallurgical processing cost for manganese.

2.2 Distribution Model of Polymetallic Nodules

Because PMN population and metal contents are very high in CCZ, the international consortium had studied PMN distribution and authorized their sites under US domestic law (Padan 1990), and most of the Pioneer Investors had presented their survey data to ISA and allotted their sites as contractors (ISA 1998). Areas having PMN abundance of 10 kg/m^2 in wet condition shown in Fig. 15.1 (7.2 kg/m^2 in dry condition) were considered as the first target sites for PMN mining in CCZ. The same value is selected as the PMN population in the distribution model. Since the water depth of CCZ is 4000–5500 m, it is assumed as 5000 m in the model. Depending on the site locations, metal contents in PMN are different, but the example values 1.12% of copper, 1.44% of nickel, and 0.2% of cobalt applied in one of previous study by the author (Yamazaki et al. 2002) are selected as the metal contents of the distribution model. Because the market demand for manganese in 2019 was about 2.5 times of the one in the 1980s and 1990s (Honkawa Data Tribune 2020), the manganese recovery from multiple PMN mining projects has been selected as the basis of an ISA's economic impact study for on-land mining (ISA

Table 15.1 Summary and comparison of earlier economic feasibility studies for PMN mining

Authors Processing method	Andrews et al. (1983) Reduction and hydrochloric acid leach process			Hillman and Gosling (1985) Cuprion ammoniacal leach process			Charles et al. (1990) Reduction and hydrochloric acid leach process			Søreide et al. (2001) High-temperature and high-pressure sulfuric acid leach process		
	Mining (wet)	Trans. (dry)	Process. (dry)	Mining (wet)	Trans. (dry)	Process. (dry)	Mining (wet)	Trans. (dry)	Process. (dry)	Mining (wet)	Trans. (dry)	Process. (dry)
Production(t/year) Operation days	2.3 M 300 days/year	1.5 M 300 days/year	1.5 M 330 days/year	4.2 M 300 days/year	3.0 M 300 days/year	3.0 M 330 days/year	2.3 M 250 days/year	1.5 M	1.5 M	1.1 M	0.7 M	0.7 M
Capital expenditure (CAPEX)	180 M$	176 M$	513 M$	590 M$	310 M$	727 M$	282 M$	188 M$	470 M$	127 M$	93 M$	271 M$
CAPEX ratio	21%	20%	59%	36%	19%	45%	30%	20%	50%	26%	19%	55%
Equity/loan	100/0			100/0			50/50			30/70		
Operating expenditure (OPEX) Loan interest Survey cost	45 M$ 0% 6 M$	25 M$	165 M$	77 M$ 0% 3 M$	37 M$	111 M$	48 M$	36 M$	156 M$	21.8 M$ 8% 1.9 M$	13.5 M$	22.9 M$
OPEX ratio	19%	11%	70%	34%	16%	50%	20%	15%	65%	38%	23%	39%

(continued)

Table 15.1 (continued)

Authors Processing method	Andrews et al. (1983) Reduction and hydrochloric acid leach process			Hillman and Gosling (1985) Cuprion ammoniacal leach process			Charles et al. (1990) Reduction and hydrochloric acid leach process			Søreide et al. (2001) High-temperature and high-pressure sulfuric acid leach process		
	Mining (wet)	Trans. (dry)	Process. (dry)	Mining (wet)	Trans. (dry)	Process. (dry)	Mining (wet)	Trans. (dry)	Process. (dry)	Mining (wet)	Trans. (dry)	Process. (dry)
Metal	**Price**	**Recovery**	**Product**	**Price**	**Recovery**	**Product**	**Price**	**Recovery**	**Product**	**Price**	**Recovery**	**Product**
Co	$ 5.5/lb	85%	3375 t/year	$ 8.53/lb	65%	5070 t/year	$ 6.8/lb	85%	3525 t/year	$ 20/lb	83%	2652 t/year
Ni	$ 3.75/lb	95%	18,525 t/year	$ 3.62/lb	92%	36,708 t/year	$ 3.6/lb	95%	19,730 t/year	$ 3.33/lb	98%	2548 t/year
Cu	$ 1.25/lb	95%	15,675 t/year	$ 1.17/lb	92%	28,704 t/year	$ 0.95/lb	95%	17,810 t/year	$ 1/lb	97%	1890 t/year
Mn	$ 0.4/lb	93%	404,550 t/year				$ 0.3/lb	93%	382,500 t/year			
Taxes NPV IRR	46% 6.4%			Total 29% 7.4%			12%			10% −81 M 9.6%		

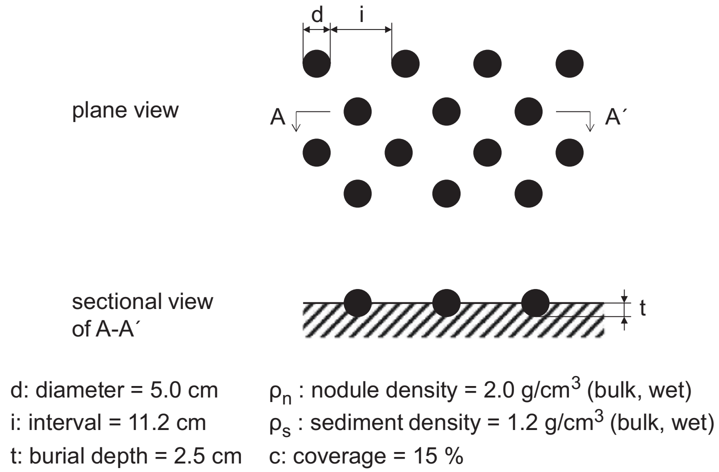


Fig. 15.1 PMN distribution model of 10 kg/m^2 (in wet condition)

Table 15.2 Metal contents of PMN assumed in the distribution model

Metal	Content (%)
Copper	1.12
Nickel	1.44
Cobalt	0.2
Manganese	20

2020). A general value 20% of manganese is selected in the distribution model. The metal contents of PMN used in this model are summarized in Table 15.2. The solid density of 3.25 g/cm^3 and porosity of 55% reported for PMN (Yamazaki et al. 1990a) are selected as the physical properties.

2.3 Production Model

One of the results obtained from the ISA workshop in 2008 (ISA 2012), a specification of mining 5000 t/day (1.5 Mt/year) in wet condition by a tracked collector with a steel riser pipe, and the transportation subsystem for 6000 nm, is assumed as the basic PMN production model. CAPEX and OPEX of the mining and the transportation subsystems calculated in the workshop are directly applied as the ones in this study.

On the other hand, for the metallurgical processing subsystem, smelting and chlorine leaching method (SCL) is selected in this study. Most of the proposed processing methods were examined in a Japan's metallurgical processing program

(Kojima 1997), and SCL was concluded to have an advantage of waste-free characteristics, though its cost was relatively higher than that of some hydro-metallurgical methods. SCL is the best choice as a sustainable production model in this study. The slag obtained after the smelting is used as aggregates for constructions and the sulfur liquid after the leaching is refreshed and reused for leaching. The recovery ratios of 80% for manganese and 94% for the other three metals in PMN with SCL (Kojima 1997) are assumed. CAPEX and OPEX of SCL subsystem are calculated on the basis of the ones estimated for a pilot-scale one in the program (Kojima 1997) by applying the following equation:

$$C_{\mathrm{A}} = C_{\mathrm{B}}\left(\frac{a_{\mathrm{A}}}{a_{\mathrm{B}}}\right)^{n} \tag{15.1}$$

where C_{A} = the value in this study; C_{B} = the value in the reference study; a_{A} = the mass in this study; a_{B} = the mass in the reference study; n = 0.6 scale factor (JCDTCC 1993).

In the mining model of PMN in this study, the following assumptions are selected as basic conditions from the mining technologies, including feasibility studies, metallurgy, and other factors:

- Hydraulic pick-up and mesh screening for sediments
- Water depth of 5000 m
- Separation of lifted PMN and sediments
- Drying of PMN and transferring to carrier vessels
- Transportation distance of 6000 nm from CCZ to the processing location in Japan's mainland
- Processed slag sales as concrete aggregate at 100 $/t
- Calculating CAPEX and OPEX of processing using Eq. (15.1) on the basis of Kojima (1997) and Park et al. (2002)

Important operating conditions in the production models are summarized in Table 15.3. The operation days are assumed as 300 days/year in Table 15.3. It looks too many in case of open ocean area by a hang-on type riser, but in the economic evaluation by ISA (ISA 2012), it was assumed and in case of the mechanical lifting with rope, it may be possible.

Table 15.3 Assumed important operating conditions in the PMN production model

Production per day	5000 t in wet
Operation days	300 days/year
Water depth	5000 m
Transportation	11,100 km (6000 nm)
Duration of mining	25 years (4 years for construction; 1 year for test mining; 20 years for full operation)

2.4 Hydraulic Lifting with Bulk-Scale Tracked Collector

The mining subsystems considered during the 1970s included shuttle miner, continuous line bucket, and hydraulic dredge. The shuttle miner system studied by France was a feasibility study for a mining system utilizing autonomous underwater vehicles (AUV) (Herrouin et al. 1989). Conceptually, the shuttle would descend down to the seafloor, gather PMN into the shuttle body, and return back to sea surface autonomously. The desired production rate would determine the number of shuttles used. The continuous line bucket (CLB) system was an effective approach for small-scale mining requiring less investment cost (Masuda and Cruickshank 1995). This concept utilizes a wireline with many buckets that is circulated from the surface ship to the seafloor. The buckets are designed to scoop up PMN as they are towed across the seafloor. Neither AUV shuttle concept nor CLB was considered effective for a bulk-scale PMN production.

The hydraulic dredge utilizing a towed or tracked collector was the primary subsystem concept selected for R&D for a bulk-scale PMN production, due to its higher reliability and larger production rate. General concept of the hydraulic dredge with a tracked collector is shown in Fig. 15.2. The three major components of the mining

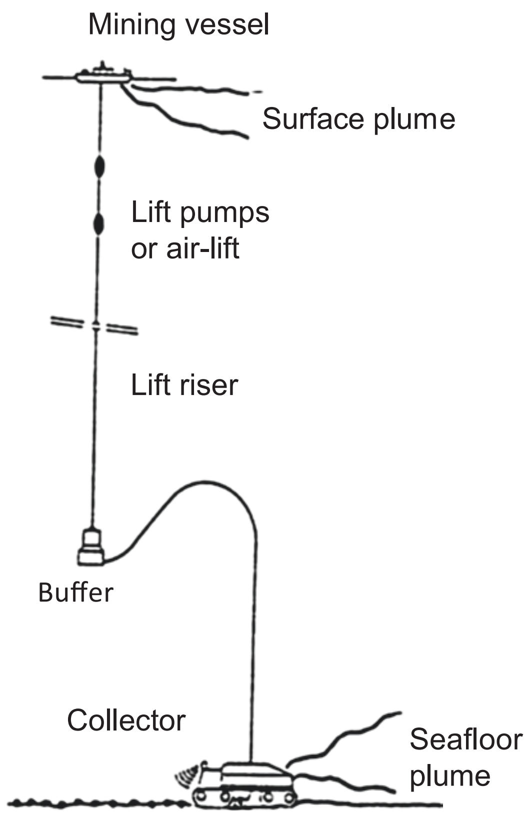


Fig. 15.2 General concept of hydraulic dredge with tracked collector

system are: a bulk-scale seafloor collector, a lift riser in some cases with a buffer, and a mining vessel on sea surface. The collector was designed to pick up PMN (half-buried in sediments on seafloor as shown in Fig. 15.1) and send them via the lift riser through the feed regulating buffer to the surface. The pick-up mechanism uses water flow generated by jet nozzle or water suction created by pump in general. Water flow generated by submersible pumps or air injection (air-lift) sends PMN up to the mining vessel through the riser. The production rate of a commercial PMN mining was assumed to be 10,000 t/day in the 1970s by the consortia. Subsequent to the national R&D programs in the 1980s, however, the commercial production rate of 5000 t/day was considered. The main reason was a result of the progress of dynamic structural analyses of the riser. In this study, hydraulic lifting by a riser and submersible pumps with a bulk-scale tracked collector is assumed as the one of basic concepts of the production model.

2.5 Mechanical Lifting by Polyethylene Ropes with Small-Scale Collectors

In this study, mechanical lifting by polyethylene ropes with small-scale collectors is assumed as another concept of the production model. The author firstly proposed a concept of multiple collectors with mechanical rope lift and current-driven transportation system (Yamada et al. 2009). It was a conceptual idea for minimum energy consumption in PMN mining and transportation system. An updated concept of the mining subsystem assumed in this study is shown in Fig. 15.3. The components are

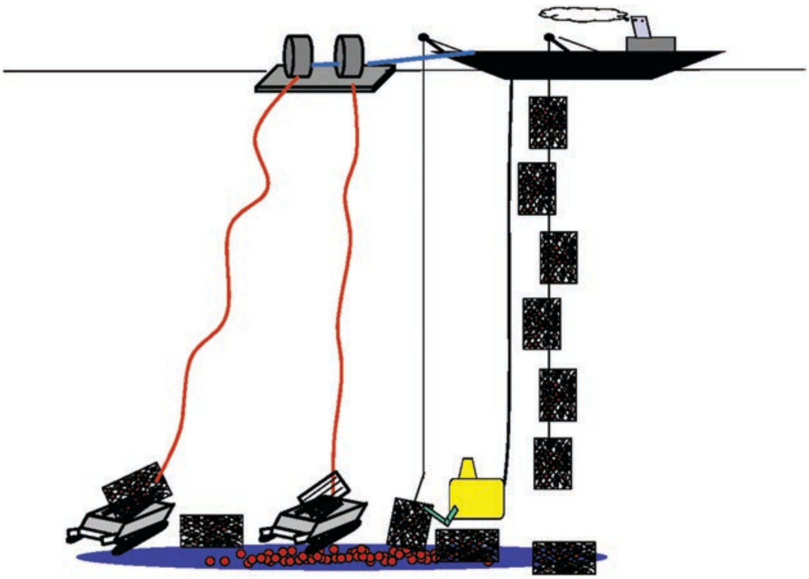


Fig. 15.3 Concept of mechanical lifting with small-scale collector

remotely operated small-scale collectors, surface vessel and platform, ROV, cables, lift ropes and their winches, and mesh bags filled with PMN.

The original small-scale collector, named MineRo-II, was designed and built in 2012 as a component of Korean bulk-scale tracked collector (Lee et al. 2013). With four hydraulic pick-up devices and four crawler tracks under 0.3 m/s forward speed, the PMN collection ability was about 1000 t/day, with four crushers and two discharge pumps to feed crushed PMN to the lifting subsystem being installed on the body. The size of the collector was 5 m wide with 4.5 m PMN pick-up coverage, 6.5 m long, 4 m high, weight of 28 ton (in air), 9 ton (in water) and was capable to operate at 5000 m water depth. It was successfully tested in 2012 at 130 m water depth and in 2013 at 1300 m water depth (Yeu et al. 2013; Hong et al. 2013).

In this study, on the basis of the above-mentioned collector, a small-scale collector installed with four crawler tracks, four hydraulic pick-up devices, a mesh-bag bed, and a bag dumping mechanism with mesh-bag mouth tie-up and release function are assumed as the basic components for a seafloor small-scale collector. The crushers and pumps installed on the original one are replaced by the mesh-bag bed and the bag dumping mechanism. The power and weight considerations are the same as the original ones. The difference of the collector operation with the original one is PMN flow and treatment in the collector. PMN are induced and stored in a polyethylene mesh-bag placed on the bed. Then, the bag is released and dumped after every 10 t (5 t in water) of PMN accumulation in the bag. The bags are laid on the seafloor for recovery.

A single mining system on the seafloor with mining capacity of 1250 t/day comprises two small-scale collectors, a polyethylene rope with an end sinker-weight, and an ROV. The two collectors collect PMN, move forward in parallel along planned paths, and place the mesh-bags filled with PMN on the seafloor as shown in Fig. 15.4. One of the collectors moves 50–100 m ahead from the other. Following the collector operation, the rope with the end sinker-weight is deployed between the two paths. The ROV controls the drop point of the sinker-weight and assists the rope deployment. Based on the PMN population, the width of PMN pick-up, and the pick-up efficiency (90%) of the collector, every 250 m is the distance between the bags on the collector path. A layout image of the collector paths, the rope

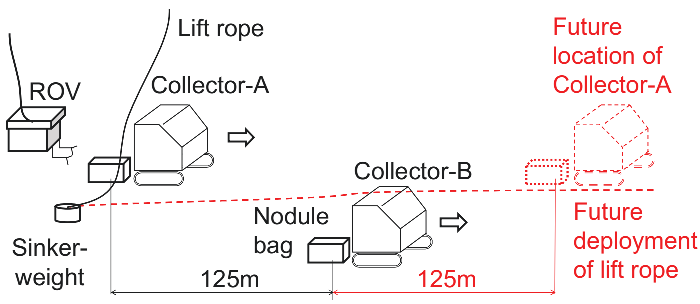


Fig. 15.4 Image of collectors and ROV operations, and lift rope deployment on the seafloor

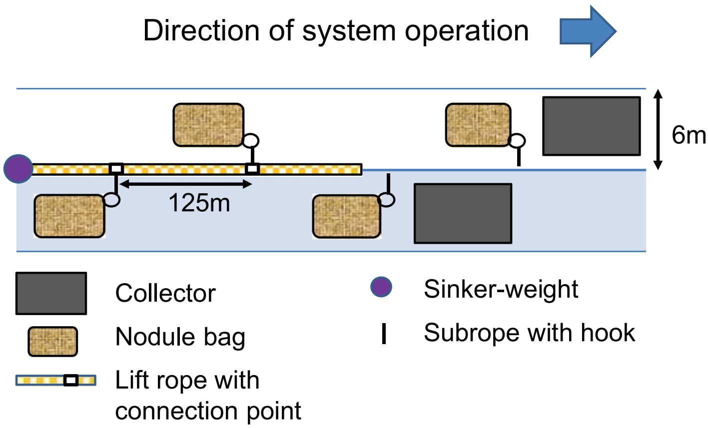
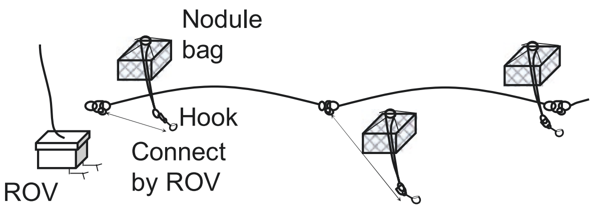


Fig. 15.5 Layout image of the collector paths, the rope deployment, and the bags on the seafloor

Fig. 15.6 Image of bag and lift rope connection by ROV



deployment, and the bags on the seafloor is shown in Fig. 15.5. The bag installs a link rope and an end hook. On the other hand, because of the length of the polyethylene fiber, named Dyneema, is limited to 130 m, a unit length of the rope is 125 m and the units are connected by thimbles and shackles. The shackle point at every 125 m becomes the connection point of the hook of the bag. Thus, a connection point of the hook is there every 125 m in the lift rope as shown in Fig. 15.5. The hook and the shackle are connected by ROV as illustrated in Fig. 15.6. The polyethylene fiber has the same tensile strength as steel wire and 0.97 g/cm^3 in specific gravity. This means the lift rope including thimbles and shackles is almost neutral weight in water. The mesh-bag is also made of the same polyethylene fiber.

For an extension of at least 8000 m rope (3000 m for bag connection and 5000 m for water depth) with 25 bags and the recovery, it takes about 4.5 h, 1.5 h for rope deployment, 1 h for rope and bags connection, and 2 h for lift-up. Five turns per day are necessary for the production of 1250 t/day and so four mining systems are necessary for the production of 5000 t/day. After storing PMN into a storage room on the surface platform, the mesh-bags are recovered for the next usage and made into a bag-package to go down to the seafloor with the sinker-weight. At the seafloor the bag-package is delivered and fixed to the collectors by ROV.

2.6 Economic Factors Applied in Analyses

In this study, 10-year average prices of metals in the period of 2008–2017 (DWE 2020) are used. The prices of nickel, copper, cobalt, and manganese used for PMN economic analyses are listed in Table 15.4.

CAPEX and OPEX of subsystems in the two PMN production models in this study are listed in Table 15.5. One of the results obtained from the ISA workshop in 2008 (ISA 2012), a specification of mining 5000 t/day by hydraulic lifting with a tracked collector, and a transportation subsystem for 6000 nm are directly used in this study. The values of mechanical lifting with small-scale collectors are also included in Table 15.5. The construction cost of MineRo-II is used as the base of calculation of the small-scale collector. On the basis of above-mentioned operational concept of the mechanical lifting by polyethylene rope with small-scale collectors, a basic design was conducted by a ship design company. Some quotations were collected from ship building, rope manufacturing, and marine generator manufacturing companies and CAPEX was calculated. OPEX was calculated based on the energy consumptions, estimated maintenance costs, etc.

CAPEX and OPEX of metallurgical processing by SCL of the production model are calculated on the basis of the ones estimated for a pilot-scale one in the program (Kojima 1997) and applying Eq. (15.1). They are included in Table 15.5.

Table 15.4 Metal prices used in economic analyses (average of 2008–2017) (DWE 2020)

Metal	Price ($/t)
Ni	16,121
Cu	6678
Co	34,698
Mn	2463

Table 15.5 CAPEX and OPEX of subsystems used in this study

Subsystem	CAPEX ($M)		OPEX ($M)	
Mining	Hydraulic	Mechanical	Hydraulic	Mechanical
	563	795	96	144
Transportation	495		93	
Metallurgy	1062		181	
Total	2120	2352	370	418

Table 15.6 Results of economic analyses

Hydraulic			Mechanical		
NPV ($M)	IRR (%)	PP (year)	NPV ($M)	IRR (%)	PP (year)
1777	13.2	8.3	892	9.7	9.1

2.7 Results of Economic Analyses

The three economic measures, the net present value (NPV), the internal rate of return (IRR), and the payback period (PP) are calculated as shown in Table 15.6. Both results are very attractive economics. One important remark is OPEX of mining subsystem in case of hydraulic lifting. The lifetime of steel riser pipe of about 5000 m in open ocean area might be less than a couple of year, because the one of 1800 m in inter-island sea area was estimated for 2–5 years (Stanton and Yu 2010). In OPEX of the hydraulic lifting model assumed in this study, the short lifetime is not considered, because the original ISA model itself did not consider (ISA 2012). Hence, as of now, better one is not concluded, because OPEX of mining subsystem for hydraulic lifting might increase.

3 Economic Feasibility Analyses for Seafloor Massive Sulfides

3.1 Previous Researches

Because the same smelting plants with on-land sulfide ores can accept SMS ores, it is considered that to start SMS mining is easier and cheaper than the other mining of deep-sea minerals. After the mining of SMS ores and the ore dressing, it is possible to sell the sulfide concentrates to customer smelters in Japan, China, and Korea. This was the reason why some SMS ventures initiated their business in the 1990s (Malnic 2001). In addition, from the geophysical properties of SMS ores (Yamazaki and Park 2003; Golder Associates 2012) and the ones of on-land sulfide ores, the design of bulk-scale SMS miner with mechanical cutting tools was considered to be possible and the production feasibility study was conducted (SRK Consulting 2010). Because of the higher metal contents and favorable social and geophysical conditions, a commercial SMS mining project in East Manus Basin, PNG, was expected to start from 2019 (Nautilus Minerals 2018).

However, there were many problems for mining of SMS in the other areas. One of the problems was how to dump waste rocks excavated together with SMS ores. If they were collected with SMS ores and lifted up to surface vessel, it caused increases in both CAPEX and OPEX of mining including the waste disposal cost (Yamazaki et al. 2013a). In order to overcome the problem, it was proposed to adapt a primary ore separation technique on the seafloor prior to the lift-up (Yamazaki et al. 2013b) on the basis of the specific gravity difference between waste rocks, 2.5 g/cm^3, and SMS ores, 3.3 g/cm^3 (Yamazaki and Park 2003). The other problem was an increase of standby days in SMS mining operation caused by stronger wave, wind, and current conditions in western Pacific SMS distribution areas (Halbach et al. 1989; Fouquet et al. 1991; Bendel et al. 1993; Iizasa et al. 1999) except PNG, because they are open ocean areas. In order to shorten the standby days, a mining method by self-standing riser was proposed and the economy was improved (Yamazaki et al. 2016).

Since 2008 the Ministry of Economy, Trade and Industry, Japan has conducted an R&D program of SMS. Based on an in-situ excavation and lifting test by a hydraulic lifting device with a small-scale test miner conducted in 2017 (JOGMEC 2017b), an economic assessment report was prepared in 2018 (METI 2018). An economic viability of SMS mining venture was proposed in the report as follows: a good economic viability exists if they can: (1) secure economically highly valuable deposits in terms of both quality and quantity higher than the target of this assessment; (2) establish efficient production technologies; (3) metal prices increase to appropriate levels. Among the production technologies, the most important but difficult problem was the heavy metal ion concentrations involved in the lifted water. Because they were higher than the environmental standard, no water was discharged at the test area. All the lift water was carried back to an on-land water treatment plant to remove the ions from the water.

3.2 Distribution Model of Seafloor Massive Sulfides

A seafloor exposed SMS mound confirmed by core drillings in Izena Caldera, Okinawa Trough in Japanese EEZ shown in Fig. 15.7 is assumed as a distribution model of SMS ore body in this study. Two ore bodies, one is the exposed and the other is the buried, were confirmed by 55 core drillings of 2712 m total length (JOGMEC 2016b). The buried one is considered to be out of mining target, because the sediment cover is difficult to remove from viewpoint of economy and ecology. Because in Okinawa Trough, many possible SMS ore bodies have been found

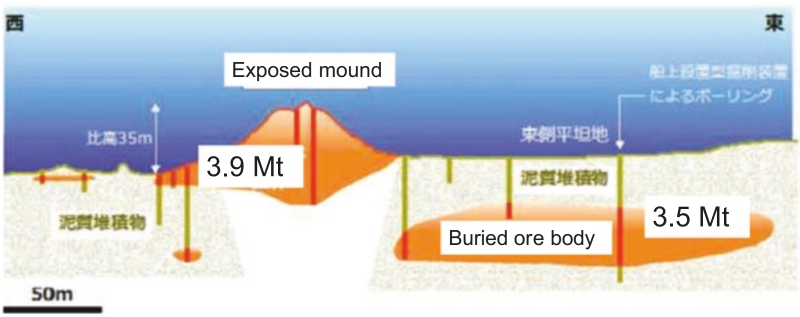


Fig. 15.7 Confirmed two SMS ore bodies in Izena Caldera, Okinawa Trough (JOGMEC 2016b)

(JOGMEC 2015; JOGMEC 2016a; JOGMEC 2017a), it is possible to assume after 3 years of mining operation in Izena Caldera, a SMS mining venture can move to next ore bodies and continue the operation.

Because no economically highly valuable SMS ore body other than the one in Izena Caldera has yet been found, the metal contents of the exposed mound in Izena Caldera (JOGMEC 2013) shown in Table 15.7 are assumed as the ones for the SMS distribution model in this study.

3.3 Production Model with Ore Separation on Seafloor

From the results of survey and drilling in PNG (Golder Associates 2012) and Japan (JOGMEC 2016b), an image of mound-type SMS ore body has been created as in Fig. 15.8. The mound size is 200–500 m in horizontal directions and 20–30 m in height. From the results of Japan's R&D program of SMS, the heavy metal ion concentrations involved in the lift water (JOGMEC 2017b) show that only two types of production models can be economically and ecologically acceptable for SMS mining venture. Both the models must include an ore separation subsystem on the seafloor to improve economic feasibility. The subsystem is composed of SMS

Table 15.7 Metal contents of SMS ore body in Izena Caldera, Okinawa Trough (JOGMEC 2013)

Metal	Content
Cu	0.41%
Au	3.2 g/t
Ag	250 g/t
Zn	9.69%
Pb	3.49%

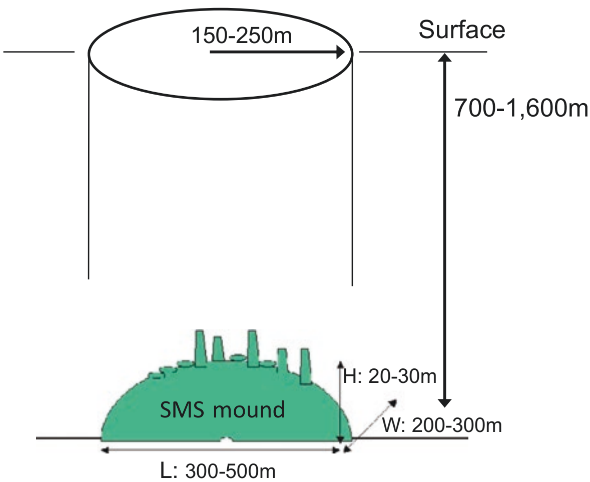


Fig. 15.8 Image of spatial extension of mound-type SMS ore body

Table 15.8 Assumed important operation conditions in the SMS production models

Excavation per day	4080 t in dry
Operation days	308 days/year
Water depth	1600 m
Transportation	1000 km
Duration of mining	18 years (3 years for construction; 1 year for test mining; 3.5 years × 3 for full operation; 0.5 years × 3 for relocation; 2 years for full operation)
Waste disposal cost	200 US$/t

ore crusher, particle size sorter, and gravity separator. Applying the subsystem, on the basis of the specific gravity difference between waste rocks, 2.5 g/cm^3, and SMS ores, 3.3 g/cm^3 (Yamazaki and Park 2003; Golder Associates 2012), it becomes possible to enrich the metal contents in SMS ores to be lifted up. Technical approaches for the gravity separation on the seafloor are introduced in previous studies (Yamazaki et al. 2013b, 2016, 2017). The waste separation ratio of 50% in the subsystem was selected in this study, because higher metal contents and more expensive metal prices were required for economic viability as per the results of Japan's R&D program (METI 2018). The waste separation technique acts like artificial quality and quantity improvements of SMS ores. The critical operating conditions assumed in the production models are listed in Table 15.8. The production scale and operation days are the same as the PNG parameters. During crushing, some amount of heavy metal ions leaches out from SMS ores. Because oxygen concentration in bottom water is very low and some water circulation is there, the ion concentrations at the bottom are expected to remain below the required environmental standards. After the transportation to Japan's mainland, the SMS ores are handled in a mineral-processing plant. Applying froth flotation, concentrates are recovered and waste rocks are removed in this plant. Then the concentrates are sold to customer smelters in Japan. The price of concentrate is a reduced one in order to consider the smelters' benefit margin (Treatment Charges-TC and Refining Charges-RC) from the summation of included metal price. The waste rock disposal cost should be included in OPEX of mineral-processing subsystem. The cost is very high in Japan as shown in Table 15.8. The land scape, rainfall, and population are the reasons.

Another important point of the production models in this study is the re-location of the seafloor plant including ore separation, sorting, and separation functions and the lifting equipment. Because of the SMS ore distribution model shown in Fig. 15.8, the mining operation remains in a small area of a few hundred meters in diameter for about 3–5 years. Therefore, both the conceptual images of mining subsystems for a hydraulic lifting and a mechanical lifting shown in Figs. 15.9 and 15.10 are designed to stay at the same location for 3–5 years. The entire re-location process is expected to take about several months. In this production model, the re-location is assumed every 4 years. The production condition in the model is 100% in the first 3 years and 50% in the last year, respectively.

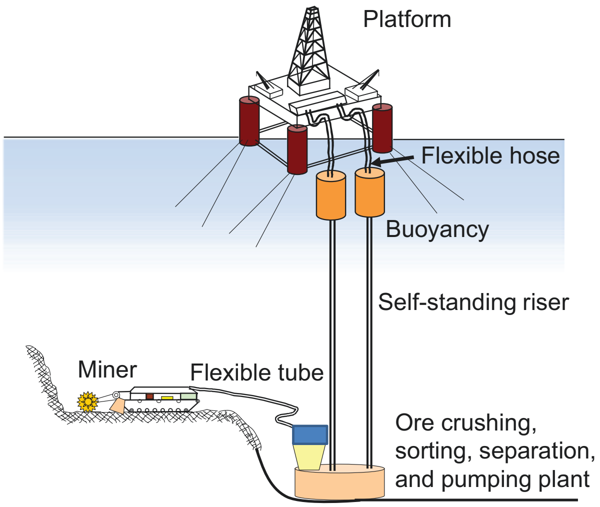


Fig. 15.9 Conceptual image of hydraulic lifting by loop self-standing risers with ore separation on the seafloor plant

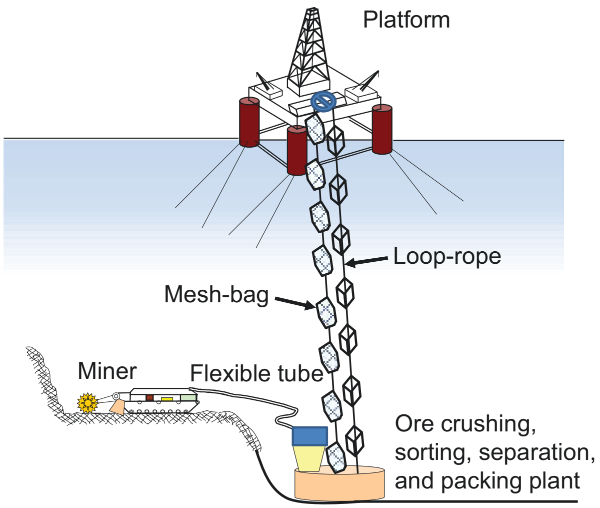


Fig. 15.10 Conceptual image of mechanical lifting by loop-rope and mesh-bag with ore separation on the seafloor plant

3.4 Hydraulic Lifting with Loop Self-Standing Risers

An economic analysis of SMS production model with single self-standing riser and ore separation on the seafloor was carried out (Okuhara et al. 2018) prior to the Japan's economic assessment report (METI 2018), and the result was attractive in economic terms. In view of the Japan's result (JOGMEC 2017b), in this study the hydraulic lifting model uses two self-standing risers and makes a water circulation loop with the two. If the hydraulic lift water circulates in the loop, we need not worry about the ecological problem due to higher heavy metal ion concentrations in lift water. In addition to the ore separation subsystem on the seafloor, an additional ore introducing equipment into the riser is necessary. A conceptual image of the loop self-standing risers and the seafloor plant is introduced in Fig. 15.9. A bulk-scale tracked miner is assumed in the model. The usage of a self-standing riser for SMS mining was originally proposed in a design of SMS mining system for open ocean area by Technip (Parenteau 2010) and the loop was also proposed by the company (Rongau 2017), after the heavy metal ion concentrations involved in the lift water became the problem (JOGMEC 2017b). Increase of operation days of the mining system in open ocean area and almost no water discharge in the water column are the great advantages. In Fig. 15.9, a combination installation of lift pump unit into the seafloor plant is also included.

3.5 Mechanical Lifting by Polyethylene Rope and Mesh-Bags

Mechanical lifting by polyethylene rope with bulk-scale miner is another production model for SMS mining. Because of the seafloor pre-processing plant, the other types of mechanical lifting such as bucket elevator, and bucket lift with wire are possible to select. The almost neutral weight in water of the polyethylene fiber, however, is very big advantage for lift rope and mesh-bag. A conceptual image of the mechanical lifting by polyethylene rope and mesh-bag is introduced in Fig. 15.10. It looks like a continuous loop-rope and mesh-bag lift. The length of loop-rope is double of the water depth. The size of mesh-bag will be enlarged than PMN in case of SMS mining. In the seafloor plant, after the waste rock separation, SMS ores are packed into mesh-bags attached on the loop-rope. Separate mechanism to connect the bag to the lift-rope by ROV as in PMN mining is not required. During the rope-lifting near surface, because of higher oxygen concentration of surface water, heavy metal ions will be dissolved into surface water from SMS ores. However, the concentrations are expected to remain below environmental standards, because the mesh-bag speed in the water column will be very high and ore crushing will not occur in the bag.

3.6 Economic Factors Applied in Analyses

In this study, 10-year average prices of metals in the period of 2007–2016 (DWE 2020) are used. The prices of copper, gold, silver, zinc, and lead used are listed in Table 15.9. CAPEX and OPEX of subsystems in the two SMS production models in this study are listed in Table 15.10. OPEX of mining subsystem in Table 15.10

Table 15.9 Metal prices used in economic analyses (average of 2007–2016) (DWE 2020)

Metal	Price
Cu	US$ 6808/t
Au	US$ 1210/oz
Ag	US$ 20/oz
Zn	US$ 2114/t
Pb	US$ 2086/t

Table 15.10 CAPEX and OPEX of subsystems assumed for SMS mining

<table>
<tr><th colspan="2" rowspan="2">Subsystem</th><th rowspan="2">Ore mass per year</th><th colspan="2">CAPEX ($M)</th><th colspan="2">OPEX ($M)</th></tr>
<tr><th>Hydraulic</th><th>Mechanical</th><th>Hydraulic</th><th>Mechanical</th></tr>
<tr><td rowspan="2">Mining</td><td>Excavation</td><td>1,260,000 in wet</td><td rowspan="2">666</td><td rowspan="2">682</td><td rowspan="2">144</td><td rowspan="2">88</td></tr>
<tr><td>Lift</td><td>946,000 in wet</td></tr>
<tr><td colspan="2">Transportation</td><td>804,000 in dry</td><td colspan="2">197</td><td colspan="2">59</td></tr>
<tr><td colspan="2">Mineral processing</td><td>804,000 in dry</td><td colspan="2">36</td><td colspan="2">73</td></tr>
<tr><td colspan="2">Total</td><td></td><td>899</td><td>915</td><td>276</td><td>220</td></tr>
</table>

includes riser and plant re-location cost, US$60 million for the re-location (US$15 million per year).

3.7 Results of Economic Analyses

The three economic measures, NPV, IRR, and PP, for both the hydraulic and mechanical models are calculated as shown in Table 15.11. Better economics might be obtained, if the downtime of production with re-location, 0.5 year, is shortened. Because the waste disposal cost is very high in Japan, even in the case of 50% waste separation ratio, the result of hydraulic lifting with loop self-standing riser is slightly negative in economics. Only mechanical lifting by polyethylene rope and mesh-bag shows an economical result. These results show the waste separation ratio of 50% or more on the seafloor is a minimum requirement in Japanese terms to realize commercial SMS mining.

Table 15.11 Results of economic analyses

Hydraulic			Mechanical		
NPV ($M)	IRR (%)	PP (year)	NPV ($M)	IRR (%)	PP (year)
−348	−13	NA	41	6.3	14.6

4 Economic Feasibility Analyses for Combined Mining of Cobalt-Rich Ferromanganese Crusts and Phosphorous Ores

4.1 Previous Researches

CRC on the Pacific seamounts have received attention as potential sources for strategic metals such as Co, Ni, Cu, and Mn, due to their vast distribution and higher cobalt content than PMN (Cronan 1980; Halbach 1982; Manheim 1986). In the earlier stage, the geological distribution characteristics were reported (Cronan 1984; Clark et al. 1984; Misawa et al. 1987; Pichocki and Hoffert 1987), and a systematic feasibility of mining was studied (Hawaii DPED 1987).

From the end of the 1980s, Japan conducted many survey cruises for CRC in and around the Mid-Pacific Mountains (Yamazaki et al. 1994; Usui and Someya 1997; Yamazaki and Sharma 1998; MMAJ 2001). Some key technological studies for mining and processing also were conducted (Aso et al. 1992; DOMA 1995; Yamazaki et al. 1995; Rokukawa 1995; Yamazaki et al. 1996; DOMA 1998). On the basis of these studies and referring some economic evaluation results for PMN mining (Andrews et al. 1983; Hillman and Gosling 1985; Charles et al. 1990; Søreide et al. 2001), the economic potential of CRC mining for Co, Ni, and Cu recovery was evaluated by Yamazaki et al. (2002). Some options and updated economics were considered in the series of the studies (Yamazaki and Park 2005; Yamazaki 2007; Goto et al. 2009, 2010). Among the studies, evaluating the excavation efficiency of CRC mining, a simulation study by a miner model under idealized distribution conditions was an important one (Goto et al. 2009). Because the thickness of CRC layer is very thin and the micro-topographic undulation of CRC distribution areas is complicated, a degradation of mined ore by the substrates during CRC mining is expected (Yamazaki et al. 1992). In the mining simulation of CRC (Goto et al. 2009), the thickness of CRC layer was assumed as 10 cm, and four types of micro-topographic undulation shown in Fig. 15.11 were used. One directional sine curve across miner track and flat (Type 1), cross-directional sine curves and flat (Type 2), one directional sine curve and 10-degree inclination across miner track (Type 3), and cross-directional sine curves and 10-degree inclination across miner track (Type 4) were the micro-topographic undulations assumed in the simulation study (Goto et al. 2009).

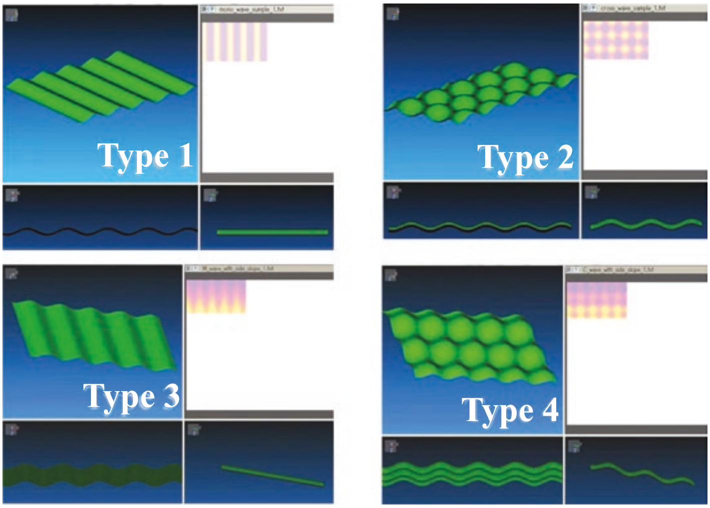


Fig. 15.11 Micro-topographic undulation models of CRC

4.2 Distribution Model of Cobalt-Rich Ferromanganese Crusts and Phosphorous Ores

One of the above distribution models in the mining simulation study (Goto et al. 2009), that is, cross-directional sine curves and 10-degree inclination across miner track (Type 4), is assumed in this study. The thickness of CRC layer is assumed as 10 cm. From these assumptions and the geotechnical properties of CRC and the substrates (Yamazaki et al. 1995), the CRC distribution density is given as 200 kg/m^2 in wet condition.

Most of substrates of CRC have recently been classified as phosphatized limestone and hyaloclastite (Hein et al. 2016). About 12–15% in their weights is phosphorous (Hein et al. 2016). The contents are the same as the on-land phosphorous ores which Japan imports from China and Morocco. This is an interesting distribution pattern for Japan, because Japan has large areas of CRC in the Japanese EEZ and the adjacent ocean areas (MMAJ 2001). Hence, Japan's mining sites of CRC could be with the phosphatized basements. These substrates that may be unavoidably recovered with CRC during the mining operation would become byproducts of phosphorous ores and hence, it would be a combined mining of CRC and phosphorous ores.

The metal and phosphorous contents of CRC and substrates in the distribution model in this study are shown in Table 15.12.

Table 15.12 Metal and phosphorous contents of CRC and substrate

Metal	Content
Copper	0.13%
Nickel	0.50%
Cobalt	0.64%
Manganese	25%
Phosphorous	14% (in substrate)

4.3 Production Model with Mechanical Lifting

The same miner and cutout models assumed in one of the previous studies shown in Figs. 15.12 and 15.13 (Goto et al. 2009) are selected for this study. The miner has five drum-type rollers with many sharp spikes for CRC cutout. Each roller width is 1 m and the cutout depths by the rollers are independently controlled. The recovery of CRC and substrates under the surface micro-topographic undulation is shown in Fig. 15.13. After the cutout, CRC and substrates are sucked up and transported to lift subsystem. The cutout depth is the most important factor to affect the recovery of CRC and accompanied substrates. Increasing cutout depth means increasing the recovery of CRC under micro-topographic undulation. However, over cutout also causes larger recovery of substrates as shown in Fig. 15.14 (Goto et al. 2009). In case of the model distribution assumed in this study, from the simulation results shown in Fig. 15.14 (Goto et al. 2009), the 20 cm of cutout is selected as the best one for the combined mining of CRC and phosphorous ores. In case of 20 cm of cutout, the ratio of about 5:3 in CRC and phosphorous ores is the favorable value.

As introduced in Tables 15.13 and 15.14, a production model for the combined mining is created. Assumed important operation conditions are introduced in Table 15.13 and assumed ore flow in Table 15.14, respectively. The basis of the production model includes the excavation mass on the seafloor and the amount of phosphorous ores imported to Japan. Because of the cutout operation and the geophysical properties of CRC and substrates (Yamazaki et al. 1995), the same level as with SMS is a reasonable excavation scale which is the first important point for consideration. The phosphorous ore production assumed from the combined mining is almost the same as the amount of phosphorous ore imported from overseas is the second important point. Mechanical lifting by polyethylene rope and mesh-bag similar to PMN mining is the fundamental component of the production model. A bulk-scale miner like the one for SMS is another important component. The bulk-scale miner excavates CRC and substrates and sorts them into mesh-bags and then leaves the bags on the seafloor. Because the mining subsystem needs to cover about 20,000 m^2 per day, in case of the miner of 5 m in width, it needs to move about 4000 m/day. The mesh-bag size is enlarged a few times larger than the one for PMN. An ROV assists the delivery of mesh-bags to the miner, the lift rope deployment by sinker-weight, and the bag connections to the lift rope.

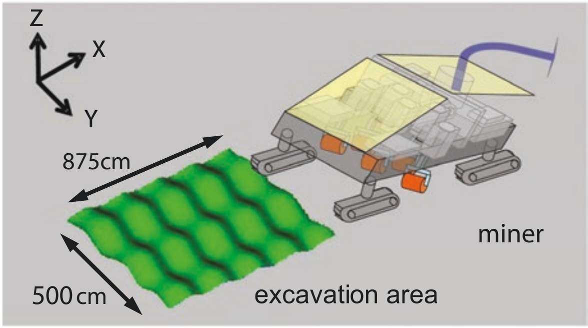


Fig. 15.12 Miner and distribution model in this study

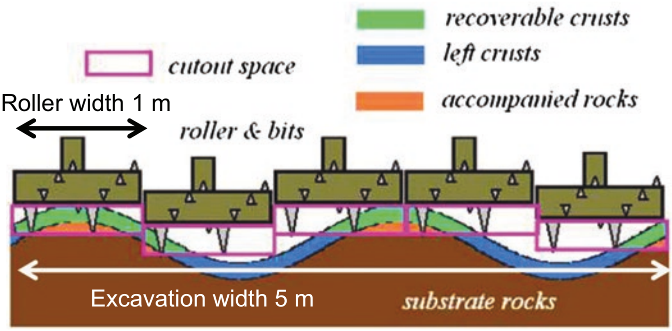


Fig. 15.13 Cutout model by miner in this study

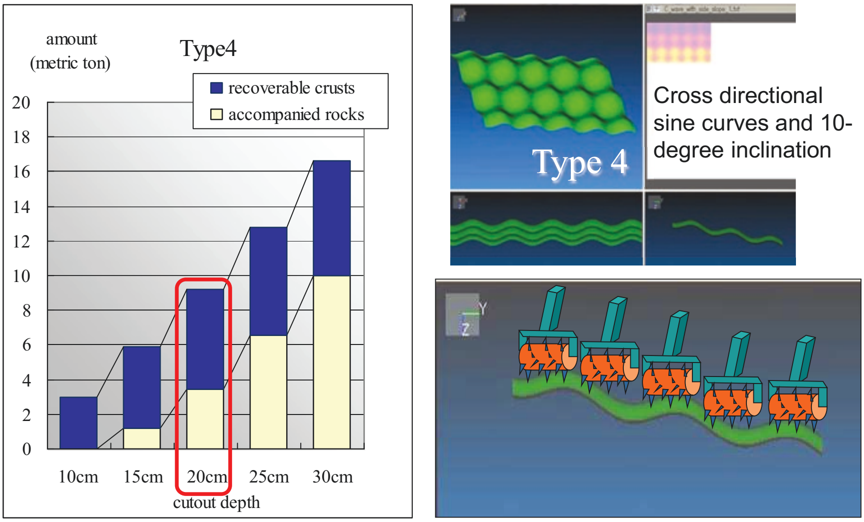


Fig. 15.14 Simulation results for Type 4 (Goto et al. 2009)

Table 15.13 Assumed important operation conditions in the combined mining production model

Excavation per day	4000 t in wet
Operation days	250 days/year
Transportation	2000 km
Duration of mining	25 years (4 years for construction; 1 year for test mining; 20 years for full operation)

Table 15.14 Assumed mass flow through subsystem processes

Subsystem	Ore flow (t/year)
Mining	1,000,000 (wet)
Transportation	800,000 (dry)
Ore dressing	800,000 (dry)
Metallurgical processing	500,000 (dry) (phosphorous ore 300,000 (dry))

The lifted CRC and substrates are dried on board of the mining vessel and transferred to carrier vessels. The masses in dry condition are calculated from the geophysical properties of CRC and substrates (Yamazaki et al. 1995). In Japan's main land, after desalination the substrates are sold as phosphorous ores and CRC are transferred to an SCL metallurgical processing subsystem, which is the same for PMN production. The slag after processing is sold as concrete aggregate in 100 $/t like PMN production. The mass supplied for the metallurgical processing subsystem is about a half of the one for PMN production.

4.4 Economic Factors Applied in the Analysis

In this study, 10-year average prices of metals in the period of 2008–2017 (DWE 2020) are basically used. Two exceptions are the prices of cobalt and phosphorous ore. If 10-year average price of cobalt is applied, it is not economical and if 10-year average price of phosphorous ore is selected, the spike-like price increase in 2008 and 2009 is included. Hence, the selected period in case of cobalt is mid-2017–mid-2018 and in case of phosphorous ore is 2012–2017. The cobalt price is about 2.5 times more than the 10-year average price of 2008–2017. The prices used in the analyses are summarized in Table 15.15. CAPEX, OPEX, and ore flow of subsystems in the combined production model in this study are listed in Table 15.16. CAPEX and OPEX are calculated from the productions of PMN and Eq. (15.1).

Table 15.15 Metal prices used in economic analysis (average of 2008–2017 except cobalt and phosphorous ore) (DWE 2020)

Metal	Price ($/t)
Copper	6678
Nickel	16,121
Cobalt	80,436 (average of mid-2017–mid-2018)
Manganese	2463
Phosphorous ore	120 (average of 2013–2017)

Table 15.16 CAPEX and OPEX of subsystems assumed for combined mining

Subsystem	CAPEX($M)	OPEX($M)
Mining	623	69
Transportation	216	65
Ore dressing	39	15
Metallurgical processing	669	84
Total	1547	233

Table 15.17 Results of economic analysis

NPV (US$M)	IRR (%)	PP (year)
922	10.6	12.8

4.5 Results of Economic Analysis

The three economic measures, NPV, IRR, and PP, are calculated as shown in Table 15.17. Because the money inflow and outflow are improved about US$ 150 million per year with the phosphorous ore and processed slag sales, it is attractive economics. The high cobalt price applied in the analysis is as per the market forecast for electric and plug-in-hybrid-type vehicles and cobalt demand as electrode for lithium-ion battery onboard of the vehicles (Avocado-festival 2021). Hence, the key of economic mining is cobalt price.

The result of economic analysis of the combined mining of CRC and phosphorous ores is attractive if cobalt price is high. The waste free characteristics including processed slag usage for aggregate may have a chance for commercial mining if cobalt price rises up.

5 Economic Feasibility Analyses for Combined Mining of Polymetallic Nodules and Rare-Earth Element-Rich Mud

5.1 Previous Researches

The presence of REE-rich mud on the Pacific seafloor which involves high contents of rare-earth elements was reported (Kato et al. 2011). Two areas with high contents of REE-rich mud in the range of 500–1500 ppm, such as off Hawaii in the northeastern equatorial Pacific and off Tahiti in the southeastern Pacific, were identified. The authors of the paper suggested the potential of REE-rich mud as a resource for rare-earth elements. Followed by few feasibility studies on the mining of REE-rich mud were conducted (Bashir et al. 2012; Abe et al. 2012; Wolgamot et al. 2013). However, because of the presence of an overlaid sediment layer, several tens of meters thick, with poor rare-earth element contents, the results showed that the 500–1500 ppm contents were not great enough for the economical mining. One of the papers (Bashir et al. 2012) proposed an in-situ chemical concentration for improving the economy. In 2013, another higher content area was found by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) near Minamitorishima (Marcus) Island in the Japanese exclusive economic zone (EEZ) (JAMSTEC Press Releases 2013). In this area, there are rare-earth element-rich layers with 5000–6500 ppm contents within 10 m below the seafloor, which is 5600–5800 m deep. The distribution aspects of this area and its potential as a rare-earth element resource have been reported in detail (Iijima et al. 2016; Takaya et al. 2018). The feasibility of mining REE-rich mud in the area using ferromanganese nodule (PMN) mining technologies was examined two times (Yamazaki et al. 2014; JOGMEC 2016c). Both the results showed unfavorable economic feasibilities.

5.2 Distribution Model of Polymetallic Nodules and Rare-Earth Element-Rich Mud

Because of the presence of an overlying sediment layer with poor rare-earth element contents, and a difficulty of the removal, an averaged rare-earth element content of about 1000 ppm from the seafloor surface to the target depth, the same as in Abe et al. (2012) shown in Table 15.18, is assumed for the distribution model of REE-rich mud near Minamitorishima Island in the Japanese EEZ. For example, the average top 5 m of the sediment column contains 0 ppm from the seafloor surface through to 4 m and 5000 ppm from 4 through to 5 m, averaging to 1000 ppm for the entire 5 m section.

In 2016, a vast PMN area of co-occurrence with REE-rich mud was found by JAMSTEC near Minamitorishima Island in the Japanese EEZ. The location and

Table 15.18 Rare-earth element contents in REE-rich mud assumed in distribution model from Abe et al. (2012)

Element	Content (ppm)
Ce	177.9
La	154.0
Pr	46.2
Nd	192.6
Sm	44.9
Eu	11.1
Gd	49.0
Tb	7.3
Dy	45.4
Y	277.2

Table 15.19 Metal contents in PMN assumed in distribution model from the Japan Agency for Marine-Earth Science and Technology (JAMSTEC Press Releases 2016)

Metal	Content (%)
Ni	0.4
Cu	0.2
Co	0.5
Mn	20.0

nodule distribution aspects were described (JAMSTEC Press Releases 2016). The area was estimated to be 44,000 km^2, and an updated information for PMN distribution in the area has been reported (Machida et al. 2021). The metal contents of PMN were similar to those of CRC on the Pacific seamounts (Machida et al. 2016). The metal contents of PMN reported by JAMSTEC (JAMSTEC Press Releases 2016) and shown in Table 15.19 are assumed in the distribution model. They are cobalt-rich, copper-poor, and nickel-poor, similar to CRC and different from PMN in CCZ. The PMN abundance is assumed as 10 kg/m^2 in wet condition (7.2 kg/m^2 in dry condition) like the first target sites for PMN mining in CCZ introduced in Fig. 15.1 in the distribution model.

5.3 Production Model with Pulp-Lifting

Because of the co-occurrence, a unique lift method is applicable for the combined mining of PMN and REE-rich mud. The method is called pulp-lifting. It was investigated in a French PMN R&D program in the 1980s (Herrouin et al. 1989). A non-Newtonian solid-water mixture with a high solid powder volumetric concentration of 55–60% was created by mixing crushed PMN, deep-sea sediments, and water in an experimental study under the R&D program. Then, the mixture was circulated in a 15 m vertical experimental pipeline by a piston pump. Because of the drastic reduction in frictional resistance between the pipe wall and the high-concentration pulp, it was found that the pipe diameter would be about half of the one required for a same-nodule mass transportation under a normal solid-liquid slurry. The pump power necessary was found to be quite lower than the one for the same mass transportation under normal solid-liquid slurry. Pulp-lifting has never been used in any deep-sea mining programs, but the method is popularly applied for coal-water mixtures (CWM) in many coal electricity power stations. CWM created by powder coal and water with a mass concentration of about 70% is supplied to a boiler through a pipeline (Ogawa and Shibata 1990).

In the combined mining model of PMN and REE-rich mud proposed here in this study, the following assumptions are selected as basic conditions from the PMN mining technologies, including feasibility studies, metallurgy, and other factors:

- Production rate of 6000 t/day in dry conditions for REE-rich mud and 3000 t/day in dry conditions for PMN
- Hydraulic cut and suction for REE-rich mud excavation
- Hydraulic suction for PMN collection followed by crushing
- Mixing and pulp-making and then feeding to a piston pump
- Pumping up through a riser
- Solid volumetric concentration of 55% and seawater concentration of 45% in pulp
- Water depth of 5800 m
- Drying the lifted pulp and transferring it to carrier vessels
- Transportation distance of 2000 km from Minamitorishima Island EEZ to the leaching and processing location in Japan's mainland
- Separation of REE-rich mud and crushed PMN
- Leaching by HCl and solvent extraction with recovery ratios of 24% for Ce and 92% for other rare-earth elements in REE-rich mud (Abe et al. 2012)
- Brick making by adding cement powder to the leached mud after neutralization and desalting and then providing it for construction material free of charge
- Processing by the smelting and chlorine leaching method (SCL) with recovery ratios of 80% for Mn and 94% for the other three metals in PMN (Kojima 1997)
- Sale of processed slag as concrete aggregate in 100 $/t
- Calculating CAPEX and OPEX of the mining model except for the brick-making and processing using Eq. (15.1)
- Calculating the CAPEX and OPEX of the brick-making on the basis of Tsuji et al. (2015)
- Calculating the CAPEX and OPEX of the processing using Eq. (15.1) on the basis of Kojima (1997) and Park et al. (2002)

One of the most important assumptions is the production rate of 6000 t/day in dry conditions for REE-rich mud. This was calculated from Japan's domestic rare-earth element consumptions and the rare-earth element contents of REE-rich mud

Table 15.20 Assumed important operation conditions in the combined mining production model

Excavation per day	PN: 3000 t in dry REE-mud: 6000 t in dry
Operation days	250 days/year
Water depth	5800 m
Transportation	2000 km
Duration of mining	25 years (4 years for construction; 1 year for test mining; 20 years for full operation)

recovered. The production rate of 3000 t/day in dry conditions for PMN was selected as half of REE-rich mud. Because higher concentrations of REE-rich mud and crushed PMN and lower quantity of seawater from the pulp-lifting are recovered on the mining vessel, all underwater and the onboard facilities including the vessel itself are smaller than those used in the previous studies (ISA 2012; Abe et al. 2012; Yamazaki et al. 2014). The direct drying of the lifted pulp is also induced from the higher concentrations. Two more important points are the brick making out of the waste and the selection of the metallurgical processing method, both of which are waste-free methods and the best choice for a sustainable development production model. Assumed important operation conditions in the combined mining production model are introduced in Table 15.20.

5.4 *Economic Factors Applied in Analyses*

Data on prices of rare-earth elements are available through paying member sites (SMM Information and Technology 2021; MetalPrices 2021). In this study, based on the 5-year average prices of rare-earth elements in the period 2013–2017 (to exclude the higher ones in 2012), the 10-year average prices of the four metals in PMN during the period 2008–2017 (DWE 2020), the contents in Tables 15.18 and 15.19, and their recovery ratios assumed in the mining model, the revenues of the mining model under the basic conditions are calculated as shown in Table 15.21. It is obvious that the revenues from PMN are 4.7 times more than the ones from REE-rich mud under the basic conditions of the combined mining model. In the economic evaluation, the first 4 years are assumed to be devoted to construction with no income, while the fourth year is assumed to be used for test operations with 50% income. Then, the next 15 years, from the 6th year to the 20th year, are assumed to be used for full mining, with 100% income. The total yearly income is calculated as about $780 M, because the revenues listed in Table 15.21 and about $50 M from the slag sales are included. The prices of rare-earth elements in REE-rich mud and metals in PMN, and their yearly revenues under the basic conditions are listed in Table 15.21. CAPEX and the OPEX of the mining system are less expensive, as shown in Table 15.22.

Table 15.21 Assumed prices and estimated revenues from their production under the basic conditions

Element and metal	Price ($/t)	Yearly revenue ($M)
Ce	15,000	1.2
La	15,000	3.8
Pr	125,833	9.6
Nd	83,333	26.6
Sm	35,000	2.6
Eu	1,500,000	27.6
Gd	100,000	8.1
Tb	1,033,333	12.5
Dy	508,333	38.2
Y	56,666	26.0
Ni	16,121	51.8
Cu	6678	11.3
Co	34,698	155.6
Mn	2463	354.7
Total		729.6

Table 15.22 Estimated capital and operating expenditures (CAPEX and OPEX) under basic conditions

Subsystem	CAPEX ($M)	OPEX ($M)
Mining	179.7	80.7
Transportation	223.8	33.7
Leaching (REE-mud)	198.3	261.9
Brock making	155.6	226.0
Processing (PMN)	863.6	110.8
Total	1621.0	713.1

5.5 *Results of Economic Analyses*

The three economic measures, NPV, IRR, and PP, are calculated as shown in Table 15.23. The results show a slightly negative economic condition.

Because the revenues from PMN shown in Table 15.21 have larger effects on economics, sensitivity analyses for PMN production rates are examined. In the analyses, the production of REE-rich mud is fixed as 6000 t/day and the ones of PMN nodules are increased from 3000 t/day to 7000 t/day. In each analysis, CAPEX, the OPEX, and the income are recalculated. The results of NPV are summarized in Fig. 15.15. About 4000 t/day is found as the point of NPV = 0.

Table 15.23 Results of the economic evaluation under basic conditions

NPV ($M)	IRR (%)	PP (year)
−526.7	3.66	15

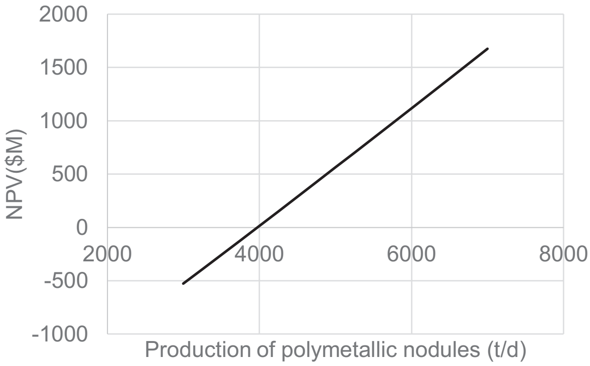


Fig. 15.15 Sensitivity analyses of net present value (NPV) using PMN production rates

From the results of economic analyses, the combined mining of PMN and REE-rich mud with pulp-lifting has a possibility for commercial mining. The following three innovative changes in the mining model have improved the economics of mining:

- Combined mining of PMN and REE-rich mud
- Pulp-lifting
- Reuse of waste mud and processed slag as construction materials

Many R&D efforts such as the following are necessary to realize the mining:

- How to make the pulp with crushed PMN and REE-rich mud
- How to excavate REE-rich mud
- How to reduce environmental impacts around seafloor
- How to lengthen the service lifetime of riser pipe

6 Concluding Summary

From the economic analyses introduced in this chapter, it is recognized that why deep-sea mining has not realized in the last 50 years. PMN might be considered to have a chance. The lifetime of riser pipe, however, is a technical and economical bottleneck of PMN. Some technical ideas to improve the economics introduced in this chapter, such as mechanical lifting, by rope and mesh-bag, ore selection on seafloor, self-standing riser, combined mining, pulp-lifting, and reuse of wastes, should be R&D targets for next generation.

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Chapter 16
Conceptual 3D Modeling and Direct Block Scheduling of a Massive Seafloor Sulfide Occurrence

Steinar L. Ellefmo

Abstract The transition toward more environmentally friendly energy production and e-mobility will increase the global demand for metals and minerals. The ocean floor might contribute to meet this demand. This would require that the mineral resources are managed well, from both governmental and industry perspectives. Strategic mine planning is an integrated part of such a management process and is here developed for deep-sea mining based on state-of-the-art methodologies developed for onshore mining. Focus is on seafloor massive sulfides (SMS) deposits known to contain anomalous amounts of, for example, copper, zinc, gold, and silver. It is known that the deposits can form cone-shaped ore geometries. This calls for a mining method inspired from onshore open pit mining. Conceptual 3D geometric and qualimetric models of the Loki's Castle occurrence along the Arctic Mid-Ocean Ridge are developed. Based on these models and the characteristics of a preferred mining system, a 3D economic block model is developed. This model is used in direct block scheduling with varying sets of assumptions to develop the ultimate pit and schedules for a potential extraction.

Keywords Deep-sea mining · Open pit optimization · Mine planning · Marine mineral resource management

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1 Introduction

1.1 Scope of Work

Mineral Resource Management (MRM) was coined by Blaauw and Trevarthen (1987) and further developed and described by Macfarlane (2006) as the identification, the optimization and the realization of the deposit value, by converting it from an inferred to indicated and measured resources to probable and proved reserves (JORC 2012) and finally a saleable product. The goal of MRM is according to Camus (2002) to develop and implement the mine plan, where the mine plan is an overview stating when the operation will extract what qualities and tonnages from where. As stated by Haugen (2015), this includes elements of planning, organization, and management of mining and related activities. In governance, MRM is often linked to awarding exploration permits, approval of mine plans, and the consideration of concession applications. From an industry perspective MRM can also be viewed as the development and the communication of mine-plans. The general principles in these definitions traditionally used for terrestrial mining include the need for a geological model quantifying the size and the quality of the deposit and the ability to evaluate some future exploitation given framework conditions like environmental, economic, and legal factors. This would be equally important for the development of deep-sea mining operations. However, only sparse data about the geometry and qualimetry of potential deposits on and in the ocean floor are available. Exceptions are the Solwara 1 deposit (Lipton 2012) and to some extent the TAG-site (Humphris et al. 1995) and other publications after the Ocean Drilling Program Leg 158, for example (Herzig et al. 1998a). In the absence of data, the option when assessing potential mining concepts is to materialize available knowledge on how these deposits form and transform this knowledge into a conceptual 3D model that can be used for exploration planning and predictions and further develop geological and economic block models that in turn can be used in testing mining scenarios and an assessment of environmental stressors linked to this mining system. This chapter devolves into the workflow of developing the necessary 3D models and illustrates strategic (long-term) mine planning in a mineral resource management perspective for deep-sea mining operations. It aims to develop procedures and approaches to assess SMS deposits on a strategic level and the optimization step is used to assess the differences between potential solutions given certain framework conditions. Any optimization is only as certain as the inputs and the inputs in this study are uncertain. The optimization step is still included to illustrate its use and link to geological modeling in its broadest sense.

In the absence of sufficient data, a number of simplifications have been made. No link between rock mass or rock strength properties and energy consumption during operation has been used. Furthermore, only one processing route is assumed. It is therefore assumed that all ore types can be processed using one processing technology and that the recovery distributions are independent of textures, mineralogy, and mineral chemistry variations in the ore types. Ore texture information and input to assessing recovery rate estimates are obtained from literature (Herzig et al. 1998a, b; Kowalczuk et al. 2018, 2019; Snook et al. 2018; Yoshizumi et al. 2015). No attempts have been made to predict future commodity prices and specific costs, but scenarios have been defined to assess the sensitivity of varying inputs.

This study is centered around the Loki's Castle occurrence discovered by Pedersen et al. (2010a). It is herein not suggested that this occurrence should be mined. That might be one potential outcome of a governmental controlled thorough assessment and management process following the principles stated in the marine mineral- and cross-sectoral legislations. The assessment workflow developed and tested in this study would be a natural part of such a process.

1.2 Software Used

The implicit geological modeling tool Leapfrog Geo version 6.0.5 (Seequent 2021) has been used in this study to develop the conceptual 3D geometric ore body model and the discretization of the geometric model into litho-dependent or mineralization-type-dependent block models. Following an export from Leapfrog, litho-dependent unconditional grade simulations have been performed in SGeMS version 2.1 (Remy et al. 2021) for the relevant commodities. The obtained normally distributed numbers have been transformed into assumed lognormal grade distributions in MS Excel where the economic block models have been developed by merging grades, mining and processing recoveries, mining system availabilities, market information, and cost structures. To generate the final input into the open pit optimization tool MiningMathversion 2.2.23 (MiningMath 2020) the litho-dependent economic block models from MS Excel were merged into one file using Matlab R2020b (9.9.0.1467703).

2 Occurrence, Geodata Availability, and Mine Site Characterization

Loki's Castle is an active hydrothermal vent field at the ultra-slow-spreading Arctic Mid-Ocean Ridge located at 73°30′N, 8°E (Baumberger et al. 2016; Pedersen et al. 2010a, b) (see Fig. 16.1).

The Loki's Castle two-mound occurrence is located at about 2300-m water depth between 300 and 350 nautical miles from Longyearbyen on Spitsbergen and the cities of Tromsø, Narvik and Hammerfest on the mainland of Norway. The hydrothermal fluids are sediment-influenced, and the occurrence lies on an axial volcanic ridge formed by young pillow lavas. Chimneys are up to 11-m high and show a maximum temperature of the fluids of 317 °C (Ludvigsen et al. 2016; Pedersen et al. 2010b). The radius of each of the two mounds is approximately 70 m and their

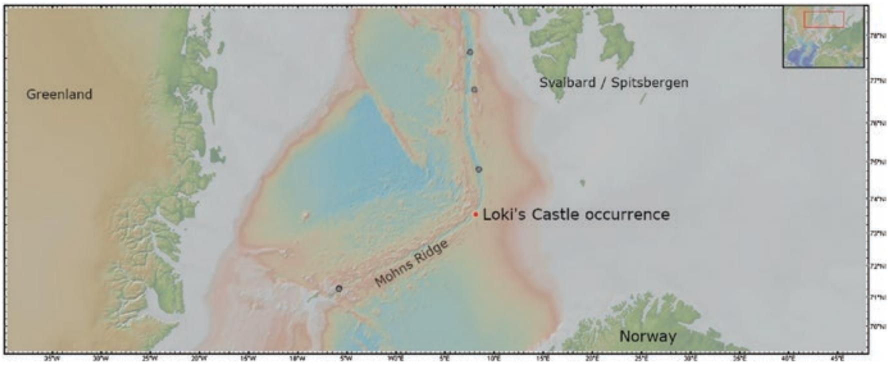

Fig. 16.1 Overview map showing the location of the Loki's Castle occurrence. (Source: GeoMapApp ver. 3.6.6 and Interridge Vents Database ver. 3.4)

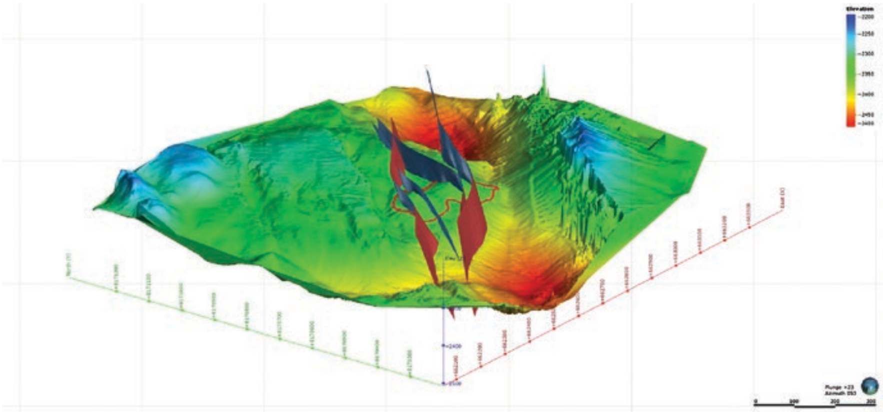

Fig. 16.2 Bathymetry of the area presented with assumed and used occurrence "outcrop" boundary (red polyline) and interpreted fault structures. Fault structures extended above the ocean floor for illustrative purposes. Bathymetric data collection during the MarMine-cruise (Ludvigsen et al. 2016)

summit is approximately 30-m above the level of the assumed occurrence outcrop (red line in Fig. 16.2). The occurrence is partly covered by sediments. Faults seen in the bathymetry data are assumed to provide channels for fluids migration and occurrence formation (Pirajno 2009). Figure 16.2 shows the ocean floor topography, assumed geometry outcrop, and interpreted fault structures. It is postulated that the interpreted 3D orientation of the faults can be used to indicate the orientation of the 3D occurrence geometry.

The Loki's Castle occurrence has not been drilled, so sample material representative for the interior does not exist. The proposed internal zonation is therefore derived from other drilled accumulations and grade data has been simulated for the purpose of illustrating a possible workflow for strategic mine planning for deep sea mining operations.

Using metocean data (Reistad et al. 2011) significant wave height, H_s, and spectral peak period, T_p, can be assessed for the area in question. The most frequent H_s is between 0.75 and 1.5 m with a probability of 37%. The T_p is between 5.7 and 7.6 s in 29% of the time. Lesage (2020) assesses the performance of a mining system inspired by the mining system planned by Nautilus Minerals Inc. (Jankowski et al. 2010) placed under these harsh weather conditions and finds that the monthly downtime of the riser and lifting system varies between 25% (summer) and almost 100% (winter).

3 Mineral Processing and Mining System

In the following economic block model development, it has been assumed that the extracted material would be processed using a combination of comminution, flotation, and pyrometallurgy to process, smelt, and refine the ore and the mineral concentrates to reach the saleable products, that is, commodities. These processing steps are covered in detail in, for example, Fuerstenau et al. (2007), Schlesinger and Biswas (2011), and Wills et al. (2015). No link between processing costs and occurrence quality variations has been developed. The concept of net smelter return has been used to take smelting, refining, and transportation costs into account.

Performing a deep-sea mining system design exercise is out of this contribution's scope. The mining system proposed by Nautilus Minerals (Jankowski et al. 2010) with associated daily costs has been used for inspiration. This proposed mining system consists of two seafloor production tools (SPTs) that combined crushes and transfer the ore to stockpiling hoods on the seafloor. Using a third SPT, the ore is collected and transferred from the stockpiles to the riser and lifting system that transports the ore-slurry to the topside production support vessel. Here the ore is dewatered and temporarily stored before it is loaded onto a bulk carrier for horizontal transportation for further processing and refining onshore. Water from the dewatering process is returned to the ocean floor. Figure 16.3 shows a conceptual mining system setup with one SPT (GRID Arendal 2014).

4 Strategic Mine Planning

Strategic mine planning and open pit optimization are about finding the best contour of a future (open) pit. Available methodologies can be traced back to the development of the Lerch-Grossmann algorithms (LG) (Lerchs and Grossmann 1965) and are thoroughly explained in textbooks like Hartman and Mutmansky (2002) and Darling (2011). More recent contributions include, but not limited to, the use of mixed integer programming (Askari-Nasab et al. 2011), neural networks (Sayadi

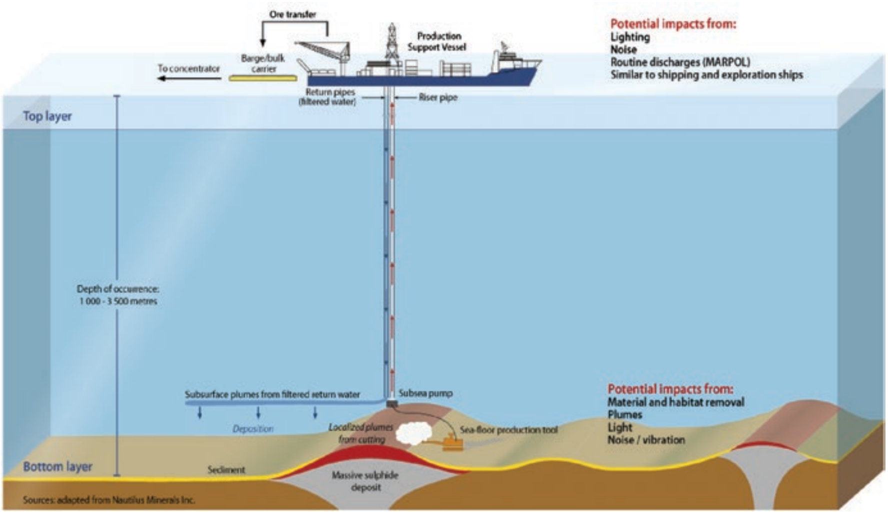

Fig. 16.3 Conceptual mining system setup. Ore is crushed by the seafloor production tools, lifted vertically to the topside/the production support vessel, and transferred to the bulk carrier for transportation to the concentrator. Water from the dewatering process is returned to the ocean floor. (Source: GRID Arendal 2014)

et al. 2011), heuristic approaches (M. J. F. Souza et al. 2010; Montiel and Dimitrakopoulos 2017), and local branching (Samavati et al. 2017). For underground stope optimization comparable methodologies have been developed by Alford et al. (2007) and Alford and Hall (2009) and scheduling methodologies by Little et al. (2008).

Development of the economic block value of the minerals in the ground is the first step toward the strategic mine plan. Normally, the deposit is discretized into regular blocks that are assigned economic values based on mining and processing costs, the mineralogical content, and processing and mining performance indicators. The block-by-block performance indicators like the processing recoveries depend on properties such as mineralogy and mineral textures, hardness, mechanical strengths, and post-crushing particle size distribution. The estimation of the input to assess the performance indicators is traditionally carried out using some linear or non-linear estimation technique like ordinary or indicator kriging (Goovaerts 1997; Chilès and Delfiner 2012). An economic block value is estimated on a block-by-block basis from the revenue obtained when the block is sold (R), the costs of extracting the block (MC), and the costs of processing the block (PC). Combined, these give the economic value block value in block i:

$$\text{Block value}_i = R_i - \left(MC_i + PC_i\right) \tag{16.1}$$

The calculation of the block value is detailed in Sect. 5.3.

The economic block value and the mine plan will be influenced by the key levers or the technical variables deciding the many, *how to do it* and *when to do it*, in the mine plan (Camus 2015; McCarthy 2015):

- Mining method selection: The key question is how to mine the deposit. Decisions will influence the cost structures and the timing of costs and revenues.
- Processing route: Given the characteristics of the raw material, how should it be processed? Decisions will influence cost structures, recoveries, product quality, and capacities (throughputs).
- Scale of operation: What annual rate of production should the mine aim for given the availability of raw inputs such as energy? The annual rate of production will influence the operational costs and the necessary investments.
- Scheduling and sequencing: Given the preferred mining method, the processing route (s) and the scale, where should mining commence and move to progressively exploit the ore body and what ratio between ore and waste rock and what equipment should be used at a given point in time?
- Cut-off policy: A cut-off is a threshold that is compared to an estimate of the decisive parameter in question and is used to find the appropriate use of the smallest mining unit (the SMU). Given key levers 1–4, the question is what cut-off policy optimizes the preferred objective function (see below) that can for example be net present value, internal rate of return or mine life, or operational costs.

These key levers are high-level factors. Rahmanpour and Osanloo (2014) make a breakdown of relevant factors for the mine plan and discusses dependent, independent, controllable, and not-controllable factors that influence the mine plan. The development of the mine plan is an iterative process, and all five key levers must be considered in parallel. Traditionally, the mine planning process consists of three phases (Ota and Martinez 2017). First, the ultimate pit is developed based on the economic block model using, for example, LG-algorithm. Secondly, pushbacks are defined inside the ultimate pit based on nested pits that are developed from varying price or cost scenarios. Thirdly, benches within the pushbacks are scheduled where decisions regarding what to mine when are made. One of the major drawbacks with this traditional approach is that the ultimate pit is developed based on an optimization of the *undiscounted* operational cash flow. Direct block scheduling (DBS) originally proposed by Johnson (1968) has, with the introduction of 64-bit computer technologies, been developed into a real alternative to the traditional approach based on the LG-algorithm (Beretta and Marinho 2015; Campos et al. 2018; Morales et al. 2019; F. R. Souza et al. 2018). DBS considers all defined mining periods simultaneously and generates pit designs that maximize the *discounted* operational cash flows while respecting operational constraints like maximum pit slope angle, production capacities, and mining widths.[1] All steps of the traditional approach are made

[1] Mining width corresponds to the minimum mining width that effectively can be mined given the preferred mining equipment. For the deep-sea mining case, this would be defined by the dimensions of the seafloor production tool (the SPT).

simultaneously using DBS and thus is more likely to result in a global optimum rather than a series of local maxima. The main input, however, is the economic block model, that in turn is based on the geological model and the cost structure, the characteristics, and the performance of the preferred mining system.

Optimization is central in strategic mine planning. As part of the optimization process, the reality must be converted to a model of that reality. This model is called the optimization model. This consists of (1) the objective function which is used to measure the quality of different solutions, (2) one or more sets of decisions which represent a solution, and (3) a set of conditions that are characteristics that must or must not be part of the solution. In optimization the goal is to find the solution that satisfies the conditions and maximizes or minimizes the objective function (the quality measure). To inform the objective function, various inputs are needed. For this case study these inputs are geological and economic data, structured in and developed from the 3D geometric model, the 3D qualimetric model, and the 3D economic block model. The development of these models is described in the following.

5 Establishing the 3D Models

5.1 3D Geometric Model

The 3D geometric model represents the outer contour of the deposit and internal ore zone geometries. Normally, modeling input is core data giving information about the different lithologies and their characteristics, geophysics giving valuable information about the outer contour and potential information about internal continuity and zoning, structural data indicating the orientation of the geometry, and the outcrop indicating the geometry boundaries on the surface or as in the present case, on the ocean floor. For the model developed herein, very limited data are available apart from an ocean floor expression in the bathymetric data and fault lines. Lim et al. (2019) published the results from a study on magnetic data collected during the MarMine cruise in 2016 (Ludvigsen et al. 2016) indicating a possible depth of the geometry. Information about the geometric characteristics of the sediment cover has been retrieved from Murton et al. (2019) along with potential ore geometries. The possible ore geometry and internal zonation have been based on the TAG site and inspired from Galley et al. (2007), Graber et al. (2020), Grant et al. (2018), and Hannington et al. (1998). Murton et al. (2019) develop and present a relationship between ore tonnage and the radius of the bathymetric expression on the ocean floor. This information has been used to cross-check the obtained volume of the geometry. Given the zoning presented by Hannington et al. (1998), the outcrop, the interpreted faults and the results presented in Lim et al. (2019), the two-mound cone-shaped geometry has been modeled down to roughly 100 m below seafloor

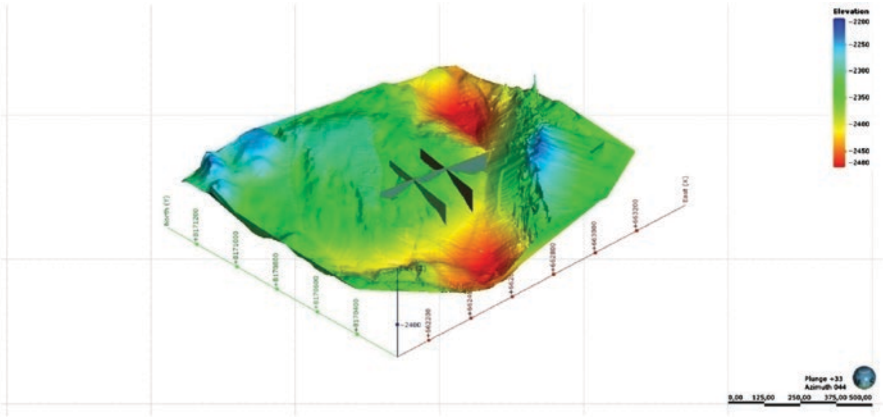

Fig. 16.4 Cross section location cutting the two mounds N-S in an eastern and western section and one cross section oriented E-W

(mbsf). Figure 16.4 shows the location of the cross sections used to illustrate the 3D geometric model in Fig. 16.5.

Following zonation descriptions in Hannington et al. (1998) and in newer related publications Grant et al. (2018), the geometry has been, sitting in unaltered volcanic rock, divided into chloritized basalt, a silicified-pyritic stockwork zone (the feeder zone), a Cu-rich core, a Zn-rich zone, and a sediment cover. Figure 16.5 illustrates the 3D geometric model including the internal zonation in the cross section shown in Fig. 16.4.

The cone-shaped geometry of the conceptual deposit calls for a mining method inspired from open pit mining operations onshore. The zone-dependent volumes and associated estimated tonnages with the given density are summarized in Table 16.1.

The general features of this geometry fit well with results in Asakawa et al. (2018), Murton et al. (2019), and de Sá et al. (2021).

5.2 *3D Qualimetric Model*

A qualimetric model is a spatial representation of the quality variations within some boundaries. In metalliferous mining, "quality" is typically measured by the metal grade, strength, mineralogy, or textures (e.g., grain size or grain shape). The qualimetric model is usually established by applying some geostatistical technique (Goovaerts 1997) on data. de Sá et al. (2020, 2021) use a combination of principal component analysis and kriging and simulation methodologies to model the quality variations and zonation in a drilled occurrence in the Hakurei Site in the Okinawa Trough, southwest Japan (Ishibashi et al. 2015). No core data is available for the Loki's Castle site, and in the absence of such data, no spatial information about the

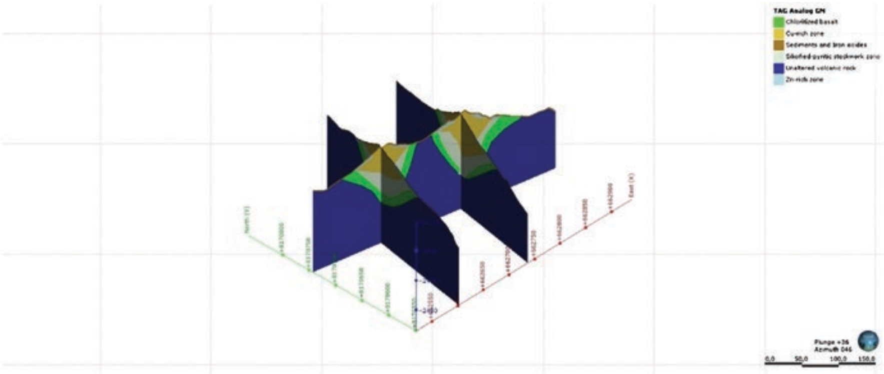

Fig. 16.5 The 3D geometric model evaluated on the cross sections in Fig. 16.4

Table 16.1 Volume and tonnage summary for the different modeled zones in the occurrence. Density derived from Fig. 16.10

Zone	Volume (m^3)	Density (ton/m^3)	Tonnage (ton)
Sediment	265,000	3.35	887,750
Stockwork	367,000	3.35	1,229,450
Cu-rich	245,000	3.35	820,750
Zn-rich	175,000	3.35	586,250
Sum tonnage hypothetical resource (no applied grade cut-off)			3,524,200

grades or any other potential quality parameter is available. Grade information is crucial for the development of the economic block model. To accommodate the development of the conceptual economic block model that allows for the open pit optimization exercise, a 3D qualimetric block model has been developed using the following procedure:

1. Develop the 3D geometric model using Leapfrog Geo.
2. Define a block model that spatially covers the 3D geometric model. A block size of $2 \times 2 \times 2$ m has been used.
3. Evaluate the zonation of the 3D geometric model onto the block model. Each block in the block model will thereby have an attribute valued according to the litho-type/zone the block sits in.
4. Make zone-dependent exports of the block model from Leapfrog Geo.
5. Import the zonation-based block models into the geostatistical software SGeMS. This contributes to assuring that the zonation is considered in the grade development.
6. Simulate unconditionally block-by-block normally distributed random values ($N(0,1)$) given the variography (spatial correlation) from Solwara 1 (Lipton 2012) with sequential Gaussian simulation (SGS) (Chilès and Delfiner 2012). Other simulation techniques could have been applied, but the SGS was used for its availability in the SGeMS-software, straightforward implementation, and its

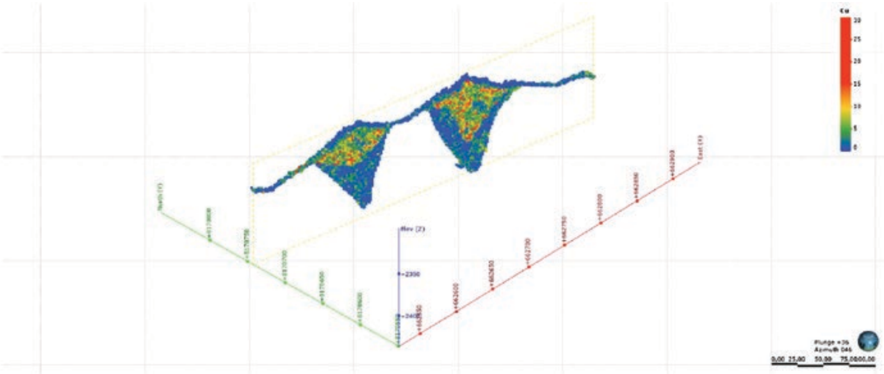

Fig. 16.6 Cu grade distribution inspired by Solwara 1 grades inside the 3D geometric model along the east-west trending cross section given in Fig. 16.4

well-proven robustness (Emery 2004). The simulation is done for the relevant commodities, in this case gold, silver, zinc, and copper, for every zone.

7. Transform the simulated data from bullet 6 into values that correspond to lognormal distributed data with the grade characteristics (mean and variance) from the literature. The transformed data are assumed to correspond to one possible outcome of the grade distribution in that zone and is used in the development of the economic block model.

Figure 16.6 shows the Cu distribution based on the Solwara 1 grades (Lipton 2012) in the east-west trending cross section of Fig. 16.4. The sediment cover contains only small amounts of Cu and the Cu-rich zone is richer than the silicified-pyritic stockwork zone, indicated by the higher density of high-grade (red) blocks. Figure 16.7 shows similar 3D grade distribution as shown in Fig. 16.6, but based on the TAG-site (Grant et al. 2018). The unaltered volcanic rock and the chloritized basalt has been assumed to be barren and their geometries/grade distributions are therefore not included in Figs. 16.6 and 16.7.

Tables 16.2 and 16.3 summarize the block-by-block grades simulated unconditionally and transformed into lognormal distributed data while obeying a maximum grade requirement given by the cited sources. Where Solwara 1 and TAG grades are the same (e.g., in the Zn-rich zone), relevant zone-dependent grades have not been available in the Solwara 1 data.

These grades can be compared to tests performed in the Indian Ocean within the German license area at, for example, the Kairei and the Edmond hydrothermal occurrences. Gallant and Von Damm (2006), Gamo et al. (2001), Han et al. (2018), and Kumagai et al. (2008) provide basic information about these sites. Weixler (2018) gives a grade summary for these two occurrences. This is presented in Table 16.4.

Compared to both the Solwara 1 (Table 16.2) and the TAG (Table 16.3) occurrences used in this study as the basis to populate the qualimetric model, the listed

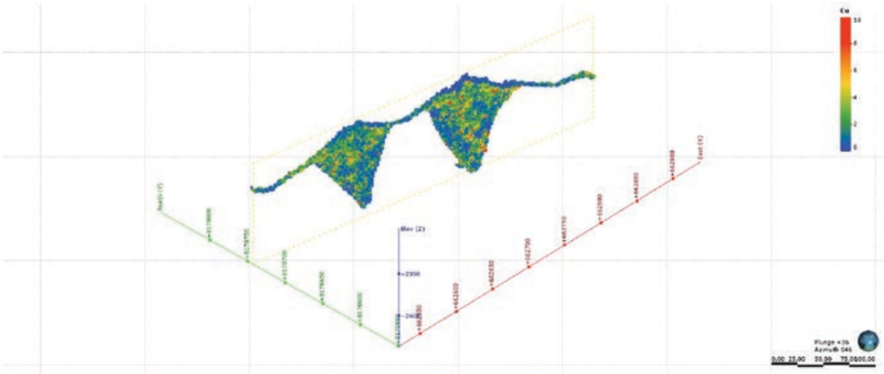

Fig. 16.7 Cu grade distribution inspired by TAG grades inside the 3D geometric model along the east-west trending cross section given in Fig. 16.4

Table 16.2 Zone-dependent summary statistics of the simulated block model based on grades from Solwara 1 (Lipton 2012)

	Cu (%)		Zn (%)		Au (ppm)		Ag (ppm)	
Zone	Mean	Stdv	Mean	Stdv	Mean	Stdv	Mean	Stdv
Cu-rich	7.3	5.7	0.4	0.7	5720	5680	30	15
Zn-rich	3.2	1.4	0.9	0.8	776	183	25	14
Stockwork	1.9	1.6	0.4	0.2	257	100	4.4	1.9
Sediment	1.4	1.9	0.19	0.3	1414	1290	11.5	15

occurrences in the Indian Ocean seem to be rich. However, very limited data and information on the sampled material, the 3D geometry, and the 3D qualimetry are available. One could expect that the analyzed material presented in Table 16.4 originates from the surface of the occurrences and that it therefore does not represent well the interior and most of the tonnage. Further, both these occurrences are found high on the rift valley wall (Wang et al. 2021), placing them in a different geological setting than both Solwara 1 and TAG.

5.3 3D Economic Block Model

3D economic block model development is using the concept of η_{asset} (*eta$_{asset}$*) from Lesage et al. (2018). η_{asset} represents a factor of mining system availability given the characteristics of the deposit, the mining site (e.g., sea state), and the mining system. Since the costs of having the mining system offshore will run independently of any produced ore, the costs of a mining system will be time dependent (*cost per day*), not ore tonnage dependent. Spagnoli et al. (2016a, b) briefly discuss this cost structure and the use of specific energy in the assessment of cutting performance. Given asset costs per day, specific energy, and the mining system availability (η_{asset}),

Table 16.3 Zone-dependent summary statistics of the simulated block model based on grades from TAG (Grant et al. 2018)

	Cu (%)		Zn (%)		Au (ppm)		Ag (ppm)	
Zone	Mean	Stdv	Mean	Stdv	Mean	Stdv	Mean	Stdv
Cu-rich	2.7	1.7	0.3	0.45	359	348	20	14
Zn-rich	3.2	1.4	0.9	0.8	776	183	25	14
Stockwork	1.9	1.6	0.4	0.2	257	100	4.4	1.9
Sediment	1.2	1	0.13	0.1	68	87	11.6	18

Table 16.4 Grade summary of the Kairei and the Edmond sites in the Indian Ocean. From (Weixler 2018)

Occurrence	Cu (wt.%)	Zn (wt.%)	Pb (wt.%)	Au (ppm)	Ag (ppm)	Co (ppm)
Kairei	28.5	4.5	0.02	3.6	52	243
Edmond	11.5	3.3	0.04	2	44	2000

production rate can be calculated and thereby the tonnage costs (mining OPEX per ton ore). Assuming that E_{sp} is the specific energy in kWh/m^3, P_c is the power in kW dedicated to the cutting machinery, and V_b is the block volume, the mining time (Eq. 16.2) and the associated block-by-block operational mining costs (OPEX, Eq. 16.3) can be calculated:

$$\text{Time}_{\text{mining}} = \frac{V_b * E_{sp}}{P_c} \tag{16.2}$$

$$\text{Blockmining costs}\left(\text{OPEX}\right) = \frac{\text{time}_{\text{mining}} * \text{Cost per day}}{\eta_{\text{asset}}} \tag{16.3}$$

A block of sediment has in the economic block model development been regarded as significantly easier to mine than a block of more consolidated lithotypes. Equation (16.2) has therefore for all sediments blocks been replaced by Eq. (16.4), where the factor 4320 ton/day is the peak production capacity of the Nautilus mining system (Jankowski et al. 2010):

$$\text{Time}_{\text{mining}} = \frac{\text{BlockTonnage}\left[\text{ton}\right]}{4320\left[\frac{\text{ton}}{\text{day}}\right]} \tag{16.4}$$

In effect, the mining time for sediments is significantly lower than for the lithified material types.

Given block dimensions and the density that give the block tonnage and unit costs for processing, the block-by-block processing costs can be estimated (Eq. 16.5):

$$\text{Block processing costs} = \text{BlockTonnage} * \text{Unit cost processing} \qquad (16.5)$$

The block revenue associated with a block is a function of the quality of the block and operational parameters and is a summation of all revenues generated from commodity *i* in the block (Eq. 16.6):

$$\text{Block revenue} = \sum_{i=1}^{n} \left(CP_i - SP_i\right) * \text{BlockTonnage} * \text{MiningRec}_i * G_i * \text{ProcRec}_i * NF_i \qquad (16.6)$$

where

CP_i	Commodity price (USD/ton) metal *i*
SP_i	Selling cost (USD/ton) metal *i*
BlockTonnage	Block tonnage (ton)
MiningRec	Mining recovery (%)
G_i	Grade of metal *i*
$ProcRec_i$	Recovery in the processing plant for metal *i*
NF_i	Net smelter return for metal *i*. The NF is applied to take smelter, refining, and transportation costs into account

To use the economic block model in a direct block scheduling exercise, a minimum of two economic block values must be associated with each block in the block model. Economic value number 1 is used if the optimization algorithm extracts and processes the block and in effect sell the extracted products (Eq. 16.7). Economic value number 2 in the economic block model is on the other hand used in the calculation of the operational cash flow if the algorithm decides that the content of the block does not contribute to optimizing the cash flow and thereby choses to consider the block as waste (Eq. 16.8):

$$\text{Dollar block value}_{\text{Processing}} = \text{Block revenue} - \text{Block mining costs} - \text{Block processing costs} \qquad (16.7)$$

$$\text{Dollar block value}_{\text{Waste}} = -\text{Block waste handling costs} - \text{Block mining costs} \qquad (16.8)$$

In the economic block model development, three different η_{asset} values have been used. Two economic block values are necessary for each η_{asset}. A total of six economic values are therefore calculated. These three η_{asset} values represent three different weather conditions forming the basis for three different production rates for a given period and have been used to model a production ramp-up (see details below) and summer and winter periods.

6 Optimization Model, Parameterization, and Setting Up the Schedule

The relevant optimization model in this study will maximize the discounted operational cash flow. The decisions are centered around what block one should mine and when, to reach the objective. The conditions that need to be met and other inputs are presented as follows. Input used in Eq. (16.1) (mining time) is given in Table 16.5.

As presented in Eqs. (16.2) to (16.8), several inputs are needed to calculate the economic block value. Table 16.6 presents the applied input. Two Cu-price scenarios have been tested following a potential future copper squeeze and high prices (Mining.com 2021b). The "Recovery in mining" inputs are taken from Lipton et al. (2018). The processing recoveries ("Rec" in Table 16.6) represent the amount of the given metal that are extracted from the ore and are quantified on a block-by-block basis through simulation and by assuming a triangular distribution with the given minimums, maximums, and modes.

Lesage et al. (2018) refer to Wellmer et al. (2008) and use a significantly lower NF than stated in Table 16.6. It is assumed in this study that the ore that is mined offshore will be transported onshore and then processed into metal concentrates in onshore processing plants using similar processing technologies used for onshore deposits.[2] Since the NF in effect is applied to the ore value (which is high) and since the absolute smelter, refining, and transportation costs should be similar to the basis used in the suggested NF percentages of (Wellmer et al. 2008), the NF percentages have been defined rather high. A high NF will also be the consequence in case of a future tightness in the concentrate markets (Snowdon 2021; Mining.com 2021a).

Figure 16.8 exemplifies the resulting processing recovery for all three ore zones. The mode of the recovery is at 85% with a slightly longer tail toward low values and minimum values down to 70% to accommodate the fact that textural and mineralogical properties of the ore might lead to a larger portion of the metals following the tailings.

Furthermore, different η_{asset} values have been used to calculate cost structures for different mining system availabilities. The used η_{asset} values were 0.2, 0.5, and 0.8 and given an assumed annual production rate of 1.8 Mt at 100% availability, this gave corresponding half year production rates (capacities) of 180 kt, 0.45 Mt, and

Table 16.5 Input to calculate the bock-by-block mining time

Parameter	Abbreviation	Value used in the modeling
Specific energy	E_{sp}	180 kWh/m^3
Available cutting power	P_c	2000 kW
Block volume	V_b	8 m^3

[2] Large assumption; although textural information from the TAG deposit is favorable and good processing performance is obtained on Solwara 1 samples, overall processing performance is uncertain.

Table 16.6 General input necessary for the economic block value calculation. "Rec" means processing recovery in the given ore zone

	Cu	Zn	Au	Ag
Commodity price (USD/ton metal)	8500/15,000	2800	55,000,000	800,000
Selling and marketing costs (USD/ton metal)	3000	3000	3000	3000
Recovery in mining	95%	95%	95%	95%
RecCu-rich, min	80%	70%	80%	80%
RecCu-rich, mode	85%	85%	85%	85%
RecCu-rich, max	95%	90%	95%	95%
RecStockwork, min	70%	70%	70%	70%
RecStockwork, mode	85%	85%	85%	85%
RecStockwork, max	95%	90%	95%	95%
RecZn-rich, min	70%	70%	70%	70%
RecZn-rich, mode	85%	85%	85%	85%
RecZn-rich, max	95%	90%	95%	95%
Rec, Sed, min	70%	70%	70%	70%
Rec, Sed, mode	85%	85%	85%	85%
Rec, Sed, max	95%	90%	95%	95%
Net smelter return (NF)	90%	70%	90%	90%
Processing costs	19 USD/ton (Lesage et al. 2018)			
Waste handling (offshore)	250 USD/ton[a]			
Daily asset costs	240000 USD/day (Jankowski et al. 2010)			

[a]Assumed. Mining- and waste-handling system and procedures must be developed to properly assess these costs. These costs would cover the extra necessary handling if waste rock must be managed and deposited on the ocean floor. These waste handling costs would come on top of the normal mining costs

0.72 Mt. These mining system capacities are used as constraints in the optimization. The η_{asset} value of 0.2 has been used to emulate the half year period from October to March (winter) and the availability of 0.8 is used to emulate the weather conditions during the summer months (April to September). See Lesage et al. (2018) for further details on monthly availabilities for a mining system similar to the mining system of Nautilus for the Solwara 1 project (Jankowski et al. 2010). Lesage (2020) shows that the availability of such a mining system in these harsh weather conditions is controlled by the availability of the riser and lifting system. The capacities, the characteristics, and the availabilities of the SPTs are therefore not discussed any further. The 0.5 availability has been used to represent the ramp-up during the summer months. See Fig. 16.9 for a summary of availabilities per period. The production rates are used as input in the open pit optimization scenarios and are associated with the corresponding economic block value in the block model.

Following the procedure in Lesage et al. (2018), ore-zone-independent densities used to calculate block tonnage have been calculated based on porosity and grain density found in Hannington et al. (1998) and Ludwig et al. (1998). A triangular distribution has been used to generate block-specific densities and the inputs are presented in Table 16.7.

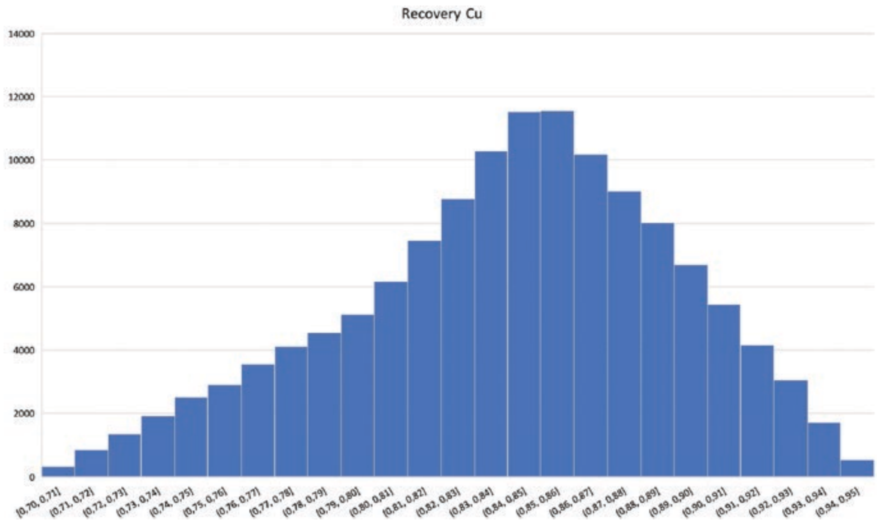

Fig. 16.8 Histogram showing the block-by-block Cu-recovery distribution in the Zn- and Cu-rich zones and the stockwork zone

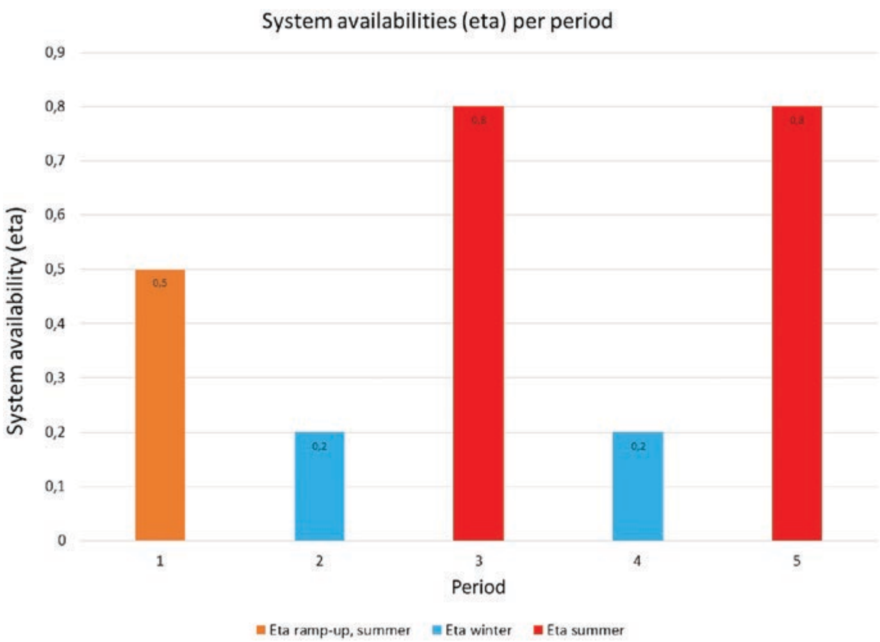

Fig. 16.9 Applied mining system availabilities per period

Table 16.7 Minimum, most likely and the maximum deposit porosity and grain density used to parameterize the triangular distributions

Parameter	Min	Mode	Max
Porosity	1	4	16
Grain density	3	3.5	5

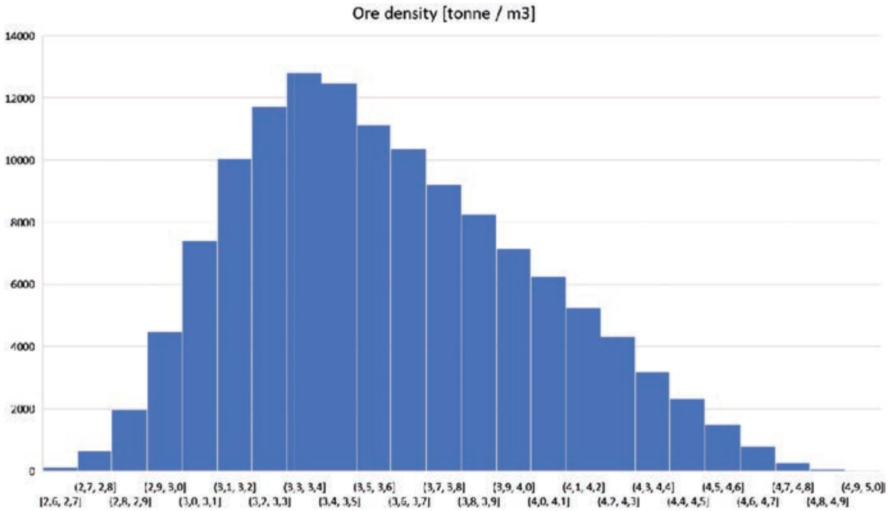

Fig. 16.10 Histogram showing the block-by-block ore density distribution in the Zn- and Cu-rich zones and the stockwork

Combined for all three ore zones this gives the block-by-block ore density distribution in Fig. 16.10. The most likely value (mode) is between 3.3 and 3.4 ton/m^3 and the minimum and the maximum values are between 2.6 and 2.7 and between 4.8 and 4.9 ton/m^3, respectively.

The densities of the chloritized basalt and the unaltered volcanic rock are not used in the calculation since they are considered barren and since the mining costs have been implemented as tonnage independent. The density of the sediments has been quantified using a triangular distribution with parameters given in Table 16.8 (Kane and Hayes 1992; Tenzer and Gladkikh 2014).

This gives a bimodal density distribution for the sediments and the lithified material types.

The mining schedule has been set up with periods with a duration of 6 months. Different etas and economic block values have been used in each period to take the different mining system availabilities and cost structures into account. The waste handling capacities of the mining system have been set to 10% of the periodic ore production capacities. No stockpiling capacities have been used but could have been implemented to emulate the use of ocean floor storage and stockpiling facilities such as the stockpiling hoods planned by Nautilus Minerals. An annual discount rate of 12% has been used. For such an early-phase and high-risk project this could

Table 16.8 Minimum, most likely and the maximum density of the sediment cover

Parameter	Min	Mode	Max
Sediment density	1.5	1.8	2.7

Table 16.9 General input used in MiningMath to setup the optimization

Waste-handling capacity	10% of period ore production capacity
Discount rate (annual)	12%
Maximum pit slope	70° (from horizontal)

be considered relatively low and must in the future be investigated further. See Table 16.9.

Planned overall pit wall slope angle for onshore open pit operations is normally in the range between 45° and 55°. The slope angle has a great influence on the ore recovery and is optimized through a study of the rock and rock mass properties and structural and hydrogeological characteristics of the site in question. Such studies are often based on the empirical Hoek-Brown failure criterion (Eberhardt 2012; Hoek 1968) and must take all risks into account. The hydrostatic pressure at 2300-m water depth is approximately 230 bars. A relevant question is whether this hydrostatic pressure will stabilize or destabilize the pit wall. If the rock mass is highly fractured, then it will behave as pseudo-isotropic medium or like a continuum (Marinos 2019). All fractures will in such a case be closed. In effect, there will not be any net water pressure in the rock mass that contributes to destabilize the pit wall. Similar if the rock mass is not fractured, then the hydrostatic pressure will stabilize the pit wall since there is no water pressure in the rock mass at all. For this reason and since there will not be any risk of casualties in case of a pit slope failure, a maximum pit wall angle of 70° has been used. Such a steep angle must in a real case be evaluated against the risk of generating a large sediment plume related to a potential pit slope failure. In the optimization, this constraint is just used as a maximum and what the actual pit slope angle becomes is dependent on the ore geometry and the ore quality variations. In-depth rock mechanical and rock engineering studies must be completed in the future to understand the true effect of hyperbaric conditions on the pit slope stability and to find the optimal maximum pit slope (see Table 16.9). For simplicity, no constraints have been used to control the minimum mining width or the maximum vertical extraction rate. Also, no grade constraints have been used, which means that it is assumed that there is no link between grade and recovery if a specific block has been labeled as either sediment or part of the stockwork, Cu-rich or Zn-rich zones.

Only the area within the assumed geometry outcrop shown in Fig. 16.2 has been made available for mining using the “restrict mining” functionality in the optimization software.

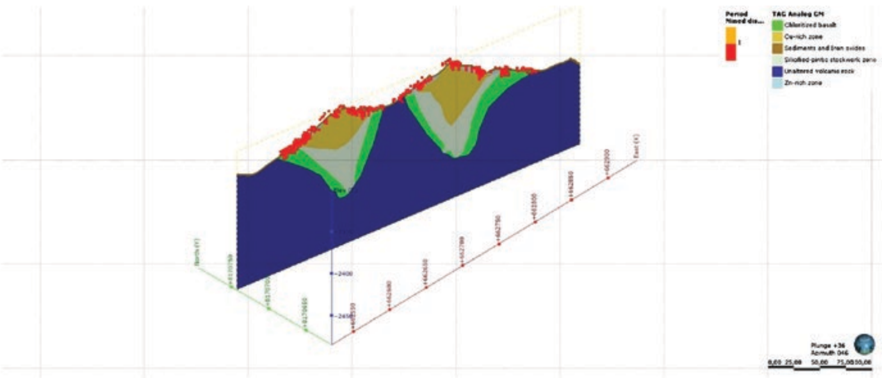

Fig. 16.11 Mined blocks in the east-west section of Fig. 16.4 where the mining system availability and mining capacities are assumed to be independent on the weather conditions

7 Results

7.1 *TAG Grade Distribution*

Two scenarios are calculated and evaluated. Production capacities and mining system availabilities are assumed to be weather independent in the first scenario and weather dependent (weather dependent availabilities in Fig. 16.9) in the second scenario. Figures 16.11 and 16.12 show the mined blocks in the east-west section in Fig. 16.4.

Table 16.10 summarizes the results from the weather-dependent and the -independent scenarios for the TAG grade distribution.

The weather-dependent scenario is mining at a higher cost due to a lower mining system availability than the weather-independent scenario, hence the lower discounted operational cash flow (NPV). The mined tonnage is mined during the first period (i.e., 6 months) in both scenarios. Tonnages and Cu-grades are comparable for both scenarios and the low tonnage confirms the impression from Figs. 16.11 and 16.12 that only the upper part of the occurrence including parts of the sediments is mined and processed.

7.2 *Solwara 1 Grade Distribution*

Two scenarios are calculated and evaluated. Production capacities and mining system availabilities are assumed to be weather independent in the first scenario and weather dependent in the second scenario. Figures 16.13 and 16.14 show the mined blocks in the east-west section in Fig. 16.4.

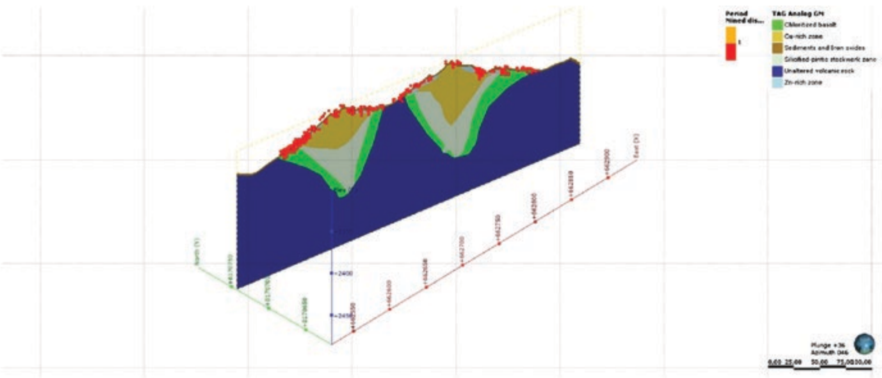

Fig. 16.12 Mined blocks in the east-west section of Fig. 16.4 where the mining system availability and mining capacities are assumed to be dependent on the weather conditions

Table 16.10 Weather-independent and weather-dependent summary statistics for the two optimizations based on the TAG-grades

Scenario	NPV (M$) at 12%	Ore tonnage (Mt)	Average Cu (%)	# of 6 months periods
Weather independent	5.9	0.14	3.6	1
Weather dependent	−4.4	0.10	3.6	1

All tonnage mined in 6 months. Average Cu in % is given for illustration. Similar averages for Zn, Ag, and Au are calculated. NPV = Cumulative discounted operational cashflow

Table 16.11 summarizes the results from the weather-dependent and the -independent scenarios for the Solwara 1 grade distribution.

Figure 16.15 (weather-independent) and Fig. 16.16 (weather-dependent) summarize the results per period. Period 1 shows for the weather-independent scenario in Fig. 16.15 a head grade of 6.8% Cu, an ore tonnage of 0.7 Mt and a waste rock tonnage of 0.47 kt (waste rock tonnage not visible in figure). For period 2, the numbers are about 5% Cu, slightly less than 0.5 Mt ore and no waste.

Period 1 shows for the weather-dependent scenario in Fig. 16.16 a head grade of lightly less than 4% Cu, an ore tonnage of less than 0.1 Mt and no waste rock. During period 2, no ore or waste are produced. The numbers for period 3 are about 7% Cu, slightly more than 0.7 Mt ore and a significant amount of waste.

The weather-dependent scenario mines also about 0.4 Mt of waste material. Some of this has a significant Cu-grade but is treated as waste to get access to better material further down that contributes to maximizing the discounted operational cash flow (NPV). The NPV of the weather-dependent scenario is significantly lower since most of the blocks are mined in period 3 and not during ramp-up in period 1. Their positive contribution is thereby more heavily discounted. In addition, this scenario mines and handles more waste rock.

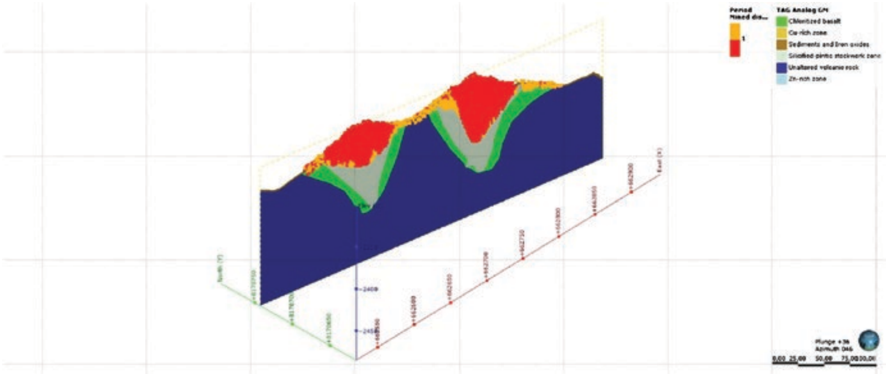

Fig. 16.13 Mined blocks in the east-west section of Fig. 16.4 where the mining system availability and mining capacities are assumed to be independent on the weather conditions. Most of the blocks are mined in period 1 (red color in figure)

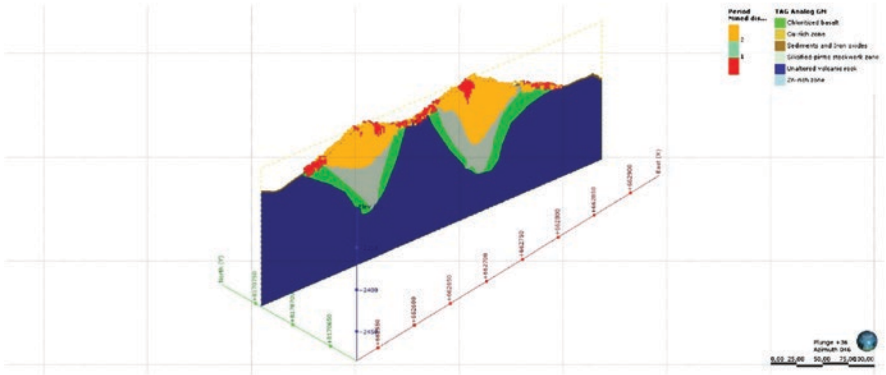

Fig. 16.14 Mined blocks in the east-west section of Fig. 16.4 where the mining system availability and mining capacities are assumed to be dependent on the weather conditions. Most of the blocks are mined during period 3 (summer months; orange blocks in figure). No blocks are mined in period 2 (winter months). Only some of the blocks are mined during ramp-up in period 1 (red blocks in figure)

7.3 TAG Grade Distribution and High Cu Price Scenario

A scenario with weather-dependent mining availabilities and mining capacities and a high Cu-price assumed has been executed (Fig. 16.17).

Table 16.12 summarizes the results from the weather-dependent and high Cu-price scenario for the TAG grade distribution.

Figure 16.18 (weather independent) summarizes the results per period. Period 1 shows head grade of 2.7% Cu, an ore tonnage of 0.02 Mt and no waste rock. No ore is produced in periode 2 due to low system availability and high costs. In period 3, the numbers are about 3.5% Cu, slightly less than 0.5 Mt ore and about 0.16 Mt of waste rock.

Table 16.11 Weather-independent and weather-dependent summary statistics for the two optimizations that are based on the Solwara 1 grades

Scenario	NPV (M$) at 12%	Ore tonnage (Mt)	Average Cu (%)	# of 6 months periods
Weather independent	311	1.2	6.1	2
Weather dependent	40.7	0.8	6.5	3

Average Cu in % is given for illustration. Similar averages for Zn, Ag, and Au are calculated. NPV = Cumulative discounted operational cashflow

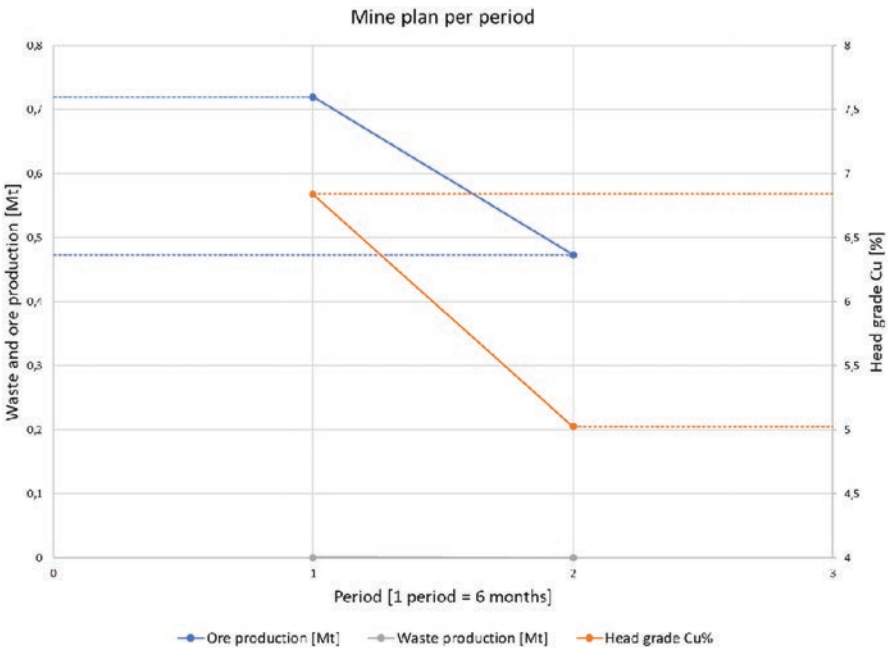

Fig. 16.15 Mine plan per period for the weather-independent scenario based on Solwara 1 grades

8 Discussion

This contribution illustrates the necessary steps in strategic open pit mine planning for deep-sea mining applications within the extended Norwegian continental shelf, specifically based on the location and the assumed geometry of the Loki's Castle occurrence. The steps include 3D geometric ore body modeling, 3D qualimetric ore body modeling, 3D economic block modeling, and optimization to define the ultimate pit contour and the schedule. The geological 3D models are hypothetical, and the cost structures and the mining systems are conceptually based on the Nautilus Minerals Inc. Solwara 1 case. It is not argued that this mining setup is relevant for

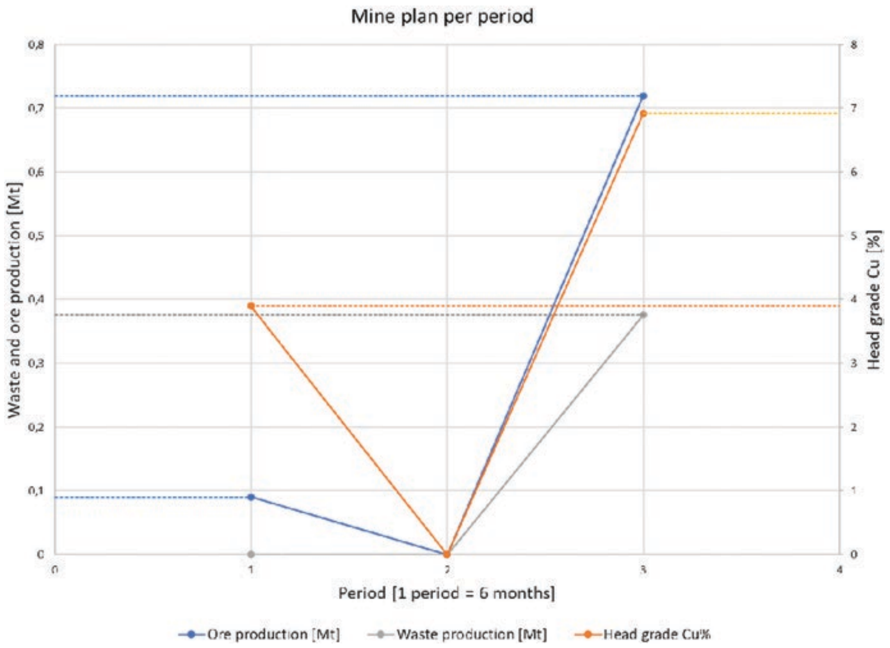

Fig. 16.16 Mine plan per period for the weather-dependent scenario based on Solwara 1 grades

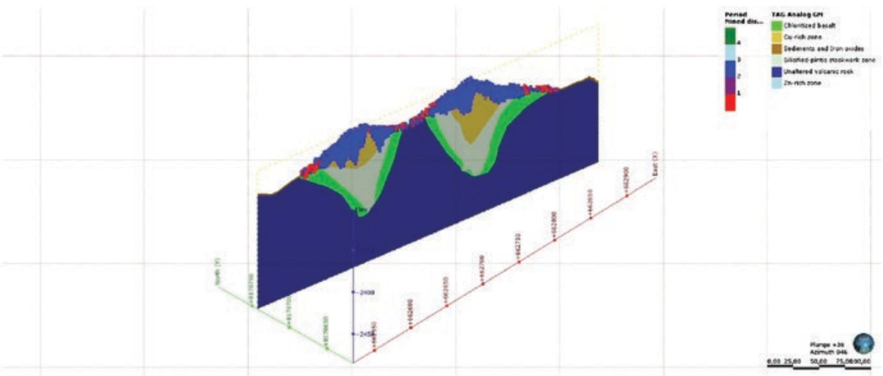

Fig. 16.17 Mined blocks in the east-west section of Fig. 16.4 where the mining system availability and mining capacities are assumed to be dependent on the weather conditions and the Cu-price have been set as high as US$15,000 to reflect the possible future Cu-squeeze. Blue blocks indicate period 3, that is, during the second summer of production. No ore or waste rock is produced during the first winter (period 2, purple color in the legend) due to low availability and low mining capacity

Table 16.12 Weather-dependent summary statistics for the optimizations with a high Cu-price

Scenario	NPV (M$) at 12%	Ore tonnage (Mt)	Average Cu (%)	# of 6 months periods
Weather-dependent, high Cu-price	4.9	0.74	3.44	3

Average Cu in % is given for illustration. Similar averages for Zn, Ag, and Au are calculated. NPV = Cumulative discounted operational cashflow

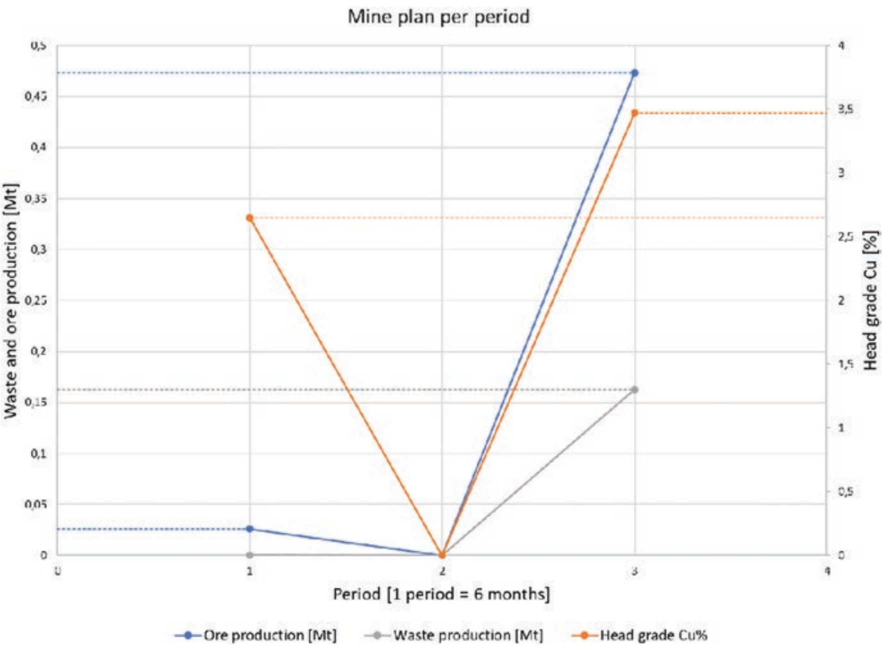

Fig. 16.18 Mine plan per period for the weather-dependent scenario based on TAG grades and a high Cu price

the hard weather conditions inside the Norwegian jurisdiction but forms a good basis to develop and test the methodologies and procedures.

The established workflow renders it possible to run scenarios with more precise cost structures once these are established. Similarly, once better and more realistic ore body models based on both hard and soft data are developed, these could be integrated with the necessary subsequent steps to generate the strategic mine plan.

In this attempt no grade information was available and ore grade realization from a simulation has been used as input. In a real situation, one would develop a kriged/estimated block model and use that as the grade input. Kriged models are known to smooth out internal variations and one should consider generating multiple conditional realizations and use those realization as input into the open pit optimization to enable a quantification and assessment of the uncertainty in the objective function (NPV).

The results clearly show the importance of mining system availability, the resulting capacities, and the cost structures. Developing novel systems that can handle the rough sea states in the Norwegian Sea is therefore of uttermost importance. The developed framework can be used to test the performance of mining systems by developing the strategic mine plan, but that would require detailed information about the cost structure and the system availabilities.

In this study, metal grade is the only parameter that has been block-modeled spatially. The porosity and the grain density have been simulated block-by-block but not with any spatial correlation built into the simulation. Surely, both the porosity and the grain density would vary both within and between the ore zones. This would have affected the calculation of the density, both the ore and waste rock tonnage and thereby also the calculated block-by-block revenue. In future research, focus should also be put on developing ore zone and grade-dependent densities which would improve the accuracy and precision of the results. Similarly, one should try to estimate the permeability, which is the driver for the challenges associated with hyperbaric rock cutting.

It is herein not argued that the spatial correlation of Solwara 1 is correct, but in the absence of enough data from another, more relevant occurrence, the use of spatial information from Solwara 1 has been considered as the preferred option. An alternative would be to use spatial correlations from onshore analogs, so-called Volcanogenic Massive Sulfides. These are the accepted analogs of seafloor massive sulfide deposits (Singer 2014) and could potentially inform the variography of SMSs. However, these ancient volcanogenic massive sulfides might have gone through post-depositional geological processes (e.g., tectonics) that would distort the spatial structure in the deposits.

SMS occurrences are known to contain cobalt and some other metals important for the future transition to greener energy production. These have not been included in this analysis. The uncertainty regarding processing technologies and the real potential of them are even larger than for the base and precious metals included here. Once technologies are available and their processing potential has been proven, they can be included in the qualimetric and economic 3D block modeling and the optimization exercises. Their inclusion might change the way any deposit is mined, and they might make a presumed unprofitable project profitable.

In this study, any area outside the assumed occurrence outcrop has been excluded from the optimization. The optimization algorithm has been restricted from accessing certain areas. Such a functionality can and should be used to assess the effect of restricting access to certain areas due to environmental considerations. One could for example restrict mining of the most active Loki's Castle mound and investigated the optimal strategic mine plan for such a case. Basically, one could use this functionality to exclude "areas of particular environmental interest" (APEIs) from being mined.

The objective function used here has been the discounted operation cash flow. In a real situation, one might need to better control where mining takes place at any point in time. In such a case some penalty based on the distance from deposit center could potentially be developed. This would potentially make sure that one minimizes the number of relocations of the seafloor mining tool. The importance of this would be mining method dependent, but one could easily imagen that it would be of uttermost importance if the preferred mining method was based on vertical mining such as the vertical trenching approach of Spagnoli et al. (2016a, b).

SMS deposits show zonation. These zones are different in terms of grade, mineralogy, and textures. These differences would naturally lead to different processing performance once they are delivered to a processing plant. Both costs and recovery might be influenced. One could therefore, with the established framework, investigate the effect of developing multiple processing routes which is one of the five important key levers in strategic mine planning. Each of these processing routes would have different properties and the different ore types, and could then theoretically be sent via different processing routes to maximize the recovery of the valuable commodities and potentially minimize the environmental footprint.

9 Conclusions

This chapter has devolved into the workflow of doing strategic (long-term) mine planning in a mineral resource management perspective for deep-sea mining operations. Procedures and approaches to assess SMS deposits on a strategic level have been developed and tested. An optimization step was used to assess the differences between solutions. The framework can be used to assess the performance of different mining systems, given constraints defined by the market, the geology, and the prevailing weather. What will the future bring? Minerals and metals are important in the green transition and the future demand for these commodities will probably increase. What role deep-sea minerals and metals can play in meeting this demand is uncertain, but the potential is huge, and in future environmentally more robust technologies based on current knowledge, expertise, and experience will emerge in parallel to the increasing demand.

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Chapter 17
Risk Assessment for Deep-Seabed Mining

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Abstract Uncertainties concerning deep-seabed mining relate to the expected impacts on the abyssal benthic and pelagic environment and its ecosystems but also include geopolitical, economic, societal and cultural uncertainty. The uncertain impacts from mining lead to anxiety and a low societal acceptance for the activity and are not the same for everybody at the same time. Hence, uncertainty is an important element of the risk involved in deep-seabed mining. This chapter describes the different risks involved, develops a methodology for risk assessment for the exploitation of marine mineral resources that takes into consideration the state of knowledge and evolving research on deep-sea ecosystems, and informs on possible environmental threshold values in relation to deep-seabed mining operations.

Keywords Deep-seabed mining · Impacts · Risk assessment · Weight of evidence · Environmental thresholds · Policy

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1 Introduction

One of the largest challenges for the development of deep-seabed mining as an industry is the uncertainty associated with potential impacts stemming from the mining activities. Uncertainties relate to the effects of mining on the deep-sea environment (e.g. risks for ecosystems, risks of pollution) but also include geopolitical uncertainty (harm to another state's sovereignty) and economic uncertainty (risks of resource exploitation). The first part of this chapter starts with a description of the environmental risks, followed by the private and social risks from an economic perspective and ends with some thoughts on legal risks. Systematic approaches for estimating the overall benefits, costs and risks stemming from seabed operations are set out based on undertaking cost-benefit and risk-benefit analyses. The second part proposes a methodology for risk assessment for the exploitation of marine mineral resources that takes into consideration the state of knowledge and evolving research on deep-sea ecosystems and their environment. First, the current international regulation on environmental risk assessment is discussed, which is necessarily limited to the exploration phase of deep-seabed mining as regulations for the exploitation phase are not in force yet. More specifically regarding the environmental hazards of mining-induced sediment plumes, methodologies like Weight of Evidence and Environmental Hazard and Impact Identification are proposed. Arguably, the identification and definition of threshold values for a wide array of environmental variables and indicators of ecosystem health can constitute an important foundation for future regulation. Finally, the focus lies on how these outcomes translate into the future regulation of deep-seabed mining.

2 Description of Risk

This section describes environmental, economic and legal risks related to deep-seabed mining. Uncertainty always introduces an element of risk. Two further elements to take into consideration are that risks are unwanted and that a risk is not the same for everyone at the same time. Alternatively, one can describe an objective risk as to the product of the probability of harm and its severity. A subjective risk adds a social dimension; i.e. that not everybody experiences the same harm in the same place at the same time (Grunwald 2016; Duvic-Paoli 2017). Another definition of risk is 'the amalgam of the probability of an event occurring and the seriousness of the consequences should it occur' (Cameron et al. 1998). These risks might be conceptualised differently (Jaeckel and Rayfuse 2017). The severity of the risks directly links to the resilience of the system (Grunwald 2016). Risks are thus helpful in dealing with uncertainty while, '[a]lthough it may be impossible to predict occurrence of specific, individual events, the logic of risk makes it possible to predict that on average we can expect a certain number of occurrences over a certain period of time' (Ambrus et al. 2017).

2.1 Environmental Risks[1]

Environmental risk is broadly defined as the likelihood that harm will occur to the environment as the result of an action or condition (Cardenas 2019). Risk is usually defined in terms of risk sources, potential events, their consequences and their likelihood (ISO (2018) 31000).

The main environmental impacts related to deep-seabed mining will typically relate to:

- Size and distribution of mining areas: Long-lasting change of seafloor integrity by the mining activity (i.e. removal of the upper active benthic surface layer, which consists of the colonised hard substrate (mineral resource) and, in the case of polymetallic nodules, its associated soft-sediment habitat; compaction by mining gear) can impact abyssal ecosystem functions and services on local to regional scale and potentially interrupt the connectivity of species if suitable management tools are not in place.
- Spreading of particles: The mining activities will lead to sediment disturbance and plume discharges, which can lead to negative impacts like smothering of benthic (seabed) habitats outside the mined areas.
- Spreading of contaminants: The sediment plume deriving from the mining area may contain particles with a high concentration of metals and other contaminants like reduced substances, which can have toxic or detrimental effects on organisms in the surrounding areas.
- Light pollution: The light used during mining activities at the surface platform (e.g. vessel) but also the mining vehicle at the seafloor can deter and disturb the activities and natural rhythms of algae, animals.
- Noise, electromagnetic radiation and vibrations: Noise and vibrations can disturb the acoustic communication of marine mammals and can influence the natural behaviour of fish and invertebrate populations in the water column (e.g. reduction in foraging ability).
- Thermal pollution: Water discharges from various processes on the surface vessel(s) can cause thermal pollution. An increase in the water temperature can have a cellular and molecular impact and increasing the organisms' metabolism. Deepwater fauna is expected to be sensitive to changes in temperature.
- Discharges to water: The surface vessel could discharge cooling water, which often contains antifouling chemicals and corrosion inhibitors and other chemicals, as well as any other utility- or process-related discharges. In addition, the potential releases of ballast water could lead to the spreading of invasive species. These alien species can put the existing ecosystems under severe stress and overgrow the native species or introduce exotic diseases.

[1] Part of this paragraph is an adapted and shortened version of the text contained in Haeckel et al. (2020) 328, 334, 335, 337 and 338.

The impacts of deep-seabed mining on the marine environment differ depending on the resources being exploited (Levin et al. 2016) but many impact types are quite similar (Boetius and Haeckel 2017). From all the potential resources on the deep ocean floor, polymetallic nodules have arguably received the most attention from the early discussion of deep-seabed mining onwards. Based on the current status of technological development, it is most likely that a remotely operated collector will mine the nodules of the ocean floor, thereby removing (hydraulic collection system) or impairing (mechanical collection system) the biologically active surface layer. A riser system will transport the potato-sized clumps of mineral to the surface, where the mining support vessel will do a first processing of the nodules (separation of nodules/dewatering) before they are transported with a carrier vessel to an onshore facility for ore processing.

Within the framework of exploration activities and large (international) research projects deep-seabed mining, numerous taxa have been identified and described in the past decades, in particular in the Clarion-Clipperton Fracture Zone (CCZ) in the Pacific Ocean where the abundance and metal content of polymetallic nodules are high. Although it is still a long way to a complete species inventory, scientific studies conducted so far indicate that the biodiversity in this area is extremely high. In principle, deep-seabed mining has two different negative effects on the fauna of the seabed: (1) a sudden decimation of the faunal populations in the directly mined area; and (2) a quasi-permanent alteration of the habitat (e.g. Vanreusel et al. 2016; Gollner et al. 2017; Vonnahme et al. 2020). The newly formed sediment surface behind the collector will have a different structure, mechanical properties, as well as biogeochemical and microbial composition to that of the original seafloor and thus no longer correspond to the natural habitat. Studies that revisited old disturbance tracks have shown long-lasting changes in abundances and compositions of benthic communities, showing that recolonisation of the soft sediment will at least take many decades, potentially centuries, even after minor disturbances (König et al. 2001; Miljutin et al. 2011; Vanreusel et al. 2016; Gollner et al. 2017; Vonnahme et al. 2020). As nodules require millions of years to grow, there will be no natural return of hard substrate and its associated fauna to the directly mined areas. Dedicated and long-lasting scientific studies are necessary in order to make reliable statements on the recolonisation potential of mined and other impacted areas. The findings are ecosystem-specific and not directly transferrable to other mineral resources. For example, comparably species-poor, high density and highly productive communities predominate at active hydrothermal vents, which are well adapted to a constantly changing habitat (Grassle 1985). In contrast, communities of abyssal polymetallic nodule ecosystems are characterised by high numbers of diverse species but low numbers of individuals (e.g. Bluhm 2001; Borowski 2001; Janssen et al. 2015; Washburn et al. 2021).

Manganese nodules lie on soft deep-sea sediment, which is expected to be partially removed and suspended during the mining of nodules, irrespective of the type of collection technology used. Many components of the collector, the riser system and the platform vessels will be new and have yet to be tested under real conditions. However, it is undisputable that plumes of resuspended sediments will develop, which, depending on the amount of sediment mobilised, may represent one of the major sources of impacts on the faunal communities that live at, on, in or close to the surrounding seabed. Such plumes drastically add to the natural sedimentation rate, which normally lies in the order of a few millimetres per thousand years only. The sinking sediments will cover the organisms that live on the seafloor sediment or on nodules in the immediate vicinity of the mining area. Furthermore, increased particle load in the water column near the ocean floor, which may additionally be contaminated by released heavy metals, is likely to affect suspension feeders that extract their food from the water column, such as sponges, corals and some fish species or larvae.

Overall, it is necessary to understand how fast the suspended sediment will be redeposited and how it will be distributed spatially due to topographic irregularities (slope) and/or with the bottom currents. The scale of the impacts and the subsequent environmental risks involved will be strongly dependent on the type of mining technology used. Important questions are: How do deep-sea sediments behave when they are suspended? How quickly do aggregates form and resettle? What quantity of sediment is redeposited, and what is the thickness of and how does blanketing thickness relate to distance from the mined area? How much labile organic matter is contained in the suspended and resettling sediments and how does this affect the availability of food for the fauna? In order to answer these questions, oceanographic conditions, such as bottom current velocity and direction at the seafloor, as well as the local bathymetry, must be studied over a period of several years (Aleynik et al. 2017; Peukert et al. 2018). Furthermore, realistic laboratory and field experiments provide important insights into sediment properties such as aggregate formation and sinking rates (Gillard et al. 2019). Finally, such information is important to model the dispersion of sediment plumes, as is being done in the European scientific project of the Joint Programming Initiative Healthy and Productive Seas and Oceans: Environmental impacts and risks of deep-sea mining (MiningImpact2). Model results must be validated by sub-industrial mining tests.

Detailed knowledge of the potential ranges of dispersion of sediment plumes is an important prerequisite for the designation of preservation reference zones (PRZs) and protected conservation areas as well as to define threshold values for 'significant adverse effects'. These studies have to be accompanied by detailed studies of the impacts on deep-sea fauna, biodiversity, community structures, ecosystem functions and services. For example, it is currently unclear which particle concentrations, sedimentation rates and sediment cover/blanketing thicknesses will negatively affect faunal communities.

2.2 *Private and Societal Risk*

While private risks refer to the risks facing the contractors undertaking the project, societal risks are carried by all stakeholders impacted by a deep-seabed mining project. In addition, private contractors focus on profits, revenues and costs accruing to the project owner. This contrasts to societal economic analyses, where the emphasis is on overall benefits and costs to all relevant stakeholders to deep-seabed mining projects. The background for this distinction is that private evaluations of deep-seabed mining projects cannot be expected to fully include all impacts from deep-seabed mining activities, nor impacts on all stakeholders affected by the mining activities.

At least two aspects of deep-seabed mining projects cause private evaluations of these activities to differ from societal economic analyses. First, as noted above, mining activities on the deep seabed may well last for decades, hence the impacts from deep-seabed mining activities will last longer than what one may expect private entities to consider. Second, private entities do not fully internalise impacts on, e.g. other industries like tourism and fisheries.

2.2.1 Private Risks

Private companies evaluate project proposals using investment analysis, where future flows of revenues and costs are discounted back to present value, allowing comparison with alternative investment opportunities. Frequently, the discount rate uses the Capital Asset Pricing Model.[2] The uncertain cash flow expected to accrue to the contractor can be decomposed into several types of cost components, see, e.g. SPC (2016) for description and detailed numerical estimates (see also Sharma (2011, 2017) for further details about the mining process):

- *Investment costs (Capital expenses, Capex)*: This part of the cash flow takes place in the first part of the lifetime of the project, investing in physical assets like (remotely operated) vessels and risers, and investment in prospecting, exploration and licenses for mining.
- *Revenues*: The revenue streams are determined by a combination of future prices and the amount of nodules harvested, adjusted for the mineral content of the nodules. For methods for evaluating the economic value of nodules on the seabed, see Abramowski (2016) and Volkmann et al. (2018). Hoagland (1993) analyses future price predictions based on hypothetical grade and recoverability of manganese nodules.
- *Production costs*: The costs of mining, lifting, processing and refining may vary considerably between regions, depths and choice of technology for the various stages of the production chain, see Volkmann et al. (2019) for an illustration of how estimates of production costs (Operating expenses, Opex) may vary for deep-seabed mining.

[2] The Capital asset pricing model is a model pricing uncertain future financial claims (e.g., expected profits). This model is an equilibrium model of financial trading, resulting in an equilibrium required rate of return demanding only estimates on the expected risk-free interest rate, the market rate and the investment's beta value (β). For an overview, see Bodie et al. (2012).

Overall, the net present value equals the expected future cash flow discounted to a reference year using a project-specific discount rate, reflecting the systematic risk of the project. The discount rate reflects the contractor's best alternative investment opportunities. See, e.g. Volkmann et al. (2019) for an application of Net Present Value analysis (NPV) of deep-seabed mining. Their estimates of economic values are similar to other recent analyses of deep-seabed mining projects; see, e.g. SPC (2016) or Van Nijen et al. (2018). The expected financial viability of the project is uncertain since expected revenues, costs, investments and resource contents are uncertain, we refer to this uncertainty as 'private risk'. The private riskiness of deep-seabed mining projects can be evaluated using standard statistical techniques, for instance, the mean and standard deviation of future net benefits.

2.2.2 Societal Risks

Sandmo (2000) discusses public economics of the environment, relevant for analyses of deep-seabed mining. This section will also incorporate views provided by Sartori et al. (2014) and NOU (2012:16). Above, it was illustrated that private contractors would consider the revenues and costs accruing to the project. Two aspects of deep-seabed mining make private analyses of deep-seabed mining less relevant for evaluating mining activities from a societal point of view. First, there are clearly externalities from deep-seabed mining activities, that is, mining will reduce the value of operations for other industries (e.g. fisheries and tourism).[3] Second, the deep ocean is a public good, or alternatively, the ecosystem services provided by the deep ocean are public goods, and with its extreme diversity of marine life and size, the current and future benefits obtainable from the deep ocean are considerable.

As outlined above, private contractors focus on profits, that is, the stream of net revenues accruing from the project over its lifetime. Translated to a societal analysis, private costs are a measure of the resources used in bringing minerals to the market, while the private benefits reflect the societal willingness to pay for the minerals, that is, a measure of the monetary benefits of deep-seabed mining. In addition to these impacts stemming directly from the project, other impacts affect regional and national public funds. For instance, increased employment may affect public budgets via increased tax revenues and reduced unemployment benefits. Similarly, the project itself may be profitable and generate tax revenues. These tax revenues are adjusted by a factor referred to as the 'cost of public funds' (Barrios et al. 2013).

Only a few analyses of private profitability of deep-seabed mining projects look into the overall societal impacts (Wakefield and Myers 2018). SPC (2016) also discuss societal impacts for Pacific islands, in particular potential negative impacts from CO_2 emissions, discharges, unplanned releases and impacts on the seabed. Hence, when deep-seabed mining activities affect a stakeholder, the project

[3] It should be noted that this excludes pecuniary externalities, that is, an externality is present if it affects the productivity of, say, a nearby fishery, not if deep-seabed mining activities affect the profitability of, e.g., terrestrial mining activities.

produces an externality. Thus, this section outlines impacts referred to as externalities and the consequences of regarding the deep ocean as a public good, using the classification from ecosystem services.

Ecosystem services in the deep ocean are public goods (Fisher et al. 2009). Benefits are obtained through provisioning, supporting and regulating services, in addition to cultural services that also provide benefits. These benefits risk destruction or degradation due to deep-seabed mining, see, e.g. Ottaviani (2020). Mining of minerals in the deep ocean will affect the ocean's ecosystem services, both today and in the future. The potential negative impacts (externalities) from deep-seabed mining on the deep seas' ability to produce public goods are classified using the ecosystem services approach.

Ottaviani (2020) defines **provisioning** services from the deep seas as, e.g. seafood, genetic and medicinal resources, and oil, gas and minerals. As noted by Van den Hove and Moreau (2007), manganese nodules are potentially one of the major exploitable mineral resources in the deep ocean. However, harvesting of minerals—a provisioning service—may affect the production of other ecosystem services, e.g. fisheries.

Two of the **supporting** services in the deep sea are biodiversity and habitat for species (Ottaviani 2020). Deep-sea ecosystems support a diverse fauna, and according to Armstrong et al. (2010), they represent both the largest and the most diverse habitats on Earth. Deep-seabed mining may well reduce—even eradicate—species and impair areas of habitat where mining takes place, and hence, negatively affect these supporting services.

Thurber et al. (2014) discuss ecosystem services, arguing that '[t]hese services can range from the valuable scientific knowledge that can be obtained from deep-sea environments'. **Cultural** ecosystem services potentially negatively impacted by deep-seabed mining relate to the scientific research on, e.g. how life adapts to extreme living conditions found only in the deep (see Ottaviani 2020). For Pacific Island indigenous people, their 'mother ocean' is an important part of their cultural heritage and religion and should not be interfered with.

The environmental risks associated with deep-seabed mining (Sect. 2.1) constitute human-made sources of risks to the public goods (ecosystem services) and hence these are the underlying causes of societal economic risk.

Private benefits and costs are measurable and can be denoted in monetary values. Societal impacts like tax revenues and other impacts on public funds are also measurable. Other impacts of deep-seabed mining are more difficult to measure and therefore difficult to denote in monetary terms. This is particularly true for the impact on many of the ecosystem services. First, the exact economic value of these services is highly uncertain (Armstrong et al. 2010). Several attempts of quantifying ecosystem services are available, e.g. using various contingent valuation techniques. However, others are sceptical about using contingent valuation methods (Diamond and Hausman 1994). Hausman (2012) reviews the literature arguing that other methods may provide better estimates. Second, the extent to which the economic value is affected—and for how long—is not well understood. Rather than estimating numerical values for all risks, experts describe nonquantified risks from deep-seabed mining using the approach in, e.g. Aven (2017). The focus is on how an activity (here: deep-seabed mining) causes a consequence (economic value destruction of, e.g. ecosystem services) and the uncertainty relates to the (lack of) knowledge about the consequences stemming from the activity. ECORYS (2014) contributes to documenting the state of knowledge for deep-seabed mining activities, and equally important, identifying areas where knowledge gaps are present. Hence, both quantified and non-quantified societal benefits and costs from deep-seabed mining activities are documented, using traditional statistical techniques and the approach of risk assessment in Aven (2017).

The final aspect of societal risks from deep-seabed mining relates to the potentially very long-term negative impacts. While private contractors use financial rates for discounting future uncertain cash flows, public discount rates should reflect the societal opportunity cost of capital in an inter-temporal perspective. This reflects how society values future benefits and costs to present ones. For a discussion, see Sartori et al. (2014). The impacts from deep-seabed mining may last for decades; hence, aspects of how to relate to (very) long interest rates are important. NOU (2012:16) discusses these aspects and reviews the literature on long-term discount rates starting with the Stern review (Stern 2007 and further discussed in Nordhaus 2007). Two complications arise due to the long-term impacts. First, what level of the social discount rate should be used? Second, should the discount rate be fixed or step-wise? There is, however, no common agreement on these questions. This is demonstrated in NOU (2012:16), where the level of social discount rates differs between nations, and while Norway and the UK use a step-wise discount rate for long-term impacts, the majority of other countries use a fixed discount rate. Second, these long-term costs and their risks are inherently difficult to quantify. More so, comparing benefits and costs from deep-seabed mining accruing to society today (denoted in monetary costs) with the very long-term costs described using nonmonetary approaches is very difficult.

2.3 Legal Risk

As shown above, it is trite that one of the largest challenges in the development of rules and regulations for mineral mining of the seabed beyond national jurisdiction is uncertainty. This uncertainty comes into play regarding the effects of mining on the deep-sea environment (risks for ecosystems, risks of pollution) but also geopolitical uncertainty (harm to another state's sovereignty) and economic uncertainty (risks of resource exploitation) can occur as a consequence of deep-seabed mining (Duvic-Paoli 2017). Moreover, the legal details concerning mining in the deep ocean are uncertain so far, at least to some extent as the regulations for the exploitation of marine minerals are still under development. The Legal and Technical Commission of the International Seabed Authority (ISA) proposed draft regulations for the part of the Mining Code that deals with mineral exploitation, but they have not been finalised yet. The central question relating to risk in international law might be whether there is sufficient scientific evidence to support a particular regulation (Peel 2010). Scientists can only deliver data and the analysis thereof for the determination of the actual and potential risks. Yet it is the legislator who needs to determine which risk is acceptable, and which measures should be taken to avoid or diminish these risks, regardless of the uncertainties involved. Ideally, the task of the legislator is exercised in close cooperation with the contractor and the public-at-large (Ellis 2006). Nevertheless, this should not necessarily be a problem and it is certainly not new: 'It is not in the nature of any law to provide mathematically certain solutions of problems which may be presented to it; for uncertainty cannot be eliminated from law so long as the possible conjunctions of facts remain infinitely various' (Brierly 1949). Law relates more to the risks of resource exploitation than to the risk for the environment as a whole. The Law of the Sea Convention reflects this primarily anthropocentric approach also by incorporating a provision on the protection of human life in its Art. 146 (Duvic-Paoli 2017).

3 Environmental Risk Assessments and Plans

An environmental risk assessment (ERA) is prepared during the scoping stage of an activity to highlight the main elements at risk from that activity. It identifies, analyses and evaluates the nature and extent of the activity, as well as the level of risk that may be expected. Moreover, it helps to structure data collection and identifies and informs the key (risk) aspects that the environmental impact assessment (EIA) should focus on. In many cases, it is worthwhile to carry out a second ERA (update) shortly before the mining operation is planned to start and when all the details of the operation are known.

3.1 Current Use and Regulation of ERAs

Risk assessments are crucial for every single exploitation activity on the seafloor beyond national jurisdiction (also called 'the Area'). A risk assessment can occur as part of an EIA but also as part of a strategic environmental assessment (SEA). The Legal and Technical Commission of the ISA has the mandate to 'prepare assessments of the environmental implications of activities in the Area' (LOSC, Art. 165 (2)(d)). The Commission also has to take these assessments into account when formulating rules, regulations and procedures (LOSC, Art. 165 (2)(f)).

The Commission shall recommend to the Council the disapproval of a particular area for exploitation when substantial evidence indicates the risk of serious environmental harm (LOSC, Arts. 165 (2)(l) and 162 (2)(x)). In addition, prospecting will also not be allowed in disapproved areas (ISA 2000, 2010, 2012). An emergency order might be necessary to prevent, contain or minimise any serious environmental harm when the activity has already started. Such an order by the Council may include the adjustment or suspension of the operation (LOSC, Art. 162 (2)(w); ISA 2000, 2010, 2012). It is significant that the Legal and Technical Commission is subject to these obligations and not the contractors. The Mining Code does not require the latter to identify any uncertainties or risks related to its activities during the exploration phase (Jaeckel 2017), although a preliminary EIA is a requirement for application for an exploration contract (ISA 2000, 2010, 2012).

ERA will however be an obligatory part of the full EIA that will be essential to any application for mineral exploitation. An EIA should be seen as a process 'to anticipate, assess and reduce environmental and social risks of a project prior to planning permission or regulatory approval being granted' (Durden et al. 2018). Before the actual EIA takes place, the first step is to decide if the threshold to do so is actually reached. A preliminary risk assessment may assist in this screening part of the process. The next step is to carry out a scoping exercise on what the EIA should cover. A qualitative ERA is a necessary part of this step to consider the most important impacts and issues. On the one hand, the on-going process might result in the exclusion of some of these issues for further consideration, i.e. those that can be shown to have a negligible effect. On the other hand, alternatives will also be scrutinised. In the case of deep-seabed mining, the scoping part of the process should motivate a continuous exchange of views between the ISA and the contractor (Durden et al. 2018), and ideally also with relevant stakeholders. On another note, strict environmental legislation of Sponsoring States is one of the clear outcomes of the Advisory Opinion by the Seabed Disputes Chamber of the International Tribunal for the Law of the Sea (ITLOS 2012). It is thus crucial that the Sponsoring States make 'all the necessary efforts to adopt and enforce measures of control, under [their] national legislation, which are proportional to the risks associated with the mining activities planned by the contractor' (Pineschi 2013). It follows that material rules concerning risk assessment will not suffice in their own right. Monitoring, control and enforcement appear indispensable.

3.2 Environmental Monitoring and Areas of Particular Environmental Interest

Regulation and surveillance of monitoring activities are not just an obligation of the Sponsoring State but also of the ISA. It is up to the Legal and Technical Commission to make recommendations to the Council regarding the establishment of a monitoring programme that controls the regular observation, measurement, evaluation and analysis of the risks and effects of pollution to the marine environment that are caused by activities in the Area. Execution of the programme has to be through recognised scientific methods. In addition, the programme shall ensure the adequacy of and compliance with regulations. The programme needs the Council's approval (LOSC, Art. 165 (2)(h)).

3.3 Weight of Evidence Approach for ERA

Weight of evidence (WoE) is an instrument often used in ERA to characterise the hazard. This procedure is commonly applied when different types of science-based evidence are needed to draw a conclusion and present a recommendation to decision-makers. The WoE can further provide information on the confidence level of the conclusion (Burton et al. 2002a, b; MERAG 2016; Stevenson and Chapman 2017; USEPA 2016; Suter et al. 2017a, b; SETAC 2018; ECHA 2019). There are three major components in a WoE procedure: (1) it is necessary to assemble the evidence; (2) this is followed by weighting the gathered evidence; and (3) the body of lines of evidence (LoE) is finally weighted. Evidence can be retrieved from the literature and complemented by new studies. Gathered evidence will be screened in order to select only the relevant and acceptable studies, and categorised into types of LoE. Data can then be extracted, reanalysed or combined with additional information in order to derive the evidence. The process of weighting the gathered evidence will weigh the relevance, the strength and reliability of each piece of evidence, by assigning scores. Weights are then combined per LoE. The whole body of evidence can be finally weighted by integrating the LoE, followed by interpreting the bodies of evidence and explaining ambiguities found. The qualitative WoE framework can be complemented to derive quantitative values. After weighting the evidence for the quality to be quantified, evidence with estimates of quantity, such as weighted mean or other meta-analysis will be merged and the best quantitative evidence selected, defining the confidence in that quantitative evidence.

The WoE framework should be incorporated in the initial stage of the risk assessment (problem formulation) and in the final stage (risk characterisation), with reassessment during the process of decision-making. Burton et al. (2002b) developed a WoE framework primarily for sediment quality assessment but useful for all types of environmental assessments. They stressed the importance of defining the key 'certainty elements' in that framework. At the problem formulation stage, it is necessary to: (1) identify the critical receptors (species, population, community) for the study site and adequate reference sites; (2) define the ecosystem quality by assessing the state of good environmental status (this is a crucial point as impairment will be decided by comparing to a reference); and (3) identify the potential stressors and associated exposure dynamics (using field and lab methods to elaborate predictive models). The previous will serve to develop the evolving conceptual model, which will additionally identify research needs to complete the model. Following this step is the selection of measurement endpoint responses that will feed the multiple LoE and which relevance, strength and reliability will need to be defined (SETAC 2018; USEPA 2016). These responses need to meet quality assurance and quality control (QA/QC) criteria and can be the physicochemical characterisation, toxicity testing on ecologically relevant and sensitive organisms, local fauna characterisation (selecting the appropriate biotic indices), tissue contamination levels and so on. The selection of reference sites and comparison methods is another critical step as they will be the basis for determining the impairment of the test site, so the natural variability at the reference site needs accurate definition (see Burton et al. 2002b for more detail on how to define reference sites). After this, the appropriate LoE combination and LoE integration methods are defined. The predefined conceptual model is linked with the gathered data to conduct the study design and the QA/QC plan to ensure maximum confidence in data. Here, the optimal methodologies and endpoint measurements are selected. In addition, the laboratory and field procedures; reference sites and number of samples; the best model to relate stress and response; natural and anthropogenic stressors and key exposure pathways identified;effects characterised using biologically based methods; and statistical methods, for LoE analyses and integration in WoE matrix are selected. The next step is the data collection and verification, verifying their validity before integrating into the WoE model (see Burton et al. 2002b on how to address the data uncertainty issues). Each LoE can then be analysed using the most adequate quantitative methods. The final step is the integration of LoE into the WoE matrix, allowing for drawing reasonable conclusions on the severity of the impairment caused by the characterised stressors. Each of the critical elements will need the involvement of a multidisciplinary team that will need to provide expert judgement in critical phases of the WoE process (Burton et al. 2002b).

The WoE approach has been applied to detect and quantify the environmental hazard of trawling on a mine tailings deposit that generated sediment plumes loaded with toxic metals (Mestre et al. 2017). In this case, the Sediqualsoft model (Piva et al. 2011) was used and the WoE integrated data from four LoEs: sediment physico-chemical properties; bioaccumulation of metals in indicator species; sublethal effects/biomarkers in indicator species; and laboratory ecotoxicological bioassays. The WoE was effective in classifying the hazard of the sediment plume in comparison to sediment quality guidelines and the reference site (Mestre et al. 2017). Further details on the model concept, thresholds and calculations within each LoE, the weights attributed to each, and how they were integrated into the final WoE model are described in previous studies (Piva et al. 2011; Benedetti et al. 2012, 2014; Regoli et al. 2014; Mestre et al. 2017).

In relation to the tests of a pre-prototype nodule collector vehicle built by the Belgian company Global Seabed Resources (GSR) that were carried out in the CCZ in April and May 2021 and intensively monitored by the European MiningImpact2 project, the WoE will be used to (1) classify the environmental hazard of the trial at the test sites, and (2) estimate the degree of confidence in the defined model. The robustness and reliability of the results will much depend on the quantity and quality of the available data from the literature (scarce) and newly acquired data, both for the test sites as well as for the appropriate reference sites. In addition, the most suitable indicators for mining-related environmental or ecological change have not yet been defined but potential indicators will be investigated, and their relevance, strength and reliability evaluated. It is also an objective to apply the WoE model to different sampling times, i.e. before impact, shortly after impact, and also one to two years after the impact in order to provide insight into the temporal evolution of impact hazards.

3.4 Environmental Threshold Levels for Deep-Seabed Mining Projects

The ISA (draft) regulations for the exploitation of mineral resources in the Area do not provide details on environmental thresholds. It simply states that thresholds may be developed as standards and guidelines to support the regulations. Based on the environmental impacts and risks listed in Sect. 2.1, existing environmental threshold levels and thoughts on how threshold levels can be developed for deep-seabed mining projects are presented in this section.

Many environmental threshold levels have already been developed for offshore activities, such as drilling and dredging. However, these are mainly developed for coastal and shallower waters and not for areas where deep-seabed mining is assumed to take place. In general, environmental threshold levels should be based on the local conditions at the actual site. Existing environmental threshold levels from these sectors can therefore not be directly applied to deep-seabed mining but they can be of help in defining a way forward.

Threshold levels for deep-seabed mining should not differ between the different mineral resources (polymetallic nodules, polymetallic sulphides and cobalt-rich crusts). This is based on the principle that there should be the same level of environmental protection irrespective of which type of ore is being mined.

The areas on the seabed that are affected by mining can be defined as ‘Mining Area’ and ‘Environmental Impact Area’, see Fig. 17.1. The Mining area is where the mining takes place and where the seabed will be directly impacted (degradation of the seabed and the habitat). The Environmental Impact Area is the area outside the mining area where no mining takes place but which still can be affected by the mining activity. This impact can originate from the spreading of suspended particles, spreading of contaminants, light pollution, and noise and vibrations.

3.4.1 Spreading of Particles

Spreading of particles from deep-seabed mining operations has two main sources:

- Spreading is caused by the mining vehicle/mining equipment. The mining vehicle will cause the spreading of particles while moving on the seabed and while the mining equipment is collecting/cutting the ore and the host sediment.
- Spreading is caused by return water with particles from the mining support vessel. In many mining concepts, the ore is pumped through a riser to the mining support vessel (IUCN 2018). Sediments will be pumped up together with the ore and these can be separated on the mining support vessel and returned through a pipe back to the seabed. This will also cause the spreading of particles. In addition, accidental failure or rupture of the riser pipe may cause a particle plume in the water column.

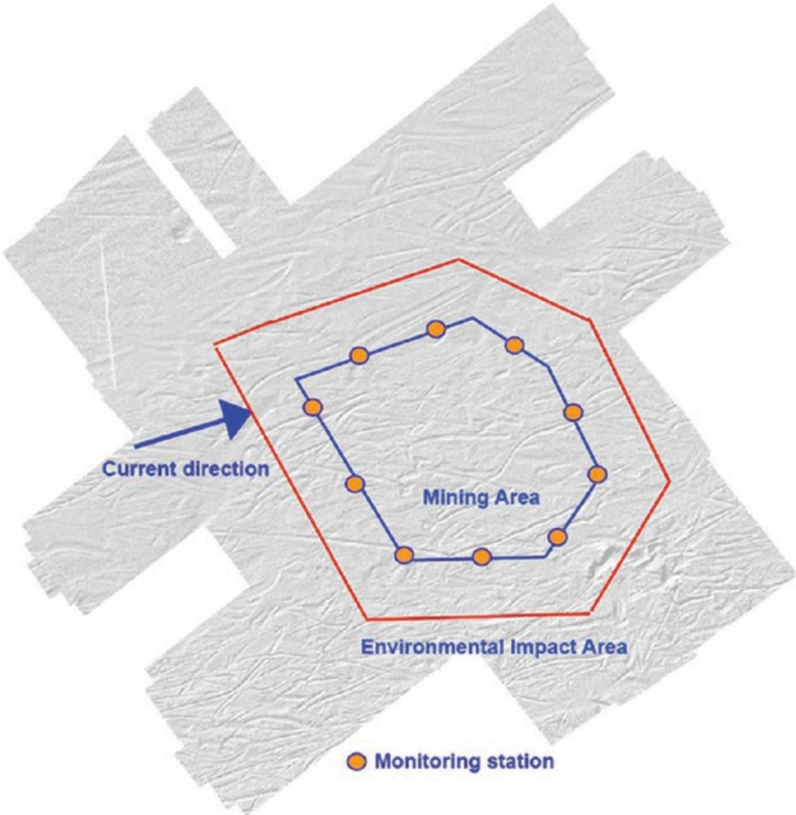

Fig. 17.1 The mining area (blue line) and the environmental impact area (red line). It is also possible to add further monitoring stations outside the mined area

The main environmental impact from the spreading of particles is smothering, i.e. sediment deposition covering the benthic habitats. The amount of sediment deposition is important for assessing the damage that is caused to the benthic habitats. As there have not been any full-scale deep-seabed mining projects so far, existing data are based on modelling and mining tests, some of which are summarised below:

- For the Solwara 1 project off Papua New Guinea, Asia-Pacific ASA (now RPS Group) modelled in 2008 the plume (clays, silts and fine sands) from the removal of unconsolidated sediments in order to be able to mine at the site. The model SSFATE was used to simulate the depositional thicknesses from the sediment plume generated by the ROV and SMT (Seafloor Mining Tool). Over a twenty-month period, the depositional thickness varied from 0.18 mm at about one km from the mining site to a peak of slightly above 500 mm at the mining site (0.003 km^2). They also modelled the sediment deposition from the return water of the surface mining vessel. The model results demonstrated that the peak depositional thickness on the seabed from the settling fines was less than 0.1 mm at the mining site (and other areas outside) for the twenty-month period (Nautilus Mineral Niugini Limited 2008).

- In their Environmental Impact Statement of 2018, GSR (DEME Group) carried out a preliminary plume modelling for the Patania II tests in 2021 where they used a model developed by IMDC (International Marine and Dredging Consultants). The model predicted that the distance that the suspended plume in the water column was likely to spread after four days of testing varied between one and three km (cut-off concentration value ten mg/L and one mg/L respectively) and five to twelve km (cut-off value 0.1 mg/L), depending on the current conditions at the seafloor. For the test in 2021, the sediment deposition from the plume was expected to reach approximately 500–750 m from the source for a cutoff value of one mm deposition and approximately five km for a cutoff value of 0.1 mm deposition (GSR 2018).
- In their EIA in 2018, BGR (German Federal Institute for Geosciences and Natural Resources) presented a preliminary sediment plume model for the Patania II test in the German contract area in 2021 that was developed by MARUM (Centre for Marine Environmental Sciences at the University of Bremen) with input from Jacobs University (Bremen, Germany). The model indicated that high plume concentrations of >1 g/L may reach a distance of one km from the test site and lower concentrations may spread up to three km from the source. The plume was predicted to not reach a height of more than thirty m above the seafloor under 'normal' flow conditions. The amount of sediment deposition from a 'normal' flow plume deposition reached a maximum of two km from the test site (0.1 mm deposition). The remaining minimal blanketing (<0.1 mm deposition) for 'normal flow' thinned out within ~3.5 km from the source. Under enhanced current speeds associated with eddy passage, this distance was shown to increase to eight km (BGR 2018).
- Spearman et al. (2020) describe field tests done outside the Canary Islands with a pump coupled to an ROV that generated a sediment plume. AUV measurements found that the plume reached background concentrations (in the order of ten μg/L) at a distance of around one km from where the plume was generated.
- Germany has set a threshold level of ten mg/L for shallow water sand mining (Federal Agency for Nature Conservation 2006). This value is set to protect demersal fish (fish that lives and feeds near the seabed).
- At the time of writing of this chapter, the Patania II tests in the GSR and BGR contract areas of the CCZ had just been completed and valuable data were collected on the plume propagation and concentration caused by the nodule collecting vehicle. These data will hopefully aid in decreasing the uncertainty in plume dispersal, verifying and adapting the sediment plume models described above to allow upscaling to (sub)industrial-scale mining projects and help to develop threshold levels for plumes generated by deep-seabed mining.

For the oil and gas sector, research on how sediment deposition affects marine life is ongoing. In a study of seabed fauna in the North Sea, the Norwegian Sea and

Table 17.1 Threshold values for harm associated with deposition of discharges/sediments (from NOROG 2019)

Deposition thickness	Degree of impact	Consequences
0−1 mm	Negligible	No detectable influence
1–3 mm	Low	Minor smothering Good ability to shed sediments, but might start to aggregate
3–10 mm	Significant	Moderate smothering Reduced ability to shed sediments. Some polyp mortality or sponge necrosis can occur
>10 mm	Considerable	Considerable smothering Potential suffocation. Polyp mortality or sponge necrosis expected. Potential for depletion of energy reserves

the Barents Sea, Smit et al. (2008) derived a deposition thickness of 6.3 mm, below which 95% of the species should not be affected by burial (the study did not include corals or sponges). A threshold level for the total concentration of suspended particles used in risk assessment models is ten mg/L (Rye et al. 2011). Pineda et al. (2017) support using ten mg/L as a lower threshold for 'no-effect' on sponges (natural sediment). Ten milligram per liter exposure over a typical drilling period (~six weeks) can be expected to be equal to 6.3 mm total deposition (e.g. Larsson et al. 2013). Based on this and other research data, threshold levels from the oil and gas sector relating to the smothering of habitats have been developed, see Table 17.1.

Referring again to the oil and gas sector, estimates based on a combination of experiences from monitoring and DREAM model simulations (numerical particle tracking model, developed by SINTEF, Norway) have been made for the drilling of one top hole section (exploration drilling). Based on these estimates, dispersion distances were proposed, see Table 17.2.

In addition to the deposition of the particles on the seafloor, the amount of suspended particles in the water column and exposure times is also important with regard to assessing the effects on the fauna (larvae, nekton and zooplankton) in the water column.

3.4.2 Spreading of Contaminants

During mining, it could also happen that particles/debris from the mined mineral ore spread to surrounding areas together with sediments from the seabed. The ore itself will have relatively high levels of metals and these could cause negative effects on the pelagic and benthic fauna (organisms in the water column or on the seabed).

There are no international threshold levels for contaminants in seawater. However, the EU has published a technical guidance for deriving environmental quality standards (EC 2017). Based on this, several European states have developed quality standards for their coastal waters. One example is Norway where the Norwegian Environment Agency (2016, rev. 2020) has set quality standards for

Table 17.2 Deposition thickness from exploration drilling at different distances from the drilling hole[a] (based on NOROG 2019)

Deposition thickness	Distance from the drilling hole (radius)
1–3 mm	250–500 m
3–10 mm	100–250 m
>10 mm	0–100 m

[a]Note that this is based on a combination of several typical single model scenarios with various current patterns, duration of drilling and amount of discharges and can be regarded as 'a rule of thumb'. In instances with strong prevailing current directions or longer durations such as during production drilling, these distances might be exceeded

Table 17.3 Quality standards used in Norway based on five categories (classes)

Class I Background	Class II Good	Class III Moderate	Class IV Bad	Class V Very bad
Background level	No toxic effects	Chronic effects at long term exposure	Acute toxic effects at short term exposure	Substantial acute toxic effects

coastal waters based on the EU Guidance. The quality standards are divided into five categories (Table 17.3), depending on the effects that can be expected on the organisms in the water column and in the sediment.

Table 17.4 shows the quality standards for the concentration of metals in Norwegian coastal waters.

Outside Europe, for example, in Australia and New Zealand, established guidelines for marine water quality are different, see Table 17.5 (ANZECC and ARMCANZ 2000). The guideline was revised in 2018 (ANZECC and ARMCANZ 2018); however, the values for metals are still the same and awaiting revision.

Suggested Threshold Levels for the Spreading of Contaminants from Deep-Seabed Mining

There are no international threshold levels for contaminants in seawater. We suggest that such threshold levels should be developed specifically for deep waters.

Existing quality standards for coastal waters as shown above provide an example of how threshold levels can be developed for the deep sea.

3.4.3 Light Pollution

In the deep ocean, there is only very dim, homochromatic and downlight available. This is supplemented by bioluminescence from marine organisms. Most species in this environment possess highly specialised visual systems, which are incredibly sensitive to even minute amounts of light. This makes these organisms extremely

Table 17.4 Norwegian environmental quality standards for metals in coastal waters (Norwegian Environment Agency 2016, revised 2020)

Class	I	II	III	IV	V
	Background	Good	Moderate	Bad	Very bad
Metals					
Arsenic (µg As/L)	0–0.15	0.15–0.6	0.6–8.5	8.5–85	>85
Lead (µg Pb/L)	0–0.02	0.02–1.3	1.3–14	14–57	>57
Cadmium (µg Cd/L)	0–0.03	0.03–0.2	[a]	[b]	[b]
Copper (µg Cu/L)	0–0.3	0.3–2.6		2.6–5.2	>5.2
Chromium (µg Cr/L)	0–0.1	0.1–3.4	3.4–35.8	35.8–358	>358
Mercury (µg Hg/L)	0–0.001	0.001–0.047	0.047–0.07	0.07–0.14	>0.14
Nickel (µg Ni/L)	0–0.5	0.5–8.6	8.6–34	34–67	>67
Zinc (µg Zn/L)	0–1.5	1.5–3.4	3.4–6	6–60	>60

[a]Class III Cd values are dependent on the hardness of water: ≤0.45 (<40 mg $CaCO_3$/L); 0.45 (40 to <50 mg $CaCO_3$/L); 0.60 (50 to <100 mg $CaCO_3$/L); 0.9 (100 to <200 mg $CaCO_3$/L); 1.5 (≥200 mg $CaCO_3$/L)

[b]Class IV Cd values are dependent on the hardness of water: ≤4.5 (<40 mg $CaCO_3$/L); 4.5 (40 to <50 mg $CaCO_3$/L); 6.0 (50 to <100 mg $CaCO_3$/L); 9 (100 to <200 mg $CaCO_3$/L); 15 (≥200 mg $CaCO_3$/L). Values above are Class V

Table 17.5 Australian and New Zealand Guidelines for fresh and marine water quality. Extract from Table 3.4.1 'Trigger values for toxicants at alternative levels of protection'. Values in grey shading are the trigger values applying to typical slightly–moderately disturbed systems (ANZECC 2000)

	Trigger values for marine water (µg/L)			
	Level of protection (% species)			
Metals	**99%**	**95%**	**90%**	**80%**
Cadmium	0.7 [B]	5.5 [B, C]	14 [B, C]	36 [B, A]
Chromium (Cr III)	7.7	27.4	48.6	90.6
Chromium (Cr VI)	0.14	4.4	20 [C]	85 [C]
Cobalt	0.005	1	14	150 [C]
Copper	0.3	1.3	3 [C]	8 [A]
Lead	2.2	4.4	6.6 [C]	12 [C]
Mercury (inorganic)	0.1	0.4 [C]	0.7 [C]	1.4 [C]
Nickel	7	70 [C]	200 [A]	560 [A]
Silver	0.8	1.4	1.8	2.6 [C]
Tributyltin (as µg/L)	0.0004	0.006 [C]	0.02 [C]	0.05 [C]
Vanadium	50	100	160	280
Zinc	7	15 [C]	23 [C]	43 [C]

A = Figure may not protect key test species from acute toxicity (and chronic). 'A' indicates that trigger value > acute toxicity figure; note that trigger value should be < **1/3** of acut**e figure**

B = Chemicals for which possible bioaccumulation and secondary poisoning effects should be considered

C = Figure may not protect key test species from chronic toxicity (this refers to experimental chronic figures or geometric mean for species) vulnerable to damage associated with bright artificial lights of manned and unmanned submersible vehicles (Kochevar 1998).

Present concepts or developments of deep-seabed mining technologies do integrate and depend on artificial light.

Suggested Threshold Levels for Light Pollution from Deep-Seabed Mining

There are no international threshold levels for light pollution in the deep ocean.

We suggest that such threshold levels should be developed.

In general, excessive use of light in the deep ocean should be avoided and the use of light for mining at the seafloor should be kept to a minimum. Furthermore, it should be assessed for each deep-seabed mining operation whether other solutions for navigation, orientation, operation and inspection can be applied. Hydroacoustic methods, such as multibeam echosounders and sonars, are suitable and available technologies in this respect.

3.4.4 Noise and Vibrations

Noise and vibrations can disturb the acoustic communication of marine mammals and can influence the natural behaviour of fish and invertebrate populations in the water column (e.g. reduction in foraging ability). Guidelines for offshore activities have suggested threshold levels for noise and vibrations. Such threshold levels are mainly based on studies related to the different effects on larvae, fish and mammals, which show that high noise levels can be stressful, harmful or even mortal.

There are some data for noise in more shallow waters. As an example, a literature study carried out for underwater noise related to an offshore wind turbine project (Xodus Group 2015) found that the behavioural disturbance threshold for marine mammals is around 120 dB re 1 μPa (rms), (rms = root-mean-square pressure).

Suggested Threshold Levels for Noise and Vibrations Generated from Deep-Seabed Mining

There are no international threshold levels for noise and vibrations in the deep ocean.

We suggest that such threshold levels should be developed. While waiting for such threshold levels, existing levels from guidelines for offshore activities could be used as a starting point. The MiningImpact project has measured the noise levels generated by the Patania II nodule collector pre-prototype during the tests in the GSR and BGR contract areas of the CCZ. The data are currently analysed and will, for the first time, provide information on noise pollution in the context of deep-sea mining.

3.4.5 Other Discharges to Water

Discharges of cooling water from the surface vessel could contain different types of chemicals that are harmful to the marine environment. Such chemicals could, for example, be antifouling chemicals, corrosion inhibitors or other utility- or process-related discharges. Biofouling is the accumulation of microorganisms, plants, algae or small animals on the hull of the vessel. It is assumed that about half of the problematic species that are brought around the world by ships are related to the hull and biofouling. In addition, the potential releases of ballast water could lead to the spreading of invasive species. These alien species can put the existing ecosystems under severe stress and overgrow the native species or introduce exotic diseases.

Suggested Threshold Levels for Other Discharges to Water from Deep-Seabed Mining

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). The Convention requires that ships treat/manage their ballast water to ensure that the ballast water satisfies the requirements for maximum organism densities when discharged.

This is controlled by installing and using ballast water management systems (BWMS) with a valid type approval certificate (TAC) on board. During type approval testing, the BWMS must document consistent performance in a series of full-scale test cycles. Several different technological solutions are available. Most BWMS are based on a two-step technology, where filtration or use of cyclone will be the first step that removes larger particles, followed by a disinfection step (typically UV-irradiation or chemical oxidants) to kill the remaining, smaller organisms.

Based on this, it is suggested to set no specific threshold levels for discharges from the surface vessel but instead to implement the rules of the BWMS convention.

For biofouling, there are so far no IMO requirements. It is recommended to follow the IMO biofouling guidelines (IMO 2011).

4 Guidelines/Policy Recommendations[4]

One crucial issue in the context of regulation of deep-seabed mining is how to transform improved ecological, environmental and risk assessment studies into better legislation. Part of the results from, for instance, the MiningImpact project have

[4] Part of this paragraph is an adapted and shortened version of the text contained in Haeckel et al. (2020) 327–331, 335–337, 339 and 340.

already been transformed into policy recommendations (Boetius and Haeckel 2018). The International Tribunal for the Law of the Sea has been active in reformulating states' due diligence obligations with regard to the preservation and protection of the marine environment (Matz-Lück and Van Doorn 2017). In the areas, however, where the mineral resource extraction directly takes place, the primary assumption is made that the fauna will be extinguished completely. In these areas, a reduction in long-term effects can be achieved by optimising mining technologies. However, the mining strategies themselves will also be important in determining the extent, degree and time scales of ecosystem damage and recovery.

A set of indicators needs to be defined for the status of the deep-sea ecosystem and threshold values for the avoidance of serious harm to the marine environment. Evidently, scientific results need to be transparent and independent international scientific assessment of the mining activities is essential. This is not only true for the exploitation phase but also for exploration and not only applicable to scientists but generally also to contractors. Moreover, EIAs—and risk assessments as a part of them—need to address the uncertainties that are present concerning for instance the dispersal of the sediment plume and the spatial variability of the ecosystem. The identification of these environmental hazards and impacts is crucial.

For the whole of humankind to profit from the benefits of deep-seabed mining on the one hand but also to contribute to the protection and preservation of the marine environment on the other, advanced and autonomous monitoring technologies will be required that are not currently in use. This increases the economic risk of the deep-seabed mining project, both private and societal. Some of these risks might primarily be borne by the contractor and Sponsoring State, but others affect society as a whole. It is not always solely the ISA that can govern these risks. The effects that deep-seabed mining has on for instance other industries such as fishing and tourism require cooperation between a spectrum of stakeholders and international institutions beyond those directly involved in mining activities.

The list of environmental and economic risks provided in this chapter might not be exclusive but aims to give a good indication of the risks associated with mining activities in the deep ocean. The WoE approach can help to identify and characterise the risks ahead, both qualitatively and quantitatively. This study gathered threshold values for a variety of environmental risks. Yet to identify threshold values for the economic risks is something that might be done differently in different parts of the world and the outcomes may depend on particular circumstances, both economically and geopolitically.

A particular issue that—taking into account both environmental and economic risks—appears indispensable for humankind when discussing deep-seabed mining is that of conservation of the deep ocean. Reference zones and habitat conservation areas must closely match ecosystem characteristics of mined areas (e.g. ocean productivity, nodule density, faunal densities and composition) to safeguard abyssal biodiversity and protect specific vulnerable and important ecosystems as well as their functions and services. Yet just Areas of Particular Environmental Interest (APEIs) alone cannot be expected to compensate for biological diversity and ecosystem functions and services lost through mining operations: additional marine protected areas are needed. Minimising large-scale impacts requires careful and adaptive spatial planning of mining operations, the establishment of a network of representative protected areas and the development of low-impact mining equipment. Science as well as technological research and development is critical to all of these requirements.

Large-scale damage caused by deep-seabed mining can at least be partially mitigated if the mined areas are separated by undisturbed, pristine areas of sufficient size. In these undisturbed (i.e. preservation) areas, the faunal community characteristic of the region can continue to thrive and organisms that do not depend on the manganese nodules as hard substrate, such as sediment-dwelling fauna, can migrate from there back to the mined areas. In addition, these undisturbed areas can act as 'stepping stones' to help prevent the isolation of distant populations, i.e. genetic connectivity of species across large areas, even at the scale of ocean basins, is ensured. Whether exploitation strategies (e.g. with regard to the geometry and arrangement of the mined and preserved areas, and the geometry and size of individual mining blocks) are suitable for minimising damage to the faunal communities depends on the spatial scales relevant for the various species. For example, organisms often need minimum sizes of coherent habitats for successful reproduction and can only spread with their larvae over limited distances. Spatial planning of mining areas and preservation areas must also account for the impact from the suspended sediment plumes that are dispersed beyond the mined areas. The actual size of the available 'undisturbed' areas ultimately depends on the spatial spread of the sediment plume and on the tolerance of the organisms towards the particle load in suspension, as well as the thickness of the sediment cover deposited from this plume.

In addition, the overarching management of mining activities by the ISA, e.g. in terms of size, number and arrangement of mining licenses in relation to designated protected areas, should also be embedded in large-scale environmental management strategies on regional and global scales. This allows for a transparent, common view on the activities of all ISA contractors and sets deep-seabed mining into a global context in which conflicting interests and uses of marine ecosystems can also be taken into account. Such interests include, but are not limited to, fisheries, shipping, underwater cable construction and marine science. For these reasons, hierarchical management plans should be developed in accordance with proposals of the United Nations Environment Programme (Weaver and Jones 2017).

There is still a need for comprehensive research in order to provide scientifically sound recommendations on suitable mining strategies. It is not yet possible to predict the extent to which spatial management options may mitigate the environmental impacts of deep-seabed mining and prevent major irreversible damage. In order to strike a balance between the need for raw materials on the one hand and a strict interpretation of the precautionary principle on the other, mining operations should develop gradually from small to large spatial scales. These include component trials, pilot mining tests and small commercial test production sites and need to be accompanied by thorough, comprehensive and independent scientific environmental investigations and risk assessments.

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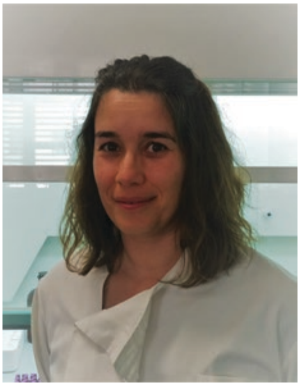

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Chapter 18
An Evaluation of the Payment Regime for Deep Seabed Polymetallic Nodule Mining in the Area

Daniel Wilde

Abstract In view of the possibility of deep seabed mining commencing in the near future, the International Seabed Authority (ISA) is considering a payment regime for polymetallic nodule mining consisting of a 2% ad valorem royalty for the first 4 years of a mine's commercial production, increasing to 6% for all subsequent years. As the ISA continues to dwell upon the draft regulations, this chapter evaluates, with the aid of a financial model, this proposed royalty only payment regime. The pros of the proposed regime include that it would be easy to administer, limit scope for tax avoidance and (under our central price and cost assumptions) is consistent with encouraging investment. However, the cons are that this royalty only payment regime is regressive (with the ISA's share of profits decreasing as the miner's pre-tax profits increase) and is only consistent with maximising ISA revenues under highly specific assumptions regarding metal prices, sponsoring state tax and costs. A payment regime including a royalty, profit share and excess profit share would be more progressive, but would also be more difficult to administer and prone to tax avoidance.

Keywords Deep sea mining · Payment regime · Mining taxes · Royalties

1 Introduction to the Payment Regime

The renewable energy transition is expected to increase demand for cobalt, copper, manganese, nickel and some other metals until at least 2050 (Arrobas et al. 2017; Dominish et al. 2019; Elshkaki et al. 2018). Deep seabed mining (DSM) is a new potential source of metal supply, with polymetallic nodules in the Clarion-Clipperton Fracture Zone (CCFZ) in the Pacific Ocean containing more cobalt, manganese and

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nickel than all land-based reserves combined (Hein et al. 2013). The CCFZ nodules also contain significant amounts of copper, molybdenum, tellurium, tungsten, lithium, niobium, rare earth oxides and yttrium (Hein et al. 2013). To date, there has been no commercial DSM of polymetallic nodules, but there is growing evidence that such mining is economically feasible (Van Nijen et al. 2018; and Volkmann et al. 2019).

The CCFZ is located in the area beyond national jurisdiction (Area). The United Nations Convention on the Law of the Sea (UNCLOS) is the constitutional document governing the Area, and it establishes the International Seabed Authority (ISA, also referred to as the Authority) to regulate DSM. The payment regime, which will determine the taxes[1] that miners will have to pay to the ISA, is an important aspect of the regulation of DSM in the Area and will significantly affect its commercial viability (van Nijen et al. 2018).

The ISA has approved the polymetallic nodules exploration regulations[2] and has awarded 19 exploration contracts for this resource. The latest draft of the exploitation regulations (Draft Regulations),[3] which will govern commercial deep-seabed polymetallic nodule mining, was published in July 2019. These Draft Regulations outline a payment regime consisting of an ad valorem royalty[4] as the only significant[5] tax. The royalty is levied on the calculated value of minerals (CVM) exported from the contract area. This CVM is equal to the weight of polymetallic nodules (mineral-bearing ore) in dry tons multiplied by the sum of the average grade of each relevant metal multiplied by the price of the relevant metal.[6] This CVM value is formally defined in Appendix 1. The Draft Regulations also specify two periods of commercial production, and that different royalty rates can apply in each period of commercial production.

The Draft Regulations do not, however, include all the details required for a functioning payment regime. Specifically, the Draft Regulations are silent on: (1)

[1] This Chapter uses the term 'tax' to refer to any fiscal instrument that has the potential to result in a significant payment from the miner to the International Seabed Authority or to a Sponsoring State, or from the processor to the jurisdiction where it is domiciled. Under this definition, a royalty is a type of tax, even though this is technically a payment for a resource and is sometimes not classified as a tax.

[2] Regulations on Prospecting and Exploration for Polymetallic Nodules in the Area, International Seabed Authority, 25th July 2013.

[3] Draft Regulations on the Exploitation of Mineral Resources in the Area, Prepared by the Legal and Technical Commission, July 2019.

[4] An ad valorem royalty is a royalty that is levied as a percentage of the value of production of a mine.

[5] The Draft Regulations also outline various fees. However, compared to a royalty or a profit share these fees are unlikely to result in the ISA receiving significant revenues or significantly reduce a miner's post-tax profits.

[6] The Draft Regulations allow for different royalty rates to be levied on different relevant metals. This Chapter, however, assumes that a uniform royalty rate will be applied to all relevant metals as this has been the working assumptions during discussions at the ISA, and is also the assumption made in the MIT Report.

the rate of the royalty in the first and second periods of commercial production; (2) the length of the first and second periods of commercial production; and (3) what metals constitute relevant metals.

The ISA contracted the Massachusetts Institute of Technology Material Systems Lab (MIT) to programme a financial model of polymetallic nodule mining and to evaluate the financial impact of different payment regimes. The MIT Report[7] includes a[8] 2%/6% royalty only payment regime as a recommended option. There is no profit share in this regime, but there are payments to a proposed environmental fund at 1% of mine revenue capped at $500 million per mine, and also various fees. The 2% royalty is applied for the first 4 years of commercial production and thereafter its rate increases to 6%. The base for the royalty is the CVM exported from the contract area.

This Chapter evaluates the proposed 2%/6% royalty payment regime. This proposed payment regime, as opposed to the other payment regimes included in the MIT Report, is evaluated as its structure is consistent with the Draft Regulations and it has been the focus of discussions at the ISA. In addition, stakeholders, such as the African Group, have interpreted the 2%/6% royalty payment regime as being the recommended payment regime (African Group 2019).

2 Overarching Goal of the Payment Regime

UNCLOS mandates that: 'The Area and its resources are the common heritage of mankind,'[9] and that DSM 'shall be carried out for the benefit of mankind as a whole'.[10] The 2%/6% royalty payment regime was designed to: 'maximise the return to the common heritage of mankind while providing sufficient revenue to motivate the construction and operation of a mine' (Kirchain and Roth 2019). In practice, this has meant determining the royalty rates that, within the economic model presented in the MIT Report, maximise ISA revenues subject to miners having a post-tax internal rate of return (IRR) of 17.5%.[11]

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[7] This Chapter uses the term 'MIT Report' to refer to Kirchain et al. (2019). We use the term 'MIT Report' as this is how the study has been referred to during discussions at the ISA.

[8] More specifically, the executive summary of the MIT Report presents six payment regimes as 'best options' for the ISA. These payment regimes are: (1) 3%/8% royalty only, (2) 2%/6% royalty only, (3) 1%/3.5% royalty only, (4) 3% royalty and 20% profit share, (5) 2% royalty and 15% profit share and (6) 1% royalty and 10% profit share. A recent update to the MIT Report outlines two alternative payments systems, namely a 2%/6% royalty only payment regime, and a payment regime where the royalty is 2% initially and then increases to between 5% and 9% depending on metal prices.

[9] UNCLOS article 136 Common Heritage of Mankind.

[10] UNCLOS article 140 Benefit of Mankind.

[11] The MIT Report appears to favour a 17.5% hurdle rate, but does consider hurdle rates above and below this.

Maximising government revenues is a common goal when designing national tax regimes (Wilde 2016). UNCLOS[12] also offers some support for this approach by providing that: '[…] the Authority shall be guided by the following objectives: (a) to ensure optimum revenues for the Authority from the proceeds of commercial production; (b) to attract investments and technology to the exploration and exploitation of the Area […]'.

However, UNCLOS and the 1994 Implementing Agreement also offer support for a range of goals other than revenue maximisation and investment promotion. Such goals include: rates of payment[13] that are within the range of those prevailing for land-based mining of the same or similar minerals, and providing revenue to compensate land-based producers whose economies have been seriously affected by deep-seabed mining.[14] There is no a priori reason to consider that a payment regime that maximises ISA revenues will result in rates of payment that are similar to land-based mining or sufficient revenue to fully compensate land-based mining countries. Indeed, if DSM as a nascent industry initially has higher costs and higher investor hurdle rates than land-based mining then mirroring the tax burden of land-based mining regimes could inhibit investment and result in low or zero ISA revenues. Similarly, if miners have low pre-tax profits and DSM increases metal supply and reduces metal prices, then a payment regime that encourages investment and maximises ISA revenue may not result in sufficient ISA revenue to fully compensate land-based mining countries.

A payment regime that maximises ISA revenues will not then necessarily achieve the other goals outlined in the Implementing Agreement. Why then was primacy given to the revenue maximisation goal? The answer may lie in the exact wording used in establishing the philosophy underpinning the design of the payment regime, namely to 'maximise the return to the common heritage of mankind (CHM)'. The actual variable used to measure the CHM is ISA revenues. Given the emphasis UNCLOS places on activities in the Area being carried out for the benefit of mankind as a whole, if indeed the CHM could be regarded as reading for all intents and purposes 'ISA revenues', then the emphasis placed on the revenue maximisation goal might be justified.

The literature, however, does not equate the CHM solely with ISA revenues. Jaeckel (2020) argues that the benefits mankind can derive from the Area include: wealth generation and redistribution, advancement of developing states, security of mineral supply, ecosystem services and scientific knowledge. Feichtner (2019) argues that developing states initially emphasised that their participating in DSM was an important part of the CHM principle, but that overtime this participation objective has given way to a focus on revenue generation and the supply of minerals.

In addition, Thiele et al. (2021) argue that ISA member states' commitments to transitioning to a sustainable economy require a consideration of the impact of

[12] UNCLOS Annex III, article 13 Financial Terms of Contracts.

[13] 1994 Implementing Agreement Section 8. Financial Terms of Contracts 1(b).

[14] 1994 Implementing Agreement Section 7. Economic Assistance.

DSM on the climate, environment and biodiversity. This study also postulates that a holistic accounting system based on true costs and natural wealth is needed to capture DSM's impacts on ecosystem resilience and its potential financial benefits, and that the payment regime should reflect all costs and risks associated with mining in the Area.

Discussions at the ISA have also concentrated on the profits and revenues from a single mine.[15] This has arguably led to proposed payment regimes being considered as either consistent or inconsistent with investment. In reality, the 18 potential miners with exploration licenses for polymetallic nodules may employ a range of technologies and face different costs of production. This implies that there may be rates of effective taxation where some, but not all, existing miners make high enough post-tax profits to motivate investment. This raises the possibility that the payment regime could be designed with the goal of limiting production to some predefined level. For example, to limit production to a single mine until the environmental impact of commercial mining is better understood, or to limit production to a level whereby there is limited impact on metal prices and land-based mining countries. Designing the payment regime to achieve such goals would also have parallels with land-based extractive industry taxation. It has, for example, been argued that higher global taxes on oil fields could increase government revenues, reduce investment in marginal fields and limit petroleum production to a level consistent with limiting climate change to 2 °C (Wilde and Price 2017).

In summary, the proposed payment regime was designed to promote investment and maximise ISA revenues. Maximising revenues is a common goal, but not the only goal, for tax policy, and it is not the only goal supported by UNCLOS or the 1994 Implementing Agreement. The emphasis on promoting investment and maximising revenue would be justifiable if ISA revenues could be equated with the CHM, but this is a narrow interpretation that is not supported by the literature.

3 Structure of the Payment Regime

The 1994 Implementing Agreement provides for the payment regime to include a royalty only, or a royalty and a profit share. These taxes are levied on different bases. A royalty is normally levied on the miner's revenue from the sale of minerals while profit shares are levied on taxable profits.

The main advantages of a royalty compared to a profit tax are that it provides early and minimum government revenue. A royalty provides these benefits because the costs of developing and operating a mine mean that mine revenues (and the base for the royalty) are larger than, and occur before, profits. The disadvantages of a royalty are that it may inhibit investment (because miners may have to pay the

[15] See the summary of discussions of the payment regime working group. Available at: Open-ended Informal Working Group advances discussions on financial model for mineral exploitation in the international seabed area | International Seabed Authority (isa.org.jm).

Table 18.1 Main extractive industry taxes[a,b]

	Names and examples
Taxes on the right to exploration or mining	Annual fees, area fees, signature bonuses and production bonuses
Taxes on costs/inputs	Customs duties and contractor withholding tax
Taxes on the value of mine output	Ad valorem royalties
Taxes on profits	Corporate income tax, ring-fenced mining or petroleum taxes, profit shares
Additional profit taxes (taxes on profits above a certain level)	R-factor taxes (e.g. the larger cumulative revenues compared to cumulative costs the higher the rate of tax applied) Additional profit taxes (e.g. a 20% tax on profits when the IRR exceeds 17.5%)
Taxes on remitted profits	Dividend withholding tax

[a]VAT is not included in the above table as VAT mainly affects miners' cash flows, and miners are often exempted from VAT.
[b]In some countries Governments also receive revenues from an equity participation in mining and petroleum projects. This can be full, carried or free equity participation.

royalty even if they don't make profits), and does not allow the Government to fairly share in any excess profits which occur due to say lower than expected costs. Table 18.1 summarises the main extractive industry taxes according to the base they are levied on.

Extractive industry tax regimes normally consist of both a royalty and profit tax.[16] The tax regimes of the three largest producers of cobalt, copper, manganese and nickel are summarised in Table 18.2. None of these jurisdictions include a royalty as the only tax on mining. In addition, none of the 22[17] land-based mining tax regimes summarised by PWC (2012) include a royalty as the only significant tax.

It has also been argued that extractive industry tax regimes should include profit taxes and royalties. This conclusion was originally made with reference to petroleum and land-based mining (Baunsgaard 2001; Wilde 2016), but recently it has been extended to DSM in Pacific countries' exclusive economic zones (Mullins and Burns 2018). The logic underpinning this conclusion is that tax regimes consisting of royalties and profit taxes allow governments to receive revenue whenever there is commercial production through the royalty, while also securing higher government

[16] Or some form of profit tax.

[17] The 22 land-based mining tax regimes summarised by PWC (2012) are: Argentina, Australia, Brazil, Canada, Chile, China, Democratic Republic of Congo, Germany, Ghana, India, Indonesia, Kazakhstan, Mexico, Peru, Philippines, Russian Federation, Republic of Congo, South Africa, Tanzania, Ukraine, United Kingdom and the United States. These countries were selected as they have significant mining industries.

Table 18.2 Summary of land-based mining tax regime[a,b,c]

Jurisdiction	Country ranking for production	Royalty or mining tax (%)	Royalty or mining tax base	Corporate income tax (%)	Additional profits tax	Dividend withholding tax (%)	Other significant taxes/fiscal impositions
Western Australia	2nd Manganese, and 3rd Cobalt	7.5	Value	30	N/A	0	N/A
Chile	1st Copper	9.5	Net operating income	27	N/A	35 (CIT is creditable)	N/A
China	2nd Copper	5	Value	25	N/A	10	N/A
DRC	1st Cobalt	10	Value	30	50%	15	10% free interest, and 0.3% community charge
Gabon	3rd Manganese	4	Value	35	N/A	20	N/A
Indonesia	1st Nickel	10	Value and profits	22	10%	10	10% export duty
Peru	2nd Copper	6.5	Operating income	29.5	6.25%	5	8% workers participation
Philippines	2nd Nickel	9	Value	25	N/A	15	Social development programmes tax at 1% of costs
South Africa	1st Manganese	7	Value	28	N/A	5	N/A
Russia	3rd Nickel and 2nd Cobalt	8	Value	20	N/A	5	N/A

[a]See Appendix 2 for data on the largest cobalt, copper, manganese and nickel producers
[b]See Appendix 3 for a detailed list of data sources
[c]See Appendix 4 for more detailed comments on the table and each tax

revenues from highly profitable mines. A royalty-only payment regime for the Area would deviate from this normal practice in extractive industry taxation.

The main justification for a royalty-only payment regime for DSM is ease of administration (Resolve 2017). There is a strong argument, well supported by the existing literature, that royalties are easier to administer than profit shares (Baunsgaard 2001; Wilde 2016). This is because miners may reduce taxable profits through transfer mispricing of costs,[18] hybrid mismatches[19] and other tax avoidance measures.

The argument that the ISA lacks the capacity and budget to administer a profits tax has been advanced throughout discussions on the payment regime (Resolve 2017). It is certainly true that at the current time the ISA does not have a tax administration department or staff with experience in the audit of extractive industry tax returns, but it is arguably well placed to build such capacity. Even low-income countries with weak tax administration implement profit taxes and raise less than 20%[20] of government revenues from the extractive industries through royalties. The ISA is well placed to build tax administrative capacity compared to low-income countries, as it pays higher wages and would be recruiting from an international talent pool.

The DSM industry's structure may, however, make raising revenue from a profit share difficult. State-owned enterprises and states themselves have been awarded polymetallic exploration licences, and these entities may be motivated to undertake unprofitable DSM to ensure a secure supply of metals; thus, potentially reducing ISA revenues from a profit share. The tripartite role of governments as shareholders in state-owned mining enterprises, sponsoring state tax authorities and ISA members may also complicate the ISA aggressively pursuing miners in tax disputes.

The DSM industry may also be vertically integrated with the miner and metallurgical processor being owned by the same parent company (van Nijen et al. 2018; Resolve 2017). In such a case, if taxes are lower in the processor's jurisdiction than under the ISA payment regime and sponsoring state, there would be a motivation to shift profits to the processor.

A miner's taxable profits are dependent on the price they sell nodules to the processor (nodule sales price). Miners can, therefore, reduce their taxable profits and profit share payments to the ISA by selling nodules to the processor at below market rates. Such transfer mispricing of nodule sales would, however, not reduce a miner's royalty payments as the proposed royalty is levied on the CVM, which is a measure of the value of metals in the nodule. The CVM is higher than, and is not directly affected by, the price the miner sells the nodules to the processor.

Transfer mispricing of the nodule sales price may be difficult for the ISA to detect as there are currently no historical data on nodule sales or benchmark prices for nodules. In addition, even after the commencement of commercial mining, it may take many years to establish fair free market prices for polymetallic nodules as

[18] Miners can also engage in transfer mispricing of mine sales, leading to lower ad valorem royalty payments. However, the existence of benchmark prices in some extractive industries may limit the scope for transfer mispricing of mine sales and contributes to mine turnover being easier to audit than mine costs. This in turn contributes to ad valorem royalties being easier to audit than taxes that are levied on profits.

[19] For example, company A in country A provides money to related company B in country B. The financial instrument providing this money is classified as a loan in country B and interest payments are an allowable deduction. In country A the financial instrument is classified as equity and dividend payments from B to A are not taxed. This reduces the tax burden of company B, but does not increase the tax burden of company A.

[20] See data in Appendix 5.

all, or the majority of, transactions may be between related parties. Attempts by the ISA to indirectly determine fair market prices for nodules by calculating the nodule price that would result in an acceptable risk-adjusted financial return for the miner and processor would also be fraught with difficulties. These difficulties include understanding processors' costs, correctly allocating risk between the processor and miner, and determining the correct risk-adjusted financial returns for both parties. The difficulties in understanding market prices for DSM are also arguably more difficult than for other extractive industries, such as the petroleum industry, where well-established benchmark prices are available.

Overall, all countries rely on royalties and profit taxes. A payment regime relying on a royalty only would be unusual and is not justified by the ISA's current lack of tax administration capacity. However, the structure of the DSM industry would complicate the administration of a profit share.

4 Financial Results for the 2%/6% Royalty Payment Regime

This section presents results from our financial model of DSM. The model's central scenario uses the same assumptions as the MIT Report and MIT Model,[21] but recalculates their results using a simpler non-stochastic method.[22] This approach is followed because the production, cost and price assumptions underpinning the MIT model are detailed, transparent and well-researched; while programming a new model allows us to readily test the impact of changes in the underlying assumptions. Our focus throughout is on the payment regime, and we do not evaluate the cost, price and production assumptions in detail.

The model's assumptions and results are summarised in Box 18.1 and Table 18.3 respectively. The miner's post-tax IRR is 17.6% and the ISA receives $3.9[23] billion in revenue over the 37-year life of the mine.[24] The miner receives a 57% share of the pre-tax profits from mining, with the remaining 43% being shared between the ISA (22%), sponsoring state (19%) and environment fund (3%).

On a discounted basis (10% discount rate) the miner's post-tax profits and ISA's revenues are $801 million and $461 million respectively. The royalty results in the ISA receiving significant revenue as soon as commercial production commences

[21] The MIT Model has been updated on numerous occasions and the results presented through presentations, briefing notes and reports (most recently in October 2020). We use the assumptions outlined in the MIT Report of 2019 as this report contains the most detailed exposition of the model, and moreover, the results from this report have been the focus of discussions at the ISA. In addition, the published excel-based model uses assumptions that are consistent with those contained in the MIT Report of 2019. The model is available at: https://isa.org.jm/files/files/documents/doclist_0.pdf

[22] The main difference is that the MIT Report presents averages from a Monte Carlo Simulation.

[23] All dollar figures in this report at in constant 2018 USD unless otherwise stated.

[24] The 37-year period includes pre-feasibility and feasibility, production occurs over 26 years.

Box 18.1 Key Assumptions Central Scenario

Miner's Costs

The miner's total costs are $12,159 million over the life of the mine. These costs consist of: feasibility stage year 1–7 $198 million in total; design and build of the collection system and surface vessel years 8–10 $1643 million in total; operation and maintenance of capital equipment years 12–36 $761 million in total; residual value of equipment—$196 million year 37 in total; operating costs years 11–36 $9754 million in total.

Miner Production

Production starts in year 11 and finishes in year 35. Peak production of three million dry tons of polymetallic nodules is achieved in year 13. Each dry ton of polymetallic nodules consists of: Cobalt 0.2%, Copper 1.1%, Manganese 28% and Nickel 1.3%.

Nodule Prices

The miner sells nodules to the processor at an amount which equalises their respective post-tax internal economic rates of return. For the central scenario, this equates to a nodule price $398.

ISA Taxes

Miners pay the following fees to the ISA: exploration license fee $0.5 million year 1; exploitation license fee $1 million year 4; annual exploration fee $0.06 million per annum years 1–6; annual exploitation fee $0.1 million per annum years 4–36.

The miner pays a royalty to the ISA of 2% (for the first 4 years of commercial production) and 6% thereafter. The royalty is levied on the CVM exported from the contract area.

Sponsoring State Tax

The miner pays sponsoring state CIT at 25%. Immediate expensing and unlimited carry forward of losses are assumed for CIT. Payments to the ISA (fees and royalties) are deductible.

Metallurgical Processor Costs

The processor's total costs are: $18,553 million (capital and operating) plus $29,852 million for the purchase of nodules. Capital costs are: feasibility years 1–7 $116 million in total; design and build years 8–10 $2071 million in total; and site residual value year 37—$311 million in total. Operating costs are: $16,667 million in total over years 11–36.

Metallurgical Processor Production

The processor processes all nodules mined by the miner. Metal recovery rates are: Cobalt 85%, Copper 90%, Manganese 90% and Nickel 95%.

Metal Prices

Long-term average metal prices over the life of the mine per ton are: Cobalt $54,651, Copper $6,844, Manganese $1,643 and Nickel $21,478.

Metallurgical Processor Taxes

The processor pays a 25% CIT. Immediate expensing and unlimited carry forward of losses are assumed.

Table 18.3 Results for the 2%/6% royalty payment regime central scenario

	$ Million over the life of the mine
Miner turnover	29,851
Miner costs	12,159
Miner pre-tax profits	17,692
Miner pre-tax IRR	22.7%
ISA payment regime results	
Fees	5
Royalty	3846
Profit tax	0
Additional profit tax	0
Total ISA (exc Environment Fund)	3852
Environment fund	500
Sponsoring state tax	3335
Miner post-tax profits	10,005
Miner post-tax IRR	17.6%
Peak miner post-tax profits per annum	683
Peak ISA revenues per annum	175
Miner percentage share	57%
Environment fund percentage share	3%
ISA percentage share	22%
Sponsoring state percentage share	19%
Effective tax rate	43%
Miner post-tax profits discounted at 10%	801
Environment fund discounted at 10%	89
ISA revenues discounted at 10%	461
Sponsoring state revenues discounted at 10%	374
Miner share discounted	46%
Environment fund share discounted	5%
ISA revenues discounted	27%
Sponsoring state revenues discounted	22%

and prior to the miner making a profit. These early revenues also lead to the ISA's share of pre-tax profits being higher in discounted than nominal terms (27% discounted compared to 22% nominal).

A key result is that the miner's post-tax IRR exceeds the 17.5% hurdle rate regarded as necessary to motivate investment. This result is unsurprising as the royalty rates (and ISA revenues) were maximised subject to the miner's post-tax IRR exceeding the hurdle rate and given the payment regimes structure.[25] Under this methodology, if different cost, price and production assumptions had resulted in

[25] The payment regime's structure consists of two periods of commercial production with the first period lasting 4 years and the royalty rate in the second period being double that of the first. The royalty rate varying between two periods allows for higher ISA revenues in discounted terms if it is assumed that the ISA has a lower discount rate than miners.

higher pre-tax profits, then MIT would have proposed higher royalty rates consistent with the miner achieving a 17.5% post-tax IRR. This methodology for determining the royalty rates would be most appropriate if pre-tax profits could be forecasted with a significant degree of certainty, or if the 2%/6% royalty payment regime had desirable outcomes for a broad range of pre-tax profits.

5 Sensitivity of ISA Revenues to Different Cost and Price Assumptions

The miner's forecasted pre-tax profits are dependent on assumptions regarding costs and nodule prices. Commercial polymetallic nodule mining has never been undertaken before, and as such, there is a significant degree of uncertainty regarding the likely costs over the 37-year life of the mine. Indeed, even for well-established extractive industries such as the petroleum industry, the costs of mega projects are difficult to predict with certainty and actual costs often substantially deviate from those budgeted (EY 2014).

There is also significant uncertainty regarding long-term commodity prices. Even for petroleum —where there is significant historical data, a well-established market and significant resources are allocated to forecasting—the price projections of the respected U.S. Energy Information Administration are highly inaccurate (Wachtmeister et al. 2018). Forecasting polymetallic nodule prices is also complicated by the fact that their sales price will likely depend not just on metal prices, but also on the metallurgical processor's costs and its required post-tax IRR.

Moreover, the supply of metals from DSM may place downward pressure on electrolytic manganese metal and low carbon ferromanganese metal prices (MIT Report). This implies that at least when forecasting long-term manganese and nodule prices, reasonable assumptions have to be made concerning the future size of the DSM industry. The price forecast in our model is taken from the MIT Report which assumes two deep-seabed mines when forecasting manganese prices. The logic underpinning the assumption that there will only be two mines is, however, not fully explained and given that there are currently 19 ISA exploration licenses, and additional nodule resources in the national jurisdictions of the Cook Islands and Kiribati, further DSM cannot be discounted.[26]

Overall, there is considerable uncertainty concerning nodule prices and miners' costs.[27] In our financial model, under the 2%/6% royalty payment regime the miner's post-tax IRR is sensitive to changes in the assumptions concerning nodule

[26] This is not, however, to imply that all 18 mine sites are likely to commence commercial production at the same time. Some contractors do not yet have the technology or finances to start commercial mining, and the downward pressure on metal prices from the first few mines may also limit the development of further mine sites in the short term and medium term.

[27] This uncertainty is sometimes modelled through a Monte-Carlo simulation. However, we do not follow that approach as it requires assumptions regarding the probability distributions for miners'

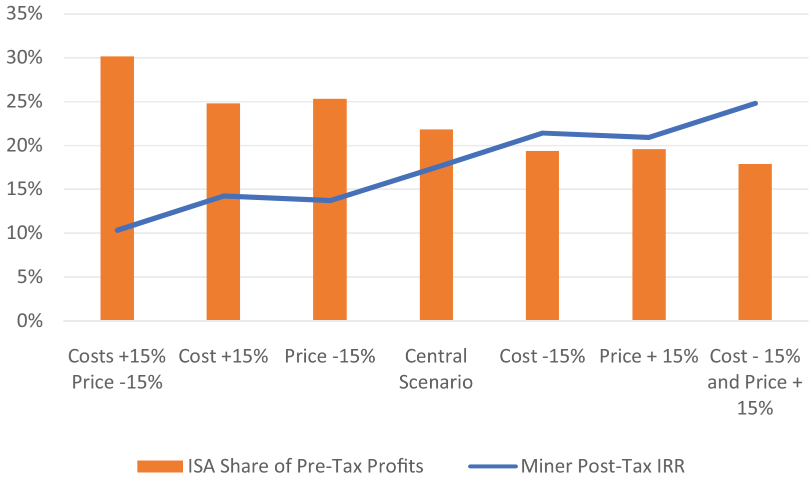

Fig. 18.1 ISA revenues and miner post-tax IRR under different assumptions

prices and costs. Specifically, the miner's post-tax IRR varies between 10.3% and 24.8% when nodule prices and costs are modified by ±15% (see Fig. 18.1).

The 2%/6% payment regime is also highly regressive; that is, as the miner's profits increase the ISA's percentage share of pre-tax profits decreases. Thus, if pre-tax profits are higher than in the central scenario, miners make post-tax profits in excess of these required to motivate investment, and the ISA could likely increase taxes without inhibiting investment. However, if pre-tax profits are lower than in the central scenario, the ISA's share of pre-tax profits increases and miner's post-tax profits fall to below the rate required to motivate investment.

The conclusion that a 2%/6% royalty is consistent with a 17.5% post-tax IRR is also not robust to changes in nodule prices. For example, if nodule prices are 10% higher than under the central scenario a 6%/18%[28] royalty is consistent with a 17.5% miner post-tax IRR (see Table 18.4).

The 2%/6% royalty regime thus only maximises ISA revenues given very specific assumptions regarding costs and nodule prices, and it does not maximise ISA revenues if profits are lower or higher than forecasted in the central scenario. It is partly due to the regressive nature of a royalty that no existing extractive industry tax regime includes a royalty as the only major tax, and that the literature and practitioners normally recommend that extractive industry tax regimes consist of

costs and nodule prices, and there is little empirical evidence to support assumptions regarding a particular distribution.

[28] The royalty rates for the first and second periods of commercial production were maximised subject to the constraints that: (a) there could only be two royalty rates; (b) that the first period of commercial production was 4 years; (c) that the royalty in the second period of commercial production must be treble that of the first period of commercial production; and (d) that the miner post-tax IRR should equal 17.5%.

Table 18.4 Royalty rates under different price assumptions

Scenario	Royalty consistent with 17.5%
Prices—10%[a]	0%/0%
Central scenario	2%/6%
Prices + 10%	6%/18%
Prices + 20%	9%/27%

[a]At these prices even zero ISA taxation does not result in the miner's post-tax IRR exceeding 17.5%

royalties, profit taxes and excess profit taxes (Baunsgaard 2001; Wilde 2016; and Mullins and Burns 2018).

6 Sensitivity of ISA Revenues to Sponsoring State Tax Assumptions

A miner may have to pay taxes to its sponsoring state as well as the ISA. Sponsoring state taxes will reduce miner's profits and the fiscal space for ISA taxes. The MIT Report assumes a miner pays a 25% corporate income tax (CIT) to its sponsoring state. Payments to the ISA are also assumed to be deductible and not creditable when determining the miner's sponsoring state CIT liability. The rationale for the 25% CIT assumption is that this is the average CIT rate across sponsoring states. The rationale for assuming miners' payments to the ISA are deductible, and not creditable, against sponsoring state CIT is not stated, and is not based on a review of tax legislation in sponsoring states.

The only way to accurately determine miners' sponsoring state CIT liability is to undertake a detailed review of sponsoring states tax laws and sponsorship agreements. It is, however, impossible to undertake such a review as the only publicly available signed sponsorship agreement is for UK Seabed Resources.[29] An unsigned draft sponsorship agreement for Nauru Ocean Resources Inc.[30] (NORI) is also publicly available.[31]

[29]The sponsorship agreement for UK Seabed Resources does not provide it with exemption from UK CIT.

[30]The unsigned draft sponsorship agreement for NORI is available at: https://www.itlos.org/en/main/cases/list-of-cases/case-no-17/ (as an annex to the written statement of the Republic of Nauru), and at: https://www.itlos.org/fileadmin/itlos/documents/cases/case_no_17/Statement_Nauru.pdf

[31]The unsigned draft sponsorship agreement for NORI includes provisions requiring that the State remedies the effects on NORI of a discriminatory change in Nauruan law. A discriminatory change in law is defined in the agreement to include any change in Nauruan law which 'materially increases the quantum of benefits required to be given by NORI or UNI (whether economic or intangible) to the State in such a way as to materially change the intent contemplated under this Agreement (including without limitation changes to Nauruan Laws resulting in a materially adverse increase in NORI's tax burden).' Nauru did not have a CIT at the date of the draft

There are, however, four general reasons to consider that the 25% CIT assumption may overstate the taxes received by sponsoring states from DSM.

Firstly, many sponsoring states operate worldwide tax systems. Under this system, countries tax resident corporations on their global profits and foreign tax payments are creditable against domestic CIT. A contractor may not be resident in its sponsoring state, and therefore profits from the Area may be classified as foreign income of a foreign entity in the sponsoring state and not taxed. Although a sponsoring state must exercise 'effective control' over its contractor, this does not necessarily mean that the contractor meets the definition of a 'resident corporation' under the tax act. In addition, for some countries with worldwide tax systems, the sponsored miner's profit share payments to the ISA would be regarded as equivalent to 'foreign tax payments' and be creditable against domestic CIT.[32] In such cases, the correct assumption in the economic model would be that ISA tax payments are creditable and not deductible when determining sponsoring state CIT liability. Payments to the ISA for royalties would, however, be unlikely to meet the definition of a 'foreign tax' for which tax credits are granted.

Secondly, in a territorial tax system, profits from foreign jurisdictions are excluded from taxable income in the domestic jurisdiction. This may provide an avenue for miners to argue, or include in sponsorship agreements, that as mining is occurring in the Area, and taxes are paid to the ISA, profits from DSM should not be included in their taxable profits when determining CIT liability in the sponsoring state.

Thirdly, CIT in sponsoring states is levied on the corporation and not the mine.[33] Corporations can offset the profits from a mine against losses from other economic activities to reduce their sponsoring state taxable income and CIT liability. It is for this reason that many extractive industry tax regimes ring-fence taxable profits around each mine, and do not allow the corporation to use losses from other economic activities or mines to reduce the tax liability of a profitable mine. In contrast, possibly because of their limited experience in mining taxation, sponsoring states

sponsorship agreement. Nauru has since introduced CIT and the current rate for large companies is 20%. The effects of the provisions in the unsigned draft sponsorship agreement would, if included in the final signed sponsorship agreement, effectively have been to exempt NORI from the 20% CIT currently in force in Nauru.

[32] Whether in actuality tax payments to the ISA would qualify as foreign tax payments and be creditable against sponsoring state CIT is dependent both on the detailed provisions of the sponsoring state's tax laws and on the detailed structure of the ISA payment regime. It is, therefore, difficult to reach a firm conclusion on this matter for sponsoring states in general (as opposed to a particular sponsoring state) and prior to the details of the ISA's payment regime being finalised. When drawing a conclusion regarding whether tax payments will be creditable under the worldwide tax system of a particular sponsoring state two issues are likely to be of particular importance. Firstly, under the sponsoring state's tax law does income accruing from mining in the Area qualify as foreign income. And secondly, under the sponsoring state's tax law do the ISA's taxes qualify as being equivalent to CIT payments.

[33] The term 'mine' is used in this section to refer to the area covered by a polymetallic nodule exploration or exploitation contract with the ISA.

have not redrafted their CIT legislation to require corporations to ring-fence taxable income around each mine in the Area. Thus, a corporation's taxable income for the purposes of sponsoring state CIT may not equal its profits from a mine in the Area.

Fourthly, miners may be in a strong position to negotiate tax exemptions with sponsoring states. Sponsoring states do not own, or fully control access to, resources in the Area. Any state, or developing state, that is a party to UNCLOS can sponsor a miner, and prior to the sponsorship agreement being finalised there is no legal constraint on the miner approaching numerous states for sponsorship. Contractors are, thus, in a strong position to negotiate tax exemptions from a sponsoring state, as if they do not receive generous exemptions, they can approach another state for sponsorship and still gain access to the same polymetallic nodule resources. This situation is quite different to that pertaining in other extractive industries, whereby miners must pay taxes to the country where the resource is located if they want to mine that resource in that location. Miners may be in a particularly strong position to negotiate sponsoring state CIT tax exemptions with small island developing states, as some of these states have limited experience negotiating tax agreements with large mining companies and even a small share of the profits from DSM may still be significant compared to their domestic economies.

However, this is not to say that sponsorship shopping is common or without cost to the miner. Some miners may invest significant amounts of time and effort in building a relationship with a potential sponsoring state, and may not wish to start negotiations again from scratch with another state to simply to secure marginally more favourable fiscal terms. Miners may also consider a range of factors, and not just taxation, when deciding which states to approach for sponsorship.

Miners may not then always be liable to pay the headline rate of CIT on profits from mining in the Area. As noted above, the inclusion of realist assumptions on miners' sponsoring state tax liability is hindered by the fact that most sponsorship agreements are not publicly available. However, Tonga Offshore Mining Limited (TOML), a miner holding an ISA exploration license in the Area, commissioned a technical report that states (AMC 2016):

> TOML has agreed to a royalty with the Tongan government of US$1.25 per dry ton of nodules for the first 3 million dry tons of nodules mined in any one year and US$0.75 per dry ton for all dry tons mined thereafter in that same year.

This does not, of course, imply that the financial relationship between TOML and the Government of Tonga is mirrored in all other sponsoring states. Different miners will be liable for different taxes in different sponsoring states.

Sponsoring state tax assumptions significantly affect a miner's post-tax profits. For example, in the Replicated Model, if sponsoring state tax is assumed to be $1.25 per dry tone of nodules and not CIT at 25%, then the post-tax IRR increases from 17.6% to 18.5%; while the sponsoring state's share of pre-tax profits decreases from 19% to 1%. Assuming lower sponsoring state taxes also provides more fiscal space for higher ISA royalties. More specifically, an ISA royalty of 3%/10% is consistent with a miner post-tax IRR above 17.5% when sponsoring state tax is $1.25 per dry ton of nodules (Table 18.5).

Table 18.5 Sponsoring state tax, ISA royalties and miners post-tax IRR

Sponsoring state tax	ISA royalty	Sponsoring state share of miner's pre-tax profits (%)	ISA share of miner's pre-tax profits (%)	Miner post-tax IRR (%)
25% CIT	2%/6%	18.9	21.8	17.6
$1.25 per ton	2%/6%	0.6	23.5	18.5
$1.25 per ton	3%/10%	0.5	36.4	17.8

It is also debateable whether sponsoring states receiving a large share of the profits from the DSM in the Area is consistent with the CHM principle. Sponsoring states are likely to use revenues from DSM in the Area to pursue their own national public policies, and sponsoring state taxes reduce the fiscal space for ISA taxes and payments to the CHM.

High sponsoring state taxes may also be inconsistent with global equity. Using the World Bank country classification,[34] no low-income country is a sponsoring state for polymetallic nodule mining, and Kiribati[35] and India are the only two lower-middle income sponsoring states. All other sponsoring states[36] are upper-middle-income countries or high-income countries. Miners that are sponsored by small island developing states are often subsidiaries of companies headquartered in developed states (Greenpeace International 2020), and low-income countries are not well placed to contribute to the DSM supply chain. The extent to which poor countries are participating in DSM in the Area through sponsorship is, thus, questionable. In contrast, low-income and lower-middle income countries such as the Democratic Republic of Congo, Ghana and the Philippines are significant land-based miners of the metals contained in polymetallic nodules.

To summarise, the assumption that miners will, on average, pay a 25% CIT to their sponsoring state is questionable. Furthermore, the conclusion that a 2%/6% royalty maximises ISA revenues is very sensitive to changes in the assumptions concerning sponsoring states taxes. Understanding sponsoring state taxes in more detail would be very useful in designing the ISA payment regime, but is stymied by the confidential status of most sponsorship agreements.

[34] This chapter uses the World Bank definitions of low-income countries and lower middle-income countries. See: https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups

[35] Kiribati is classified as a least developed country by the United Nations. See: https://www.un.org/development/desa/dpad/least-developed-country-category/ldcs-at-a-glance.html

[36] Neither the World Bank nor the United Nations includes the Cook Islands in their country classification indexes.

7 Effective Rates of Taxation for Land-Based Mining and DSM

DSM and land-based mining should arguably face a similar tax burden. For if DSM were to face a significantly lower overall burden of taxation than land-based mining then this would encourage capital to be allocated to DSM even if it was a less efficient and higher cost way of producing the same minerals as land-based mining. Analogously, if DSM faced a significantly higher overall burden of taxation than land-based mining it may struggle to attract capital even if it were a lower cost and more efficient way of producing the same minerals. The principle that the payment regime should not advantage or disadvantage DSM relative to land-based mining is also supported by the 1994 Implementing Agreement,[37] which states:

> 'The rates of payments under the system shall be within the range of those prevailing in respect of land-based mining of the same or similar minerals in order to avoid giving deep-seabed miners an artificial competitive advantage or imposing on them a competitive disadvantage'

The term 'rates of payment' is not defined in the 1994 Implementing Agreement, and there would appear to be two possible interpretations. The first is that the rates of individual taxes in the payment regime should be similar to those for land-based mining. This would lead to an analysis which compared say the 2% royalty for the first period of commercial production in the Area to say the 7.5% royalty on crushed and screened manganese in Western Australia. Such an analysis is, however, from an economic viewpoint, almost meaningless as the proposed payment regime only includes one tax—the royalty—while land-based mining regimes include multiple taxes. The royalty in the Area could be higher than a royalty for land-based mining, but the overall burden of taxation faced by land-based miners might still be higher due to the other taxes they pay.

In addition, the bases for the royalty in the Area and land-based mining regimes are different.[38] The payment regime levies the royalty on the CVM in the nodule. In contrast, many land-based regimes levy the royalty on the invoiced sales value of mine output. The nodule sales price in our financial model's central scenario (broadly analogously to the invoiced sales value of mine output) is 46% of the CVM. A 2% royalty levied on CVM will therefore raise more revenue and result in a higher burden of taxation than a 2% royalty levied on invoiced sales value. Thus, due to differences in the base the royalty is applied to, there is little economic justification for directly comparing the royalty rates from land-based mining and DSM.

A second interpretation of the term 'rates of payment' is that it refers to the effective tax rates for DSM and land-based mining. The term 'effective tax rate'

[37] 1994 Implementing Agreement, Section 8 1(b).

[38] The payment regime in the Area levies the royalty on CMV. In contrast, many land-based mining regimes level the royalty on invoiced sales value. In our model's central scenario, the invoiced sales value of nodules is 46% of their CMV.

refers to a miner's total tax payments divided by its pre-tax profits.[39] Thus, an effective tax rate of 40% indicates that for $100 dollars of pre-tax profits over the life of the mine, the government receives $40 in government revenue, and the miner receives $60 in post-tax profits. This interpretation is rational from an economic perspective as it is the impact of the effective tax rate on miner's post tax profits, and not the rates of individual taxes, that is normally considered in investment decisions.

This Chapter, therefore, proceeds by comparing the effective tax rates for DSM and land-based mining. Such an analysis is, however, complicated by whether sponsoring state corporate income tax (CIT) should be included when comparing effective tax rates for DSM and land-based mining. On the one hand, the term 'the system' in the 1994 Implementing Agreement appears to refer to the payment regime in the Area and does not encompass sponsoring state taxes. Buttressing this argument, land-based mining effective tax rates only include taxes paid in the jurisdiction where mining occurs and do not include taxes paid in foreign jurisdictions by say the parent company of the miner. Any CIT paid by a miner to a sponsoring state is arguably analogous to the CIT paid by the parent company in jurisdiction A on the remitted profits of a subsidiary company undertaking land-based mining in jurisdiction B. Overall, these two arguments provide a strong basis for not including sponsoring state tax when comparing effective tax rates for DSM and land-based mining.

On the other hand, there are also strong arguments for including sponsoring state tax when comparing effective tax rates between DSM and land-based mining. Miners in the Area potentially face taxation in three jurisdictions; namely the Area, their sponsoring state and where their parent company is domiciled (which may be a different jurisdiction from the sponsoring state). In contrast, land-based miners may face taxes in two main jurisdictions, namely the jurisdiction where mining occurs and the jurisdiction where the parent company is headquartered. From this viewpoint, deep-seabed miners face taxes in an additional jurisdiction compared to land-based miners, namely the sponsoring state. In addition, the tax burden borne by the parent company of a land-based miner on remitted profits from mining undertaken in a different jurisdiction may be limited due to double tax agreements, tax credits under a worldwide system or the exclusion of foreign income under a territorial tax system. In contrast, there are no double tax agreements between the Area and Sponsoring States, and, partly due to sponsorship agreements not being published, it is unclear how income from the Area will be treated in calculating tax liability in sponsoring states.

We calculate effective tax rates for the 2%/6% royalty payment regime and nine land-based mining jurisdictions. Land-based mining countries were selected as they are one of the ten largest three producers of cobalt, copper, nickel or manganese. The taxes and tax rates applied for each land-based mining jurisdiction are those

[39] More formally the term 'profits' in this sentence refers to net cash flows.

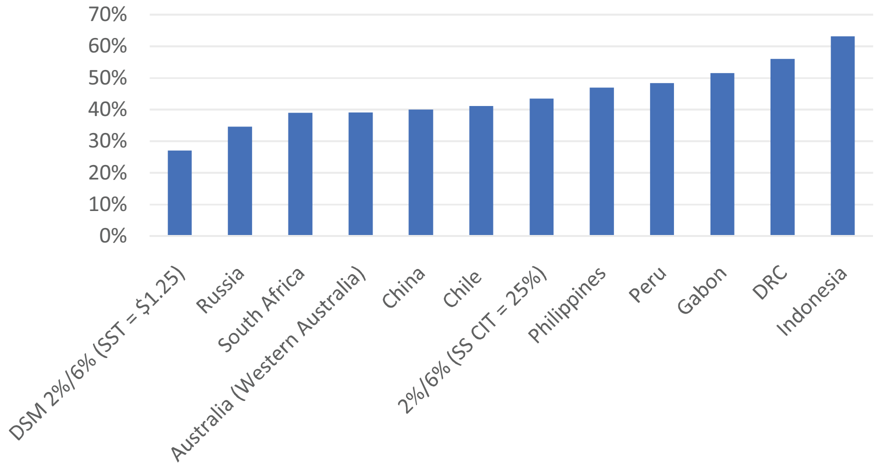

Fig. 18.2 Effective tax rates

outlined in Table 18.2,[40] and the pre-tax cash flows are those from the central scenario of our model.

Figure 18.2 shows effective tax rates for land-based mining and DSM in the Area. The average effective tax rate across the nine land-based jurisdictions modelled is at 46%. This is significantly higher than the 27% effective tax rate for DSM in the Area (assuming sponsoring state tax at $1.25 per dry ton of nodules). Earlier studies of land-based mining effective tax rates show similar results, with Otto (2006) and the Commonwealth (2009) reporting average effective tax rates for land-based mining of 47% and 49% respectively.

The 27% DSM effective tax rate is lower than for any of the land-based mining jurisdictions modelled. However, it is also sensitive to assumptions regarding sponsoring state tax, with the DSM effective tax rate increasing to 43% if sponsoring state CIT at 25% is assumed. Thus, the uncertainty concerning sponsoring state taxes makes it difficult to reach a firm conclusion concerning whether a 2%/6% payment regime is, or is not, consistent with rates of payment within the range of those prevailing in respect of land-based mining of the same or similar minerals.

[40] For ease of calculation immediate expensing and unlimited loss carry forward are assumed for all tax regimes. The effective tax rates calculated do not include VAT (as this mainly affects cash flows), area fees (due to the difficulty equating a deep-seabed mine to a certain sized land-based mine) or discretionary tax holidays. For some jurisdictions the tax rates shown in Table 18.2 are averages of tax rates that vary with profits or net operating income; in such cases, the varying rates were modelled when calculating the effective tax rate for that jurisdiction.

8 Alternative Payment Regimes

This section discusses an alternative payment regime which includes a royalty, profit tax and excess profit tax. The rate of the royalty is 5%, and it is levied on the CVM exported from the contract area. The rates of the profit tax and excess profit tax are 20% and 25% respectively, and the excess profit tax is levied when the miner's IRR (ex-post payments to the ISA) exceeds 17%. The results from this payment regime under the cost, price and production assumption outlined in Box 18.1 and sponsoring state tax at $1.25 per ton of nodules are shown in the Table 18.6.

This payment regime has a number of desirable properties. The royalty guarantees the ISA early and significant revenues, while the profit and excess profits taxes mean that the payment regime is progressive (see Fig. 18.3). The effective tax rate for this payment regime is 45% and ISA revenues are higher than under the 2%/6% royalty payment regime.

There are, however, also disadvantages to this multi-tax payment regime. The profit tax and additional profit tax might be vulnerable to tax avoidance through transfer mispricing of nodule sales or costs, although in such cases the 5% royalty would still provide the ISA with significant revenue.

9 Conclusion

In conclusion, we may ask: does a royalty only regime for nodule mining in the Area conform to international best practice in extractive industries taxation and the goals mandated in UNCLOS and the 1994 Implementing Agreement?

All land-based mining and petroleum tax regimes include both royalties and profits taxes. The reason few, if any, extractive industry tax regimes include only a royalty is that such a regime would be highly regressive, with the effective tax rate declining as profits increased. The financial modelling undertaken in this Chapter demonstrates that this is the case for a 2%/6% royalty payment regime for the Area, with the ISA's share of profits decreasing as the miner's profits increase.

The conclusion that a 2%/6% royalty only payment regime maximises ISA revenues is also highly sensitive to uncertain assumptions regarding metal prices, costs and sponsoring state taxes. The difficulties in accurately forecasting metal prices and costs are well noted in the literature, and given the sensitivity of the results, the logic of fine-tuning royalty rates to uncertain forecasts of future profits is questionable. There would be significant advantages to a more progressive payment regime whereby ISA revenues increased with profits.

The 1994 Implementing Agreement specifies objectives for the payment regime. These objectives include attracting investment in the Area, administrative simplicity and optimum revenues for the ISA. The 2%/6% royalty payment regime would be administratively simple and limit the scope for tax avoidance. It is also, under our central assumptions, consistent with post-tax profits that would encourage

Table 18.6 Alternative payment regime: royalty, profit tax, and excess profit tax

	$ Million over life of the mine
Miner turnover	30,067
Miner costs	12,159
Miner pre-tax profits	17,908
Miner pre-tax IRR	22.9%
ISA payment regime results	
Fees	5
Royalty	3,573
Profit tax	2,766
Additional profit tax	1,097
Total ISA (exc environment fund)	7,441
Environment fund	500
Sponsoring state tax	94
Miner post-tax profits	9,873
Miner post-tax IRR	17.4%
Peak miner post-tax profits per annum	608
Peak ISA revenues per annum	423
Miner percentage share	55%
Environment fund percentage share	3%
ISA percentage share	42%
Sponsoring state percentage share	1%
Effective tax rate	45%
	0
Miner post-tax profits discounted at 10%	813
Environment fund discounted at 10%	89
ISA revenues discounted at 10%	854
Sponsoring state revenues discounted at 10%	13
Miner share discounted	46%
Environment fund share discounted	5%
ISA revenues discounted	48%
Sponsoring state revenues discounted	1%

investment in the Area. However, it only maximises ISA revenues under very specific assumptions, and is sensitive to variations in those assumptions. Given the high uncertainty associated with forecasting profits for the nascent DSM industry, these underlying assumptions may well prove incorrect, and in reality, the ISA's revenues are unlikely to be optimised by a royalty only payment regime.

The 1994 Implementing Agreement also mandates that the payment regime should have similar rates of payment to land-based mining. It is, however, difficult to draw a firm conclusion when comparing effective taxes rates for DSM and land-based mining as, due to the non-publication of sponsorship agreements, there is uncertainty regarding miners' sponsoring state tax liability.

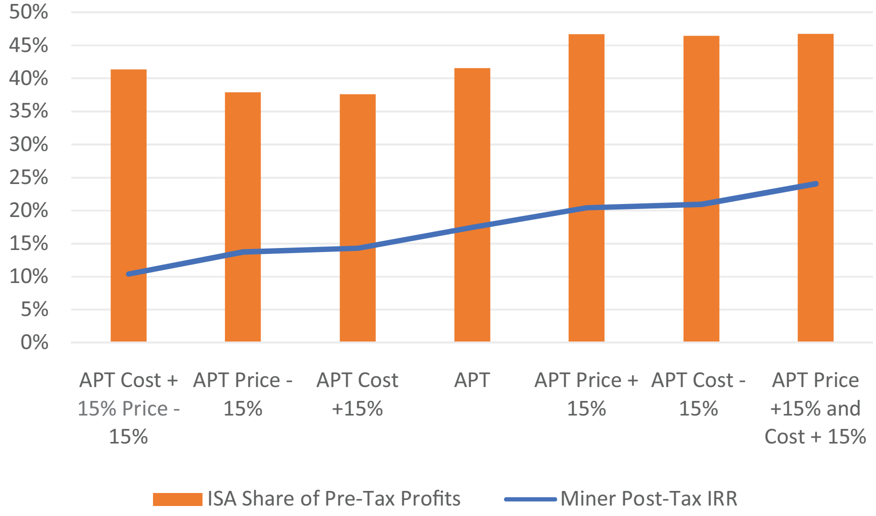

Fig. 18.3 ISA share of pre-tax profits under different profit scenarios

We may also ask whether the approach to designing the payment regime was consistent with the CHM principle. In designing the payment regime, maximising ISA revenues was equated with maximising the CHM. This is a narrow interpretation, and it has been argued that the CHM concept encompasses participation by, and the advancement of, developing states. The proposed payment regime does nothing to encourage such participation and was designed assuming significant taxation by sponsoring states many of whom are not low-income countries. The extent to which the design of the current payment regime maximises benefits to the CHM is then questionable.

10 Appendix 1: Mathematical Notation for the Royalty Payment

Box 18.2 Royalty Payment Calculation

$$\mathrm{CVM}_t = Q_t \sum_i \left[G_i P_{it} \right]$$

When:

CVM = Value of minerals exported from the contract area
Q = Total quantity of mineral bearing ore (in tons) exported from the contract area
G_i = The average metal content of relevant metal i expressed as percentage per ton of the mineral bearing ore

P_i = The price of metal i

Appendix 2: Largest Producers of Cobalt, Copper, Manganese and Nickel[41]

Country	Cobalt production (metric tons)
Australia	5100
Democratic Republic of Congo	100,000
Russia	6100
All others	28,800
Total	140,000

Country	Copper production (metric tons)
Chile	5600
China	1600
Peru	2400
All other	9100
Total	20,000

[41] All data taken from: US Geological Survey. (2020). Mineral commodity summaries 2020.

Country	Manganese production (metric tons)
South Africa	5500
Australia	3200
Gabon	2400
All others	7900
Total	19,000

Country	Nickel production (metric tons)
Indonesia	800,000
Philippines	420,000
Russia	270,000
All others	1,210,000
Total	2,700,000

Appendix 3: Data Sources for Table 18.2

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Appendix 4: Notes on Table 18.2

General Comments

This table is a simplification of the complex tax regimes existing in the jurisdictions listed. VAT was not included as it mainly affects cash flows and not overall profits. Area fees were not included due to their normally small impact on effective tax rates. For tax rates that vary within a range the simple average is normally shown with the exception of South Africa where the upper limit for the royalty normally applies and is shown. For withholding tax, if the jurisdiction has tax treaties with most countries which are likely to be large investors then the reduced rate of withholding tax is shown. For all countries the tax regime shown is that applicable to the mineral listed in the second column.

Western Australia

Manganese royalties vary with beneficiation and are 7.5% crushed and screened, and 5% if further beneficiated in Western Australia.

Cobalt royalties vary with beneficiation and are 7.5% crushed and screened, 5% when sold as concentrate and 2.5% when sold in metal form.

Deductions for transport and packing costs are allowed when calculating the base for the royalty.

Withholding tax is 0% for franked dividends. For non-franked dividends the headline withholding tax rate is 30%, but this is reduced for the many countries that Australia has tax treaties with.

Chile

The mining tax varies from 0% to 14% with annual sales and is levied on the net operating income of the miner. For large mines with sales in excess of 50,000 tons of refined copper the rate ranges from 5% to 14%.

Chile operates a two-stage CIT tax structure. Large mining entities are liable for a first category tax at 27% which may be partially or fully creditable against CIT.

Corporate income tax paid is fully creditable against this withholding tax.

China

The royalty for copper concentrate varies between 2% and 8%.

The rate of withholding tax is 10% for many countries including the USA that have tax treaties with China. Other countries have tax treaties with China that reduce dividend withholding tax to 5%.

Democratic Republic of Congo

The royalty is levied on invoiced sales value less transport, insurance and marketing costs.

The DRC also levies an additional profits tax of 50% of profits when prices exceed those stated in the feasibility study by more than 25%. Taxable income subject to the additional profits tax is not subject to the CIT.

Gabon

The rate of the royalty varies from 3% to 5%, with the exact rate stated in the mining agreement.

The general rate of CIT is 30%, but this is increased to 35% for companies operating in the mining and petroleum sectors.

Twenty percent 20% is the headline withholding tax rate for dividends. Gabon only has tax treaties with Belgium, Canada, France and Morocco.

Indonesia

The royalty rate is 10% for nickel ore.

Tax holidays are available for the integrated upstream basic metals industry. It is unclear how many miners have qualified for these tax holidays. For the fiscal year 2020/2021 CIT is scheduled to be reduced to 22% and then to 20% in 2022. Prior to 2020/2021 the CIT rate was 25%.

Holders of IUPK licenses are required to pay an additional tax at 10% of net profits.

The withholding tax rate is 20% for jurisdictions that Indonesia does not have a tax treat with. Indonesia has tax treaties with many jurisdictions, and in such cases the withholding tax rate for substantial holdings/FDI is reduced to 10%.

Peru

The modified mining royalty is applied to operating income and varies from 1% to 12% with operating profit margin.

Operating income is defined as revenue generated from the sale of mineral resources less: (1) cost of goods sold, and (2) operating expenditure.

Miners may benefit from an income tax holiday of 4–8 years.

There is a special mining tax on operating profits which ranges from 2% to 8.4% and is deductible against CIT.

Philippines

There is a base royalty of 4% plus 5% (in mineral reservation), 1–1.5% in indigenous people area or 2% if there are surface owners of the land.

Miners are required to pay 10% of their approved budget during exploration, and 1.5% of their direct mining costs for social development.

The headline rate of dividend withholding tax is 30%, but this is reduced to 15% by tax treaty for investment from many jurisdictions.

South Africa

The royalty rate for unrefined minerals is determined by the formulae: 0.5 + [earnings before interest and taxes/(gross sales in respect of unrefined mineral resources × 9)] × 100, but cannot exceed 7%.

The headline rate of withholding tax on dividends is 20%, but this rate is reduced by tax treaty for many countries to 5%.

Russia

There is a 5% royalty rate for nickel and cobalt.

The headline rate is 15%, but it is reduced by tax treaty to 5% for large investments.

Appendix 5: Government Extractive Industry Revenues in Low Income Countries[42]

	Royalty revenue	All other extractive industry revenue	Royalty % total revenue
Afghanistan	32	6	84
Burkina Faso	73	183	29
Chad	0	547	0
DRC	277	1405	16
Ethiopia	7	78	8
Guinea	85	413	17
Liberia	9	20	30
Madagascar	1	47	3
Malawi	0	9	4
Mali	49	398	11
Sierra Leone	16	10	62
Tajikistan	43	90	32
Togo	3	21	13
Total	597	3228	16

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[42] Countries shown are those low-income countries with Extractive Industry Transparency Initiative Reports in 2016 or 2017. Data is from the relevant EITI report available at: https://eiti.org/explore-data-portal

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Chapter 19
Sharing Financial Benefits from Deep Seabed Mining: The Case for a Seabed Sustainability Fund

Michael W. Lodge and Marie Bourrel-McKinnon

Abstract As the prospect of commercial deep seabed mining comes closer to reality, the International Seabed Authority (ISA) has begun to turn its attention to the question of how to achieve equitable sharing of the benefits from such mining as mandated by the UN Convention on the Law of the Sea. One approach to equitable distribution is to develop a methodology for distribution of net financial benefits based on agreed rules or formulae. Under this scenario, ISA would collect the net financial benefits and transfer the monetary proceeds to a pool of qualified beneficiaries. However, there are inherent weaknesses to this approach. We propose, in line with similar suggestions by the Finance Committee of ISA, that an alternative form of distribution could be a Seabed Sustainability Fund, similar to a sovereign wealth fund, administered by ISA. Such a fund would support and enhance knowledge about the deep-sea for the benefit of all humanity. In line with this, it is envisaged that the Fund could also support other global public goods that benefit all of humanity, such as adaptation or mitigation of climate change, advancing scientific knowledge of the ocean and deep-sea ecosystems, and ensuring biodiversity conservation. These are known to be underprovided and underfunded and could also benefit from funding sourced from and returned to all humanity.

Keywords UNCLOS · Deep seabed · Equitable sharing · Financial and other economic benefits · Sustainability · Benefit of humanity · Marine science · Equity

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The views expressed in this paper are those of the authors alone and do not necessarily reflect the position of the International Seabed Authority or any of its member States.

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1 Introduction

The principles that exploitation of the mineral resources of the deep seabed should be carried out for the benefit of all humanity and that the proceeds from such exploitation should be shared on the basis of equity, were recognized from the beginning of discussions on the subject in the Sea-Bed Committee in the United Nations in the late 1960s. These principles were also recognized in the Declaration of Principles Governing the Seabed and Ocean Floor, and the Subsoil Thereof, Beyond the Limits of National Jurisdiction adopted by the UN General Assembly in 1970.[1] As a result, equitable sharing of the financial and other economic benefits from activities in the international seabed area (the Area) is fundamental to the legal regime created by Part XI of the United Nations Convention on the Law of the Sea (UNCLOS)[2] and the 1994 Agreement for the Implementation of Part XI of the Convention (1994 Agreement).[3]

Although the principle of equitable benefit sharing was broadly agreed, the detailed mechanics of the issue did not receive significant attention during the Third United Nations Conference on the Law of the Sea. The issue was not addressed further either during the Preparatory Commission for the International Seabed Authority and the International Tribunal for the Law of the Sea from 1984 to 1994 nor in the early years of the operation of the International Seabed Authority (ISA), which is the organization mandated by UNCLOS to organize and control all activities of exploration for and exploitation of marine minerals in the Area.[4]

It is only in recent years, as the prospect of commercial deep seabed mining has become a reality, that ISA has begun to turn its attention to the issue of how to implement the requirement of equitable sharing of the benefits from such mining. This responsibility is explicitly assigned by UNCLOS to ISA which is required to develop rules, regulations and procedures to enable the equitable sharing of any payments received from deep sea miners, for the benefit of mankind as a whole. However, what this means and how it is to be accomplished are undetermined.

One obvious approach to equitable distribution would clearly be to develop a methodology for distribution of the net financial benefits based on agreed rules or formulae. Under this scenario, ISA would collect the net financial benefits and

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[1] General Assembly resolution 2749 (XXV), 17 December 1970.

[2] United Nations Convention on the Law of the Sea, 1982: A/CONF.62/122 and Corr. 1–11, ILM 21 (1982) 1261. The Law of the Sea: Compendium of Basic Documents (International Seabed Authority/The Caribbean Law Publishing Company 2001) 1.

[3] Agreement relating to the Implementation of Part XI of the United Nations Convention on the Law of the Sea of 10 December 1982, A/RES/48/263, annex. Also reproduced in The Law of the Sea: Compendium of Basic Documents (International Seabed Authority/The Caribbean Law Publishing Company 2001) 206. The Part XI Agreement was provisionally applied from 16 November 1994 (the date of entry into force of the Convention) and entered into force itself on 28 July 1996.

[4] The Area is defined in article 1, paragraph 1(1), of UNCLOS as 'the seabed and the ocean floor and the subsoil thereof, beyond the limits of national jurisdiction.'

transfer the monetary proceeds to a pool of qualified beneficiaries. The Finance Committee of ISA has given consideration to this issue and has developed alternative formulae for consideration by ISA members.[5] However, the Committee also identified the weaknesses inherent in this approach and suggested that an alternative approach may bring about greater equity whilst also promoting environmental protection.[6]

In this Chapter, we review the discussions that have taken place on this issue so far in the Finance Committee. We propose, in line with similar suggestions by the Finance Committee, that an alternative form of distribution could be a Seabed Sustainability Fund, similar to a sovereign wealth fund, administered by ISA. Such a fund would support and enhance knowledge about the deep-sea, conceived as a global public good that benefits all of humanity. In line with this, it is envisaged that the Fund could also support other global public goods that benefit all of humanity, such as adaptation or mitigation of climate change, advancing scientific knowledge of the ocean and deep-sea ecosystems, and ensuring biodiversity conservation. These are known to be underprovided and underfunded and could also benefit from funding sourced from and returned to all humanity.

2 Legal Basis for Equitable Sharing

Provisions concerning the equitable sharing of benefits from activities in the Area are found in Article 140, paragraph 2, article 155, paragraph 1(f), article 160, paragraph 2(f), (i) and (g), and article 162, paragraph 2(o)(i), of UNCLOS and in section 9, paragraph 7(f), of the annex to the 1994 Agreement. Relevant provisions also appear in article 171 and article 173, paragraph 2, of UNCLOS.

Article 140 of UNCLOS, which belongs to section 2 (Principles governing the Area) of Part XI, reads as follows:

2.1 Benefit of Mankind

1. *Activities in the Area shall, as specifically provided for in [part XI], be carried out for the benefit of mankind as a whole, irrespective of the geographical location of States, whether coastal or landlocked, and taking into particular consideration the interests and needs of developing States and of peoples who have not attained full independence or other self-governing status recognized by the United Nations in accordance with General Assembly resolution 1514 (XV) and other relevant General Assembly resolutions.*

[5] Development of rules, regulations and procedures on the equitable sharing of financial and other economic benefits derived from activities in the Area pursuant to section 9, paragraph 7 (f), of the annex to the 1994 Agreement, Report of the Finance Committee of the International Seabed Authority, ISBA/26/A/24-ISBA/26/C/39.

[6] Ibid. para. 47.

2. *The Authority shall provide for the equitable sharing of financial and other economic benefits derived from activities in the Area through any appropriate mechanism, on a non-discriminatory basis, in accordance with article 160, paragraph 2(f)(i).*

Ultimately, it is the responsibility of the Assembly of ISA, under article 160, paragraph 2(f) and (i), to approve rules, regulations and procedures on the equitable sharing of financial and other economic benefits derived from activities in the Area. As is the case with many other powers exercised by it, the Assembly must act in this respect upon the recommendation of the Council. If the Assembly does not approve the recommendations of the Council, it is to return them to the Council for reconsideration in the light of the views expressed by the Assembly. As a result of the 1994 Agreement, both the Assembly and the Council are to take into account recommendations of the Finance Committee when considering this issue.[7]

The Finance Committee began consideration of issues relating to equitable sharing of financial and other economic benefits in 2017. The Committee requested the Secretary-General to prepare a report for its 24th session (2018) to assist the Committee in its consideration of the question of equitable sharing. In his report,[8] the Secretary-General identified key elements requiring interpretation and elaboration and made suggestions as to how the Committee might conduct the development of such rules, regulations and procedures in parallel with the development by the Legal and Technical Commission of the regulations on the exploitation of mineral resources in the Area. The Committee took note of the report and requested the Secretary-General to prepare a technical study including suggested sharing criteria for consideration at the 25th session.[9]

In response to the request made by the Committee, a report on criteria for the equitable sharing of financial and other economic benefits derived from deep seabed mining was prepared and considered by the Committee in 2019. Subsequently, in 2020, at the request of the Committee, a supplementary report was prepared which presented and evaluated, according to widely accepted measures of relative inequality and global social welfare, three alternative formulae for the fair and equitable allocation of a given sum of royalties available for distribution. Having considered the various reports prepared for its consideration and after discussion within the Committee, the Committee decided in 2021 to report its initial findings and considerations to the Council and Assembly with a view to seeking guidance on how to proceed further.[10]

[7] 1994 Agreement, annex, Sect. 9, para. 7 (f).

[8] ISBA/24/FC/4.

[9] See ISBA/24/A/6 (Report of the Finance Committee)

[10] ISBA/26/A/24-ISBA/26/C/39. The reports presented for the Committee are summarized in *Equitable Sharing of Financial and Other Economic Benefits from Deep-Seabed Mining*, ISA Technical Study No. 31 (2021).

3 Monetary Benefits from Deep Sea Mining

Monetary (financial) benefits from deep sea mining will flow to ISA primarily in the form of payments from contractors. These may be in the form of royalties or shares in profits from mining operations. At the time of writing, the precise nature of the payment regime is still under discussion in the ISA Council. The draft regulations for mineral exploitation recommended to the Council by the Legal and Technical Commission[11] propose a system of *ad valorem* royalty payments based on the value of the minerals recovered from the Area. In 2019, the Council established an open-ended working group to further consider this matter. Although the group has not yet finished its work, it has begun to focus its discussions on a two-stage progressive *ad valorem* royalty system, whereby royalties would begin at a relatively low level and increase as commercial activities become more established.[12] It is not possible today to accurately estimate the likely extent of annual payments that will flow to ISA, particularly in the early stages of commercial mining. Nevertheless, a financial model of the *ad valorem* royalty system presented to the working group of the Council in 2019 postulated revenue to ISA of $4 billion over the life of an exploitation contract.[13] Whilst this must be regarded as speculative, it suggests that income available to ISA for distribution could eventually reach very large amounts.

It is important to stress that not all funds received from deep sea mining will be available for equitable sharing. Article 173, paragraph 2, of UNCLOS specifies how the funds must be allocated.

The first priority will be to pay the administrative expenses of ISA. At present these expenses are funded by assessed contributions from member States, determined according to the scale used for the regular budget of the United Nations, adjusted for differences in membership. As revenue from mining increases, these assessed contributions will theoretically reduce, and eventually be eliminated altogether. How long this will take is uncertain and, in the short term, it is likely that reductions in assessed contributions could be offset by increased demand for budgetary resources while ISA upscales its regulatory capacity and develops additional programmes, for example, an inspection and monitoring programme.[14] Furthermore, some of the administrative costs will be met through cost-recovery fees charged to contractors, including an expected $1 million application fee for processing every

[11] The latest draft is contained in ISBA/25/C/WP.1.

[12] Report of the Chair on the outcome of the third meeting of the open-ended working group of the Council in respect of the development and negotiation of the financial terms of a contract under article 13, paragraph 1, of annex III to the United Nations Convention on the Law of the Sea and section 8 of the annex to the Agreement relating to the Implementation of Part XI of the United Nations Convention on the Law of the Sea of 10 December 1982, ISBA/26/C/8.

[13] Kirchain, Peacock and Roth, *Decision Analysis Framework & Review of Cash Flow Approach Model*, 13 February 2020, available at https://isa.org.jm/files/files/documents/dec-analysis_0.pdf

[14] Some of these issues are addressed in a separate report prepared for the Finance Committee on future financing of the Authority (*Report of the Secretary-General on Future Financing of the International Seabed Authority*, ISBA/26/FC/7).

application for a plan of work for exploitation, as well as a $1 million per annum fixed fee.[15]

The second priority would be to fund the economic assistance fund to be established pursuant to article 151, paragraph 10, of UNCLOS and Section 7 of the 1994 Agreement.

Article 151, paragraph 10, establishes the principle that the Assembly shall establish a system of compensation or take other measures of economic adjustment assistance including cooperation with specialized agencies and other international organizations to assist developing countries which suffer serious adverse effects on their export earnings or economies resulting from a reduction in the price of an affected mineral or in the volume of exports of that mineral, to the extent that such reduction is caused by activities in the Area. The system is to be established by the Assembly upon the recommendation of the Council based on advice from the Economic Planning Commission. The 1994 Agreement made several important modifications to the implementation of this provision. Most importantly, it provides (annex, Section 7) that the form of assistance to be provided under article 151, paragraph 10 shall be through an economic assistance fund created from a portion of ISA's funds (i.e. the funds derived from activities in the Area) exceeding those necessary to cover its administrative expenses. The amount of the fund is to be determined by the Council, based on a recommendation of the Finance Committee.

An initial study prepared by the ISA in 2020 on the potential impact of mineral production from the Area on the economies of developing land-based producers of those minerals[16] concluded that it would only be possible to assess specific impacts once mining in the Area has commenced and would depend upon several variable factors, including the number of operators in the Area and the global consumption of the relevant minerals. It is likely therefore that the amount needed for the fund will vary from year to year, as will the disbursements from the fund. Guidelines will certainly need to be developed to govern the use of such a fund; however, this matter falls within the mandate of the Economic Planning Commission, which is yet to be established.[17]

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[15] See Draft regulations for exploitation of marine mineral in the Area (ISBA/25/C/WP.1) regulation 85. Whilst the draft regulations state that the annual fixed fee shall be determined by the Council, discussions so far have proceeded on the basis that the fee should be not less than the US$1 million originally prescribed in UNCLOS, Annex III, Art. 13, paragraph 3 (which 'no longer applies' as a result of the 1994 Agreement).

[16] ISA, Study of the Potential Impact of Polymetallic Nodules Production from the Area on the Economies of Developing Land-based Producers of those Metals which are Likely to be Most Seriously Affected (2020) https://www.isa.org.jm/files/documents/impactstudy.pdf

[17] Pursuant to the 1994 Agreement, the Legal and Technical Commission shall perform the functions of the Economic Planning Commission until the Council decides otherwise or until the approval of the first plan of work for exploitation. In July 2020, the Commission recommended that the Council should consider the establishment of the Economic Planning Commission before the approval of any plan of work for exploitation. See *Report of the Chair of the Legal and Technical Commission on the Work of the Commission at the second part of its twenty-sixth ses-*

In summary, therefore, the monetary benefits that will be available to be shared will be the net funds remaining to ISA after payment of administrative costs and any payments into the economic assistance fund. Considering that deep sea mining will likely start on a relatively small scale, with activity expected to increase over time as technology develops and contractors become more experienced, funds available for distribution may be quite limited in the early years. This is likely to raise a number of operational and administrative questions, such as, for example, whether a minimum fund should be built up prior to the first distribution, whether funds should be invested pending distribution, and the frequency of distribution (monthly, annual, biannual).

4 Non-monetary Benefits

Several provisions of UNCLOS and in particular article 140, give equal weight to non-monetary benefit-sharing as a means of giving effect to the overall objective of 'benefit to mankind'. There is no limit to the category of non-monetary benefits, and it is not possible to quantify all these benefits as they may change over time. For example, the fact that UNCLOS and the 1994 Agreement establish a legal regime for the Area that limits access to resources, prevents unconstrained exploitation of seabed minerals and ensures effective protection of the marine environment is itself a benefit to mankind. This is implicit in the 1970 Declaration of Principles that called for the establishment of an international regime to provide for the 'orderly, safe and rational management of the Area and its resources'.[18] The purpose of the international regime is to create and enforce a set of rules and standards governing deep sea mining and related activities, including marine scientific research in the Area that balances the need for resource extraction with the preservation of the marine environment while ensuring that the less technologically advanced States can effectively participate.

Other non-monetary benefits include better protection of the marine environment and conservation of marine biodiversity through the rules, regulations and procedures of ISA, increased knowledge of the marine environment and the deep seabed,[19] increased availability of marine technology, and importantly capacity-building and technology transfer. The latter may be mandatory, as in the case of the training programmes required of contractors, or developed through international cooperation in the case of programmes developed through ISA.

sion, ISBA/26/C/12/Add.1, para. 19. At the time of the writing, the Council has not yet met to consider the recommendation of the Commission.

[18] General Assembly resolution 2749 (XXV).

[19] This includes increased scientific knowledge made available through the Authority as a result of exploration activities, as well as international cooperation in marine science and the results of marine scientific research in the Area carried out pursuant to Articles 143 and 144 of UNCLOS.

Article 150 of UNCLOS, which sets out the policies relating to activities in the Area, also recognizes non-monetary benefits flowing from the international regime for the Area. These include the orderly, safe and rational management of the resources of the Area, the efficient conduct of activities in the Area, increased availability of the minerals derived from the Area, and the enhancement of opportunities for all States parties, irrespective of their social and economic systems or geographical location, to participate in the development of the resources of the Area and the prevention of monopolization of activities in the Area.

5 Developing a Formula for Equitable Sharing

As a general principle, the equitable sharing of resource rents can be based on two possible rationales. The first is simply based on the concept of shared ownership. Alternatively, equitable sharing can reflect an implicit or explicit desire to redistribute income or wealth, for example from wealthier States (or individuals) to poorer States (or individuals). In this case, shares should be distributed based on some indicator of the relevant State's priority in the redistribution goal. Typically, the formula would also embody some form of progressivity that favours poorer States in the distribution scheme. Progressivity can be defined in various ways. For example, it can mean that the share of rents received by a low-income State is higher than the share received by a high-income State, or that the total amount received as a percentage of income is higher for low-income States than for high-income States. Both imply a redistribution of income or wealth relative to what would be required by a proportional distribution scheme based solely on ownership rights.[20]

If we apply this theoretical background to deep sea mining in the Area, article 140 of UNCLOS provides that mining must be carried out for the benefit of mankind, irrespective of the geographical location of States, whether coastal or landlocked. This implies an underlying joint ownership rationale for equitable sharing. At the same time, however, article 140 also requires ISA to take into particular consideration the interests and needs of developing States and of peoples who have not attained full independence or other self-governing status, implying an income redistribution rationale as well.

In addressing these issues, the Finance Committee noted various ambiguities and textual inconsistencies in the provisions of UNCLOS but decided nevertheless to work on the basis that the appropriate beneficiary unit for any distribution would be the States parties to UNCLOS.[21]

[20] ISA Technical Study No. 31, Chapter III.

[21] Despite the references to 'benefit of mankind' in UNCLOS, it is States, not cosmopolitan individuals, that are the primary subjects and have personality under international law. Philosophically, individuals represented by States or States representing individuals can receive greater weight in sharing rule formulae through choice of ethical principles, their balance, and formulae. This issue is covered in more detail in ISA Technical Study No. 31.

The Finance Committee reviewed three alternative formulae for equitable distribution of a given sum of money amongst States Parties. These formulae, the rationales behind them and the methodologies used for calculation (as well as formulae that were considered but rejected), are fully explained and elaborated in the reports presented to the Committee in 2019 and 2020 and it is not necessary to review them further here.[22] The basic concept behind each of the formulae is to calculate each country's population as a percentage of the total population of all States parties, which would be fully consistent with Aristotle's principle of equity or proportionality and also reflect the common heritage nature of the resource.[23] This basic distribution would then be adjusted through a social distribution weight in such a way as to redistribute income from higher-income States parties to the developing countries prioritized in article 140.[24] To test the relative merit of each of the three formulae, the Committee also reviewed an *ex-post* evaluation of equity and impact upon global social welfare from the allocated share to each State party using established measures of relative inequality and social welfare.[25]

Empirical results from the studies commissioned by the Finance Committee show that allocated shares from one allocation formula (geometric mean functional form) had the greatest global social welfare and produced the lowest relative inequality compared to others, although the differences between all formulae were not great. An important conclusion was that, regardless of the formula used, the impact of population share meant that a limited number of States parties would enjoy exceptionally large gains in allocated shares compared to others. The converse of this is that the comparatively small dollar amounts available to some States parties (particularly Small Island Developing States (SIDS) which typically have small populations and a relatively higher gross national income) means that the benefits of the common heritage may be dissipated.

An additional concern was that, especially in the early years when revenue available for disbursement is likely to be relatively low, the total amount allocated to each of the 167 individual claimant States parties is likely to be rather small and not sufficient to support either major initiatives that could have a significant beneficial

[22] ISA Technical Study No. 31.

[23] Aristotle's equity principle or proportionality principle states that the goods or services of concern should be divided in proportion to each claimant's contribution (or claim). See Aristotle, Nicomachean Ethics. Oxford University Press, Oxford (2009). In the case of revenue from deep sea mining, the good is homogeneous, divisible, and measured on a cardinal scale in a common metric (US$), and each individual has an equal claim to share article 140 benefits from deep sea mining in the Area due to the status of mineral resources as the common heritage of mankind. This equal claim is adjusted for progressivity in response to requirements of the Convention to redistribute income on a more equitable basis, so that the distribution is not an exact or even one. Instead, the distribution is an even one with unequal entitlements with claimants weighted by social distribution weights.

[24] ISA has also developed a web-based model to enable visualization and comparison of the impact of each of three alternative formulae on any member of ISA under the different scenarios.

[25] These measures included the Gini Coefficient, Lorenz curve, Pen's Parade of Dwarves, Atkinson Inequality Index and Generalized Entropy Measures.

impact on the population of an individual State, or projects that have high levels of uncertainty, such as projects related to deep sea exploration.

For these reasons, a different approach, which may be an adjunct or an alternative to direct distribution, could be to make a qualitative distribution. In this way, the financial benefits from deep sea mining would be used wisely to generate qualitative benefits that would be made available to all humanity. These qualitative benefits would take the form of knowledge and competence related to the Area as well as improved environmental stewardship.

6 Seabed Sustainability Fund

A potential vehicle for the delivery of such qualitative benefits could be a global fund, which we refer to here as a Seabed Sustainability Fund. In the following section, we outline the conceptual basis for such a Fund, how it might operate and be managed, and the potential uses of the Fund.

6.1 Conceptual Basis

Marine scientific knowledge is a global public good and all peoples of the world benefit from it directly or indirectly (the non-excludability property of a public good). Benefits accruing to one individual do not reduce the benefits accruing to others (the non-rivalry property of a public good). Since all potential claimants—in this case, the sum population of all States parties—have equal claims and benefit equally from the increases in scientific knowledge, capacity building, and research and development, the benefits also satisfy Aristotle's equity or proportionality principle. An added benefit is that better scientific knowledge about the deep-sea environment contributes to more sustainable mining that minimizes any impairment of ecosystem services that may result from deep seabed mining and that may adversely impact the global population.

A global fund supporting global public goods and smoothing consumption spending over time (given variations in revenue from varying production volumes and prices) also addresses inter-generational equity by allowing for the distribution of current revenue from deep sea mining to future generations. This may be in the form of investment in human, physical, financial and natural capital or by investment in a fund where the returns on investment could be used to finance consumption benefits in the future.

The experience of multilateral institutions shows how difficult it is to mobilize financial resources for common purposes[26] and this deficit also affects ISA.[27] The OECD has identified a financing gap of about $2.5 trillion a year for the Sustainable Development Goals in developing countries,[28] with SDG14 (Life below water) among the least-funded SDGs both by Official Development Assistance and philanthropic developing funding.[29] Indeed, considering the breadth of its mandate (over 50% of the global seafloor) and scope of its activities, ISA is woefully underfunded.[30] It makes little sense, in this respect, to simply collect financial returns and distribute them without reinvesting in the ocean. Everyone depends on the ocean for the supply of essential ecosystem services and accordingly better understanding and knowledge of the deep sea, and its ecosystems, will benefit all humanity. Creating the enabling conditions for rigorous management of the Area and its resources is also consistent with the precautionary approach.

A resource fund—like a sovereign wealth fund—could also help smooth out the flow of disbursements over time, delink disbursements from the dynamics of resource revenue (such as price and revenue pro-cyclicality), help address uncertainty over the overall wealth to be shared, and contribute to macroeconomic stability, thereby providing a useful tool for macro-fiscal management. With appropriate restrictions on drawing down the fund's principal and limiting disbursements to the returns earned on that principal, the fund could even provide an enduring flow of benefits for generations that follow the cessation of deep-sea mining.

[26] For example, the Global Environment Facility (GEF), which claims to be 'the largest funding mechanism for multi-country collaboration on waters and oceans' allocated only 11.4% of the $4.4bn pledged under the GEF-7 replenishment to its 'international waters' programme. In reality most of that funding is allocated to management of transboundary marine resources rather than deep sea science. See GEF/R.7/22, 2 April 2018, available at https://www.thegef.org/sites/default/files/council-meeting-documents/GEF-7%20Resource%20Allocation%20and%20Targets%20-%20GEF_R.7_22.pdf and https://iwlearn.net/abt_iwlearn/gef-international-waters-focal-area. See also the comments of economist Jeffrey Sachs to the UN Food Systems Pre-Summit, 26 July 2021, https://www.youtube.com/watch?v=WZ1xc491mnU

[27] The ISA Endowment Fund for Marine Scientific Research has attracted funding of only $900,000 over 15 years, which severely constrains the effectiveness of the Fund.

[28] OECD, Global Outlook on Financing for Sustainable Development 2021 https://www.oecd-ilibrary.org/development/global-outlook-on-financing-for-sustainable-development-2021_6ea613f4-en

[29] OECD, Sustainable Ocean for All (2020) https://www.oecd-ilibrary.org/development/sdg-14-is-among-the-least-funded-sdgs-by-both-official-development-assistance-and-philanthropic-development-funding_202afb81-en

[30] Since it became financially autonomous in 1998, the budget of ISA has increased at an annualized rate of less than 1% and remains below $10m per year. Only 11 new staff posts have been created over the past 22 years, despite a significant increase in the complexity and the range of responsibilities allocated to the secretariat by the member States.

6.2 Potential Drawbacks

A global fund is not a panacea and there will still be fundamental issues for ISA to address in the administration and management of such a fund. Even with a long-term fiscal sustainability framework (which is a clear prerequisite for the management of a fund), ISA will need to identify the means by which the money available to be spent at a given point in time will be distributed. UNCLOS provides no guidance on this issue.

At least three alternative approaches are possible, alone or in combination:

(a) Distribute the money through cash payments to the appropriate States or claimants.
(b) Fund projects designed to provide goods and services (such as sanitation and health care, housing, and food) to benefit current populations of claimant States.
(c) Invest in public goods such as human capital (through education) or physical capital (such as infrastructure) that will primarily benefit future generations.

One could argue that cash disbursement is preferred because it would be both simpler for ISA to administer and allow recipient States, acting on behalf of their populations, to use the money in the ways that they deem to be most beneficial to their populations. However, there are at least two cogent arguments for funding projects rather than making cash disbursements.

First, there is no guarantee, for various reasons, that funds distributed to governments would be used for the benefit of their populations, as implied by the 'benefit to mankind' mandate. Second, because ISA is an organization charged with managing returns from deep sea mining for the benefit of mankind as a whole rather than for the benefit of individual States or governments, it should encourage uses of the money that generate the greatest good for mankind as a whole, for example, to invest in global public goods that are otherwise underprovided. This would certainly apply to ocean science, which according to IOC-UNESCO attracts only 1.7% of total gross domestic expenditure on research and development,[31] with only a very small proportion of that spent on international waters and the deep sea. A global fund should promote uses that have the potential to benefit multiple States, and discourage uses that have negative spillovers on, for example, other States, specific groups within a State (e.g. indigenous peoples), or future generations. There is a risk that these spillover effects (positive and negative) may not be considered by individual States in making their spending decisions.

The risks of providing global public goods are minimized by spreading costs across humanity. Some provision of global public goods, notably climate change

[31] IOC-UNESCO, Global Ocean Science Report 2020, https://unesdoc.unesco.org/in/documentViewer.xhtml?v=2.1.196&id=p::usmarcdef_0000375147&file=/in/rest/annotationSVC/DownloadWatermarkedAttachment/attach_import_d52d8a6c-ac51-4ed6-8a97-8736c55545b0%3F_%3D375147eng.pdf&locale=en&multi=true&ark=/ark:/48223/pf0000375147/PDF/375147eng.pdf#1063_20_en_int_GOSR2020_5.indd%3A.68797%3A2753

mitigation, may also be progressive in that lowest income populations gain but by themselves are often most disproportionately impacted and least capable of adjusting to the adverse impacts (a classic case in point may be SIDS).

By funding projects rather than making cash disbursements, ISA could overcome these limitations. In addition to funding projects designed primarily to benefit current populations, ISA could also fund projects that are designed primarily to generate benefits for future generations, thereby addressing inter-generational equity, such as investment in physical and human capital and research and development (e.g. of new technologies).

The downside of funding projects rather than distributing cash is that ISA would need to develop mechanisms for choosing which projects to fund and for overseeing and evaluating the projects to ensure that funds are spent appropriately and benefit the intended recipients. Significant administrative costs and overheads could therefore be anticipated and would need to be considered in any development of the Seabed Sustainability Fund.

6.3 Scope and Purpose

The broad objective of the Fund would be to invest in knowledge and competence related to the Area. This can be broken down into basic and applied research, capacity-building and funding of related public goods.

Basic and applied research and innovation is critical to sustainable management of the Area and is specifically called out in the 1994 Agreement as one of the early priority tasks of ISA.[32] The Seabed Sustainability Fund could offer a unique opportunity to scale up these efforts, which would be a logical step in the concept of the evolutionary approach, and which would allow to undertake more types of research and make it even more inclusive. ISA could further develop in its role as a platform for research and cooperation and accelerate the implementation of existing initiatives such as DeepData.[33] This objective should be pursued in a way that is aligned with the objectives of ISA's Strategic Plan and a strategy to carry out research in a decentralized manner so as to foster maximum involvement of all parties and taking due account of the need for technology transfer.

The second broad objective is capacity-building. This should aim at developing tools of inclusivity, offering an opportunity to all people of the entire planet (in particular women, indigenous people and those from vulnerable communities) to participate through basic or advanced seabed education and specific technical training. It is suboptimal to set up governance tools or to generate scientific knowledge

[32] 1994 Agreement, annex, Sect. 1, para. 5(i).

[33] The ISA Deep Seabed and Ocean Database (DeepData) is a spatial, Internet-based, data management system. It hosts environmental, oceanographic and geological data collected by contractors as well as other relevant environmental and resources related data for the Area. https://www.isa.org.jm/index.php/deepdata

unless a wide group of participants from all ISA member States are capable of fully understanding and using the outcome. Pure scientific knowledge will not suffice. There will also be a need for technicians, engineers, analysts, observers etc. At present there are virtually no generally accessible possibilities to build these competences. Apart from capacity-building aimed at highly skilled professionals, there could also be an effort to create awareness and offer basic technical insight to the general public (otherwise known as 'deep sea literacy').

The dual importance of good governance and inclusivity has been identified as a basis for economic prosperity.[34] As the seabed and its wealth are the common heritage of mankind, everybody should feel involved or at least have the opportunity to become involved. The inclusivity toolbox under the Fund should therefore aim at building capacity in the most vulnerable developing States, including Least Developed Countries (LDCs), Landlocked Developing Countries (LLDCs)[35] and SIDS. The objective should be to bring a high number of participants up to the highest level of knowledge and competence and to create the conditions for retaining and using these competences on a local basis. Therefore, it is also important to encourage capacity-building on an institutional and regional level.

The third broad objective, as the Fund grows in size, would be to use the Fund to support other public goods (whether ocean-related or not) that benefit humanity as a whole. This may include, for example, research and monitoring of the effects of climate change on the world's ocean, as well as applied research into the potential uses of marine genetic resources.

6.4 Governance

The primary advantage of setting up a fund that is financed by a steady autonomous flow of revenue, as opposed to calling on budgetary contributions or pledges, lies in the stability and the predictability of the financial resources. As noted above, it may take time before flows into the fund stabilize and become predictable. Nevertheless, the terms under which the Fund is established, and its governance mechanisms can greatly enhance its capacity to perform.

Having previously identified the advantages and disadvantages to different approaches to disbursement (cash distribution, project financing, infrastructure investment) we also identify alternative approaches to revenue management that will need to be considered.

A very basic approach would be to collect the revenue and spend it directly. To the extent that the underlying economic activity is perfectly stable and predictable, this might work. Yet it is evident that this basic assumption might not always remain

[34] Acemoglu and Robinson, *Why nations fail, the origins of power, prosperity and poverty*, Profile Books Ltd, London (2012).

[35] Among the members of the ISA, 27 States are least developed countries (including 10 that are landlocked) and 10 States are both developing and landlocked countries.

valid—and will certainly not be valid in the initial years—which might create problems to the extent that a predefined spending commitment would need to be met with an uncertain income pattern.

A second option would therefore be to collect the revenue, invest the principal and use the return on investment to finance the projects.[36] This is the model that has been used to date for the ISA Endowment Fund for Marine Scientific Research. The disadvantage here lies in the long period needed to generate enough spendable revenue. Moreover, applied in its purest form, this option also generates an uncertain income because the return on the invested principal will necessarily also be variable.

A combination of these two approaches could be considered as a way of generating resources quickly and yet offering a predictable financial flow. For example, surplus royalties could be invested until a reserve is created and then an amount equal to the income generated on the principal plus a percentage of all new proceeds could be made available for commitments.

A further avenue to explore is whether other financing pools would be willing to provide starting capital to the Fund, through grants or soft loans provided at advantageous rates.[37] Article 174 of UNCLOS foresees the possibility for ISA to borrow funds (except for financing its administrative budget)[38] and this could allow for frontloading of the Seabed Sustainability Fund. This approach could be particularly relevant given that several scientists and organizations argue that some of the scientific research activities identified above need to be carried out before mining starts. At the very least, this approach could be used to vastly accelerate the scientific activities that are already being undertaken by ISA and fill some of the critical gaps in scientific understanding of the deep ocean.

In terms of governance architecture, the Finance Committee paid particular attention to the need to apply an evolutionary approach to the functioning of ISA, as reflected in the 1994 Agreement. Accordingly, it recommended that the existing governance architecture of ISA should be used as far as possible to support the Fund, whilst acknowledging that new structures, procedures and systems would need to be defined.

Given the uncertainties around the early years of operation of the Fund, we very much agree with that approach. Inevitably, new procedures will be needed to bring precision to the objectives and operational targets of the Fund, on efficiency and effectiveness, on avoiding wasteful action and on safeguarding against financial mismanagement and fraud. The functional requirements appear to include:

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[36] It is difficult to speculate on the returns that could be generated, but we assume that the Fund would be capable of seeking a balanced long-term high yield on its investment. This implies investing in assets that yield a high long-term return inter alia equity, high yield bonds and real estate. It would thus follow the example of a respectable institution like the United Nations Joint Staff Pension Fund, which realizes a 4.5% annual return net of inflation.

[37] This could also help to avoid the need for developing countries to borrow (if they are able to borrow at all) at rates between 5% and 10% higher than those available to the rich countries.

[38] 1994 Agreement, Annex, Sect. 1 para. 14.

(a) A management board (which could be the present Finance Committee) to set the general policy and objectives (including the investment policy), and to report annually to the ISA Assembly
(b) A scientific guidance board (which could be the present Legal and Technical Commission) to advise the management board on all scientific matters, identify scientific issues of global concern and translate the overall objectives of the Fund into scientific objectives as well as give guidance for the evaluation of the results
(c) An audit body, which would need to be independent both from existing ISA structures and from the existing financial audit of ISA's administrative budget
(d) An executive body to administer the fund and support the management board, which could be an autonomous unit of the existing ISA secretariat

6.5 Potential Activities

Many potential activities could be supported by the Seabed Sustainability Fund, but two primary avenues could be prioritized.

First, as discussed further in the section below, the Fund could be used to support specific actions identified by ISA members through its Strategic Plan and High-Level Action Plan as well as any other strategic frameworks endorsed by the ISA Assembly (such as the six Strategic Research Priorities identified under the ISA's Research Plan in support of the UN Decade of Ocean Science for Sustainable Development). In this way, the Fund would allow ISA to scale up its present level of activity and its policy of global communication and information to the general public.

Second, the Fund could support projects proposed by ISA members and third parties. The Fund could, for example, define desired outcomes and qualitative criteria and allow third parties to propose concrete projects to be supported or co-financed. The type of intervention should be adapted to the nature of the project and the beneficiary but may include instruments such as grants, loans, guarantees, co-financing and blended finance.

A third possibility, potentially more contentious, could be to utilize the Fund to co-finance the early operations of the Enterprise, either by way of investment loans, or project support to build the technical and managerial capacity of the Enterprise.

6.6 Regional Approach

The importance of a regional approach has already been highlighted under the heading of inclusivity. There are many reasons why it is important to bring the Fund close to its intended beneficiaries. However, the income generated by the exploitation of the resources of the Area could also be used to implement other important, yet underfunded, provisions of UNCLOS, in particular those in Part XIV, Section 3 regarding regional marine scientific and technological centres (Articles 275–277).

Such regional centres could implement the functions described in Article 277, which include training and educational programmes, technical cooperation and study programmes relating to the protection and preservation of the marine environment and the prevention, reduction and control of pollution. This could also be expanded to questions of current concern such as the effects of climate change on the ocean, ocean acidification, and so on. A regional approach could also support the implementation of the provisions of UNCLOS in Part XIII (Marine Scientific Research) and Part XIV (Development and Transfer of Marine Technology).

This could be achieved in various manners, although a first option would be to set up regional ISA offices hosted by appropriate regional institutions. How these are selected and distributed around the world would need to be considered.

7 Aligning the Seabed Sustainability Fund with the Sustainable Development Goals and ISA's Strategic Plan

As the organization exclusively mandated to manage activities in the Area, ISA is required to promote and encourage the conduct of marine scientific research in the Area, as well as coordinate and disseminate the results of scientific research and analysis, when available. As part of its unique responsibilities, ISA also has the duty to encourage development and implementation of appropriate programmes for strengthening the research capabilities of developing States and technologically less developed States. ISA's commitment to this important mission has been well reflected especially through the strategic direction 4 (Promote and encourage marine scientific research in the Area) of the ISA Strategic Plan for the period 2019–2023,[39] which is being implemented according to the High-level Action Plan for 2019–2023.[40]

Since 2015, there is also a broader context to ISA's work that needs to be taken into consideration, in the form of the United Nations' 2030 Agenda for Sustainable Development and its constituent Sustainable Development Goals (SDGs). The work ISA does to advance the development of marine science and global understanding of the deep-sea and ecosystems functions makes a significant contribution to the SDGs, particularly SDG14 (Life Below Water). This work also enables the development of evidence-based environmental regulation and strengthens the rule of law through ensuring that evolving rules in the new sector of deep-sea mining are consistent with the best available science. In this way, ISA also contributes to SDG16 (Peace, Justice and Strong Institutions). Other SDGs to which ISA contributes through its regulatory, scientific research and capacity development mandates

[39] ISBA/24/A/10, 27 July 2018.

[40] ISBA/25/A/15, 24 July 2019.

include SDG 1 (No Poverty), SDG 4 (Quality Education), SDG 5 (Gender Equality), SDG 8 (Decent work and economic growth), SDG 9 (Industry, innovation and infrastructure), SDG 10 (Reduced Inequality), SDG 12 (Responsible consumption and production), SDG 13 (Climate Action), SDG 16 (Peace, justice and strong institutions) and SDG 17 (Partnerships).[41]

It is critical therefore that the objectives of the Seabed Sustainability Fund are fully aligned with both the ISA Strategic Plan and the relevant SDGs. When considered in this context, the Fund could also make an important contribution to the 2030 Agenda.

Two recent decisions of the ISA Assembly further reinforce ISA's commitment to the 2030 Agenda and provide an indication of the way in which a Seabed Sustainability Fund could be leveraged to accelerate progress.

The first is a decision by the Assembly to implement a programmatic approach to capacity development.[42] In this decision, the Assembly emphasized the importance of a dedicated strategy for capacity development that addresses the needs identified by members of ISA and requested the Secretary-General to develop and implement a dedicated strategy for capacity development as well as to explore options to mobilize additional resources to provide financial support for the implementation of the dedicated strategy. Aligning the objectives of the Seabed Sustainability Fund with such a dedicated strategy could provide an opportunity to mobilize such resources.

The second is the adoption by the Assembly in December 2020 of the ISA Action Plan in support of the United Nations Decade of Ocean Science for Sustainable Development 2021–2030.[43] This is a highly important decision because it identifies six strategic research priorities to guide the scientific work of ISA which are firmly based on the strategic directions, high-level actions and associated outputs contained in the Strategic Plan and the High-level Action Plan. The strategic research priorities include advancing scientific knowledge and understanding of deep-sea ecosystems, including biodiversity and ecosystem functions, in the Area; standardizing and innovating methodologies for deep-sea biodiversity assessment; technology development, including ocean observation and monitoring; and, enhancing scientific knowledge and understanding of potential impacts of activities in the Area.

This decision is highly important, not least because it is evident that there is a lack of well-coordinated and directed basic research into deep sea ecosystems. If not addressed, this may present an impediment to further development of the resources of the Area, notwithstanding the expenditure of millions of dollars on poorly coordinated research efforts. For example, some authors point to the lack of authoritative faunal lists for the Clarion Clipperton Zone, despite tens of thousands of biological samples having been collected over many hundreds of scientific

[41] Report on ISA's Contribution to the Sustainable Development Goals, 2021 (in press).

[42] ISBA/26/A/18, 17 December 2020.

[43] ISBA/26/A/17, 17 December 2020.

expeditions.[44] These authors argue that there is an urgent need for systematic archiving of faunal data with accessible, vouchered and databased material in open, curated collections. Whilst ISA has tried to address this issue in various ways since 2013, with the latest workshop in September 2020 focusing on identifying strategic approaches for collaboration to advance deep-sea taxonomy, these, and similar, efforts need to be upscaled on a global basis. The Seabed Sustainability Fund could provide a vehicle to upscale such efforts.

8 Conclusion

Equitable sharing of the financial and other economic benefits from deep-sea mineral exploitation in the Area is fundamental to the legal regime created by Part XI of UNCLOS and the 1994 Agreement. Exploitation has not yet started, and it is difficult to quantify potential financial returns to the ISA (on behalf of all humanity) at this stage, but they have the potential to be transformative.

Direct distribution to ISA member States through an agreed allocation formula is superficially attractive but presents several drawbacks that may detract from the objectives of equity and environmental justice inherent in the notion that the resources of the Area are the common heritage of mankind. A different approach, which may be an adjunct or an alternative to direct distribution, could be to make a qualitative distribution. In this way, the financial benefits from deep sea mining would be used wisely to generate qualitative benefits that would be made available to all humanity. These qualitative benefits would take the form of knowledge and competence related to the Area as well as improved environmental stewardship.

Such a distribution, in the form of a Seabed Sustainability Fund, could more broadly satisfy the requirements of inter-generational equity and promote ocean sustainability. By aligning the objectives of the Fund to the 2030 Agenda for Sustainable Development as well as relevant decisions of the ISA Assembly, the Fund provides a mechanism to use common heritage resources to support underprovided and underfunded global public goods.

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[44] Adrian Glover, Helena Wiklund, Chong Chen and Thomas Dahlgren, *Managing a sustainable deep-sea 'blue economy' requires knowledge of what actually lives there*, elifesciences.org 2018, https://doi.org/10.7554/eLife.41319

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Part V
Legal and Socio-Cultural Frameworks

Chapter 20
Achieving Effective Seabed Mining Regulation and Management: A Missing Link

Philomène Verlaan

Abstract Myriad types of experts participate in developing regulations to manage seabed mining (SBM) in the Area under the auspices of the International Seabed Authority (ISA) pursuant to its mandate under the United Nations Convention on the Law of the Sea, which requires, inter alia, taking "effective measures" to achieve environmentally, socially, economically, and commercially responsible SBM. Interdisciplinary expert contributions to this complex endeavor are essential to designing these measures. Yet continuous, detailed, constructive dialogue between different experts and joint drafting of legally, scientifically, and technologically accurate language to further the "effective measures" objective are often lacking, such that despite the best intentions of everyone concerned, its achievement risks being impeded, and even thwarted, to the detriment of the health of our planet and ourselves. This chapter examines aspects of this "missing link," drawing on examples from the regulatory process at the ISA. A way forward is proposed for SBM that could also be useful for other activities (marine, terrestrial and atmospheric) requiring continuous, constructive interaction between different groups of experts for their effective regulation and management that is consistent with the legal and institutional framework, adaptable to accommodate improved knowledge and experience, as well as being implementable, enforceable, operationally feasible, and cost-effective.

Keywords Deep-seabed mining · Effective regulation and management · Legal and institutional framework · Law of the Sea Convention

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1 Introduction

International and regional intergovernmental organizations (IGOs), as well as individual states, generally have at least one formal institutional consultative mechanism for obtaining the best available technical expertise to inform their legislative and regulatory objectives. Often many different types of expertise (e.g., in alphabetical order: administrative, commercial, cultural, economic, engineering, environmental, financial, fiscal, legal, scientific, social and technological), plus the views of the general public, are necessary, such as in developing laws and regulations addressing environmental issues or with environmental ramifications. Yet continuous, detailed, constructive dialogue between different experts and joint drafting of accurate language to further the legislative and regulatory objectives are often lacking, such that despite the best intentions of everyone concerned, their achievement risks being impeded, and even thwarted, to the detriment of those objectives. Where those objectives involve the protection and preservation of the marine environment of the world required by the United Nations Convention on the Law of the Sea (LOSC),[1] the adverse consequences of not consulting all the relevant experts include threatening the very health of our planet, and of ourselves.

The institutional consultative mechanism(s) must encourage and facilitate the input from all relevant experts from the beginning of the regulatory process. With regard to this input, the mechanism(s) must operate on two axes to be effective. The vertical axis is between experts and the governing regulatory body. The horizontal axis is between experts inter se. Improving the latter is the primary purpose of this chapter. It draws on examples from the regulatory process at the International Seabed Authority (ISA),[2] with a particular focus on the ISA's approach to the development of marine environmental regulations pursuant to the requirements of the LOSC and on the interaction between experts from other disciplines on the one hand and lawyers on the other hand.

2 The "Missing Link"

The current consultative mechanism at the ISA for the development of legally binding regulations governing activities in the Area is unique—to the best of this author's knowledge—among IGOs with legally binding regulatory powers, in making proposed regulations in their various stages of evolution publicly available on its

[1] United Nations Convention on the Law of the Sea (Montego Bay, 10 December 1982, in force 16 November 1994) 1833 *UNTS* 397 (LOSC), Art. 192; also relevant in this context is the Agreement Relating to the Implementation of Part XI of the United Nations Convention on the Law of the Sea of 10 December 1982 (New York, 28 July 1994, in force 28 July 1996) 1836 *UNTS* 3 (IA).

[2] ISA website: https://www.isa.org.jm. It also organizes and publishes the results of interdisciplinary workshops, as do other IGOs.

website for written comments submitted directly to it by any juridical or natural person(s) from anywhere in the world. Crucially for enabling horizontal communications, the ISA makes the comments received publicly available.

Some of the comments and papers submitted to the ISA directly and to its workshops illustrate the "missing link" addressed in this chapter. They lack evidence of substantive dialogue between, on the one hand, recognized experts with formal legal qualifications, including expertise in international law and law of the sea, and, on the other hand, recognized experts from other disciplines, but usually without formal legal qualifications.

Particularly concerning are proposals by the latter experts of arguments they seek to base on law, without apparently having them verified by lawyers. Such seemingly unverified "legal" arguments also appear in papers by non-lawyers in *refereed*[3] international publications, offering further evidence of this "missing link." See, for example, a recent paper by ten scientists describing their *scientifically* justifiable concerns about various environmental aspects, including related regulatory efforts by the ISA, of conducting seabed mining (SBM) in the Area.[4] Unfortunately, their noble purpose, that is, improving the legally mandated protection and preservation of the marine environment from the adverse effects of SBM,[5] was not assisted, and indeed was crucially weakened, by their erroneous citation and interpretation of certain provisions of the LOSC they chose to adduce, as the present author pointed out in a published comment on their paper.[6]

Support for the presumed absence of legal advice in such comments and papers, and hence for the existence of this "missing link," at least with regard to SBM, is derived from the presence of basic legal errors in the arguments invoked. Of these errors, the most fundamental and frequent is the paraphrasing and/or misquoting of the applicable law.[7] Such an elementary error would be immediately caught and ruthlessly excised by any competent lawyer from any draft legal argument in a paper presented to that lawyer for review. An argument based on inaccurate citation of the applicable law in formal publications and written and oral comments by non-lawyers suggests, inter alia, that competent lawyers either have not been consulted, or that their advice has been ignored. Any recommendations presented as based on such demonstrably erroneous legal premises are at best weakened, but more usually

[3] Their presence in refereed publications is particularly disquieting and is further addressed *infra:* see Sect. 8.

[4] Smith, C.R. et al. (2020) 'Deep-sea misconceptions cause underestimation of seabed-mining impacts.' *Trends in Ecology and Evolution* https://doi.org/10.1016/j.tree.2020.07.002

[5] For example, LOSC Art. 145.

[6] Verlaan, P.A. (2020) 'Environmental protection requires accurate legal analysis: Response to Smith et al.' *Trends in Ecology and Evolution* 36(1):13–14; https://doi.org/10.1016/j.tree.2020.09.009

[7] For SBM, the applicable law is the LOSC. This error is even found in the ISA's own draft exploitation regulations: see, e.g., Verlaan, P.A. (2018) 'Draft ISA Exploitation Regulations: ISBA/24/LTC/WP.1/Rev.1—comments submitted to the International Seabed Authority;' available at https://www.isa.org.jm

fatally undermined, regardless of their potential merits in their own right. Risking the loss of good ideas for such an easily avoidable reason is a pity, and wastes scarce time and resources. The same rigor, ethics, and methodology applied to demonstrate and apply scientific and technological results and discussions by reference to primary sources must be applied to the citation, interpretation, and application of legally binding instruments, as described in detail below.

3 Words Matter

The importance of the statement made in this heading cannot be overemphasized. It is the bedrock of the rule of law. It is why all legally binding instruments at all levels of government, from the most international to the most local, require meticulous drafting. In these instruments every word has a meaning, and that meaning has legal consequences. In the case of legally binding instruments that must be translated into a legally specified number of languages,[8] and especially when, as in the LOSC,[9] each of these language versions has the same legal validity,[10] painstaking drafting, including punctuation,[11] as well as judicious choice of words and phrases, is critical to expressing the exact negotiated substantive items agreed between the parties and the correct operation[12] of those instruments in accordance with what the parties agreed.

[8] For example, the six official UN languages are Arabic, Chinese, English, French, Russian and Spanish. The six official languages of the UN reflect several legal systems and myriad cultures, yet they account for but a modest share of the rich spectrum of these systems and cultures, and a minute proportion of the languages, in active use in our culturally diverse world.

[9] LOSC Art. 305: "… the Arabic, Chinese, English, French, Russian and Spanish texts [of this Convention] are equally authentic …".

[10] The LOSC negotiations, for example, took over 10 years, accompanied by a dedicated drafting committee composed of high-ranking State representatives from each of the six official UN languages to help ensure that the negotiated substantive text was accurately reflected in the six languages. However, translation rigor must not be confused with substantive drafting rigor. With regard to the latter, the LOSC would have benefited from another drafting round. Unfortunately, this was made impossible by the premature vote imposed by the United States on the negotiating process and thereby also on the form of the draft text of the LOSC as it then stood. This vote terminated the negotiations, such that the adopted final text of the LOSC is that imperfect draft.

[11] The importance of punctuation in legally binding documents must not be forgotten. Consider the endless and not yet settled regulatory problems, caused by the comma, on the right to bear arms as set out in the second amendment to the US Constitution, an instrument written by its native speakers in their native language for their own country. Note that these points also apply nationally in States with two or more official languages (see, e.g., in a selection of examples from Western Europe and North America, with the States and languages in alphabetical order: Belgium: Flemish/French/German; Canada: /English/French; Switzerland: French/German/Italian).

[12] "Operation" includes interpretation, application and implementation. These are particularly complex for legally binding instruments, such as the LOSC, that are governed by the rules of public international law. See further discussion *infra* (n 19).

This verbal choice is not unconstrained. Many words and phrases have acquired a legal pedigree of agreed meaning in at least the six UN languages, forged over decades through, in particular, judicial (including arbitral) interpretation by international (and, as appropriate, national) courts and tribunals, as well as published scholarly analyses by internationally respected entities, such as, the International Law Commission[13] and the International Law Association.[14] Therefore, wherever possible, words and phrases with internationally understood and accepted pedigrees in all six official UN languages are used in international treaties conducted under UN auspices or according to UN standards. This is another reason why legally binding language must not be paraphrased. Furthermore, it entails that new words and phrases for inclusion in legally binding international instruments must be proposed with caution.[15] Their adoption in one or even several legally binding international instruments alone does not guarantee this pedigree, or justify, let alone mandate, their use in regulations to implement existing legally binding international instruments, such as LOSC, where the word or phrase does not appear.[16]

4 Confidence-Building in the Tower of Babel

Consider the practical implications of requiring equal legal validity of multiple language versions of a legally binding international instrument as described in the preceding section. For some 75 years, English has been the de facto default negotiating and drafting language in international treaty-making fora when simultaneous interpretation and rapid document translation, respectively, are unavailable. Even when all six official UN languages are employed for interpretation and translation, at international level most of the delegations must still operate in a language of which they are not a native speaker on the negotiation, drafting and adoption of laws to which their state will become subject. The consequent risk of unfair advantage to native Anglophones commenting on, negotiating, and drafting legally binding international instruments places an even higher standard of linguistic care and responsibility on them than on their counterparts from other languages. This is because the latter will be inclined to defer to the former (even if the former are not lawyers) in linguistic matters, especially where interpretation and translation are absent.

[13] See International Law Commission website: https://legal.un.org/ilc/

[14] See International Law Association website: https://www.ila-hq.org/

[15] For example, "biological diversity" or "biodiversity": see discussion of selected pitfalls in Verlaan, P. A. (2020) The interface of science and law: A challenge to the privileging of 'marine biodiversity' over 'marine environment', in: Barnes, R.A. and Long, R. (Eds.) *Frontiers in International Environmental Law: Oceans and Climate Challenges*. Brill (Leiden).

[16] For example, the use of 'approach' vs. 'principle' with the adjective 'precautionary' in the ISA draft exploitation regulations: see, e.g., the discussion in written comments on the various drafts of these regulations and records of oral interventions by delegations at meetings of the ISA Council; available on the ISA website *supra* (n 2).

Building mutual confidence and trust under these circumstances is essential but difficult, especially with frequently changing members of delegations. Hence, the requirement is to quote a legally binding instrument *verbatim* in constructing an argument based on law, implementing existing instruments[17] and developing new ones, as well as the recommendation to use, where appropriate, pedigreed legal terminology.

5 Treaties as "Contracts"

A common feature of legally unverified input by non-lawyers into the regulatory process at the ISA is a misunderstanding of the legal nature of treaties. In some respects, including those under discussion here, treaties function as a type of contract.[18] That States are parties rather than natural private persons or, for example, incorporated legal entities (juridical persons), does not change the contractual aspects of the relationship. The rights, duties, obligations and commitments set out in a treaty are just as binding on their States-Parties as are those set out in a contract between private (non-State) parties. A strict hierarchy of rules governs the interpretation, implementation, and application of contracts. The same applies to treaties, albeit with important distinctions.[19] Of these, the most fundamental one is highlighted here. Colloquially known in contract law as "the four corners rule," if a

[17] For example, such as in the ISA Draft regulations for exploitation of mineral resources in the Area (ISBA/25/C/WP.1), https://undocs.org/en/ISBA/25/C/WP.1, last accessed 13 March 2021.

[18] ***Caveat***: contract terminology is used here as a conceptual analogy in order to facilitate this discussion for the multi-disciplinary audience reading this book. A primary difference between a private contract and a treaty is that the latter eventually results in making law applicable to the nationals of the States-Parties to the treaty. A private contract binds only the natural or juridical persons who are the parties to that contract.

[19] The rules governing treaty interpretation are considerably more complex than for private contracts. The LOSC is part of a larger, intricately woven legal fabric of diverse rules and principles of international law, judicial and arbitral interpretations, institutional mechanisms, and other applicable treaties. The LOSC cannot be interpreted accurately without at least a minimum understanding of this fabric. See the Vienna Convention on the Law of Treaties (VCLT) (8 ILM 1969; Vienna, 23 May 1969; in force 17 January 1980); McLachlan, C. (2005) 'The principle of systemic integration and Article 31(3)(c) of the Vienna Convention.' 54 *International and Comparative Law Quarterly* 279–320; Aust, A. (2013) *Modern Treaty Law and Practice*, 3rd ed., Cambridge University Press, Cambridge. See also for a further illustration of the broader legal complexities within which all work with legally binding international instruments is situated and which must be observed: Crawford, J. (2019) *Brownlie's Principles of Public International Law*, 9th ed., Oxford University Press, Oxford; https://10.1093/he/9780198737445.001.0001. The LOSC invokes these complexities in, e.g., Arts. 237 and 311; see also Boyle, A. (2005) 'Further development of the Law of the Sea Convention: Mechanisms for change.' 54 *International and Comparative Law Quarterly* 563–84; https://doi.org/10.1093/iclq/lei017. This excellent and comprehensive paper also addresses the IA (*supra*, n (1)) in this context.

given objective[20] or obligation[21] or concept,[22] no matter how noble and worthy—including for protection and preservation of the marine environment—is not explicitly stated in the currently applicable legally binding governing instrument, it cannot be assumed that these may simply be imported into that instrument and imposed on the parties, especially if the formal requirements for amendment set out in that instrument have not been met.[23] The same applies to the development of regulations implementing a legally binding instrument. Attempts to import these extraneous elements into the regulatory process without the legally required prerequisite procedures usually indicate the "missing link" in operation.

Another corollary of this misunderstanding is the persistent confusion of the "law" with "governance" and "policy." These three terms are not synonymous. They are subject to very different analytical frameworks and criteria, which must be scrupulously distinguished and observed. One common consequence of this absence of rigor in treaty interpretation and implementation exercises by non-lawyers is to ignore the actual requirement(s) of the instrument and to substitute the new objective(s), obligation(s), and/or concept(s) for regulatory implementation instead of what the instrument actually requires.[24] This aspect is further addressed in the next section, with particular attention to conducting legally relevant research.

6 Unintended Consequences

The foregoing are examples of wishful thinking rather than legal thinking. Despite the noble intentions, the consequences of this wishful thinking would be wholly counterproductive where protection of the marine environment is at stake. Three examples are given.

First, in the case of the marine environment, as I have lamented elsewhere,[25] and contrary (or at least it is to be hoped) to the best intentions of the proponents of these

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[20] Examples include: "sustainable development," "compensating the common heritage."

[21] Examples include: precautionary approach/principle, polluter-pays principle.

[22] Examples include: biodiversity, "ecosystem-based management."

[23] For the LOSC, these are Articles 312–316. Special provisions exist for amendments relating to Part XI: LOSC Articles 155 (as modified by IA Section 4), 311(6), 314 and 316(5) & (6); IA Section 4. See also references and discussion *supra* (n 19).

[24] Verlaan, P.A. (2020) *supra* n (15); Verlaan, P. A. (2021) Future of deep-sea mineral resources: Environmental issues, in: Nordquist, M. et al. (Eds.) *Legal, Scientific and Economic Aspects of Deep Seabed Mining: The International Seabed Authority at 25*. Brill, Leiden; references and discussion *supra* (n 19).

[25] Ibid.; Verlaan, P.A. (2020) *supra* n (6); Verlaan, P.A. (2019) Environmental issues of deep-sea mining—a Law of the Sea perspective, in: Rahul Sharma (Ed.) *Environmental Issues of Deep-Sea Mining*, Springer Nature, Switzerland; Verlaan, P.A. (2009) 'Geo-engineering, the Law of the Sea, and climate change.' *Carbon and Climate Law Review* 2009 (4):446–458 (2009); see also Winther, J-G., Dai, M., et al. 2020. *Integrated Ocean Management*. World Resources Institute, Washington, DC. A Blue Paper commissioned by the High-Level Panel for a Sustainable Ocean Economy and

legally and scientifically flawed proposals, the result—were these proposals to be accepted—would be to destroy the marine environment even faster than is already occurring under the far more stringent requirements for its protection set out in the LOSC and that are, alas, to date being largely ignored.[26] A major (albeit by no means new) lesson that it is hoped the world might perhaps this time learn from the current COVID-19 global vaccination distribution challenge is that none of us is protected against this new scourge until all of us are protected. The same is true for the ocean. ***None of the ocean is protected until all of the ocean is protected***.

Second, incorporation of elementary legal mistakes such as those outlined above in a legally binding instrument and in implementing regulations exposes them to challenge in court, with all the attendant expenditure on litigation of already scarce resources that could have been far better spent on actually protecting the marine environment. A further detrimental effect on the marine environment from a court case is caused by the challenged instrument/regulations remaining in limbo while they are *sub judice*. The marine environment does not benefit from yet more excuses for delaying the already long overdue actions still needed to protect it.

Third, it impedes the conduct of legally relevant research. For example, in the case of SBM and its associated marine environmental protection requirements,[27] implementing the LOSC requires specific (in alphabetical order) engineering, scientific, and technological (EST)[28] input to assist the regulator (here, the ISA) in regulating this activity correctly, that is, according to both the law and the best available EST information.

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available online at https://www.oceanpanel.org/blue-papers/integrated-ocean-management (last accessed 15 March 2021). The premise of this Blue Paper is correct both legally (i.e., under the LOSC) and scientifically (i.e., recognizing the fundamentally and inseparably interconnected nature of the marine environment). It wholly contradicts the premise of the proposed BBNJ instrument, which claims to protect only a small component of the marine environment: high seas biodiversity (see also Verlaan (2020) *supra* (n 15). If the marine environmental provisions of the LOSC, which ***also apply to the high seas*** (see LOSC Art. 87(1)) had been implemented and enforced by the LOSC States Parties (SPLOS), which meet annually, from the date of the LOSC's entry into force in 1994, the oceans would be in better shape, and the concerns underlying the initial formation of the process that led to the current UN General Assembly Resolution A/RES/72/249: International legally binding instrument [ILBI] under the United Nations Convention on the Law of the Sea on the conservation and sustainable use of marine biological diversity of areas beyond national jurisdiction (hereinafter: BBNJ process), available at http://www.un.org/depts/los/general_assembly/general_assembly_resolutions.htm; accessed 6 March 2021, could have been addressed in a manner that is both legally and scientifically sound.

[26] Ibid. The BBNJ process should review its premise and amend the draft ILBI proposal accordingly.

[27] See, e.g., LOSC Art. 145, which requires "effective measures", including regulations to, e.g.: "includ[e] the coastline"; identify "other hazards", define "ecological balance of the marine environment" and "interference" therewith; "[prevent, reduce and control] pollution", "hazards" and "interference"; "[protect and conserve] natural resources of the Area"; and "[prevent] damage to the flora and fauna of the marine environment". Other marine environmental protection requirements relevant to SBM are found in, e.g., LOSC Article 1 and LOSC Part XII, a chapter dedicated entirely to the marine environment (e.g., Arts. 209, 215).

[28] Financial and economic information is also important here, but the modalities of their contributions are beyond the scope of this paper and the qualifications of its author. See also *infra* (n 31).

The regulator is wholly dependent on the technical experts (e.g., in EST disciplines) to inform it early and in detail whether the research requested by the regulator will indeed contribute the EST information it needs to regulate, and if not, to advise the regulator on what kind of research will provide this information. The LOSC sets requirements for the EST information needed to regulate correctly. If the LOSC requires EST information that is either not or no longer suitable to achieve this purpose, then EST specialists are professionally obliged at least to so inform the regulator. Neither they nor the regulator can legally proceed as if the LOSC's requirements do not exist.[29] EST specialists may prefer not to engage in research requested by the regulator that will contribute to responsible environmental regulation. But it is pointless for EST specialists to develop research programs that they hope will assist the regulator in protecting the marine environment if those programs are based on their misunderstanding of what the LOSC requires to that end. Legal misconceptions resulting in EST research that does not provide answers to the EST questions needed for responsible regulation under the LOSC consumes yet more scarce time and resources to address issues of, at best, little legal relevance under the law of the sea.

7 Joint Is Better than Several

The crucial interplay between EST relevance and legal relevance to achieving responsible regulation for marine environmental protection illustrates why it is imperative for legally binding regulatory instruments to be drafted ab initio with joint input from EST specialists and lawyers. Both groups play equally indispensable roles. It is impossible to regulate SBM responsibly without accurate and continuously updated understanding of SBM and the natural environment wherein it is conducted.[30] The EST specialists are essential because they must provide this information and explain it to the lawyers. The lawyers are essential because they must provide legally binding regulatory language that both accurately reflects the EST input and is consistent with and implementable in the context of the applicable existing complex legal and institutional framework, in particular the LOSC and the

[29] This is one reason why "marine biodiversity" is neither a legally nor a scientifically acceptable proxy or substitute for "the marine environment" when implementation of the LOSC's marine environmental protection requirements (such as in Part XI and Part XII) is concerned. See also Verlaan (2020) *op. cit. supra* (n 15).

[30] Relevant EST questions that lawyers are unlikely to ask include: Will this work in a force 9 gale? What mesh size must be specified for this purpose? See further Verlaan, P.A. (1997) 'New seafloor mapping technology and Article 76 of the 1982 United Nations Convention on the Law of the Sea.' *Marine Policy* 21(5):425–434.

ISA, as well as adaptable to accommodate improved knowledge over time, and appropriately translatable into at least the six official UN languages.[31]

However, even when the substantive content of the proposed instrument is agreed, the "wordsmithing" stage of responsible regulatory development for protection of the marine environment cannot be left solely to lawyers. An invaluable but, alas, sadly underappreciated contribution that EST specialists could make to the drafting process is informing the lawyers what various types of legal formulation could mean to them as non-lawyers.[32] Their inclusion at the drafting stage would add clarity and precision to the resulting text, as well as reducing the likelihood of possible misunderstanding, confusion, accidents, and potential litigation later on, thereby freeing up resources and time to, for example, protect the marine environment instead. For the process to benefit from EST input on drafting, these specialists must again be formally integrated into that process ab initio. Both EST and legal specialists must view themselves and be treated as equal valued partners during the entire regulatory drafting process. The ISA could lead the way in demonstrating how this could work on a practical level by building on its innovative consultative process in developing the exploitation regulations for SBM.

8 Equality of Rigor

It should be "a truth universally acknowledged"[33] that when experts in one discipline cite, interpret and apply elements from other disciplines, the former will verify their accuracy with experts from the latter before presenting their conclusions and proposals. This is why judges and arbitrators call expert witnesses to testify at their

[31] For SBM, the LOSC set up the Legal and Technical Commission (LTC) for this precise interdisciplinary purpose, as indicated by its name (LOSC Article 165). Economic expertise is included (see also *supra* (n 28)). The LTC is an embodiment, enshrined in law, of an ambitious attempt to fix the missing link for SBM. Whether or not the LTC ***in practice*** actually operates as effectively as could be wished in an ideal world is a different and important question which merits extensive discussion that is beyond the scope of this paper. As could be inferred from reflections on the role of the SPLOS in marine environmental protection (or rather the absence thereof) and the *impetus* for the BBNJ process set out *supra* in (n 25) above, problems in the *functioning* of a particular body are usually not solved by setting up a different body, let alone a different legally binding instrument. Instead, the problems more likely risk being exacerbated, particularly if the first body must remain operational as well. This would be the case for the LTC in the context of SBM, were, for example, an Environment Committee to be established by the ISA. Seeking to find fault with the law itself, rather than with its *implementation,* when the latter is unsatisfactory *for reasons unrelated to its legal basis*, is at the very least unhelpful.

[32] For example, the careless use of the word "significant …" which seems to have become a synonym for "a lot of" or, perhaps more accurately in actual practice, an uncertain quantity which the proponent appears to reserve the right to further specify under undefined circumstances also solely determined by the proponent—in other words, on no clear, objective, predictable, independently and externally verifiable basis.

[33] Austen, J. (1813) *Pride and Prejudice*. T. Egerton, London.

hearings. This is why technical expert bodies are represented, with the right to participate, orally and in writing, in intergovernmental meetings. Nevertheless, at least with regard to comments and publications by non-lawyers on the law related to SBM issues, this interdisciplinary consultation does not occur as a matter of course. Why this is the case merits exploration in its own right, but is beyond the scope of this chapter.[34]

This persistent lack of interdisciplinary consultation is of particular concern when it occurs in refereed publications.[35] The following adjustment of the peer review process in those publications is suggested to help address this issue.

Refereed journals usually inquire at the time of first submission, that is, before the journal's own external peer review begins, whether the paper has been checked by a native speaker of the language in which the paper is being submitted if the author is not a native speaker of that language. A concomitant inquiry could ascertain whether this procedure has been followed for disciplines addressed in the proposed submission for which the author is not formally qualified. If the answer is no, the paper should be returned to the author for resubmission after this step has been completed, with the expert(s) consulted identified. Editors of refereed publications (including books) must seek similar appropriate external expertise in the peer review process preceding final acceptance for publication of the manuscript. This simple procedural change could easily be integrated into the ISA's consultative and drafting processes, serve as an example to other bodies confronted with the need to improve vertical and horizontal interdisciplinary consultations, communications and advice, and encourage the community of specialists to do so as well.

9 A Promise or a Threat?

A profound insight into the nature of the ocean is offered by Professor Dr. John Craven, an ocean engineer and a lawyer (thereby straddling the EST and legal disciplines that are the primary focus of this chapter): "If you bring something new to the sea, the sea will bring something new to you."[36] This embodies both a promise and a threat. The LOSC is humanity's legally binding promise to bring the rule of law to the sea, including for the protection of the marine environment, informed by

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[34] It is hoped that this paper will stimulate this investigation.

[35] This can even occur in papers published by the most prestigious scientists in the most prestigious refereed journals: see, e.g., Rona, P.A. (2003): "The discovery of vent ecosystems was so unexpected that they fall outside the legal framework of UNCLOS." "Resources of the sea floor." *Science* 299 (5607): 673–674; https://10.1126/science.1080679. This statement is incorrect. ***All*** marine ecosystems, including those lucky enough to still remain undiscovered, fall with the legal framework of the LOSC.

[36] Craven, J.P. (2002). *The Silent War: The Cold War battle beneath the sea*. Simon & Schuster, New York. His proposition may well also offer an insight into the nature of the environment of the planet as a whole.

the best available EST knowledge. Unfortunately, the promise that humanity set out through the LOSC to bring to the sea is far outweighed by the threat humanity also brings to the sea through unremitting environmental degradation. The sea will surely bring humanity something new in response. But humanity is recklessly squandering the sea's capacity for bringing humanity something new that is positive, rather than negative.

Bringing all the disciplines together to implement the LOSC based on an accurate shared understanding of this uniquely powerful legally binding international governing instrument for the protection and preservation of the marine environment by the EST and the legal specialists could help tip the balance back towards a positive response from the sea. Its response might even bring humanity "something rich and strange …"[37] Repairing the missing link addressed in this chapter, at least in the SBM process being undertaken under the auspices of the ISA, as governed by the LOSC, would be a practical start towards such a tantalizing end.

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[37] Shakespeare, W. (1610–1611). From Ariel's Song (2d stanza). *The Tempest*, Act 1, Scene 2.

Chapter 21
Operational Aspects of Implementing Regulatory Frameworks to Manage Deep-Sea Mining Activities

Roland Cormier and Andrew Minkiewicz

Abstract There are several regulatory frameworks that are already in place from an international context for maritime activities at sea that would apply to deep-sea mining operations and guide the operational implementation of such frameworks. There are also many examples of regulatory frameworks that are implemented by national authorities which are in line with United Nations conventions and agreements that could provide insights for the development and implementation of regulatory and non-regulatory framework for deep-sea mining. This chapter uses analogies drawn from maritime spatial planning and other international regulatory frameworks such as shipping and fisheries to provide insight and lessons learned for the development and implementation of deep-sea mining regulatory and non-regulatory frameworks.

Keywords Deep seabed mining · Regulatory frameworks · Summary of operational boundaries · Bow-tie analysis · Maritime spatial planning

1 Introduction

The International Seabed Authority (ISA) is currently drafting a regulatory framework for the exploitation of mineral resources in the area. The draft regulations[1] establish the regulatory and non-regulatory framework to implement Part XI of the

[1] Draft regulations on exploitation of mineral resources in the Area. https://isa.org.jm/files/files/documents/isba_25_c_wp1-e_0.pdf

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United Nations Convention on the Law of the Sea[2] (UNCLOS) regarding the exploitation of the mineral resources of the seabed in the area. The draft regulations and guidelines are intended to address environmental, health and safety including potential conflict between maritime activities in the area recognizing that State Parties to UNCLOS still retain the freedom to carry out their maritime activities and scientific research on the high seas (e.g., superjacent and surface waters) and scientific research of the seabed in the area. Given the increasing interest for minerals in the area, there is a need to develop a suite of operational controls to enable the exploitation of minerals in view of the concerns to the marine environment as well as the health and safety of personnel involved in the mining operations and other maritime activities in the area.

In addition to the draft regulations, the Legal and Technical Commission has recently produced a series of draft guidelines for establishing baselines,[3] for environmental impact assessments,[4] environmental impact statements,[5] environmental management and monitoring plans[6] and hazard identification and risk assessment tools and techniques.[7] This very comprehensive set of guidelines promotes the use of best available scientific evidence, techniques, environmental practices and industry practices for mining undertakings in the area. These best practices will form the basis for the management measures, procedures, monitoring and corrective actions that the contractor would have to implement within their operations in addition to the national legislations of the Sponsoring State that would be applicable to any vessel or structure flying their flag. Although a Sponsoring State may not impose conditions on a contractor that is not compatible with UNCLOS and the rules, regulations and procedures of the ISA, the Sponsoring State may apply environmental or other national legislation and regulations that are more stringent as long as they are not inconsistent with the ISA. As for the area, maritime activities in the high seas and sovereign waters are managed through diverse legislative and regulatory frameworks from multiple states. Given this diversity, international codes and standards, such as the ones established by the International Maritime Organization (IMO),[8] ensure that the legislation and regulations that are implemented by State Parties

2 United Nations Convention on the Law of the Sea. https://www.un.org/Depts/los/convention_agreements/texts/unclos/unclos_e.pdf

3 Draft Guidelines for the establishment of baseline environmental data. https://isa.org.jm/files/files/documents/expected_scope_and_standard_of_baseline_data_collection.pdf

4 Draft Standard and Guidelines for environmental impact assessment process. https://isa.org.jm/files/files/documents/Standard_and_Guidelines_for_environmental_impact_assessment.pdf

5 Draft Guidelines for the preparation of an environmental impact statement. https://isa.org.jm/files/files/documents/preparation_of_an_environmental_impact_statement.pdf

6 Draft Guidelines for the preparation of environmental management and monitoring plans. https://isa.org.jm/files/files/documents/environmental_management_monitoring_plans.pdf

7 Draft Guidelines on tools and techniques for hazard identification and risk assessments. https://isa.org.jm/files/files/documents/tools_and_techniques_for_hazard_identification_and_risk_assessments.pdf

8 IMO. IMO What it is. https://www.cdn.imo.org/localresources/en/About/Documents/What%20it%20is%20Oct%202013_Web.pdf

address the obligations of the conventions and agreements that they have ratified. This provides assurance that the activities of maritime entities flying different flags are being managed coherently and regulated equivalently by their Flag State legislations and regulations.

In the area, other maritime entities operating on the surface and the superjacent waters such as shipping, fisheries and research already have to comply with the legislation and regulations of their Flag States to address the obligation of these States to relevant international codes and standards for the high seas. This implies that the mining entities operating on the seabed of the area would be managed by international codes established by the ISA, while the maritime entities operating on the high seas would be managed by codes of other international bodies such as the IMO or a Regional Fisheries Organization. One of the key needs for consultation and cooperation between the ISA, the Sponsoring States, the Flag States and other international organizations is to integrate the relevant international codes that are at play for both mining and maritime entities to ensure some coherence between the management approaches for these entities because of the spatial overlap of the area and the high seas. This integration is also needed for the Sponsoring States to ensure that their regulatory frameworks for mining operations provide equivalent levels of environmental, health and safety protection as the other regulatory frameworks of the Sponsoring States for their mining operations in the area.

This is a situation where a maritime spatial planning (MSP) approach common in most Coastal States could provide a structured process to identify the hazards and concerns of all State Parties involved and to produce a maritime spatial plan of activities to ensure that maritime entities can pursue their operational activities safely with due consideration to the marine environment (Zaucha and Gee 2019; ICES 2021). A maritime spatial plan is an effective way to integrate the jurisdictional requirements of multiple maritime activities occurring in a management area to promote the sustainable growth of maritime economies, the sustainable development of marine areas and the sustainable use of marine resources (MSPD 2014). A maritime spatial plan can also establish the context and scope of the potential hazards and concerns that should be considered for environmental impacts assessments (EIA) thus ensuring coherence across such assessments in a management area (Duarte and Sánchez 2020). This could also help EIAs for proposed mining areas to improve the equivalency of the prevention, reduction and control measures that would be implemented to address the specific physicochemical, biological, socio-economic hazards and concerns across the area being managed (de Jonge et al. 2020; Drazen et al. 2020). One would assume that there are significant differences in the potential impacts between the mining operations involved for polymetallic nodules, polymetallic sulphides and cobalt-rich ferromanganese crusts as well as environmental and health and safety concerns from States Parties and their maritime entities operating, for example, in the Atlantic and the Pacific.

Using a simplified list of mining operations that would occur on the seabed of a mining area, we demonstrate the use of a maritime spatial planning process to:

1. Establish the context of the concerns that State Parties may have regarding the potential deleterious effects of mining operations in the area and the overlapping high seas.
2. Identify the potential hazards that may be introduced by mining operations and the other maritime operations.
3. Identify the potential marine environmental pressures that could be introduced by mining operations on the seabed, the superjacent waters and the surface.
4. Demonstrate how a maritime spatial planning approach would integrate existing international conventions and agreements used to manage maritime entities in the high seas with mining regulations and codes used to manage mining entities in the area (based on the current drafts).
5. Demonstrate how a maritime spatial plan would also promote a coherence in the management strategies and equivalency of the regulatory frameworks across Sponsoring States and the contractors operating in a designated mining site.

Here, it is assumed that such a planning process would require the oversight of the ISA and the consultation and cooperation of relevant State Parties, Flag States and Coastal States having concerns regarding mining activities in the area. It also uses international risk assessment techniques (IEC/ISO 2019) to integrate the risks of hazards and deleterious effects to the relevant obligations of UNCLOS and other international conventions that could apply to the area and the high seas. Throughout this document, hazards refer to the health and safety concerns, while pressures refer to the impacts on the marine environment. We hope that such planning and analytical approaches will contribute to the current discussions and exchanges regarding mining exploitation of the seabed while promoting an effective and transparent communication, information and participation processes for those involved.

2 Establishing the Maritime Spatial Context of the Area and the High Seas

For States that have ratified and implemented the convention, UNCLOS outlines the spatial distribution of the State Parties sovereign rights to explore and exploit living and physical natural resources. It also outlines the authorities to regulate activities within their jurisdictions and the high seas through the flag of their registered vessels, platforms or aircraft operating. UNCLOS also establishes that the physical resources of the seabed are vested in mankind and are managed by the ISA. From a maritime spatial planning perspective, this introduces two spatial dimensions under consideration, the spatial overlap between the area and the seas including the vertical space used for mining and maritime activities from the surface, the superjacent waters and the seabed (Fig. 21.1). These dimensions also reflect the sovereignty and jurisdictions of the Coastal States in contrast to the Flag States freedom on the high seas and the authority of the ISA over the physical resources of the seabed in the area. This establishes the spatial context for a maritime spatial analysis of the

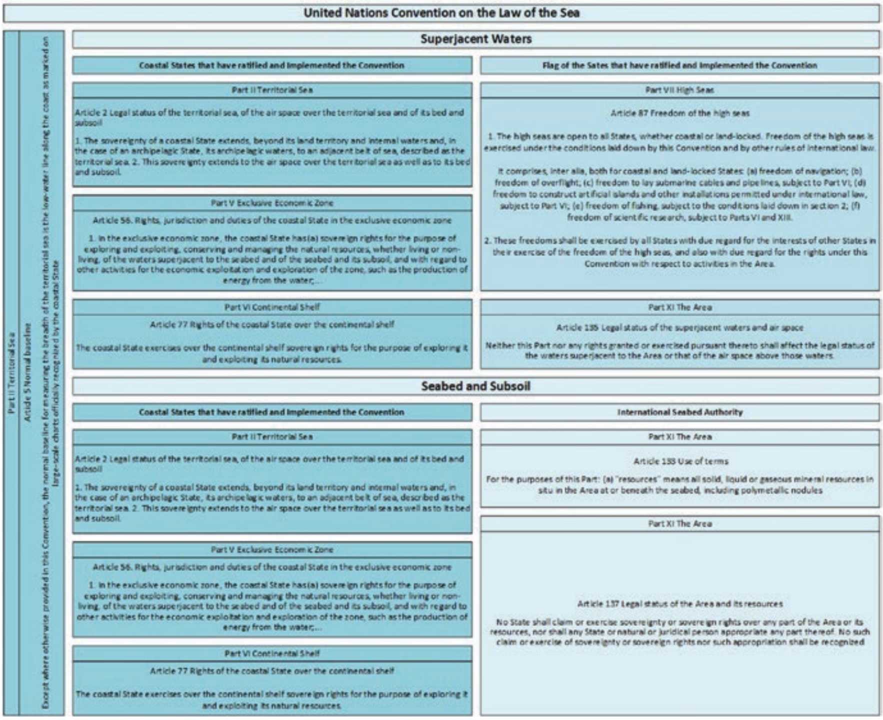

Fig. 21.1 Spatial context of the sovereignty of Coastal States, the freedom of Flag States and the authority of the International Seabed Authority

potential hazards and effects that could arise from the multiple maritime uses of the high seas and the mining operations in the area. As part of a maritime spatial planning process, the collaboration of Coastal States, Flag States and Sponsoring States is required to identify and validate the concerns identified under the oversight of the ISA.

A summary of operational boundaries (SOOB) identifies the States that may have concerns in relation to the mining operations in the area (Detman and Groot 2011; CCPS 2018) which is also similar to a Manual of Permitted Operations (MOPO) that is typically used in oil and gas drilling industries. For example, the concerns could be related to hazards to navigations, the location of cables and archaeological objects on seafloor, the safety of those operating the mining equipment or the impacts of mining to marine life on the seafloor, superjacent waters or at the surface. However, they could also be related to deleterious effects that could arise from transboundary issues (ICES 2021) such as the potential of accidental spill occurring in one jurisdiction that can contaminate the waters of another jurisdiction and, in particular, the seafood consumed by people in another jurisdiction as well as other pressures that do not have any spatial characteristics such as the introduction of noise, litter or non-indigenous species from activities outside a given jurisdiction. As such, a SOOB can provide a more detailed overview of the '*deleterious effects*' outlined in Article 1 and reiterated in Part XI UNCLOS as '*being harm to living resources and marine life, hazards to human health, hindrance to marine activities, including fishing and other legitimate uses of the sea, impairment of quality for use of sea water, and reduction of amenities*'. Maritime spatial planning is not only about identifying hazards and effects between maritime users. It is also about finding spatial and temporal solutions for the users of the maritime spaces (Stelzenmüller et al. 2021). Not all activities occur in the same space at the same time.

3 Simplified Mining Operations

A maritime spatial and temporal analysis of potential hazards and deleterious effects are typically conducted for each individual operation of an activity in relation to other activities. The following outlines a very simplified set of operations as a means to demonstrate an analysis of the mining operations occurring at the surface, in superjacent waters and on the seabed (Fig. 21.2). Working from the premise that other maritime activities can continue to take place on the surface and in the superjacent water (Part XI Article 137), the specific mining operations could introduce different hazards and deleterious effects of concern to Flag States navigating and fishing in the areas. For example, the stationary or semi-stationary operations of the mining vessel or platform (S1) could become a hazard for shipping in contrast to

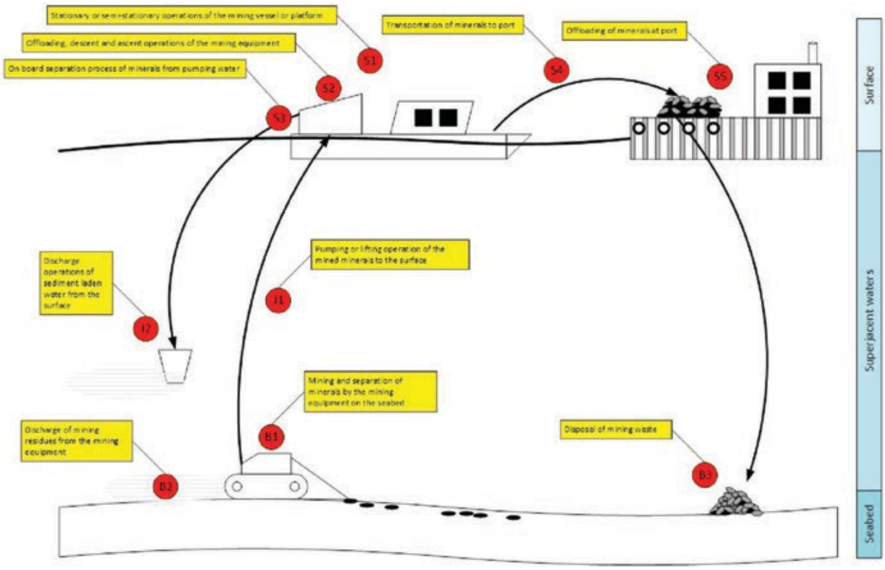

Fig. 21.2 Simplified mining operations

offloading, descent and ascent operations of the mining equipment (S2) could introduce safety hazards to employees. However, the on-board separation process of minerals from the pumping water (S3) could also introduce substances to surface waters that could have a deleterious effect on the quality of the water. Depending on the location and depth of the mining operations, the mining equipment operating on the seabed (B1) could also introduce a hazard to electrical transmission lines and pipelines on the bottom that would be of concern to Coastal States.

4 Analysing the Potential Concerns Emerging from Mining Operations

Three SOOB analyses are used to demonstrate how such an analysis is used to identify the likely, possible and unlikely concerns (Fig. 21.3) from the perspective of the State Parties that have ratified UNCLOS. For example, some of the State Parties that may not have plans to partake in mining activities may still have concerns regarding environmental issues, while the Coastal States and the Flag States may have concerns of being inadvertently impacted by mining operations. As part of a maritime spatial planning process led by the ISA, a preliminary SOOB analysis could be conducted to establish the context of the concerns that would be discussed through collaboration and consultation processes with relevant State Parties, contractors and stakeholders. The first matrix (Fig. 21.4) outlines the potential concerns in relation to the deleterious effects that could occur from the mining operations. The second matrix (Fig. 21.5) outlines the potential hazards that could occur between the mining operations and the maritime activities that are both taking place in the mining area. The third matrix (Fig. 21.6) outlines the potential marine environmental pressures that could be introduced by the mining operations in the mining area.

The SOOB matrix of Fig. 21.4 would indicate that Flag States could have concerns regarding the potential hindrance to their maritime and fisheries activities from surface mining operations. The Flag States and the Coastal States could also have concerns regarding the harm to living resources, marine life and human health from mining operations that could introduce contaminants that could impair the

Fig. 21.3 Classification of the state concerns to mining operations in the area

	Likely Concerns	Possible Concerns	Unlikely Concerns
State Parties	SPL	SPP	SPU
Coastal States	CSL	CSP	CSU
Flag States	FSL	FSP	FSU
Sponsoring States	SSL	SSP	SSU

	Likely Concerns	Possible Concerns	Unlikely Concerns
State Parties	SPL	SPP	SPU
Coastal States	CSL	CSP	CSU
Flag States	FSL	FSP	FSU
Sponsoring States	SSL	SSP	SSU

		Stationary or semi-stationary operations of the vessel or platform	Offloading, descent and ascent operations of mining equipment	On board separation process of minerals from pumping water	Transportation of minerals to port	Offloading operations of minerals at port		Pumping or lifting operation of the mined minerals to the surface	Discharge operations of sediment laden water of pumping or lifting operations		Mining and separation of minerals by the mining equipment on the seabed	Discharge of mining residues from extracte minerals	Disposal operations mining waste
Deep-seabed mining operational Risk Factors	Surface	S1	S2	S3	S4	S5	Superjacent waters	J1	J2	Seabed	B1	B2	B3
UNCLOS Part I Potential deleterious effects													
Harm to living resources and marine life		FSL	FSL	FSL	FSP	CSP		FSP	FSP		SPL	SPL	CSL
Hazards to human health		FSL	FSP	FSL	CSL	CSL		FSP	FSP		FSP	FSP	CSP
Hindrance to marine activities, including fishing and other legitimate uses of the sea		FSL	FSP	FSL	FSP	CSP		FSU	FSU		FSU	FSU	FSP
Impairment of quality for use of sea water		FSL	FSU	FSL	FSP	CSL		FSP	FSP		FSP	FSP	FSP
Reduction of amenities		FSP	FSU	FSP	FSP	CSP		FSP	FSP		FSP	FSP	FSP

Fig. 21.4 Summary of operational boundaries (SOOB) of potential deleterious effects (BowTieXP 10.0.5.0)

	Likely Concerns	Possible Concerns	Unlikely Concerns
State Parties	SPL	SPP	SPU
Coastal States	CSL	CSP	CSU
Flag States	FSL	FSP	FSU
Sponsoring States	SSL	SSP	SSU

		Stationary or semi-stationary operations of the vessel or platform	Offloading, descent and ascent operations of mining equipment	On board separation process of minerals from pumping water	Transportation of minerals to port	Offloading operations of minerals at port		Pumping or lifting operation of the mined minerals to the surface	Discharge operations of sediment laden water of pumping or lifting operations		Mining and separation of minerals by the mining equipment on the seabed	Discharge of mining residues from extracte minerals	Disposal operations mining waste
Deep-seabed mining operations	Surface	S1	S2	S3	S4	S5	Superjacent waters	J1	J2	Seabed	B1	B2	B3
Other maritime activities occurring in the Area													
Physical restructuring of rivers, coastline or seabed (water management)													
Land claim Canalisation and other watercourse modifications		NA	NA	NA	NA	NA		NA	NA		NA	NA	NA
Coastal defence and flood protection		NA	NA	NA	NA	NA		NA	NA		NA	NA	NA
Offshore structures (other than for oil/ gas/ renewables)		FSL	FSP	FSU	FSU	FSU		FSP	FSP		FSL	FSP	FSP
Restructuring of seabed morphology, including dredging and depositing of materials		FSL	FSU	FSU	CSP	CSP		FSP	FSP		FSL	FSP	FSP
Extraction of non-living resources													
Extraction of minerals (rock, metal ores, gravel, sand, shell)		FSP	FSU	FSU	CSU	CSU		FSU	FSU		FSP	FSU	FSU
Extraction of oil and gas, including infrastructure		FSL	FSP	FSU	FSU	FSU		FSU	FSU		FSU	FSU	FSU
Extraction of salt		NA	NA	NA	NA	NA		NA	NA		NA	NA	NA
Extraction of water		NA	NA	NA	NA	NA		NA	NA		NA	NA	NA
Production of energy													
Renewable energy generation (wind, wave and tidal power), including infrastructure		FSP	FSU	FSU	FSU	FSU		FSU	FSU		FSP	FSU	FSU
Non-renewable energy generation		NA	NA	NA	NA	NA		NA	NA		NA	NA	NA
Transmission of electricity and communications (cables)		CSU	CSP	CSU	CSU	CSU		CSU	CSU		CSL	CSL	CSL
Extraction of living resources													
Fish and shellfish harvesting (professional, recreational)		FSL	FSP	FSL	FSU	FSU		FSP	FSL		FSP	FSP	FSP
Fish and shellfish processing		NA	NA	NA	NA	NA		NA	NA		NA	NA	NA
Marine plant harvesting		FSL	FSP	FSL	FSU	FSU		FSP	FSL		FSP	FSP	FSP
Hunting and collecting for other purposes		NA	NA	NA	NA	NA		NA	NA		NA	NA	NA
Cultivation of living resources													
Aquaculture —marine, including infrastructure		FSU	FSU	FSU	FSU	FSU		FSU	FSU		FSU	FSU	FSU
Aquaculture —freshwater		NA	NA	NA	NA	NA		NA	NA		NA	NA	NA
Agriculture		NA	NA	NA	NA	NA		NA	NA		NA	NA	NA
Forestry		NA	NA	NA	NA	NA		NA	NA		NA	NA	NA
Transport													
Transport infrastructure Transport —shipping		FSL	FSP	FSU	FSU	FSU		FSU	FSU		FSU	FSU	FSP
Transport —air		NA	NA	NA	NA	NA		NA	NA		NA	NA	NA
Transport —land		NA	NA	NA	NA	NA		NA	NA		NA	NA	NA
Urban and industrial uses													
Urban uses		NA	NA	NA	NA	NA		NA	NA		NA	NA	NA
Industrial uses		NA	NA	NA	NA	NA		NA	NA		NA	NA	NA
Waste treatment and disposal		NA	NA	NA	NA	NA		NA	NA		NA	NA	NA
Tourism and leisure													
Tourism and leisure infrastructure		NA	NA	NA	NA	NA		NA	NA		NA	NA	NA
Tourism and leisure activities		FSP	FSP	FSU	FSU	FSU		FSU	FSU		FSU	FSU	FSU
Security and defence													
Military operations		FSL	FSL	FSL	FSL	FSL		FSL	FSL		FSL	FSL	FSL
Education and Science													
Research, survey and educational activities		FSL	FSP	FSL	FSU	FSU		FSP	FSL		FSL	FSP	FSP

Fig. 21.5 Summary of operational boundaries (SOOB) of potential hazards from other maritime activities (BowTieXP 10.0.5.0)

quality of the water and ultimately the safety of the seafood they produce from the fish they harvest.

This matrix is presented to show that an analysis of concerns regarding the deleterious effects of UNCLOS does not provide the level of detailed description of the hazards to human health and safety and the pressures that could cause the deleterious effects to the marine environment. This level of detail linking specific hazards and pressures to specific operations is ultimately needed to develop a comprehensive suite of prevention, reduction and control measures that would be needed to

	Likely Concerns	Possible Concerns	Unlikely Concerns
State Parties	SPL	SPP	SPU
Coastal States	CSL	CSP	CSU
Flag States	FSL	FSP	FSU
Sponsoring States	SSL	SSP	SSU

Deep-seabed mining operations	Surface	S1 Stationary or semi-stationary operations of the vessel or platform	S2 Offloading, descent and ascent operations of mining equipment	S3 On board separation process of minerals from pumping water	S4 Transportation of minerals to port	S5 Offloading operations of minerals at port	Superjacent waters	J1 Pumping or lifting operation of the mined minerals to the surface	J2 Discharge operations of sediment laden water of pumping or lifting operations	Seabed	B1 Mining and separation of minerals by the mining equipment on the seabed	B2 Discharge of mining residues from extracte minerals	B3 Disposal operations mining waste
MSFD Potential marine pressures													
Biological													
Input or spread of non-indigenous species		FSU	FSP	FSL	CSP	CSP		FSP	FSP		SPP	SPP	SPP
Input of microbial pathogens		FSU	FSP	FSL	CSP	CSP		FSP	FSP		SPP	SPP	SPP
Input of genetically modified species and translocation of native species		NA	NA	NA	NA	NA		NA	NA		NA	NA	NA
Loss of, or change to, natural biological communities due to cultivation of animal or plant species		NA	NA	NA	NA	NA		NA	NA		NA	NA	NA
Disturbance of species (e.g. where they breed, rest and feed) due to human presence		FSP	FSP	FSL	FSU	CSU		FSP	FSP		SPL	SPL	SPL
Extraction of, or mortality/injury to, wild species (by commercial and recreational fishing and other activities)		FSP	FSP	FSL	FSU	CSU		FSP	FSP		SPL	SPL	SPL
Physical													
Physical disturbance to seabed (temporary or reversible)		FSU	FSP	FSP	FSU	CSU		FSP	FSP		SPL	SPL	SPL
Physical loss (due to permanent change of seabed substrate or morphology and to extraction of seabed substrate)		FSU	FSU	FSU	FSU	CSU		FSU	FSU		SPL	SPL	SPL
Changes to hydrological conditions		NA	NA	NA	NA	NA		NA	NA		NA	NA	NA
Substances, litter and energy													
Input of nutrients —diffuse sources, point sources, atmospheric deposition		FSU	FSU	FSP	FSU	CSU		FSU	FSU		SPU	SPP	CSL
Input of organic matter —diffuse sources and point sources		FSU	FSU	FSL	FSU	CSU		FSL	FSL		SPU	SPP	CSL
Input of other substances (e.g. synthetic substances, non-synthetic substances, radionuclides) - diffuse sources, point sources, atmospheric deposition, acute events		FSU	FSP	FSL	FSP	CSL		FSP	FSP		SPL	SPL	CSL
Input of litter (solid waste matter, including micro-sized litter)		FSP	FSP	FSP	FSP	CSP		FSU	FSU		SPL	SPL	CSL
Input of anthropogenic sound (impulsive, continuous)		FSP	FSL	FSL	FSU	CSU		FSP	FSP		SPL	SPP	CSU
Input of other forms of energy (including electromagnetic fields, light and heat)		FSP	FSP	FSL	FSU	CSU		FSU	FSU		SPP	SPP	CSU
Input of water —point sources (e.g. brine)		NA	NA	NA	NA	NA		NA	NA		NA	NA	NA

Fig. 21.6 Summary of operational boundaries (SOOB) of potential pressures to the marine environment from mining operations (BowTieXP 10.0.5.0)

manage these risks. Such a matrix provides a strategic overview of the overall concerns to inform the ISA and its members during a planning process and identify the States and stakeholders should be consulted.

5 Identifying the Potential Hazards and Conflicts Between Mining and Other Maritime Operations

The SOOB matrix of Fig. 21.5 demonstrates why an analysis of the potential hazards between the mining and other maritime operations requires a more detailed list of maritime activities. For this SOOB, a comprehensive list of maritime activities (MSFD 2017) is used in relation to the mining operations of Fig. 21.2. This matrix provides more specific details into the types of 'hindrances' that could occur between mining and other maritime operations. This matrix represents an analysis of the health and safety hazards and conflicts between spatial uses. It is not an analysis of the pressures to the marine environment as in Fig. 21.6. Similar matrices are used in maritime spatial planning to identify the activities that can't operate in the same space (e.g. safety reasons) as well as the activities that can take place in the same space or at different timeframes (Scotland 2011). The planning process is mainly used to identify spatial and temporal needs of the various maritime sectors and users to reduce conflicts and ensure their economic viability (MSPD 2014). In the matrix, the maritime activities that are not occurring in the area are marked as not applicable (NA). These activities are kept in the list to avoid the possibility of inadvertently omitting or discounting activities without validation and confirmation by State Parties and stakeholders and to promote transparency in how the findings were derived from the analysis.

For discussion purposes, the Flag States and the Coastal State may have concerns regarding the maritime operations and infrastructure in the mining area. The maritime activities of the Flag States could vary greatly from offshore oil and gas operations to renewable energy infrastructure including fisheries, shipping and potential for military operations. Once validated by the relevant States and stakeholders Parties, Flag States and Coastal States, a maritime spatial planning process would produce a spatial plan of mining and maritime operations for the area. For example, some of these hazards could require spatial reallocation or rerouting of maritime operations to reduce the chance of accidents with the mining infrastructure and operations. It may also include the need to notify maritime entities when and where mining operations are taking place. However, stationary infrastructure such as cables or pipelines between Coastal States may not be easily relocated. Although there may not be cables and pipelines that are currently located within planned mining areas, such infrastructure could come into play given that the area and its physical resources could become of interest anywhere outside exclusive economic zones and at depths greater than 2000 m (Carter et al. 2009). Damage to mining equipment could also happen from abandoned cables, pipes, ship wrecks and archaeological sites. The maritime spatial plan would then be a key input for EIAs for the mining area to develop environmental management plans for the contractors and their Sponsoring States.

6 Identifying the Potential Marine Environmental Pressures Introduced by Mining Operations

The SOOB matrix of Fig. 21.6 demonstrates why an analysis of deleterious effects to natural resources and marine life resulting from mining operations requires a more detailed list of the marine environment pressures generated by these operations (Elliott et al. 2017). For this SOOB, a comprehensive list of pressures (MSFD 2017) is used in relation to the mining operations (Fig. 21.2). As with the SOOB above, some pressures are marked as not applicable to avoid the possibility of inadvertently omitting or discounting pressures without validation and confirmation. In contrast to the SOOB matrix of potential hazards for mining and maritime operations (Fig. 21.5), this matrix provides more insight into the specific pressures that individual mining operations generate that could result in deleterious effects on marine habitats, living resources, marine life and water quality (Evans et al. 2021). Some of the pressures are restricted to the footprint of mining operations such as the alteration to the seabed from the mining equipment while others generate pressures outside the mining area such as sediment dispersal or noise (Elliott et al. 2020).

Similar to the above, the Flag States and the Coastal States may have concerns for pressures introduced by mining operations at surface and superjacent waters. For example, the concerns may be related to the introduction of non-indigenous species, pathogens, disturbances or injury to species that could lead to deleterious effects to marine life including living resources such as the abundance of fish stocks of their fisheries. The same could be said for the introduction of organic matter as well as synthetic and non-synthetic substances that could render the seafood produced from these fisheries unsafe for human consumption as well as limiting their market access (Valdimarsson et al. 2004). The Coastal States could also have concerns regarding spills and leaching of synthetic and non-synthetic substances while offloading the mineral at port. Not specifically referenced here, State Parties could have broader concerns regarding marine mammals and biodiversity for the area and the high seas in relation to their obligations regarding international protection and conservation conventions and agreements.

More importantly, each pressure requires different preventive, reduction and control measures to be implemented for each of the relevant mining operations to address protection and conservation concerns (e.g. UNCLOS Article 145) (Cormier et al. 2019). Compared to a maritime spatial plan to address hazards and conflicts between marine users, a marine spatial plan would also be produced from such a planning process to identify the measures needed to reduce the pressures on the vulnerable ecological and biological components within the mining site as well as spatial protection and conservation measures such as the current implementation of 'Area of particular environmental interest' (Cormier 2019).

Any prevention, reduction and control measures produce residual pressures simply because they are never perfectly effective and fail safe (Cormier et al. 2018). Improving the effectiveness of these measures to further reduce the residual pressures are increasingly being flagged to reduce cumulative effects of the marine environment (Stelzenmüller et al. 2018, 2020; Evans et al. 2021). Similar to the above SOOB, a marine spatial plan would also be a key input for EIA's for the mining area to develop environmental management plans for the contractors and their Sponsoring States.

7 Integrating the High Seas Conventions and Agreements with Mining Regulations and Codes in the Area

In addition to scoping the concerns that should be considered for an EIA, the SOOBs also establish the context and the scope for the analysis of the potential prevention, reduction and control measures that would be needed to address hazards and conflicts between maritime users and the pressures on the marine environment. Without the policy context and the scope of the hazards and pressures to analyse the potential measures, any risk assessment techniques, such as the Bow-tie analysis discussed below, are rendered ineffective and impractical because of scope creep during the analysis producing an endless number of hazards and measures that are not reasonably managed. Once the analysis and the evaluation completed, such measures provide a coherent suite of management measures to develop international codes and standards. These can also be used by the Sponsoring States to develop their mining legislation and regulatory frameworks and, thus, ensure that regulatory and non-regulatory frameworks used by the Sponsoring States and their contractors are producing an equivalent level of protection for the area.

Using a qualitative representation of a fault tree and event tree analysis, the Bow-tie analysis is used here to identify the potential prevention, reduction and control measures that Sponsoring States could use to address hazards between maritime users and the marine environmental pressures generated by mining operations (Fig. 21.2) (de Ruijter and Guldenmund 2016; IEC/ISO 2019). A Bow-tie analysis is conducted for the mining operations occurring on the surface, the superjacent waters and the seabed because of the different hazards and pressures involved and the different management measures needed to address them (Figs. 21.7, 21.8, and 21.9). The examples of the management measures to be implemented for each mining operation in the mining area are shown on the left side of the Bow-tie while the maritime spatial planning considerations for the area are shown on the right side of the Bow-tie. The management measures being analysed are shown as having been validated by State Parties, Flag States and Coastal States. The management measures for the mining site are of importance to the Sponsoring State while the maritime spatial planning considerations for the area are of concern for the ISA.

In addition to the hazards and pressures, a Bow-tie analysis of the measures is done within the context of the requirements or obligations established in policy or legislation. Here, each management measure is linked to the relevant articles of UNCLOS to ensure that the suite of management measures produced is coherent with the obligations stipulated by UNCLOS. However, the management measures are also linked to other relevant international conventions and agreements because of the obligations that these are established for the high seas including sovereign waters. This is the integrating aspect of the analysis providing the basis for the development of a management strategy that is coherent with the obligation of UNCLOS and other international conventions and agreements for the area in relation to other maritime operations in the high seas.

Such a Bow-tie analysis also provides the basis to identify the legislations and regulations that Sponsoring States should consider for the contractors that they are going to sponsor. As a reminder, State Parties typically ratify most international conventions and agreements through the implementation of legislation and regulations to address their obligations. The intent of the international codes and standards developed under these conventions and agreements is to ensure equivalency in the management of the maritime entities and their activities across the multiple jurisdictions involved.

8 Discussion

The risk management context of any industry undertakings and activities should avoid the bias of the need to manage the concerns of perceived risks without a comprehensive analysis to validate the risks as is outlined in the draft ISA guideline for

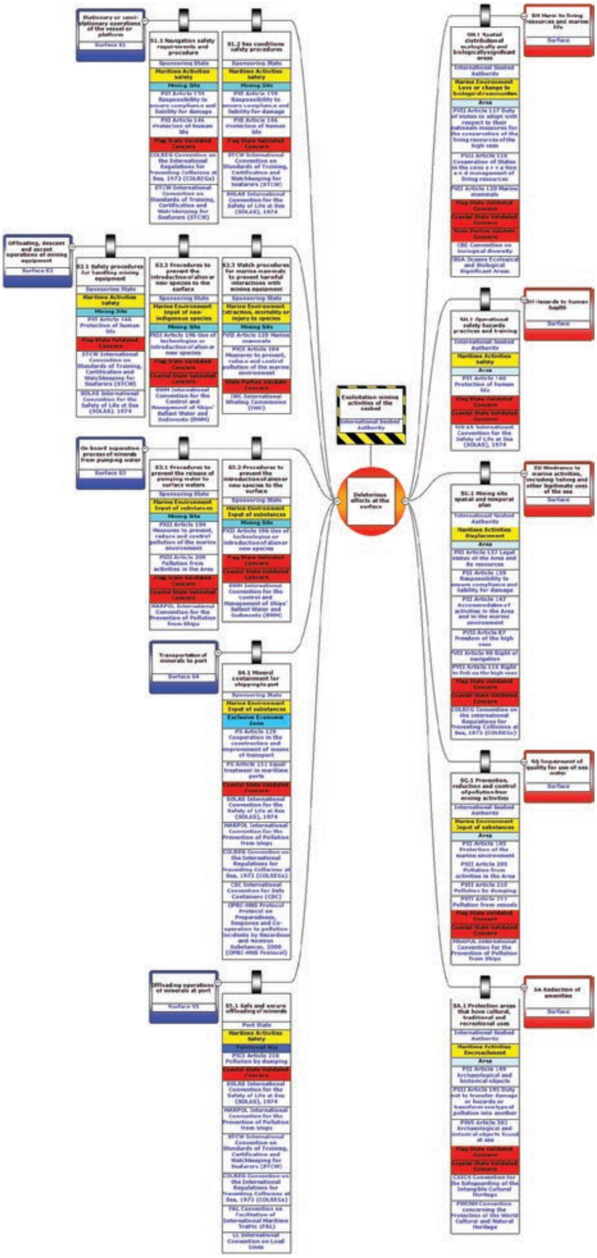

Fig. 21.7 Surface mining operations hazards (BowTieXP 10.0.5.0)

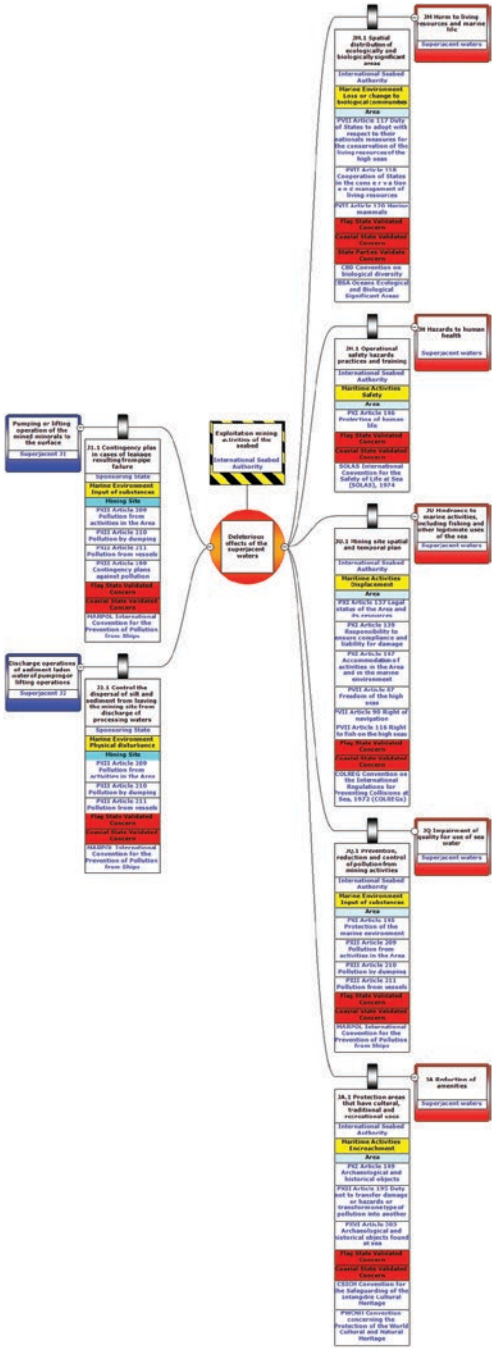

Fig. 21.8 Superjacent waters mining operations hazards (BowTieXP 10.0.5.0)

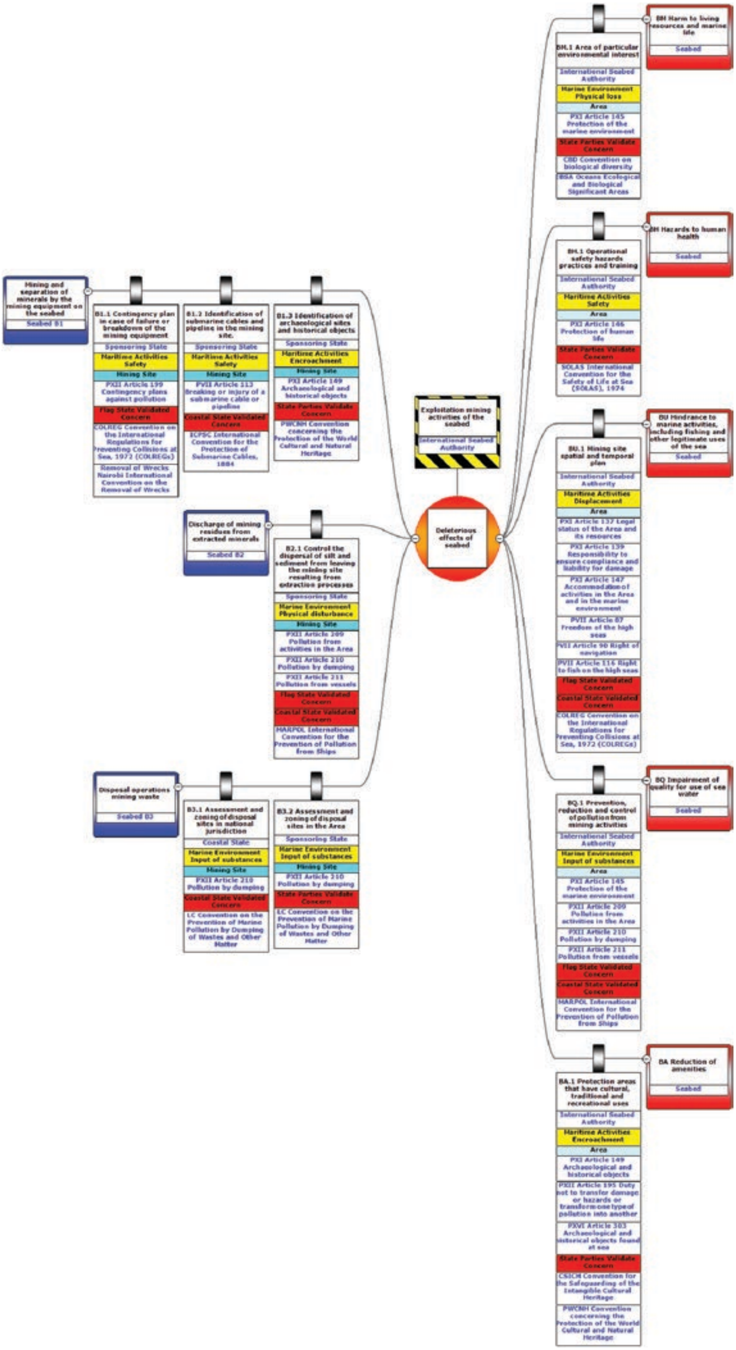

Fig. 21.9 Seabed mining operations hazards (BowTieXP 10.0.5.0)

risk analysis and assessment. Environmental impact assessments are typically scoped to the ecological and biological impacts of a project proposal. Depending on the environmental assessment legislation of a State, an environmental assessment may include all the deleterious effects listed in Article 1 of UNCLOS such as health and safety and hindrance to other maritime activities. A maritime spatial planning process can establish a more comprehensive regional context of both the marine environment and the maritime activities that could be impacted by the introduction of mining operations in the area (Zaucha and Gee 2019).

A more comprehensive environmental assessment approach is needed because there are very different regulatory and non-regulatory frameworks used to manage maritime concerns by the jurisdictions of individual States. International codes recommended for State regulations are intended to provide a coherent management approach for State Parties from a transboundary context. There are a myriad of international conventions as well as State legislative and regulatory frameworks that are already in place to manage the activities of maritime entities within jurisdictional boundaries of States and the high seas. The undertaking of seabed mining in the area is but another maritime activity that would be submitted to the same requirements of the high seas in addition to the regulations and guidelines being drafted by the ISA for that industry.

From a maritime spatial planning perspective, the first SOOB demonstrates the potential concerns regarding mining operations in the area in relation to the deleterious effects of UNCLOS (Fig. 21.4). Such a matrix could be used to develop a communication and consultation strategy at the onset of a planning initiative. However, the two subsequent SOOBs demonstrate the level of detail that would be needed in maritime spatial planning to adequately identify and validate the hazards and conflicts between mining operations and maritime activities (Fig. 21.5) including the pressures to the marine environment generated by these operations (Fig. 21.6). These SOOBs are also useful to analyse hazards and pressures that could occur at the surface, the superjacent waters, and the seabed given that they would need different prevention, reduction and control measures. An SOOB is a valuable technique to scope the hazards and pressures that would be considered in a maritime spatial planning initiative and provide a regional context and scope for an EIA. An SOOB analysis does require pre-established criteria such as the maritime activities and pressures provided here by EU Directives (MSPD 2014; MSFD 2017). Criteria play an important role to avoid bias and inadvertent omissions in such a process.

In addition to using the SOOB analysis to scope the hazards and pressures, the Bow-tie analysis is used to structure the prevention, reduction and control measures that would be needed to address the hazards and pressures. Here, the right side of the Bow-tie structures the hazards and pressures from a maritime spatial planning perspective for the area while the left side of the Bow-tie structures the prevention, reduction and control measures that manage the hazards and pressures for specific mining operations in the mining area. The logic is that an effective management strategy of the mining operations and their hazards and pressures should reduce the likelihood of deleterious effects expressed on the right side of the Bow-tie. Linking the relevant UNCLOS and other conventions and agreements to the measures being analysed provides the basis for integrating the multiple obligations that State Parties have ratified to develop a coherent management strategy for mining operations in the area in collaboration with maritime entities and Flag States operating in the high seas. It also provides the basis to evaluate equivalencies between State legislation and regulations that are used to implement the conventions.

Another challenge that a regulator faces in many maritime management situations is the fact that hazards and pressures are not all managed by the same regulator within a jurisdiction of a State and across jurisdictions of multiple States. A regulator may have authorities to manage pressures to the marine environment and not for the safety of employees working on ships or for the location of fishing activities. In addition, a regulator may not even have the information and the competence to assess such hazards and pressures. Maritime spatial planning was introduced decades ago to facilitate collaboration between regulators and stakeholders to develop comprehensive management strategies to address multiple hazards and pressures generated from multiple maritime activities operating in a management area. Although this can be challenging within one jurisdiction, it is even more challenging to collaborate in a transboundary context that has to integrate the legislation and regulatory requirements from multiple States. Maritime spatial planning that integrates codes and standards from international conventions and agreements can provide a common benchmark that regulators can use to evaluate equivalence across legislative and regulatory frameworks.

The SOOB and Bow-tie analysis in this chapter are used to demonstrate the need for legislation and regulatory analysis in the development of management codes that regulators could use for regulatory approval by a Sponsoring State and the ISA. Given the considerable amount of work that such an analysis can represent, such codes introduce efficiencies and coherence in the environmental assessments, the regulatory approval processes and the actual implementation of rules, regulations and procedures used to manage mining activities.

9 Conclusion

Even though regulatory and non-regulatory frameworks such as codes of practices, best industry practices or best environmental practices may be implemented with the best of care, the hazards and pressures can still generate deleterious effects. In the daily operations of any industry, these frameworks reduce the risks through procedures to follow, controls to check, inspection and maintenance to conduct, monitoring and corrective actions to take, to name a few. These are intended to reduce the chances of human error and equipment failure that can result in accidents and environmental damage. Their effectiveness and reliability not only depend on the design and state of repair of the equipment (Tobias and Trindade 2012), but also depend on the performance of the personnel that operate the equipment and the production processes that are, in turn, influenced by the qualifications and training, the quality controls procedures, the management of the processes as well as the organizations' culture (ISO 2009; Green 2015).

In risk management, risk can never be zero as long as the source of the risk is present (Baybutt 2014). Risk arising from the hazards and pressures of mining operations can only be eliminated by not undertaking this specific activity. When developing a regulatory and non-regulatory framework for specific activities, a regulator only has the authority to establish conditions to reduce the hazards and the pressures for the specific operations. Given the potential risks, these frameworks have to balance the urge to over-regulate to a level that is not reasonable or practical for those that have to implement them with the urge to under-regulate which exposes people and industry to risk (UNECE 2012). Thus, abiding to the reality that any risk management framework can only reduce risk to 'a level as reasonably practicable'.

Regulatory and non-regulatory frameworks are used to manage a wide range of industry undertakings and activities within the span of authority of the legislation within the boundaries of the jurisdictions of individual States. The current draft seabed mining regulations and guidelines of the ISA will ultimately establish the foundation for the Sponsoring States to develop such frameworks. Given that the Sponsoring States will be the ones ensuring compliance of the contractors flying their flags, there will likely be a need to ensure that the frameworks of each Sponsoring State provide equivalent levels of protection from such hazards and pressures. In the longer term, the ISA may need to consider developing codes applicable to the area that are similar to the detailed codes established by the International Maritime Organization that are used to ensure regulatory equivalencies between Flag States operating in the high seas.

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Chapter 22
Traditional and Socio-Ecological Dimensions of Seabed Resource Management and Applicable Legal Frameworks in the Pacific Island States

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Abstract Traditional knowledge, customary marine management approaches and integrated relationships between biodiversity, ecosystems and local communities promote conservation and ensure that marine benefits are reaped in a holistic, sustainable and equitable manner as fostered by contemporary ocean governance. However, the interaction between traditional knowledge, the present scientific approach to marine resource management and specific regulatory frameworks has often been challenging. To a certain extent, the value of community practices and customary rules, which has provided an incentive for regional cooperation and coordination, is acknowledged in several legal systems of the Pacific Island States and a number of regional and international instruments, but this important interconnectivity can certainly be perfected.

Based on recent multidisciplinary research (Tilot et al., Front Mar Sci, 8:637938. 10.3389/fmars.2021.637938, 2021; Tilot et al., Front. Mar. Sci, 2021), this chapter presents a science-based overview of the marine habitats and activities that would be affected by deep Sea mining (DSM) in the Pacific region, along with an analysis of the traditional dimensions and their interconnectivity with the socio-ecological aspects of marine resource management. We then assess whether the applicable regulatory frameworks attach sufficient importance to these traditional dimensions of seabed resource management and cultural representation in the Pacific region. On basis of this analysis, we identify best practices and formulate recommendations with regard to the current regulatory frameworks and seabed resource management approaches to reconcile competing values of the Pacific communities and to sustain the health of the Global Ocean.

Keywords Pacific Island communities · Ocean connectivity · Sustainability · Marine ecosystems · Law of the sea · Deep-sea mining · Global change · Science–policy–society

1 Introduction

The Pacific region (Fig. 22.1) has conflicting ambitions of conservation and of exploitation as it is one of the largest oceans renowned as a hotspot for its biodiversity as well as its marine resources of commercial importance (Dahl and Carew-Reid 1985; D'Arcy 2006; Petterson 2008; Trichet and Leblic 2008; Vieux et al. 2008; Kingsford et al. 2009; Cardno Limited 2016; Tilot 2006; Tilot et al. 2021b). The region has the richest deposits of minerals on its seabed (polymetallic nodules, rare earths, metal-rich muds, cobalt-rich ferromanganese crusts and hydrosulphide deposits) (Ernst and Young 2011; Kato et al. 2011; Hein and Koschinsky 2014)

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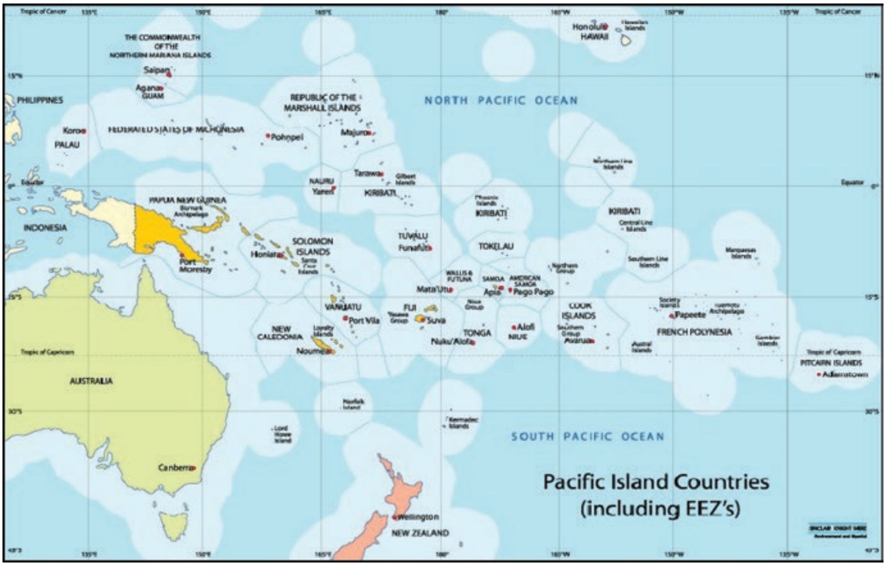

Fig. 22.1 Map of the Pacific region including the Island States with the 200-mile Exclusive Economic Zones (EEZs) and the international waters within the region. (Source: CartoGIS Services, College of Asia and the Pacific, The Australian National University (https://asiapacific.anu.edu.au/mapsonline/base-maps/pacific-eez-zones-II))

which are targeted by the deep-sea mining (DSM) industry (Hein et al. 2013; Havice and Zalik 2019). These deposits are located on the seabed both within the limits of national jurisdiction of several island states, as well as beyond.

Within national jurisdiction, on the (legal) continental shelf, deep-sea mining activities are regulated by the national legislation of the coastal state (UNCLOS, Art. 77). Beyond the limits of national jurisdiction, however, the seabed and subsoil that comprise 'the Area' (UNCLOS, Art. 1(1)) are governed by a comprehensive international regime and managed by the International Seabed Authority (ISA) (UNCLOS, Art. 157(1)). The ISA has already awarded contracts to 31 states—of which several Pacific Island States such as Tonga, Nauru, Kiribati and the Cook Islands have sponsored non-state actors or private enterprise—for exploration activities in the area, and many of these exploration efforts take place in the Clarion–Clipperton Zone (CCZ), where polymetallic nodules and cobalt-rich crust deposits of commercial importance are heavily concentrated. Similar activities are also being conducted or anticipated on the continental shelves of certain coastal states, subject to domestic laws and without interference from the ISA.

The future exploitation of the mineral resources of the seabed presents unique opportunities for the Pacific Island States for economic growth via scientific and technological progress, as well as to the world to satisfy the increasing metal demand in the global shift towards sustainable energy (Hein et al. 2013; Zalik 2018; Havice and Zalik 2019). However, it also poses additional challenges to the preservation and sustainable management of the planet's richest ecosystems and marine genetic resources and to the ecosystem services they provide (Leary et al. 2010; Tilot 2010, 2019; McCauley et al. 2015; Niner et al. 2018). Therefore, potential harm to the marine environment and the interests of coastal communities, as well as to the rest of the planet, should be adequately assessed and prevented (Tilot et al. 2018, 2021a).

Local and traditional communities of many of the Pacific Island States have long-held attachments to the sea, envisioned as a continuum with Nature and Peoples (Bambridge 2016; Bambridge et al. 2021), in particular to species and specific marine areas, processes, habitats, islands and natural seabed formations (Lewis 1972; Lohmann et al. 2008). In this region, the conservation and sustainable management of the marine environment and its resources, generally of economic importance, is promoted through traditional knowledge and customary practices, emphasizing the interconnectivity between species and ecosystems (Ruddle and Johannes 1989; Akimichi 1995; Bambridge 2016; Tilot et al. 2021b).

Combined with centuries of acquaintance, these traditional and indigenous approaches constitute keystones to holistic forms of marine resource management, mainly linked to fisheries and protected areas and species (Pomeroy 1995; Veitayaki 2004; Gavin et al. 2015; Friedlander 2018). These approaches occupy an important place in the culture, the society, the spirituality and the traditions of the Pacific Island communities (Bambridge 2016; Bambridge et al. 2019) and represent opportunities for the region (Friedlander and Gaymer 2020). Thus, if seabed mining activities do not take these interests and visions into account, the impact on the local and traditional communities with rich maritime cultures (Malinowski 1935; Kent 1980; Johannes 1981; Hviding and Baines 1992; Hau'ofa 2008) might be significant and could seriously affect their Human Well-being and Sustainable Livelihoods(HWSL)[1] (D'Arcy 2013). Especially considering the fact that Pacific Island States are presently subject to multiple stress factors such as population growth, extreme weather events, unsustainable fisheries practices, alien species invasions, sea level rise, acidification and coral bleaching associated with global warming, in particular in the Marshall Islands, Guam, Northern Mariana Islands, the North-West Hawaiian Islands and Kiribati (Pacific Community 2012; IPCC SROCC 2019). As these newly recognized HWSL dimensions, in particular traditional knowledge of the Pacific Island communities, rely on the resources from the deep sea and open waters (D'Arcy 2013), these would require an innovative regulatory framework for the management of the exploitation of deep-sea mineral resources which would ensure the preservation of the seabed and the water column, considering the cumulative impacts of DSM and other human activities (Woodall et al. 2014) and of global change (Levin et al. 2020).

[1] HWSL are commonly used in the Convention for Biological Diversity (CBD) and the international fora on sustainable development. HWSL are the social, spiritual, cultural and traditional characteristics and the capabilities, tangible assets and means of living that set the stage for sustainability, resilience and adaptability of people to change collectively (WCED 1987; Holden et al. 2014).

2 Socio-Ecological Interconnectivity with the Ocean Realm in the Pacific Region: Main Natural Resources and Activities That Would Be Affected by DSM in the Pacific Region

It is important to outline that DSM activities, which occur in different geographic areas with varied mineralogy and associated value chains (Petterson and Tawake 2018), take place in a tridimensional perspective from the seabed, through the water column to the surface and the air above (Miller et al. 2018). The extraction of ore might take place at the seabed through a process of cutting and disaggregation, but it is then pumped upwards through the water column as slurry, concentrated with the release of diluted seawater, and then transported across the sea to a terrestrial processing centre (Miller et al. 2018).

Thus, DSM would affect the main natural resources and activities located within coastal waters (near shore pelagic and deep-water bottom fish), as well as in the open oceans and the deep sea (Tilot 2010; Dyment et al. 2014; Tilot et al. 2018). An overview of the zones and activities that would be affected by DSM is presented here:

The EEZs of the 22 Pacific Island States span across much of the tropical and subtropical Pacific Ocean, encompassing an area that exceeds 27 million km^2 or 8% of the global ocean (Fig. 22.1). While coastal fishing areas across the Pacific account for only 1.25% of this ocean area (FAO 2020), the marine environment plays a major role in the economic, social and cultural well-being of Pacific Islanders by sustaining a multitude of important activities that fuel local, national and international economies and provide livelihoods and food security for millions of people (Pauwels and Fache 2016).

Coastal fishing in the Pacific region encompasses artisanal fishing supplying domestic markets and subsistence fisheries, which support rural economies and the industrial-scale shrimp fisheries (Gillett 2010). Almost all the coastal catch is taken by Pacific Island Countries (Solomon I., Cook I., Fiji, Kiribati, Marshall I., Federated States of Micronesia [FSM], Nauru, Vanuatu, Niue, PNG, Palau, Tonga, Tuvalu and Samoa) with very little access by foreign fishing vessels. However, there is concern about whether benefits and services currently derived from coastal ecosystems in terms of food security, culture, employment and recreation can sustain livelihoods in the Pacific Island States as coastal fisheries are declining (Hilmi et al. 2016). This concern has accelerated efforts to enhance the socio-ecological resilience of coastal communities in the Pacific which depend heavily on healthy ecosystems and sustainable fisheries (David 2016; Gillett and Tauati 2018). Efforts have been made to reduce the pressure on coastal ecosystems by improving the management of coastal fisheries, establishing protected areas and developing near shore pelagic fisheries and deep-sea fisheries which target reef slopes, outside barrier reefs, and shallow and deeper seamounts at more than 500 m depth (Goldstein et al. 2016).

Deep-water bottom fishing has been known for many years in the Pacific region and has been practised for generations in some of the remote island communities of the Pacific, particularly in Polynesia (SPC 1999). The most active export-oriented deep-water bottom-fish fisheries in the Pacific Islands are presently in Fiji and Tonga (The Western and Central Pacific Fisheries Commission 2019). As deep-sea fisheries typically concentrate on shallow seamounts which are assessed as highly vulnerable (Tilot 2013; Williams et al. 2020), there may as well be competing uses with planned deep-sea mining on seamounts where commercially interesting cobalt-rich crusts are located.

The target species of offshore fishing, undertaken mainly by large industrial-scale fishing vessels, are swordfish, skipjack tunas, yellowfin tunas, albacore, big-eye tuna, black marlin, blue marlin, Indo-Pacific sail-fish, shortbill spearfish, striped marlin and blue shark which are essentially open water species migrating over large routes across the Pacific region (Luschi 2013). The Western and Central Pacific Ocean (WCPO) tuna fishery is the world's largest and most valuable fishery with different seasons according to the targeted species. It accounts for nearly 60% of global tuna production and has a value of around US$4.5 billion annually (The Western and Central Pacific Fisheries Commission 2019). Tuna taken within Pacific Island Countries waters account for about 45% of the WCPO catch by volume and provide around 25% of the world's canned tuna supply (mainly for EU and US) (Havice et al. 2019; WCPFC 2019). But only 20% of this catch is taken by Pacific Island fleets with not more than 10% processed locally, the main benefits for Pacific Island Countries derive mostly from the fishing access fees (Pacific Islands Forum Fisheries Agency 2019).

In open seas of the Pacific, numerous species use different depths in the water column as feeding grounds, e.g., bluefin tunas from the surface to 200 m depth, yellowfin and bigeye tunas and swordfishes up to 1000 m depth (FAO 2000; Block et al. 2011; Schor et al. 2014). Whales can be found in open oceans at great depths (Ponganis 2016), e.g., to 1500 m for Bottlenose whales, 2400 m for sperm whales which are generally associated with seamounts (Bouchet et al. 2014), 3000 m for Cuvier's beaked whale and possibly at 4258 m for unidentified large vertebrates according to geomorphological evidence recorded on the seafloor in the CCZ (Marsh et al. 2018).

Whales have long formed part of the stories and traditions of Pacific Island peoples (Cressy 1998; Flood et al. 1999; Creason 2004; Firestone and Lilley 2007). The movements and migrations of whales (Fig. 22.2) have many parallels with the voyaging of the Pacific Island people (Feinberg 1995; Gladwin 1970; Gooley 2016; Finney 1998; Lewis 1972; New York Times Magazine 2016). During the last century, the great whales of the South Pacific were hunted to the brink of extinction. However, this century has seen a strengthening of regional and national initiatives to conserve whales.

Open water ecosystems in the Pacific region provide important ecosystem services and societal benefits, not only for the people in the Pacific Islands but also for people around the world due to the migrating nature of many marine species (De Groot et al. 2012). Indigenous Peoples and Local Communities (IPLCs) have a role as custodians of significant ecosystems and of species generally travelling between coastal waters and high seas (Ey and Sherval 2016; Eckstein and Schwarz 2019). They are central to the debate addressing gaps in governance in Areas Beyond

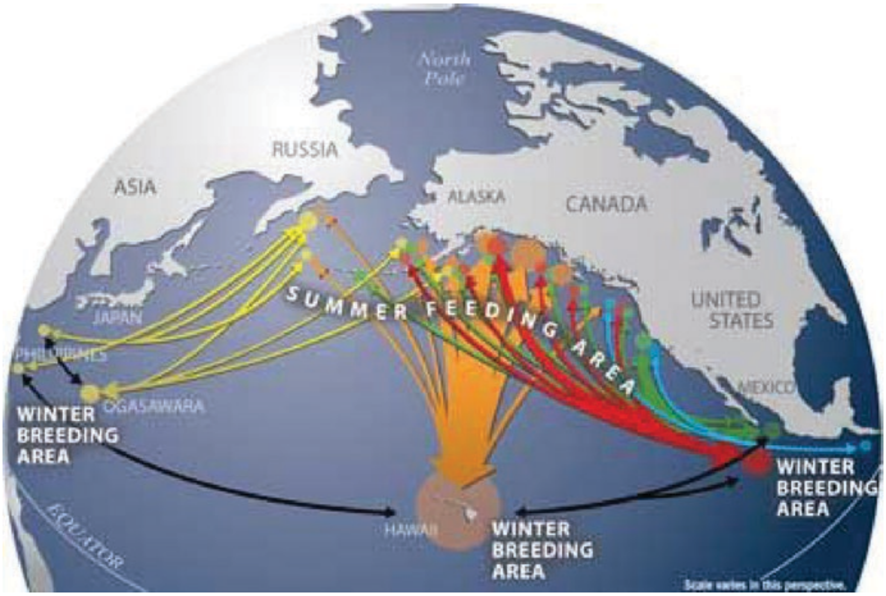

Fig. 22.2 Map of humpback whale migration routes in the Pacific region (https://hawaiihumpbackwhale.noaa.gov). The dark arrows pass by the tropical Pacific Islands range

National Jurisdiction (ABNJ) and the lack of a comprehensive framework for biodiversity conservation and management (Vierros et al. 2020).

It is also important to outline that in the mesopelagic, bathyal (200–2000 m) and abyssal realms (2000–6000 m) and especially in the deeper hadal realm (more than 6000 m), there is a significant lack of knowledge on species, biodiversity and on the relationships with the functioning of deep-sea ecosystems where trophic input is generally very low. Deep ocean environments represent the least explored areas on the planet and are assumed to be the largest reservoirs of mostly unknown species and ecosystems which might serve as a cradle of nonrenewable resources and contribute significantly to planetary biodiversity and global livelihoods. Specific adaptations, processes and communication such as bioluminescence and long-range acoustic communication occur in these most vulnerable and now coveted realms. Deep-sea faunal communities are characterized by slow biological mechanisms, taxonomically high diversity and non-random sparse distribution over large areas (Tilot 2006).

Deep midwater ecosystems (in the mesopelagic and bathypelagic depth zones) importantly represent more than 90% of the biosphere (Robison 2009), connecting to shallow and deep-sea ecosystems and playing key roles in carbon export (Boyd et al. 2019), nutrient regeneration and provisioning of harvestable fish stocks (Drazen and Sutton 2017). The fish biomass of deep midwater ecosystems is assessed as 100 times greater than the global annual fish catch (Irigoien et al. 2014).

Recent global conservation and biodiversity issues, particularly the concern for potential and real threats to the high seas and deep-sea diversity, have provided an incentive to efforts aiming at exploring the structure and function of faunal communities in the water column and the bathyal and abyssal zones and developing marine spatial planning strategies and tools (Ardron et al. 2008). As connections between the different layers of the ocean are being studied, in particular to ocean circulation, it is becoming increasingly apparent that global changes and environmental impacts are affecting all marine organisms from phytoplankton to higher marine vertebrates and all oceanic processes (Tilot et al. 2018; Tilot 2019; Drazen et al. 2020).

3 Characteristics of the Main Mineral Resources Targeted by DSM and Vulnerability of Associated Ecosystems in the Pacific Region

The characteristics and the vulnerability of the three main mineral ecosystems to be mined in the Pacific region (SPREP 2020) are as follows:

- *Ferromanganese polymetallic nodules* are rock concretions, 4–14 cm in diameter and variable in shape (Hein et al. 2015). They are generally found on the seafloor or buried in extensive fine sediment-covered abyssal plains and hills between 3500 and 6500 m depth. Polymetallic nodules are composed primarily of concentric layers of iron and manganese oxides/hydroxides enriched with a variety of metals including Mn, Fe, Cu, Ni, Co, Pb and Zn (Mero 1965). The growth of polymetallic nodules is relatively very slow. Nodules originate when precipitation occurs concentrically around a pre-existing nucleus (e.g. a shark's tooth/lithic fragment) and accretes at a rate of c. 1–10 mm per million years (hydrogenetic nodules) or 1–300 mm per year (diagenetic nodules). The most commercially important nodule deposit in the world oceans is located in international waters, in the Clarion–Clipperton Fracture Zone (CCZ) within the North East tropical Pacific Ocean. This area has been assessed to contain more nickel, manganese and cobalt than all terrestrial resources combined (Halbach et al. 1988; Bernhard and Blissenbach 1988; Hein et al. 2020). The CCZ includes the highest density of seabed mineral exploration licences on the planet. Other areas of potential interest are the Central Indian Ocean basin and the Economic Exclusive Zones (EEZs) of the Cook Islands, Kiribati and French Polynesia (Cronan and Hodkinson 1989; Hein et al. 2013; SPC 2013).

- The biological parameters of ecosystems associated with polymetallic nodules correspond to those characterizing abyssal benthic faunal communities, which are relatively slow with longer life spans and smaller biomasses. There is an adaptation to deep-sea environment with true deep-sea species with reproductive viability and durable radiations of species (Vanreusel et al. 2016). A series of preferential habitats for megafaunal assemblages have been identified in the CCZ ranked according to nodule coverage, slope degree, topography and currents with suspension feeders and detritus feeders prevalent in nodule areas as emphasized by a factor analysis of Reciprocal Averaging (Tilot 2006). These results were confirmed by Vanreusel et al. (2016). However, information is lacking on sensitivity to spatial-scale dependence of recolonization of benthic communities (Tilot 2019).

– Vulnerability of Polymetallic Nodule Associated Ecosystems to DSM

– During the collection of polymetallic nodules, impact would generate sediment plumes and noise disturbances on the seabed and above, in the abyssopelagic domain (5000-3000m). During the dewatering and other processing phases, impacts would occur in the bathypelagic (3000-1000m), the mesopelagic (1000-200m), and epipelagic domains (200m-surface) where in highly sensitive marine mammals are located. Impacts from deep-sea mining would intertefere with commercial fishing as well in these domains (Tilot, 2010). Diel vertical migration of marine species in general would also be affected as well as all biological, physiological and sensorial processes enabling communication (bioluminescence), feeding and reproduction (Miller et al. 2018). Deep-sea communities associated with polymetallic nodules are predicted to be quite sensitive to environmental changes and in particular to hyper-sedimentation as expected by mining the seafloor. As detailed studies show that benthic habitats display heterogeneity at scales of 10–100 m, terrain knowledge is necessary when engaging in nodule resource abundance assessment and predicting the scale of the impact of hyper-sedimentation during mining operations (Tilot 2010; Peukert et al. 2018; Tilot et al. 2018). The spatial extent of direct mining impacts is estimated to be 300–600 km^2 per year per contractor for manganese nodule mining (Oebius et al. 2001). Collector plume modelling to date suggests that the area of seafloor indirectly impacted would be many times larger (Aleynik et al. 2017; Jones et al. 2017; Gillard 2019). The lack of data on spatial and temporal species distribution signifies that the full impact of mining on species is unknown (Miller et al. 2018; Tilot et al. 2018).

The recovery time of a reorganization of food webs would take longer in view of the slowness of biological mechanisms and the fact that the relatively high biodiversity of this ecosystem relies principally on the dependence of sessile fauna and epifauna to nodule deposits (Tilot 2010). The associated ecosystem would probably be permanently altered by the fact that polymetallic nodules take such a long time to grow, if ever still possible. The impact of mining operations in the water column would be greater where water masses have been assessed as highly sensitive (Catalá et al. 2015). In the CCZ, these are located in two bathymetric zones, a zone from 500m to1500m with water masses characterized by a great molecular diversity and another zone from 1800m to 3500m were the oldest water masses of the oceans have been identified (Tilot et al. 2018). At around 4000–6000 m depth in the CCZ, bottom currents are variable, from 1–2 to 25 cm/s and more in the case of benthic storms and other events impinging on the sediment surface and associated faunal communities.

- *Cobalt-rich ferro-manganese crusts or cobalt-rich crusts (CRCs)* are located on seamounts, intra-plate volcanoes, volcanic chains and on volcanic or carbonate platforms from approximately 400 to 7000 m depth. Cobalt-rich crusts are formed by layers of iron and manganese oxides enriched with metals such as Co, Fe, Mg, Ti, Ni, Pl and rare earth elements (REE). CRCs originate by chemical precipitation and form very slowly from 1 to 6 mm per million years. Most CRCs of economic interest are between 800 and 2500 m depth (He et al. 2011; Hein et al. 2013; Hein and Petersen 2014). There would be around 11,000 seamounts with CRCs in the Pacific Ocean (Yesson et al. 2011a, b; Beaulieu 2010). CRCs are particularly abundant close to the Federated States of Micronesia, Marshall Islands, Kiribati, Tuvalu, Cook Islands and French Polynesia (Cronan and Hodkinson 1989). The most prospective area for cobalt crusts is located in the Magellan Seamounts in the Pacific Ocean, east of Japan and the Mariana Islands (Cronan 1984; von Stackelberg et al. 1984; Hein and Koschinsky 2014).
- Cobalt-rich associated biotopes are hot spots of marine biodiversity due to the fact that these are generally located on seamounts where topography, hydrodynamism and upwelling processes favour transport and trapping of nutrients. Isolated seamount hotspots would induce important speciation, endemism and higher abundance. Seamounts play a major role as stepping stones for population dynamics, biological connection and colonization. Moreover, seamounts attract a large trophic chain among which the bentho-pelagic communities which are targeted by fisheries. Thus seamounts have different competing interests to DSM (Clark et al. 2016).

  – Vulnerability of CRC Associated Ecosystems to DSM

  The vulnerability of crust ecosystems is high as sessile organisms are characterized by slow biological processes, long life spans, slow growth rates, genetic isolation and for most, a low dispersion rate of larvae, reasons for which seamounts have been considered globally as vulnerable marine ecosystems (VMEs) to be managed accordingly (Watling and Auster 2017). These characteristics imply that the impact of mining on relatively small areas could lead to the extinction of these biocenoses (Tilot 2013; Levin et al. 2016; Watling and Auster 2017). CRC mining may also cause benthic, mesopelagic (200–1000 m) and bathypelagic (1000–4000 m) fish mortality (Gollner et al. 2017), based on studies on the impact of deep-sea trawling on seamounts. The cumulative effects of natural impacts and other anthropic activities on the seabed and in the water column, such as fishing, are not well known but would be assessed as high. The spatial extent of direct mining impacts is estimated to be tens of km^2 for crust mining (He et al. 2011). The area impacted indirectly would be many times larger (Gillard et al. 2019; Aleynik et al. 2017).

- *Seafloor massive sulphide (SMS) deposits* originate from hydrothermal activity in active tectonic settings such as volcanic arcs, back-arcs and mid-ocean ridges (Dyment et al. 2014). The main metals are copper, iron and gold with small quantities of silver and zinc (Hannington et al. 2005, 2010, 2011). These polymetallic sulphides occur at depths of between 1000 and 4000 m in average. SMS deposits require a long-lived hydrothermal system (several million to several hundred million years) (Boschen et al. 2013). They are distributed in small, discontinuous areas (several 100 m^2) and strictly associated with emissions at hydrothermal vents emitting at high temperatures (350 °C) that vary in time and space. Within the Pacific Islands region, SMS deposits are most abundant in the EEZs of Papua New Guinea, Solomon Islands, Vanuatu, Fiji, Tonga and New Zealand but not in the Cook Islands EEZ (SPC 2013). The SMS chimio-synthetic microorganisms and bacteria (free or symbiotic) are the basis of the food chain. Associated faunal communities have narrow ecological niches within variations in physical parameters (T°C, pH, H_2S, CO_2 and O_2) at hydrothermal vents (Martin et al. 2008; Tyler et al. 2003).
- Globally, hydrothermal ecosystems are unstable (smokers, active sites and diffuse vents) with a life span of organisms relatively short and very fast growth and reproduction rates (approximately 6 months). Their biomass is very important and can reach several kg/m^2 (1000–10,000 times the biomass in proximate areas). Species richness is relatively poor as most species are strictly restricted to hydrothermal habitats with 95% endemism (Wolff 2005). Genetic flux is principally ensured by the propagation of large numbers of larvae, as most adults are characterized by small dispersal capacities. Complex bottom current patterns, local topography, such as discontinuity of transform faults along ocean ridges, and distances between sites are barriers to genetic flux and thus delineate biogeographical provinces (Van Dover et al. 2002).

  – Vulnerability of SMSs to DSM

    Van Dover (2010) estimates that mining would alter the distribution of vents but the mineral component of chimneys could reform quite rapidly in an active zone (a growth of 40 cm over 5 days has been recorded in the East pacific Rise (Hekinian et al. 1983)); however, it is unknown how long it would take for the recovery of the vent-associated ecosystem (Van Dover 2010). Despite the fact that these species are adapted to rapid extinctions and recolonizations, the exploitation of a total hydrothermal area would interrupt the genetic flux and hinder any recolonization. As well, a highly repetitive exploitation of the mineral resources would not leave enough time for the species to complete their life cycle (Boschen et al. 2013; Van Dover 2010, 2014). A hydrothermal vent operation could discharge 22,000–38,000 m^3 of material and sediment plume over the lifetime of one operation (Hoagland et al. 2010;

Okamoto et al. 2019). These discharges could run continuously for up to 30 years, producing 500,000,000 m^3 of discharge over the lifetime of one mine site. The spatial extent of direct mining impacts is estimated to be tens of km^2 for sulphide mining (Van Dover et al. 2018).

In summary, DSM would probably have a considerable negative biological impact on a long term and at a regional scale, on the deep-sea floor, overall the water column, the surface and the air over the ocean (Tilot 2006, 2010; Miller et al. 2018). The changes to the seabed and overlying water-column that would be brought by mining activities would inevitably impact all faunal communities present including those in pelagic ecosystems, in particular targeted species and activities as stressed in the previous section (ASOM 2011; Tilot 2011, 2016, 2019; JPI 2016; Niner et al. 2018; Tilot et al. 2018; Christiansen et al. 2019; Drazen et al. 2020). Mining-generated plumes may cause distress by their toxicity, reducing feeding, communication, causing buoyancy issues and by clogging respiratory and olfactory surfaces in particular for suspension feeders (Miller et al. 2018; Wilber and Clarke 2001). At a population level, it could induce changes in community composition, emigration, decreased fitness and reproduction and at a certain level of discharge, it could cause mortality or irreversible changes to the community structure with the complete removal of the substrate (Miller et al. 2018). The discharge of metals and toxins into the mesopelagic zone could contaminate seafood, impact fisheries, carbon transport and biodiversity in general (Blum et al. 2013; Miller et al. 2018). Sediment plumes will also absorb light and change backscatter properties, reducing visual communication and bioluminescent signalling that are essential for prey-capture and reproduction in midwater animals (Haddock et al. 2010). The temperature of seawater would increase when return water would be pumped back into the sea (Miller et al. 2018). Noise from mining activities could cause physiological stress or interfere with larval settlement (Lin et al. 2019), foraging and communication, such as by marine mammals (Gomez et al. 2016). Concerning water masses and ocean circulation, there would most probably be long lasting impacts of sediments plumes and noise leading to massive reductions in ecosystem services (Drazen et al. 2020; Rolinski et al. 2001) with multiple effects due to complexity, seasonal variations and global change. The low oxygen values of the thermohaline and intermediate waters would hinder the organic material decomposition, thus increase the sinking rates to the ocean floor.

On the seabed, due to limited nutrients sinking down from the surface, faunal communities are characterized as taxonomically highly diverse and distributed non-randomly over large areas. Recent research evidences rapid adaptation to variable trophic input and an opportunistic behaviour. Thus abyssal fauna is quite vulnerable to any change, presently it is affected by climate change with a reduction of primary production and carbon export to the deep sea (Levin et al. 2018). The characteristics of an extreme environment may become harsher to fauna to survive with alternative states of the environment after impact (Tilot 2016).

Furthermore, as technologies of extraction are not totally finalized, impacts cannot be correctly assessed on spatio-temporal scales. One must consider cumulative impacts, within the water column and the seabed, with both natural impacts (natural climate variation, El Niño events, earthquakes, tsunamis, underwater vulcanism and benthic storms) and anthropogenic disturbances (pollution, fishing, seabed mining, oil and gas extraction and disposal of wastes) generally resulting in degradation and homogenization of habitats across broad tridimensional areas (Glover and Smith 2003; Smith et al. 2008; Thiel 2003; Tilot 2010; Woodall et al. 2014; Levin et al. 2016; Gollner et al. 2017; Van Dover et al. 2017; Miller et al. 2018). One would have to test the response of abyssal fauna to deep-sea mining activities and identify thresholds of impact for survivors and reorganization of food chains (Tilot et al. 2018; Tilot 2019).

4 Traditional Knowledge, Visions and Interests Regarding Marine Resources and DSM in the Pacific Island Countries

Following the recognition by the UNCLOS of the special regimes of archipelagic waters (Part IV) and the EEZ (Part V), the Pacific transformed from islands in 'a far sea' to a 'sea of islands'. This last term is drawn from Epeli Hau'ofa, an islander who grew up in Papua New Guinea, Tonga and Fiji. Hau'ofa addressed the European framing of the islands as being about mentality as much as maps. The old map of tiny specks in a vast expanse of blue gives way to 'a sea of islands' with all big nations in a connected 'new Oceania' that the social networks call 'the ocean in us' (Hau'ofa 1992). The nexus of Islander's identity in terms of belonging and connection according to Hau'ofa (1994) reminisces the traditional perspective of the first seafarers (Carson 2018). These navigators would have conquered the Pacific in island-hopping voyages starting from Taiwan, a theory confirmed by extensive genomic analysis and the Austronesian language dispersal (Soares et al. 2016; Skoglund et al. 2016).

The Oceanian Peoples, the 'people of the sea' (D'Arcy 2006), are proficient navigators capable of reaching in giant outrigger canoes the different archipelagos, establishing colonies or maintaining trade with distant lands, relying on their intimate knowledge of marine species and processes (amongst other natural elements) to guide their voyages (Gooley 2016; Kuhn 2008; Lewis 1972). Numerous Pacific Island Countries still practice the traditional art of navigating, using only one's senses and knowledge passed by oral tradition from master to apprentice, by memorizing the motion of specific stars, reading the shape of clouds, the colours of the sea, recording wildlife species, the shape of waves, currents and water temperature, in summary, using a 'sensory ecology of ocean navigation' (Lohmann et al. 2008). This would resemble the sensory navigation used by migrating species in open seas such as sea turtles, sharks and cetaceans (Lohmann et al. 2008). It is also a way to

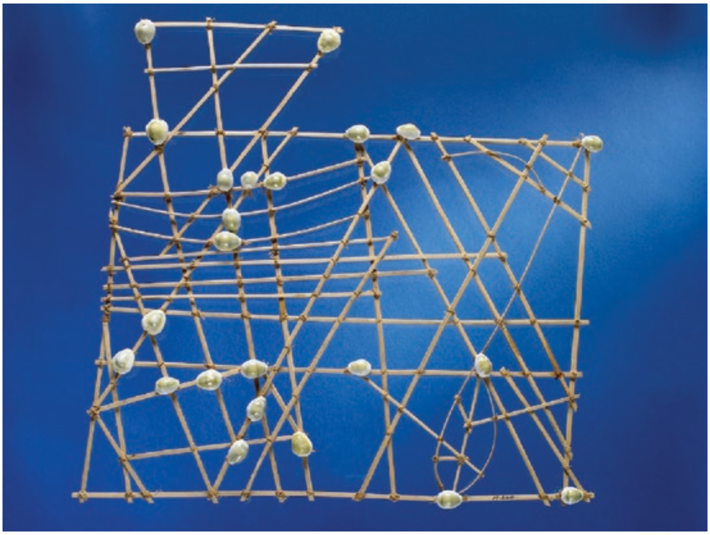

Fig. 22.3 Ancient Polynesian stick chart using a sensory ecology of ocean navigation. The shells indicate islands or island groups. The sticks show ocean swells and their direction (with swell refraction patterns around an island). (Photo E398227, Department of Anthropology, Smithsonian Institution, Photo by Donald E. Hurlbert)

show the deep connection to Nature of the Oceanian Peoples. These navigation routes were represented by ancient Polynesian stick charts and by star compasses displayed by shells on sand (Figs. 22.3 and 22.4). These ancient navigation means appeared to be far more sophisticated in the Marshall Islands than present navigation with sextant, compass and maps (Romm 2015).

Polynesians are said to have one of the richest, most diverse and complex collections of mythological tales and legends. There is also a spiritual connection, such as for the aboriginals of Australia on land and the Torres Straits Islander peoples, who have navigated their way across the lands and seas using paths called songlines or dreaming tracks. A songline is based around the creator beings and their formation of the lands and waters during the ‘Dreaming’ (creation of earth) (James 2016; Norris and Harney 2014).

In Oceania, there is an ancestor veneration which has for role to cultivate kinship and continuity of family lineage. Depending on their lives, accomplishments, lineages and importance, deceased humans can become guardian spirits or family gods (aumakua in Hawaiian) for their clans. Many creatures can be guardian spirits (Fig. 22.5), some are emblematic for certain island nations such as octopuses (*Na kika* in the Gilbert islands), turtles (*Tabakea* in Samoa), eels (*Riki* in Samoa), sharks (*Dakuwaqa* in Fidji) and whales (*Tangaroa* for Maori) (Grimble 2019; Loebel-Fried 2002).

The core expression of today’s regionalism, the ‘Blue Pacific’, is built on Epeli’s ‘new Oceania’ and the social networks he called ‘the ocean in us’, drawing on other

Fig. 22.4 Star compass of Mau Piailug, a famous Micronesian navigator, taught in the Caroline Islands, with North at top. The ‘compass’ that Mau Piailug carried was not magnetic but a mental model of where islands are located and the star points that one could use to navigate between them. This mental model would have taken years of study to build; dances, chants (rong) and stories help the navigator to recall complex relationships of geography and location. The stars give him highly reliable position information when visible, but navigators such as Mau Piailug managed to keep their position and tracks in mind even when blocked by clouds, using other references such as wind and swell as proxies (Thompson 2007). The photo represents a re-creation with shells on sand, with Satawalese (Trukic) text labels. (Star Compasses from the Polynesian Voyaging Society)

indigenous thinkers (Wendt 1976; Waddell 2000). Shortly after the independence of most of Pacific Island States, the Fijian Prime Minister Ratu Mara (1920–2004) advocated the concept of ‘Pacific Way’, a cultural norm elevated to the political level during UNCLOS III negotiations (1973–1982) (Wallace et al. 1998). It promotes shared local values, including the respect for the *Vanua* encompassing the sea and relies on a ‘unanimous’ mode of decision making that stems from facilitative dialogue amongst the members of the community (Haas 1992; Mara 1997; see also the Talanoa dialogue within the framework of the 1992 United Nations Framework Convention on Climate Change). For generations, this ‘oceanian way of being’ has helped islanders transmit their identity and unique relationship to each other and to their environment, taking a variety of forms, not always directly tied to nature (Bambridge 2016). Myths, oral traditions and cosmologies of the Samoan, Cook islander, Niuean, Tokelau, Kiribati, Fijian, Tongan, Maori (from Aotearoa, New Zealand), native Hawaiian, Kanak, M¯a’ohi (in French Polynesia), Ni-Vanuatu, Solomons and Papuan peoples show that they conceived their world in holistic terms, dissolving classic western distinctions between human and non-human, nature and culture, as objects (Figs. 22.5 and 22.6).

Fig. 22.5 An etching called 'Dokeran' produced in 2008 by Dennis Nona, a fisherman and a professional artist of Torres Strait. Dokeran is the story of a fisherman that has been transformed into a rock by a spirit that was in a turtle that he captured. This rock is now a sacred site on Badu Island. (Courtesy Dennis Nona/www.artsdaustralie.com)

The Oceanian understandings of the world or 'tidal thoughts' in most Pacific Islands emphasize relations regarding the land and surrounding waters as a continuum, a whole, including animals and peoples (Bambridge 2016; Bambridge et al. 2021). The peoples of Oceania came to develop an understanding of the fragility of marine environments (Fache et al. 2016; Mawyer and Jacka 2018; Bambridge et al. 2021). A sustainable practice in traditional Oceanic terms requires sufficient knowledge of the resource to understand how its exploitation will affect surrounding life cycles. In Papua New Guinea for example, it corresponds to a relational ontology that defines 'beings', 'spirits' and 'nature' as co-shapers of the *graun* (the world or the cosmos) and not of separate realms (Childs 2019).

Fig. 22.6 An etching (216 × 513 cm) called 'Mutuk' produced in 2008 by Dennis Nona, a fisherman and a professional artist of Torres Strait. Mutuk is a traditional legend unique to the artist's island of Badu. It depicts the continuum between visible and invisible word, the close connection between living humans and deceased, marine animals and the spirits of the sea. (Australian National Maritime Museum (ANMM))

5 The Traditional Perspective of Marine Resource Management in the Pacific Island States

In many of the Pacific Islands, local communities have traditional, cultural and spiritual attachments to the sea, in particular to species and specific marine areas, processes, habitats, reefs, islands and natural formations. Centuries of acquaintance with the interconnectivity of terrestrial and marine ecosystems underlay traditional indigenous knowledge and constitute keystones to holistic forms of marine resource management. These adaptive management techniques, practices and forms generally preserve or protect areas in an equitable manner and vastly precede their earliest formulations in Western models for marine conservation. Also traditional knowledge and customary management are not static but adapt according to ecological, societal and economic changes (Johannes 1998; Govan et al. 2008; Veitayaki et al. 2011; Bambridge 2016).

The most important marine conservation measure in Oceania was local marine tenure, where the right to fish in a location was controlled by a clan, chief or family (Johannes 1978; Ruddle et al. 1992). Spatial closures within these tenure systems were employed throughout Oceania for various purposes, and these closures were often imposed to ensure large catches for special events or as a cache for when resources in the commonly accessed fishing grounds ran low (Johannes 1978; Cinner et al. 2006). Temporal closures were widely used to reduce intensive harvest of spawning fishes or other predictable aggregations (e.g. migration routes) (Johannes 1978, 1981). These customary practices include seasonal bans on harvesting, temporary closed (no-take) areas and restrictions being placed on certain times, places, species or classes of persons. Closed areas include the 'tabu' areas of Fiji, Vanuatu and Kiribati, the 'ra'ui' in the Cook Islands, the 'kapu' in Hawaii, the 'tambu' in PNG, the 'bul' in Palau, the 'mo' in the Marshall Islands, the 'tapu' in Tonga and the 'rahui' in New Zealand (Mori). The 'tabu' or 'tapu' would design a permanent prohibition associated with an intrinsic sacralization and the 'rāhui' or 'ra'ui' concept would be a temporary ban on resources (or resource areas) expressing a political power rather than a control on these resources in an ecological perspective, e.g., from having free access either to food resources or to land and water (Bambridge et al. 2019).

In order to ensure the ongoing well-being of the people and their environment, these unwritten rules are often used to revive or build up stocks, in anticipation of upcoming celebrations or food shortages (Vieux et al. 2004). These concepts cover a complex system of communautary rules and prohibitions in many Pacific Island traditions and uses such as in Fiji, Samoa, Kiribati, Rapanui, Tahiti, Hawaii, Vanuatu and Tonga. Supernatural sanctions could rise if contravening to these traditional institutions (Grey 2019; Juster 2016; Mead 2003; Love 2021). Some traditional management systems are highly consistent with the ecosystem approach, presently recommended in science-based area management, such as the Hawaiian 'ahupua'a' where extended elements of Hawaiian spirituality are integrated into the natural landscape. This same approach is observed as well with the Yap 'tabinau', the Fijian 'vanua', the Marovo 'puava' of the Solomon Islands and the 'tapere' in the Cook Islands (Ruddle and Hickey 2008).

The cultural and spiritual values associated with the natural environment and an important and respectful interaction with Nature has led to a Universal Declaration on the Rights of Nature, with a shared vision for collective action on global challenges. Community territory and property rights have extended to the sea in a habit of sustainable management of marine resources over generations (Pratt and Govan 2010). Maritime cultures often traverse territorial boundaries to form fluid and mobile networks with little adherence to demarcations drawn by administrators or conservationists (Acton et al. 2019).

Thus from Oceanian IPLCs perspective, DSM is not distanced from the island environment because the ocean is at the heart of one's identity, and part of each individual's future (Hau'ofa, 1994, 2008; Mawyer and Jacka 2018). For example, *Lavongai* communities from New Hanover Island in Papua New Guinea, living several kilometres away from the Solwara 1 marine mineral deposit where *Nautilus Minerals Inc.* invested in a commercial seafloor massive sulphide mining, expressed their concern, when consulted on their perspective of future DSM activities that they would not be able to join their ancestors after death anymore, as the place where spirits are supposed to pass over was located within the targeted area (Navarre and Lammens 2017; Nautilus Minerals, 2018). These communities also claimed that DSM could alter the development of shark populations and thereby affecting a traditional fishing practice, known as 'shark calling', an indigenous rite of passage from Papua New Guinea in which young men lure sharks from the deep using magic to catch and kill them barehanded (Messner 1990). For example, Lavongai communities from New Hanover Island in Papua New Guinea, living several kilometers away from the Solwara 1 marine mineral deposit where Nautilus Minerals Inc. invested in a commercial seafloor massive sulfide mining, expressed their concern, when consulted on their perspective of future DSM activities, that they would not be able to join their ancestors after death anymore, as the place where spirits are supposed to pass over was located within the targeted area (Navarre and Lammens, 2017; Nautilus Minerals, 2018).

During the 1990s, in the context of an international funded project for assessing economic impact of natural resource conservation in the Pacific Island coastal waters, sites were identified with activities involving local communities for their management practices with objectives of sustainable use of marine resources with Marine Managed Areas (MMAs) (Jeudy de Grissac 2003; Govan et al. 2009). In 2000, a network of 743 MMAs has been recorded amongst which 565 Locally Managed Marine Areas (LMMAs) (Jupiter et al. 2014). In this perspective, the denominated Polynesia Mana Node (Cook Islands, French Polynesia, Kiribati, Niue, Tokelau, Tonga and Wallis and Futuna) includes a network of marine protected areas (MPAs) in the coral reef areas where local populations participate, reviving their culture and traditions as a basis for sustainable reef management (Tilot et al. 2021a). Today the network of LMMAs includes community members, land owning groups, traditional leaders, elected decision makers, conservation staff, university scientists and researchers and donors who promote a diverse range of objectives, including biodiversity conservation, fisheries management, livelihood diversification and climate change adaptation (Govan et al. 2008, 2009; Jeudy de Grissac 2016; Weeks and Jupiter 2013).

Furthermore, the first Large-Scale no-take MPAs (LSMPAs) and shark sanctuaries in the Pacific region have been initiated in the mid-2000s (Toonen et al. 2013; Wilhelm et al. 2014). These LSMPAs offer benefits that are not obtainable at smaller scales, primarily the ability to protect whole ecosystems and interdependent habitats so that biologically connected ecosystems can be included within the same management area (Toonen et al. 2013). Large no-take LSMPAs have been established in several areas (e.g. Hawai'i and US Pacific, Palau, Pitcairn, Kiribati), while a few jurisdictions have declared or promised to create their entire EEZs as multi-use LSMPAs (O'Leary et al. 2018). These actions have for objective to comply with their international commitments with regard to protecting marine ecosystems, to seek international recognition through environmental issues or to increase control over their EEZ with regard to illegal fishing pressure (Leenhardt et al. 2013; Giron 2016). The LSMPAs created after 2006 are mainly positioned on areas with high geostrategic stakes, notably in relation to the Asia-Pacific maritime pivot on tuna fisheries (Giron 2016) or the presently denominated political Indo-Pacific pivot (Heiduk and Wacker 2020).

The 'Papahānaumokuākea Marine National Monument' (/whc.unesco.org/en/list/1326/) is a LSMPA in Hawaiian waters that protects sacred cultural sites on the islands of Nihoa and Mokumanamana, the latter having spiritual significance in Hawaiian cosmology (Kikiloi 2010). Many Pacific Island countries have protected whales, often considered sacred, within their waters by creating whale sanctuaries which cover now more than 30 million km^2 of the South Pacific Ocean, encompassing the EEZs of 11 South Pacific countries, including Important Marine Mammal Areas (IMMA) (Fig. 22.7). This largest whale sanctuary in the world represents a global blueprint for whale conservation and the management of shared resources.[2] Pacific Island Countries have demonstrated their commitment to whale conservation

[2] Available online at: https://www.wwfpacific.org/what_we_do/species/whales (accessed 30 April 2021).

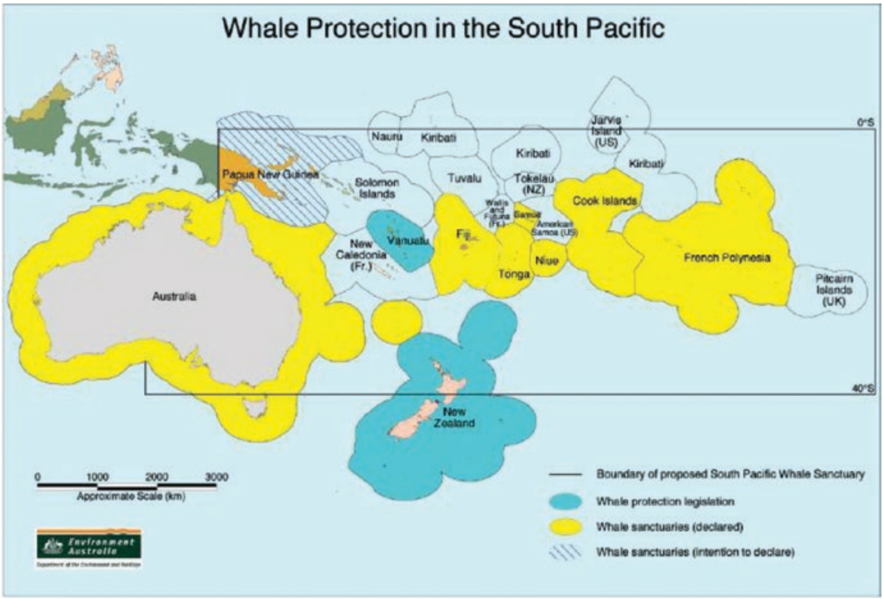

Fig. 22.7 Map of whale protection in the South Pacific including areas under whale protection legislation, declared whale sanctuaries and those that are in the process to be declared. (Source: Environment Australia)

by joining a variety of international agreements promoting the conservation of whales, including the Memorandum of Understanding for the Conservation of Cetaceans and their Habitats in the Pacific Islands.[3] Whale watching, an industry in the Pacific, is growing much faster than whale numbers that are recovering and is proving to be by far the most lucrative use of whales (Hoyt 1995), with the added attraction of doing them no harm, provided that the operations are well managed (Surma and Pitcher 2015). As well, numerous shark sanctuaries are located in the Pacific Region, in New Caledonia, Tokelau, Samoa, Cook Islands, French Polynesia, Palau, Micronesia, Marshall Islands, Kiribati (Atlas of Marine Protection (mpatlas.org), Marine Conservation Institute). The first regional shark sanctuary in the world is in Micronesia (https://www.pewtrusts.org).

All these traditional management practices and tools could presently be considered as Other Effective area-based Conservation Measures (OECMs) as designated in the Aichi biodiversity target 11, concerning terrestrial and marine conservation, adopted in 2010 as part of the Strategic Plan for Biodiversity 2011–2020 by the Parties to the Convention on Biological Diversity (CBD) (Jeudy de Grissac 2016). They are not an alternative but complementary to MPAs, in particular in countries

[3] Memorandum of Understanding for the Conservation of Cetaceans and their Habitats in the Pacific Islands$_{x}$ adopted in 2006 (https://www.cms.int/sites/default/files/document/Inf_03_PacificCetaceans_MoU%26AP_0.pdf, accessed April 20, 2021) (accessed 30 April 2021).

where the central administration is far from local preoccupations, the national legislation is incomplete and where there is a lack of implementation on marine conservation aspects.

In the recent years, the Pacific Island States have collectively established some of the world's most sophisticated and highly collaborative conservation and management tools. Through the establishment of cooperative capacity building institutions, these island states, characterized by minimal institutional capacity and large maritime domains, provide an important example of the benefits of regional and subregional cooperative approaches (Jeudy de Grissac, pers. comm.). Clearly, traditional knowledge and community-based marine managed areas have a central role to play in complementing science-based tools in the protection of the cultural and biological biodiversity and reaching national, regional and international targets related to conservation and the sustainable use of the biodiversity (Tuqiri 2001; SPC 2005; Jeudy de Grissac 2016; Friedlander and Gaymer 2020). In particular, the traditional knowledge role is explicitly recognized in the CBD work programme of island biodiversity,[4] in the development of the Nagoya protocol on Access to Genetic resources and the Fair and Equitable Benefit-Sharing, in the designation of Ecologically or Biologically Significant Marine Areas (EBSAs) and in the development of an international legally binding instrument under the UNCLOS on the conservation and sustainable use of marine Biological diversity of areas Beyond National Jurisdiction (BBNJ) (Mulalap et al. 2020). As well, it is included in the Intergovernmental science-policy Platform on Biodiversity and Ecosystem Services (IPBES) assessments to strengthen the science–policy interface for biodiversity, long-term human well-being and sustainable development, in fisheries management (FAO 2017) and in climate change action (Paris Agreement) (DOSI 2021). Incorporating knowledge systems, biocultural approaches enable adaptive management and resilience in the face of environmental, social and economic change (Sterling et al. 2017) and increase the chances of long-term success of conservation interventions (Gavin et al. 2015; Jeudy de Grissac 2015, 2016; DOSI 2021).

6 Integration of Traditional Dimensions into Regulatory Frameworks on Seabed Mining in the Pacific

The wide array of activities which we refer to as DSM is not governed by one universal framework but rather by an extensive set of legal instruments. The United Nations Convention on the Law of the Sea (UNCLOS 1982)[5] sets out the overarching regime, but important distinctions must be made depending on the marine space (within and beyond the limits of national jurisdiction), the activities conducted

[4] [4]Available online at: https://www.cbd.int/island/ (accessed 16 June 2021).

[5] UNCLOS was signed on 10 December 1982 by 119 States and entered into force on 16 November 1994. It has 168 State parties as of May 2021: United Nations Treaty Series vol. 1833, p. 3.

(prospecting, exploration and exploitation) and the type of resources. As mentioned earlier, the seabed and subsoil beyond national jurisdiction are referred to as 'the Area' and are governed by a comprehensive international regime: the fundamental principles are contained in UNCLOS and the 1994 Implementation Agreement, while the more detailed rules are elaborated in the 'Mining Code', comprising the relevant regulations, standards, guidelines and procedures adopted by the ISA.[6] The ISA has currently issued regulations for the first phases of mining activities (prospecting and exploration), divided into separate sets for three distinct categories of resources, viz., polymetallic nodules, polymetallic sulphides and cobalt-rich ferromanganese crusts (ISA 2010, 2012, 2013) but has yet to adopt exploitation regulations (ISA 2019a). Moreover, taking into account that non-state actors conducting deep-sea mining operations in the Area must be sponsored by a state, national legislation, defining the conditions to obtain and maintain a certificate of sponsorship from the sponsoring state, would also play an important role (Willaert 2020a).

When taking place on the continental shelf, which comprises the seabed and subsoil beyond the territorial sea up to a distance of 200 nautical miles from the baselines (and may be extended to the outer edge of the continental margin when this exceeds the stipulated 200 nautical miles) (UNCLOS, Art. 76), deep-sea mining activities would fall under national jurisdiction and will be governed by the domestic law of the coastal state, which possesses exclusive sovereign rights over the natural resources that are located there.[7]

Zooming in on the integration of traditional dimensions in this extensive collection of regulatory frameworks, a number of encouraging examples can be identified. For instance, the 2017 Marae Moana Act of the Cook Islands created a multiple-use marine park 'Marae Moana' (which can be translated as 'ocean sanctuary'), encompassing their entire territorial sea and EEZ of almost 2 million km^2, that serves to protect and conserve the ecology, biodiversity and heritage values of the Cook Islands marine environment (IUCN 2018; Willaert 2021). Amongst others, it reinvigorates the local practice of 'ra'ui' by designating marine protected areas around each of the 15 islands, reserved for the local communities and closed to seabed mineral activities. The 2019 Seabed Minerals Act also takes the visions and interests of the Cook Islanders into account by prescribing that seabed mineral activities in the Area may not result in irreparable harm to any community, environment or cultural practice in the Cook Islands (McCormack 2016).

Furthermore, the Federated States of Micronesia (FSM) Seabed Resources Act recognizes the duty to 'employ best environmental practices in accordance with prevailing international standards in order to avoid, remedy or mitigate the adverse effects of DSM on the Environment',[8] as well as to secure Free Prior Informed Consent (FPIC) (including through compensation) 'if marine or coastal users likely to be directly adversely affected by DSM Activities' are identified by the relevant

[6] For more information, see https://www.isa.org.jm/mining-code

[7] See infra, section 5.

[8] FSM Seabed Resources Act of 2014, §403(a).

governing entity at any time, including through the environmental impact assessment process.[9] Tellingly, these provisions do not specify Indigenous Peoples or similarly situated local communities, although an argument could be made that such Peoples and communities are included as 'marine or coastal users'. Especially, if the reference to 'prevailing international standards' in connection to best environmental practices is interpreted to include FPIC and similar rights afforded to Indigenous Peoples by international law. Such users arguably include native inhabitants of the FSM who engage in instrument-free traditional navigation on the open Ocean, perpetuating a centuries-old practice in the FSM and other Pacific Island Countries that rely on a keen understanding of marine life and processes (Feinberg 1995; Gladwin 1970; Gooley 2016; Finney 1998; Lewis 1972; New York Times Magazine 2016).

On the regional level, several initiatives have also been taken. For example, the 1986 Noumea Convention for the Protection of Natural Resources and the Environment of the South Pacific Region (in force on November 24, 1990) contain an indirect reference to the cultural value of areas and the exercise of traditional customary rights in its Protocol concerning Cooperation in Combating Pollution Emergencies in the South Pacific Region. Also the Pacific-ACP States Regional Legislative and Regulatory Framework (RLRF) for Deep Sea Minerals Exploration and Exploitation, which was supported by EU funding, serves as a roadmap to guide policy makers and government agencies of Pacific Island States towards effective legislation, taking into account the long-term interests and visions of the island communities and future generations through several provisions (Tilot et al. 2021a). It clearly acknowledges the fact that Pacific Island communities rely for their livelihoods upon the sustainable use of the ocean and its resources by stating that new activities should not unduly interfere with the various existing uses (including uses relating to highly migratory marine species and marine ecosystems adjacent to areas beyond national jurisdiction), therefore promoting integrated legislative or management regimes that take into account all sea uses and their mutual impact. Fishing of—and other activities relating to—highly migratory species (such as tuna, swordfish, marlin, sailfish, spearfish, sharks, turtles and whales) and other customary rights linked to the ocean (including cultural, social, political and spiritual rights) should be respected or adequately compensated. Significant importance is also attached to transparency and public participation, in order to enhance public knowledge and to ensure that all relevant information and visions are taken into account (Kakee 2020). Although the areas, which will be directly affected by seabed mining activities, are to be largely outside customary fishing zones, it is deemed important for all Pacific Island States to identify all customary marine tenure in their EEZ and avoid any conflicts, for example by concluding agreements with traditional leaders or local councils.

In addition, the Pacific region—through its regional organizations and in collaboration with WIPO, UNESCO and other partners—has developed a regional framework for the protection of traditional knowledge and expressions of culture,

[9] Ibid., Seabed Resources Act of 2014, §403(d).

guiding the Pacific Island States towards the development of appropriate national legislation on this vital topic in close consultation with indigenous peoples and local communities. Of specific relevance to seabed resource management, 'traditional biological knowledge' is defined as 'knowledge whether embodied in tangible form or not, belonging to a social group and gained from having lived in close contact with nature, regarding: (a) living things, their spiritual significance, their constituent parts, their life cycles, behaviour and functions, and their effects on and interactions with other living things, including humans, and with their physical environment; (b) the physical environment; (c) the obtaining and utilizing of living or non-living things for the purpose of maintaining, facilitating or improving human life'. To the extent that DSM impacts such living things, their physical environments and/or the ways in which holders of traditional knowledge utilize them for maintaining, facilitating or improving human life (e.g. traditional knowledge and practices pertaining to highly migratory marine species of cultural significance, as well as to open ocean traditional navigation routes), the regional framework should play a key role in addressing such impacts (Tilot et al. 2021a).

Despite these encouraging examples of traditional knowledge, practices and interests of Pacific Island communities being considered by regulatory frameworks on marine resource management and seabed mining, it has to be noted, however, that these do not weigh up against the numerous instances in relevant legal instruments where no reference is made to these elements (e.g. see Tilot et al. 2021a, especially the detailed analysis, displayed in Table 2). Thus, if adequate integration or at least consideration of traditional and indigenous dimensions and visions would be prioritized, there is still a long road ahead. For example, the international legal framework governing seabed mining activities in the Area, which—despite its remote location—is part of the sacred ocean and may affect numerous marine species of cultural significance that migrate between coastal areas and high seas, and contains very few provisions related to traditional knowledge and interests. Although the overarching status of the deep seabed and its mineral resources as the Common Heritage of Mankind (CHM) (article 136) reflect the idea of collective ownership and preservation for future generations, the associated measures and mechanisms have yet to be adequately implemented by the ISA (Willaert 2020b) and no explicit references to traditional dimensions have been integrated in the Mining Code (Jaeckel et al. 2017; Bourrel et al. 2018). Moreover, overall improvements to the international regime for the deep seabed in terms of transparency and public participation—which might serve as powerful catalysts to promote the integration and consideration of traditional knowledge in the relevant legal frameworks and decision making—are certainly desirable (Willaert 2020c).

Nevertheless, cautious steps toward increased integration of these aspects within the international seabed regime have been taken. Indeed, the current ISA Draft Exploitation Regulations attempts to implement article 149 UNCLOS by including rules regarding the preservation of human remains or objects and sites of an archaeological or historical nature that are found in the course of deep-sea mining activities, which might serve as a recognition of the cultural values and traditional dimensions attached thereto (ISA 2019a). Moreover, a proposal regarding a template with required minimum content for Regional Environmental Management Plans (REMPs) listed traditional knowledge of IPLCs as one of the guiding principles for the development of REMPs (ISA 2020a). Attention is paid to cultural heritage and interests by taking into account the connectivity of migratory species which are of cultural significance to indigenous peoples, traditional marine management areas and measures, as well as routes and marine features used by local communities for traditional instrument-free navigation. The ISA Council decided that the Legal and Technical Commission should take this proposal into account when further developing the guidance on the development of REMPs and a relevant template (ISA 2020b).

Suggestions were also made to promote participation of and particular regard to 'vulnerable communities' within the context of the Environmental Compensation Fund. These suggested amendments to the Draft Exploitation Regulations were welcomed during the first part of the 26th session of the ISA Council meetings (ISA 2020c, d), and one of the delegates suggested to refer specifically to indigenous people and local communities who reside in adjacent coastal states and are likely to be impacted (ISA 2019b).

7 Conclusion

In the Pacific Island States, 'community-based' and 'participatory' approaches, through the integration of 'traditional' knowledge and marine tenure, have become very popular means to reconcile the issues of marine conservation, fisheries management and the development of coastal communities (Ruddle and Johannes 1989; Akimichi 1995; Pomeroy 1995; Veitayaki 2004). The traditional holistic approach of marine resources management and sustainable use has been developed for a long time by local communities of islands of the Pacific and Southeast Asia. Where the interconnected nature of island ecosystems requires a holistic, integrated management approach, customary practices with their nature–people relations continuum perspective (Bambridge 2016) have been effective in meeting community and ecosystem goals by preventing communities from exceeding their local carrying capacity.

In many countries of the world, these traditional practices have slowly disappeared, facing both development pressures and the disintegration of cultural and social ties at the local level. The absence of a formal inclusion of these traditional practices in regulatory texts has led to their disappearance as well as the disappearance of the knowledge of the natural environment that supported them (Jeudy de Grissac 2015). That is why, the Pacific region is unique in view of the perpetration of its holistic approach and traditional management practices of marine areas and resources where nature, communities and open ocean are interconnected or even unified, in an ontological perspective. The Pacific Island States can pave the way to react to present global issues in marine conservation and ocean governance by completing, if not inspiring, science-based strategies and methodologies in the matter (Giron 2016; Tilot et al. 2021a).

The integration of traditional dimensions in this extensive collection of regulatory frameworks concerning DSM has been achieved at different degrees. Pacific Island States generally recognize the precautionary principle/approach as well as the applicability of prevailing standards of international law, particularly with regard to averting, minimizing or remedying harm to the marine environment. Several Pacific Island States explicitly recognize Indigenous rights or other relevant human rights, Free Prior Informed Consent (FPIC), including in connection with consultations with potentially affected 'marine or coastal users'. But few of those Pacific Island States also explicitly reference Indigenous Peoples and attendant Indigenous Rights (with the exception of FPIC), which introduces a vagueness in the legislation that could be exploited to minimize or dismiss the full application of FPIC and similar rights and considerations to IPLCs in those States (Hunter et al. 2018; Aguon and Hunter 2019; Mamo 2020).

The Pacific Island States could benefit from combining their resources and expertise on traditional knowledge on ocean matters to include in a regional integrated strategy, such as in the Pacific Islands Regional Ocean Policy and Framework for Integrated Strategic Action (Tuqiri 2001; SPC 2005), for addressing the challenges of DSM, as fostered by Lily (2016), which would include innovations, cooperative planning and the involvement of all stakeholders which would encourage partnerships and collaboration locally and internationally. DSM mitigation responses and adaptations in the Pacific Islands have to be appropriate for each of these nations. Simulations and various scenarios can be applied to explore anticipated impacts (Bradley and Swaddling 2018).

It will likely require some legal creativity to shoehorn considerations of traditional dimensions of seabed resource management in all these Pacific Island States solely based on their relevant national DSM legislation and policies, but the 'hooks' are there, if interested stakeholders wish to utilize them. The integration of traditional knowledge generated by local communities into multi-actor and multi-scale decision-making processes and governance systems still depends on variable and complex socio-ecological systems. Those systems and circumstances influence and shape the development and implementation of norms, knowledge, innovations, practices and capacities highly relevant for managing interconnectivity and extensive human activities and ecosystems, such as deep seabed mining and ecosystems and must therefore also be addressed in that regard.

A balance between all competing interests must be struck, and the environmental, social and cultural costs should not outweigh the potential benefits and the HWSL of the island communities. Admittedly, the potential conflicts arising out of seabed mining activities are numerous and significant, but there also seem to be ample opportunities for symbiosis, given the traditional approaches concerning marine resource management of the Pacific island communities. Therefore, if the interests and visions of the Pacific islanders are duly taken into account, this might lead to a balanced regime that reconciles the concerns and needs of all stakeholders.

The traditional knowledge is based on the Oceanian understanding or 'tidal thoughts' of the world in most Pacific Island States regarding the land and the oceans as a continuum, a whole including animals and peoples (Bambridge et al. 2021). This concept is well in phase with the present science-based integrated approach of socio-ecological interconnectivity to marine environment management and governance and, therefore would be an added value to the present unifying vision of the Systems View of Life (Capra and Luisi 2014).

Indeed, the holistic, integrated and trans-disciplinary approach is proven to better address global challenges such as global climate change, energy security, ecological degradation, environmental threats to human health and resource scarcity in a sustainable perspective, assessing the marine environment according to its environmental, economic and social values. The unifying vision was promoted in the mid-1980s by many international scientific organizations, in 1987 by the Brundtland Commission's report 'Our Common Future', in the 'Agenda 21' plan that emerged from the United Nations Conference on Environment and Development in 1992 and further developed at the World Summit on Sustainable Development held in Johannesburg in 2002. This new approach of sustainability science has for objective to understand the integrated 'whole' of planetary and human systems by means of cooperation between scientific, social and economic disciplines, public and private sectors, academia and government to improve linkages between relevant research and innovation communities and relevant policy and management communities and foster shared prosperity and reduced poverty while protecting the environment.

If responsibility, openness and interconnection are indeed to be the watchwords of progress in the twenty-first century (Kacenelenbogen 2010, 2017), then these concepts should be paramount in guiding the design of a pertinent – that is, inclusive and based on a recognition of the politics of mining as 'embedded in a world of things, bodies, networks and socio-economic relations' (Bakker and Bridge 2006)—regulatory framework establishing standards and guidelines for deep-sea mining. An essential first step in that direction would be to consider the vast oceanic space as not only bursting with precious (and, for the most part, unknown) life but also as a highly social and political locus, a 'voluminous' (Bridge 2013; Elden 2013) or 'ontological' space, that is, a political—even *moral*—actor in its own right (Steinberg and Peters 2015; Lehman 2013).

8 Recommended Actions

We have integrated here some of the recommendations on the topic from a recent publication (Tilot et al. 2021a) and from a policy brief on the topic that we coauthored (DOSI 2021):

- *For consideration of the UN system and international agreements:*
  - To align the sectoral mandates and activities in ABNJ (e.g. between the ISA and the IMO (shipping), FAO and RFMOs (fisheries), ICPC (submarine

cables) and the ongoing negotiating process for the conservation and sustainable use of marine Biodiversity of areas Beyond National Jurisdiction (BBNJ)) (DOSI 2021).

- *For consideration of the ISA:*
  - To mainstream the conservation and sustainable use of marine biodiversity and marine resources in deep seabed mining define deep seabed mining activities.
  - To precise all deep seabed mining impacts (sea-bottom, water column, surface and air above, small distance and long distance, duration of impacts, primary and secondary impacts and cumulative impacts).
  - To foster an adaptive context-based socio-ecological governance that relies on the active participation (with their Free, Prior and Informed Consent (FPIC), in accordance with the United Nations Declaration on the Rights of Indigenous Peoples) of local and traditional communities in decision making as well as in the implementation of DSM projects because traditional knowledge and practices about resource management in the Pacific fundamentally rely on reciprocal relationships.
  - To recognize the cultural and social values attached to traditional knowledge and traditional practices relative to deep-sea ecosystems through national legislations and ISA regulations.
  - To encourage ISA Member States to undertake a strategic level of engagement with 'the public' on matters that are beyond the scope of individual Environmental Impact Assessments (EIAs) for each exploitation and Strategic Environmental Assessments (SEAs) for multiple exploitations in the same basin, region or ocean (DOSI 2021).
  - To develop a mechanism for compensation in case of damage/impacts to the quality of environment and future region (environmental fund) considering all the potential impacts of DSM, on the seabed, in the water column and at the surface, and the spread of these impacts far from the exploitation area and inside waters under national jurisdiction, in addition to the creation of a fund for receiving and distributing the benefits of DSM exploitation, part of the fund could be allocated to riparian states for compensation of environmental damage and destruction.

- *For integration/dissemination of traditional knowledge, traditional knowledge holders, IPLCs at the local and national levels.*
  - To collect traditional knowledge on marine ecosystems and resource management practices, to produce and circulate the information at all levels of stakeholders.
  - To collect the perspectives that traditional knowledge holders have of DSM and of the DSM areas when agreed upon by local and traditional communities. Wider consultation is needed to fully understand the significance of deep seabed mining areas to traditional knowledge holders and communities with different cultural and historical values. A broader diversity of deep-sea perspectives including multi-cultural and spiritual significance warrant consideration in collective decision making (Worm et al. 2021).

- To integrate traditional knowledge related to environment into risk assessment measures through a precautionary approach (DOSI 2021).
- To integrate traditional knowledge into marine spatial planning and governance processes in DSM projects (DOSI 2021).
- To collect traditional knowledge at the local and national level and identify relations with traditional management and sustainable use of natural resources. Public awareness of traditional knowledge can be raised through: an online portal for and by Indigenous Peoples (Mamo 2020), One Ocean Hub Code of Practice, The International Indigenous Youth Council, Elder councils, showcasing traditional knowledge in the most appropriate medium (DOSI 2021). An important first step would be to have traditional knowledge data repositories that are consistent with the IOC Oceanographic Data Exchange Policy or the relevant UN subordinate body data policy. Such repositories must be formed with the FPIC of the relevant traditional knowledge holders through a culturally appropriate and rights-sensitive manner in accordance with the United Nations Declaration on the Rights of Indigenous Peoples (DOSI 2021).
- To evaluate importance of natural resources, in particular mineral seabed resources and the Human Well-being and Sustainable Livelihoods (HWSL) of local communities (social and economic values).
- To develop the recognition of traditional knowledge and traditional practices at the national level, as a precautionary approach, and consider to transfer the informal practices of the local communities in formal legislation and/or regulations.

• *For consideration of scientists and experts*:

- To collect scientific knowledge related to marine ecosystems and seabed resource functioning in an ecosystem-based approach integrating the socio-ecological aspects of marine uses in order to better appreciate the holistic approach of traditional knowledge related to marine ecosystems and seabed resource management for Island States of the Pacific Region.
- To analyse and monitor the variability of socio-ecological factors intervening in the functioning of marine ecosystems in order to adapt progressively the seabed resource management.
- To investigate on hybrid forms (traditional knowledge practices with science-based management/conservation practices) of marine resource management applicable to DSM and, in this context, their replicability in different oceans in the world.

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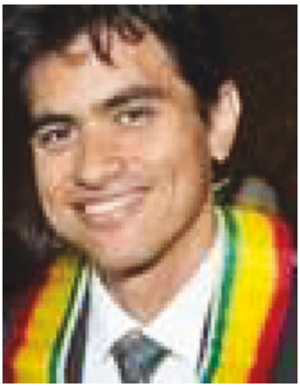

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Chapter 23
Safeguarding the Interests of Developing States Within the Context of Deep-Sea Mining in the Area

Klaas Willaert

Abstract In view of the principle of the common heritage of mankind and the duty to carry out activities in the Area for the benefit of mankind as a whole, the interests and needs of developing states must be taken into account. Diverse mechanisms were devised to make sure that developing states are able to participate in deep-sea mining activities in the Area and receive an equitable share of the benefits, but most of these measures are yet to be implemented and the recent trend of partnerships between private deep-sea mining companies and developing states might jeopardize the original objectives.

Keywords Law of the sea · Deep-sea mining · Common heritage of mankind · Sponsoring states · Developing states

1 Introduction

Beyond the boundaries of national jurisdiction, the deep seabed (also known as "the Area")[1] and its mineral resources are designated as the "common heritage of mankind."[2] This, among others, entails that activities in the Area must be carried out for the benefit of mankind as a whole, taking into particular consideration the

[1] United Nations Convention on the Law of the Sea (Montego Bay, 10 December 1982, in force 16 November 1994) 1833 *UNTS* 396 (LOSC), Article 1(1).

[2] *Ibid.*, Article 136.

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interests and needs of developing states.[3] Part XI and Annexes III and IV of the 1982 Law of the Sea Convention (LOSC),[4] which were later modified by the 1994 Implementation Agreement,[5] set out the main principles of the comprehensive international deep seabed regime, while the International Seabed Authority (ISA)[6] further elaborates these fundamental precepts through detailed rules and provisions. Specific regulations for the first two phases of deep-sea mining activities (prospecting and exploration)[7] are already adopted and exploitation regulations, governing actual mining and recovery of mineral resources for commercial purposes, are currently being developed.[8] Moreover, non-state actors wishing to pursue exploration or exploitation activities in the Area must be sponsored by a state,[9] so national legislation defining the conditions to obtain and maintain the sponsorship of a given state should also be adhered to in these situations.

As will be demonstrated in this chapter, diverse measures were envisioned to make sure that developing states are able to participate in deep-sea mining activities in the Area[10] and receive an equitable share of the benefits.[11] For example, a payment and equitable distribution system for revenue stemming from deep-sea mining activities in the Area was devised,[12] the establishment of the Enterprise—an organ through which the ISA can develop its own mining activities in the Area[13]—would generate revenue to be redistributed through the aforementioned system and could facilitate participation of developing states by means of joint ventures, reserved areas were conceived to be set aside for the Enterprise and developing states,[14] and the original text of the Law of the Sea Convention included far-reaching provisions

[3] *Ibid.*, Article 140(1).

[4] *Ibid.*, Part XI and Annexes III–IV.

[5] Agreement relating to the Implementation of Part XI of the United Nations Convention on the Law of the Sea (New York, 28 July 1994, in force 28 July 1996) 1836 *UNTS* 42 (Implementation Agreement 1994).

[6] LOSC (n 1), Articles 156–157.

[7] Regulations on Prospecting and Exploration for Polymetallic Nodules in the Area (22 July 2013), *ISA Doc.* ISBA/19/C/17 (2013) (Exploration Regulations PMN); Regulations on Prospecting and Exploration for Polymetallic Sulphides in the Area (15 November 2010), *ISA Doc.* ISBA/16/A/12/Rev.1 (2010) (Exploration Regulations PMS); Regulations on Prospecting and Exploration for Cobalt-rich Ferromanganese Crusts in the Area (22 October 2012), *ISA Doc.* ISBA/18/A/11 (2012) (Exploration Regulations FMC).

[8] A draft version, which was originally scheduled to be approved in July 2020, provides a good indication of the current state of play (Draft Regulations on Exploitation of Mineral Resources in the Area (25 March 2019), *ISA Doc.* ISBA/25/C/WP.1 (2019) (Draft Exploitation Regulations)).

[9] LOSC (n 1), Article 153(2)(b), Annex III Article 4(1) and (3).

[10] *Ibid.*, Article 148.

[11] *Ibid.*, Article 140.

[12] *Ibid.*, Article 140(2).

[13] *Ibid.*, Articles 153(2)(a) and 170, Annex III Article 3(1)–(2), Annex IV Article 1; Implementation Agreement 1994 (n 5), Annex Section 2.

[14] LOSC (n 1), Annex III Articles 8 and 9(4).

concerning transfer of technology to the Enterprise and developing states.[15] However, most of these mechanisms are yet to be implemented and the recent trend of partnerships between private deep-sea mining companies and developing states might jeopardize the original objectives. Indeed, although such collaborations might be beneficial to both parties and could provide developing states with the required financial and technical capacity to engage in deep-sea mining activities in the Area, it should be closely scrutinized whether these partnerships do not undermine the fundamental principles of the international deep seabed regime.

On the basis of a thorough analysis of treaty provisions, ISA documents, legal literature and recent developments, this chapter intends to assess to what extent the interests and needs of developing states are considered in the current deep seabed regime. Following a concise overview of the relevant principles and components of the international legal framework governing the Area, the main mechanisms conceived to protect the interests of developing states are discussed. Subsequently, current developments that might complicate the realization of this important objective are critically analyzed, and potential solutions are put forward. What are the main mechanisms to protect the interests of developing states within the context of deep-sea mining in the Area and have these been fully implemented by the ISA? Are partnerships between private foreign companies and developing states in line with the fundamental principles of the international deep seabed regime? Which weaknesses of the current regulatory framework are revealed by this emerging trend and how can these be alleviated? Is the ISA in a position to tackle these issues? And what can developing states undertake themselves to safeguard their interests? In order to shed more light on this topical subject, this chapter attempts to answer these pertinent questions.

2 The Deep-Sea Mining Regime in the Area

As indicated in the introduction, the Area is governed by a comprehensive international regime, consisting of a multitude of treaties and legal instruments. The fundamental principles are set out in the 1982 Law of the Sea Convention and the 1994 Implementation Agreement, while more detailed rules are established in the so-called "Mining Code," encompassing an extensive set of regulations and procedures developed by the ISA. The cornerstone of the international deep seabed regime is the status of the Area and its mineral resources as the "common heritage of mankind."[16] This revolutionary concept was introduced to prevent a free-for-all, first-come first-serve race to the bottom of the ocean, which would mainly entitle developed nations—possessing the capacities and means to invest in deep-sea mining—to the mineral resources of the deep seabed and would exclude most

[15] *Ibid.*, Annex III former Article 5.

[16] *Ibid.*, Article 136.

developing states from these economic opportunities.[17] Furthermore, the philosophically inspired status also proved to be an elegant solution to avoid the dreaded phenomenon of the tragedy of the commons, as the absence of an accountable authority and an established management regime would pose a significant risk of unbridled exploitation and drastic ecological decline.[18] Taking into account the significant difficulties to reconcile the interests of developed and developing states,[19] as well as the seemingly conflicting ambitions of exploitation and conservation, the principle of the common heritage of mankind is often viewed as a remarkable achievement in diplomatic terms.[20]

The Law of the Sea Convention confirmed the crucial importance of this concept by excluding it from potential revisions[21] and embedded its objectives in various ways, including a ban on appropriation,[22] exclusive use for peaceful purposes,[23] protection of the marine environment,[24] international cooperation and knowledge dissemination,[25] and equitable sharing of financial and economic benefits derived from activities in the Area.[26] In summary, the mineral resources of the Area can only be prospected, explored, and exploited according to the rules laid down by the Law of the Sea Convention—as amended by the 1994 Implementation Agreement—and

[17] R Wolfrum (1983) The Principle of the Common Heritage of Mankind. Heidelb J Int Law 43:317; J Frakes (2003) The Common Heritage of Mankind Principle and the Deep Seabed, Outer Space, and Antarctica: Will Developed and Developing Nations Reach a Compromise. Wisc Int Law J 21:433; E Guntrip (2003) The Common Heritage of Mankind: An Adequate Regime for Managing the Deep Seabed. Melb J Int Law 4:380–381.

[18] SJ Shackelford (2009) The Tragedy of the Common Heritage of Mankind. Stanf Environ Law J 28:109–110; E Franckx (2010) The International Seabed Authority and the Common Heritage of Mankind: The Need for States to Establish the Outer Limits of their Continental Shelf. Int J Mar Coast Law 25(4):566, doi: https://doi.org/10.1163/157180810X525377; G Hardin (1968) The Tragedy of the Commons. Science 162:1243–1248, doi: https://doi.org/10.1126/science.162.3859.1243

[19] Cf. J Dingwall (2020) Commercial Mining Activities in the Deep Seabed beyond National Jurisdiction: the International Legal Framework. In: Banet C (ed), The Law of the Seabed. Access, Uses, and Protection of Seabed Resources, Brill Nijhoff, Leiden, 142; JE Noyes (2012) The Common Heritage of Mankind: Past, Present, and Future. Denv J Int Law & Pol 40: 459–460; M Koskenniemi & M Lehto (1996) The Privilege of Universality: International Law, Economic Ideology and Seabed Resources. Nord J Int Law 65(3–4):536–552, doi: https://doi.org/10.1163/15718109620294960; E Holmila (2005) Common Heritage of Mankind in the Law of the Sea. Acta Societatis Martensis 1:187.

[20] A Jaeckel, JA Ardron, KM Gjerde (2016) Sharing benefits of the common heritage of mankind – Is the deep seabed mining regime ready? Mar Policy 70:199, doi: https://doi.org/10.1016/j.marpol.2016.03.009; BH Weston, D Bollier (2013) Green Governance: Ecological Survival, Human Rights, and the Law of the Commons. Cambridge University Press, Cambridge, p 219.

[21] LOSC (n 1), Articles 155(2) and 311(6).

[22] *Ibid.*, Article 137.

[23] *Ibid.*, Article 141.

[24] *Ibid.*, Article 145.

[25] *Ibid.*, Articles 143–144.

[26] *Ibid.*, Article 140.

the regulations adopted by the ISA. Prospecting can be undertaken without formal approval of the ISA,[27] but in order to conduct exploration and exploitation activities in the Area, explicit permission is required. Applicants need to submit a plan of work to the ISA, which upon approval takes the form of a contract.[28]

However, notwithstanding the predominantly international character of the deep seabed regime, national legislation also plays a considerable role. Indeed, it must be noted that non-state actors can only file an application if they are sponsored by a state.[29] This sponsoring state bears the responsibility to ensure that the sponsored entity acts in accordance with the terms of its contract and its obligations under the Law of the Sea Convention, although infractions of the sponsored party do not result in state liability if the sponsoring state has adopted necessary legislation and has taken measures that are, within the framework of its legal order, reasonably appropriate to secure effective compliance by persons under its jurisdiction.[30] With regard to the states that are eligible to take on that role, two criteria are listed: nationality and effective control. All non-state actors must in any case secure and maintain the sponsorship of the state of which they are nationals, but in case of multiple nationalities or the state by which they are effectively controlled (directly or indirectly, through its nationals) not coinciding with the state of nationality, all states involved must act as sponsoring states.[31] Therefore, domestic laws defining the conditions to obtain and maintain a certificate of sponsorship can also be considered an important part of the multi-faceted legal framework on deep-sea mining in the Area. Despite several parallels, this national legislation on deep-sea mining is quite diverse though, since it may for the most part be designed at a country's own discretion.[32] The Law of the Sea Convention explicitly states that every state is allowed to adopt environmental or other laws that are more stringent, but no conditions that are inconsistent with the relevant international rules may be imposed.[33]

[27] *Ibid.*, Annex III Article 2(1); Exploration Regulations PMN (n 7), Articles 2(1) and 3–4.

[28] LOSC (n 1), Article 153(2)–(3), Annex III Article 3; Implementation Agreement 1994 (n 5), Annex Section 1(6).

[29] LOSC (n 1), Article 153(2)(b), Annex III Article 4(1) and (3).

[30] *Ibid.*, Article 139, Annex III Article 4(4); ITLOS, *Responsibilities and obligations of States sponsoring persons and entities with respect to activities in the Area*, Advisory Opinion, 1 February 2011, *ITLOS Reports* 2011, 10 (ITLOS Advisory Opinion), paras 228–230.

[31] LOSC (n 1), Annex III Article 4(3); ITLOS Advisory Opinion (n 30), paras 77 and 190.

[32] Cf. K Willaert (2020) Crafting the perfect deep sea mining legislation: a patchwork of national laws. Mar Policy, doi: https://doi.org/10.1016/j.marpol.2020.104055

[33] LOSC (n 1), Annex III Article 21(3).

3 Main Mechanisms to Protect the Interests of Developing States

Taking into account the principle of the common heritage of mankind, as well as the duty to carry out activities in the Area for the benefit of mankind as a whole, several mechanisms were conceived to protect the interests of developing states. Indeed, while stipulating that the interests and needs of developing states should be taken into particular consideration,[34] Article 140 of the LOSC also instructs the ISA to provide for the equitable sharing of financial and other economic benefits derived from activities in the Area.[35] In the exploitation phase, contractors will be obliged to pay premiums to the ISA for the mineral resources they mine,[36] and the ISA will be charged to equitably distribute this revenue among all member states through an appropriate mechanism. However, it remains to be seen how the payment system and the applicable rates, as well as the distribution system will be designed.[37] On the basis of a minimum attractive rate of return for deep-sea mining contractors and with a view to maximize the returns to the ISA,[38] several payment models are currently being considered by a specifically established open-ended working group.[39] Meanwhile, the Finance Committee of the ISA is pondering options regarding the equitable distribution of the financial and economic benefits. Although alternative approaches are contemplated, the distribution formulae that are currently being discussed are all based on the population of states as a percentage of the world's total, with adjustments to redistribute income from higher-income states to developing countries.[40]

The establishment of the Enterprise, that would allow the ISA to conduct its own deep-sea mining activities in the Area,[41] could contribute to this redistribution of wealth by producing direct revenue and might also facilitate the participation of

[34] *Ibid.*, Article 140(1).

[35] *Ibid.*, Article 140(2).

[36] Draft Exploitation Regulations (n 8), Articles 64–73, Appendix IV.

[37] K Willaert (2019) The financial aspects of deep sea mining: common heritage of mankind or first-come-first-served? J Int Mar Law 25(5):387–395.

[38] R Kirchain, R Roth, FR Field et al. (2019) Report to the International Seabed Authority on the Development of an Economic Model and System of Payments for the Exploitation of Polymetallic Nodules in the Area, p 5.

[39] Cf. Report of the Chair on the outcome of the third meeting of the open ended working group of the Council in respect of the development and negotiation of the financial terms of a contract under article 13, paragraph 1, of annex III to the United Nations Convention on the Law of the Sea and section 8 of the annex to the Agreement relating to the Implementation of Part XI of the United Nations Convention on the Law of the Sea of 10 December 1982 (17 February 2020), *ISA Doc*. ISBA/26/C/8 (2020).

[40] Report of the Finance Committee (25 September 2020), *ISA Doc*. ISBA/26/C/21 (2020), paras 19–23.

[41] LOSC (n 1), Articles 153(2)(a) and 170, Annex III Article 3(1)–(2), Annex IV Article 1; Implementation Agreement 1994 (n 5), Annex Section 2.

developing states—which often do not possess the necessary financial and technical capacity to conduct deep-sea mining activities in the Area—through joint ventures.[42] Despite the fact that member states have expressed interest in cooperating with the Enterprise and the conclusion of a joint venture agreement should trigger its creation,[43] the process towards the eventual operationalization of this ISA organ is still clouded in ambiguity.[44] Taking into account that the powers conferred on the Enterprise are now exercised by the Secretariat through a Special Representative for the Enterprise,[45] the 1994 Implementation Agreement merely states that the Council shall take up the issue of the independent functioning of the Enterprise when a plan of work for exploitation of another entity is approved or upon receipt of an application for a joint venture.[46] However, the language of the current Draft Exploitation Regulations is more firm and clearly stipulates that the Council shall enable the Enterprise to engage in seabed mining at the same time as other entities.[47]

In accordance with the Law of the Sea Convention's intention to promote the effective participation of developing states in activities in the Area,[48] another important measure is the introduction of reserved areas. When an applicant submits a plan of work for exploration to the ISA, the proposed exploration zone should be divided into two parts of equal estimated commercial value.[49] The ISA then decides to assign one of the two parts to the contractor, while the other is designated as a reserved area, set aside for deep-sea mining activities by the Enterprise or developing states.[50] Therefore, developing states and their sponsored entities can apply for exploration contracts in areas with documented resource potential,[51] which are not

[42] Cf. Implementation Agreement 1994 (n 5), Annex Section 2(2); Draft Exploitation Regulations (n 8), Article 19(1).

[43] For example, Report of the Special Representative of the Secretary-General of the International Seabed Authority for the Enterprise on the proposal by the Government of Poland for a joint venture with the Enterprise (3 January 2019), *ISA Doc.* ISBA/25/C/7 (2019).

[44] K Willaert (2020) Effective protection of the marine environment and equitable benefit-sharing in the Area: empty promises or feasible goals? Ocean Dev. Int. Law 51(2):185–186, https://doi.org/10.1080/00908320.2020.1737444; K Willaert (2021) The Enterprise: state of affairs, challenges and way forward. Mar Policy, https://doi.org/10.1016/j.marpol.2021.104590; Report of the Chair of the Legal and Technical Commission on the work of the Commission at the first part of its twenty-sixth session (9 March 2020), *ISA Doc*. ISBA/26/C/12 (2020), paras 37–41.

[45] Implementation Agreement 1994 (n 5), Annex Section 2(1).

[46] *Ibid.*, Annex Section 2(2).

[47] Draft Exploitation Regulations (n 8), Article 19(2).

[48] LOSC (n 1), Article 148.

[49] As this poses some practical problems in case of polymetallic sulphides and cobalt-rich ferromanganese crusts, the relevant regulations provide for the option to offer an equity interest in a joint venture arrangement with the Enterprise instead (Exploration Regulations PMS (n 7), Articles 16 and 19; Exploration Regulations FMC (n 7), Articles 16 and 19).

[50] LOSC (n 1), Annex III Article 8; Exploration Regulations PMN (n 7), Articles 15–16.

[51] Besides the fact that an application for an exploration contract was filed for that specific zone, indicating promising prospects for the recovery of mineral resources, the ISA Secretariat also undertakes efforts to evaluate the resource potential of reserved areas (International Seabed

accessible for developed states or applicants sponsored by them. This evidently is a favorable position, as no data and coordinates regarding the division of the proposed area into two parts of equal estimated commercial value must be submitted and prior prospecting activities can be skipped. If the Enterprise—through its Special Representative—decides that it does not intend to carry out activities in that zone, which has so far been the case for all applications with regard to reserved areas,[52] an exploration contract can be awarded to a developing state or its sponsored entity.[53]

In the original text of the Law of the Sea Convention, far-reaching provisions regarding transfer of technology to the Enterprise and developing states were also included,[54] but this was attenuated significantly by the 1994 Implementation Agreement.[55] Nonetheless, the current provisions still stipulate that the ISA shall take measures to encourage the transfer of relevant technology and scientific knowledge to developing states.[56] Specific initiatives to that end should be undertaken and the ISA and its contractors must set up programs in order to provide training opportunities to personnel from the Enterprise and developing states.[57] International cooperation with regard to marine scientific research and relevant technical developments is promoted[58] and in case developing states or the Enterprise are unable to obtain the necessary technology or scientific knowledge, the ISA may request contractors and their sponsoring states to help facilitate the acquisition thereof.[59] Finally, specific funds were established to ensure the participation of delegations from developing states in the meetings of the ISA organs, but it has to be noted that these funds rely on voluntary contributions from contractors and member states, and

Authority (2019) Current Status of the Reserved Areas with the International Seabed Authority, pp. 4–5; LOSC (n 1), Article 143(2)).

[52] For example, Report and recommendations to the Council of the International Seabed Authority relating to an application for the approval of a plan of work for exploration by Nauru Ocean Resources Inc. (11 July 2011), *ISA Doc*. ISBA/17/C/9 (2011), para 3; Report and recommendations to the Council of the International Seabed Authority relating to an application for the approval of a plan of work for exploration for polymetallic nodules by Tonga Offshore Mining Limited (8 July 2011), *ISA Doc*. ISBA/17/C/10 (2011), para 3; Report and recommendations of the Legal and Technical Commission to the Council of the International Seabed Authority relating to an application for the approval of a plan of work for exploration for polymetallic nodules by Marawa Research and Exploration Ltd. (18 July 2012), *ISA Doc*. ISBA/18/C/18 (2012), para 3.

[53] LOSC (n 1), Annex III Article 9; Exploration Regulations PMN (n 7), Article 17.

[54] LOSC (n 1), Annex III former Article 5.

[55] Implementation Agreement 1994 (n 5), Annex Section 5.

[56] LOSC (n 1), Article 144(1)(b).

[57] *Ibid.*, Articles 143(3)(b)(ii) and 144(2), Annex III Article 15; e.g., Report of the Chair of the Legal and Technical Commission on the work of the Commission at the first part of its twenty-sixth session (9 March 2020), *ISA Doc*. ISBA/26/C/12 (2020), paras 4–7.

[58] Implementation Agreement 1994 (n 5), Annex Section 5(1)(c); LOSC (n 1), Article 143.

[59] Implementation Agreement 1994 (n 5), Annex Section 5(1)(b).

deficits in these funds already prevented representatives from developing states to participate.[60]

4 Current Developments Jeopardizing the Interests of Developing States

Despite the ambition of the Law of the Sea Convention to take into account the interests of developing states, current developments might put this important objective at risk. Indeed, the phenomenon of forum shopping within the context of deep-sea mining in the Area, whereby non-state actors—similar to the use of flags of convenience in modern shipping[61]—can choose their "sponsoring state of convenience," appears to be a potential threat,[62] and the recent trend of partnerships between private deep-sea mining companies (based in developed states) and developing states(see for example the applications sponsored by Nauru, Tonga, Kiribati, and the Cook Islands)[63] can produce similar effects.[64] After all, non-state actors might not only choose an alternative sponsoring state because of more lenient regulatory or procedural requirements, lower tax rates, less stringent supervision or favorable political conditions, but can also be tempted by the fact that a sponsorship by a developing state would provide access to reserved areas. It could be argued that these collaborations are exactly the type of cooperation envisioned by the Law of the Sea Convention and the 1994 Implementation Agreement in the context of capacity building and technology transfer.[65] However, given the attached risks that have already been acknowledged in the 2011 Advisory Opinion of the Seabed

[60] Report of the Finance Committee (25 September 2020), *ISA Doc*. ISBA/26/C/21 (2020), paras 14–15; Report of the Chair of the Legal and Technical Commission on the work of the Commission at the first part of its twenty-sixth session (9 March 2020), *ISA Doc*. ISBA/26/C/12 (2020), paras 2 and 43.

[61] Cf. Y Tanaka (2015) The international law of the sea. Cambridge University Press, Cambridge, pp. 162–164.

[62] K Willaert (2020) Forum shopping within the context of deep sea mining: towards sponsoring states of convenience? Bel Rev Int Law 2019(1–2):116–138.

[63] Canadian enterprise DeepGreen enjoys exploration rights in the Area through ISA contracts sponsored by Nauru, Tonga and Kiribati, respectively, while Belgian deep sea mining company Global Sea Mineral Resources (GSR) has partnered with the Cook Islands to explore the zone that has been assigned to the state-owned Cook Islands Investment Corporation (DeepGreen (2020) Sponsoring states; Report and recommendations of the Legal and Technical Commission to the Council of the International Seabed Authority relating to an application for the approval of a plan of work for exploration for polymetallic nodules by the Cook Islands Investment Corporation (9 July 2014), *ISA Doc*. ISBA/20/C/18 (2014), para 19).

[64] Cf. Issues related to the sponsorship of contracts for exploration in the Area, monopolization, effective control and related matters (21 June 2016), *ISA Doc.* ISBA/22/LTC/13 (2016), paras 5–8.

[65] LOSC (n 1), Article 144; Implementation Agreement 1994 (n 5), Annex Section 5.

Disputes Chamber of the International Tribunal for the Law of the Sea (ITLOS),[66] close scrutiny is warranted.[67] A factual dominance of developed states in reserved areas (through private entities that are based in these countries) must be prevented, as this would largely annul the effects of this mechanism and would therefore jeopardize the overriding principle of the common heritage of mankind.

The reason why large-scale forum shopping within the context of deep-sea mining is a real possibility can be explained by focusing on the eligibility criteria for sponsoring states. As discussed earlier, the sponsorship of the state of nationality must in any case be secured, but in the event of multiple nationalities or the state(s) of effective control (directly or indirectly, through its nationals) not coinciding with the state of nationality, all states involved must act as sponsoring states.[68] Therefore, the concept of "effective control" plays a decisive role, but its interpretation is not quite straightforward. A certain link between the entity and the state (expressed by the registration of a company, the fact of being governed by a country's laws or the nationality or domicile of a parent company) is required, but "effective control" can mean either regulatory control, economic control or both.[69] Currently, the ISA seems to take the easy way out by applying the regulatory control criterion, on the basis of which effective control is simply determined by the incorporation or the conferring of nationality.[70] When reviewing applications by non-state actors, the ISA assesses the formal eligibility of the applicant by solely checking its proof of registration or incorporation in the sponsoring state and the sponsorship certificate.[71] By not digging any deeper, the economic reality of controlling influences and corporate structures is disregarded[72] and this leaves the door wide open for easy

[66] "Equality of treatment between developing and developed sponsoring states is consistent with the need to prevent commercial enterprises based in developed states from setting up companies in developing states, acquiring their nationality and obtaining their sponsorship in the hope of being subjected to less burdensome regulations and controls. The spread of sponsoring states 'of convenience' would jeopardize uniform application of the highest standards of protection of the marine environment, the safe development of activities in the Area and the protection of the common heritage of mankind." (ITLOS Advisory Opinion (n 30), para 159)

[67] K Willaert, P Singh (2021) Deep sea mining partnerships with developing states: favorable collaborations or opportunistic endeavours? Int J Mar Coast Law, doi: https://doi.org/10.1163/15718085-BJA10052

[68] LOSC (n 1), Article 153(2)(b), Annex III Article 4(1) and (3); ITLOS Advisory Opinion (n 30), paras 77 and 190.

[69] AS Rojas, FK Phillips (2019) Effective control and deep seabed mining: Toward a definition. Liability Issues for Deep Seabed Mining Paper Series, p 2.

[70] Cf. Analysis of regulation 11.2 of the Regulations on Prospecting and Exploration for Polymetallic Nodules and Polymetallic Sulphides in the Area (5 June 2014), *ISA Doc.* ISBA/20/LTC/10 (2014), paras 20–22; Issues related to the sponsorship of contracts for exploration in the Area, monopolization, effective control and related matters (21 June 2016), *ISA Doc.* ISBA/22/LTC/13 (2016), paras 5–7 and 11.

[71] For example, Report and recommendations to the Council of the International Seabed Authority relating to an application for the approval of a plan of work for exploration by Nauru Ocean Resources Inc. (11 July 2011), *ISA Doc*. ISBA/17/C/9 (2011), paras 12–21.

[72] AS Rojas, FK Phillips (n 69), p 10.

forum shopping through foreign subsidiaries. Furthermore, conflating the concepts of nationality and effective control seems to contradict treaty language,[73] which clearly treats these as two distinct concepts.[74]

Not only access to reserved areas as such, but also the financial arrangements between foreign enterprises and developing states might thwart the original objectives of the international deep seabed regime. Indeed, taking into account that developing states often have to rely on external expertise, technology, and financial means to engage in deep-sea mining activities in the Area, they find themselves in a vulnerable position. It could be posited that these partnerships provide developing states with an opportunity to participate and thus— in an arguably individualistic way, which largely disregards the collective long-term interests of developing states—represent a more direct approach to ensure that they receive their fair share, regardless of the forthcoming equitable benefit-sharing mechanism,[75] but the confidential nature of the arrangements between private foreign companies and developing states (as well as the fact that the ISA currently does not conduct an in-depth examination into the nature and modalities of these collaborations) precludes an evaluation of the envisioned distribution of the financial proceeds. Although this might be considered a commercial agreement between business partners that should not be reviewed or interfered with by the ISA or other stakeholders, it could be argued that lopsided arrangements here cannot be reconciled with the principle of the common heritage of mankind[76] and the duty to carry out activities in the Area for the benefit of mankind as a whole, "taking into particular consideration the interests and needs of developing states."[77]

5 Safeguarding the Interests of Developing States

5.1 Adapting the Interpretation of Effective Control?

Probably the most effective measure to prevent potential abuses and avoid escalation of the above-mentioned issues, is a change in interpretation of "effective control." By integrating economic control factors (including ownership of a majority of the shares, ownership of a majority of the capital, possession of a majority of the voting rights, the right to elect a majority of the board of directors, sufficient influence to determine the company's decision, or any combination of the above

[73] LOSC (n 1), Articles 139 and 153(2)(b); ITLOS Advisory Opinion (n 30), para 77.

[74] AS Rojas, FK Phillips (n 69), pp. 4, 10.

[75] LOSC (n 1), Article 140(2).

[76] LOSC (n 1), Article 136.

[77] LOSC (n 1), Article 140(1).

elements)[78] in the definition of effective control, easy forum shopping would be precluded. In contrast to the regulatory control interpretation, which is completely oblivious to the economic reality of strategic corporate structures, the suggested approach would stay true to the treaty text and would prevent access to reserved areas in evident "sponsoring state of convenience" situations. Indeed, when it is determined that a developed state exercises effective control over the sponsored entity, an additional sponsorship from that state would be required and this would deny access of the said entity to a reserved area, as the Law of the Sea Convention stipulates that a non-state actor must be sponsored by and be under the effective control of a developing state in order to be eligible to submit an application with respect to a reserved area.[79] However, the proposed correction would only be effective in case of clearly discernable controlling influences from another state or one of its nationals. For example, partnerships characterized by wholly owned subsidiaries incorporated in the sponsoring state (e.g., the exploration contracts held by Canadian enterprise The Metals Company and sponsored by Nauru and Tonga respectively)[80] would be impacted, while joint ventures functioning as subcontractors to the sponsored entity (e.g., the partnership between Belgian deep-sea mining company GSR and the Cook Islands, and arguably also the collaboration between The Metals Company and Kiribati)[81] would not require additional sponsorships if the interpretation shifts towards economic control.

Of course, a change in interpretation of the effective control criterion would need to be combined with a more proactive approach of the ISA in reviewing applications and corporate ownership structures of contractors. Indeed, the relationship between the sponsored entity, its partners and the sponsoring state should be duly investigated by the ISA before an exploration or exploitation contract can be granted, and permanent monitoring of the ownership of the contractor and potential controlling influences should be ensured during the term of the contract. After all, it seems

[78] Cf. ICJ, *Barcelona Traction, Light and Power Company, Limited* (Belgium v Spain), Judgment, *ICJ Reports* 1970, 3, para 70; AS Rojas, FK Phillips (n 69), p 9.

[79] LOSC (n 1), Annex III Article 9(4).

[80] Decision of the Council relating to a request for approval of a plan of work for exploration for polymetallic nodules submitted by Nauru Ocean Resources Inc. (19 July 2011), *ISA Doc*. ISBA/17/C/14 (2011); Decision of the Council relating to a request for approval of a plan of work for exploration for polymetallic nodules submitted by Tonga Offshore Mining Limited (19 July 2011), *ISA Doc*. ISBA/17/C/15 (2011); Government of the Republic of Nauru (2018) Nauru partners with deep sea mining company on quest for sustainable future; DeepGreen (2020) DeepGreen acquires third seabed contract area.

[81] Decision of the Council relating to an application for the approval of a plan of work for exploration for polymetallic nodules submitted by the Cook Islands Investment Corporation (21 July 2014), *ISA Doc*. ISBA/20/C/29 (2014); Report and recommendations of the Legal and Technical Commission to the Council of the International Seabed Authority relating to an application for the approval of a plan of work for exploration for polymetallic nodules by the Cook Islands Investment Corporation (9 July 2014), *ISA Doc*. ISBA/20/C/18 (2014), para 19; Decision of the Council relating to a request for approval of a plan of work for exploration for polymetallic nodules submitted by Marawa Research and Exploration Ltd. (26 July 2012), *ISA Doc*. ISBA/18/C/25 (2012); DeepGreen (2020) Sponsoring states.

inconsistent that the expertise, technology, and financial means of parent companies and other partners are duly taken into account by the ISA when evaluating the financial and technical capacity of applicants, while these relationships and corporate structures are disregarded in order to determine "effective control."

These efforts by the ISA should be facilitated by the full disclosure of all relevant information by the applicant or contractor, which is currently lacking. For example, the fact that The Metals Company (formerly DeepGreen) has obtained three exploration contracts (in reserved areas) without even a mention of its name in any one of the applications that were submitted to and approved by the ISA, is indicative of the lack of transparency in this context.[82] Therefore, it is paramount to impose clear rules concerning the disclosure of information with regard to partnerships involving the applicant or contractor. Moreover, assuming that a more advanced interpretation of effective control will not withhold private foreign entities from forum shopping through creative corporate structures and arrangements, it might be desirable to apply certain standards in terms of distribution of financial proceeds when developing states are involved as sponsoring states, in order to ensure that they receive their fair share.

5.2 Creeping National Interests in Domestic Legislation of Developing States?

Pending the establishment of effective international safeguards, sponsoring states might also protect their own interests through specific provisions in their national deep-sea mining laws. However, such creeping national interests can—oddly enough—be considered debatable in light of the principle of the common heritage of mankind and the duty to carry out activities in the Area for the benefit of mankind as a whole.[83] After all, it might be argued that sponsoring states should solely serve as guardians of the global public interests and must refrain from pursuing national benefits in that role, as this could lead to conflicts of interest. Nevertheless, it should be stressed that different degrees of creeping national interests can be discerned in terms of their nature and possible impact. For example, imposing a condition that the proposed deep-sea mining activities should be in the public interest of the sponsoring state is fairly innocent and does not necessarily conflict with the interests of

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[82] Application for approval of a plan of work for exploration by Tonga Offshore Mining Ltd. (14 June 2011), *ISA Doc*. ISBA/17/LTC/L.5 (2011); Application for approval of a plan of work for exploration for polymetallic nodules in the Area by Nauru Ocean Resources Incorporated (21 June 2011), *ISA Doc*. ISBA/17/LTC/L.4 (2011); Application for approval of a plan of work for exploration for polymetallic nodules in the Area by Marawa Research and Exploration Ltd. (11 June 2012), *ISA Doc*. ISBA/18/LTC/L.6 (2012).

[83] K Willaert (2020) On the legitimacy of national interests of sponsoring states: a deep sea mining conundrum. Int J Mar Coast Law, doi: https://doi.org/10.1163/15718085-BJA10011

mankind as a whole.[84] The fact that several Pacific island states have included such provisions in their legislation is no coincidence, as the Pacific Community (SPC) has developed a regional legislative framework for deep-sea mining activities in the Area, which pays significant attention to the interests of the island communities by promoting local employment, foreign investment, capacity building and long term economic benefits.[85] For developing states, this can prove useful criteria to avoid one-sided partnerships with foreign entities, although it seems more appropriate to turn these conditions around by stating that the activities may not lead to irreversible harm to any community, cultural practice or public interests of the sponsoring state.

However, some domestic provisions go even further in order to secure national interests. Introducing recovery fees based on the amount and value of the mineral resources that are mined, for example, does not seem perfectly legitimate, as this generates direct revenue for the sponsoring state and thus inevitably skims the financial benefits that are intended to be distributed among mankind as a whole.[86] Indeed, recalling that the ISA payment models are currently being designed on the basis of a minimum attractive rate of return for contractors, which is among others informed by substantiated assumptions concerning the fees and levies imposed by sponsoring states, it is clear that ISA revenue and sponsoring state revenue can be considered communicating vessels: every penny earned by the sponsoring state is one that cannot be collected and (after deduction of administrative expenses)[87] be distributed by the ISA for the benefit of mankind as a whole.[88] The same reasoning applies to corporate income tax regimes of sponsoring states, for that matter, as these equally produce revenue flowing from deep-sea mining activities in the Area when imposed on contractors. Moreover, significant differences in tax rates evidently serve the national interests of states that impose higher tariffs, creating unjust differences in revenue collection between sponsoring states.

In order to guarantee compliance with the status of the Area and its mineral resources as the common heritage of mankind, recovery fees, and excessive corporate tax rates should be avoided, as it essentially comes down to sponsoring states single-handedly taking a piece of the pie before it can be equally divided among all member states.[89] Nevertheless, given the particular consideration for their interests

[84] For example, Tonga Seabed Minerals Act 2014, Section 77(5)(ii); Nauru International Seabed Minerals Act 2015, Section 23(1)(c)(ii); Kiribati Seabed Minerals Act 2017, Section 87(2)(ii); Cook Islands Seabed Minerals Act 2019, Section 134(1)(c).

[85] Pacific Community (2012) Pacific-ACP States Regional Legislative and Regulatory Framework for Deep Sea Minerals Exploration and Exploitation.

[86] For example, Tonga Seabed Minerals Act 2014, Section 91(2)(b); Nauru International Seabed Minerals Act 2015, Section 40(4); Kiribati Seabed Minerals Act 2017, Section 105(4)(b); Cook Islands Seabed Minerals Act 2019, Section 153(4).

[87] LOSC (n 1), Article 173(2); Report of the Finance Committee (12 July 2019), *ISA Doc.* ISBA/25/C/31 (2019), para 29.

[88] R Kirchain et al. (n 38), pp. 5, 54, 71–73.

[89] However, these proposed corrections come with a caveat: as soon as the levies of the sponsoring states are taken into account and the payment system is introduced by the ISA, lowering corporate tax rates and eliminating recovery fees will not automatically lead to higher benefits for mankind

and needs in the Law of the Sea Convention,[90] it could definitely be argued that developing states enjoy more leeway. Some might claim that only the ISA is qualified to elaborate and operationalize this particular consideration through the development of an extensive regulatory framework, but it has been demonstrated earlier that several crucial aspects of the envisioned regime are not yet implemented. Therefore, it seems reasonable to allow developing states to secure some of its national interests through domestic legislation. Indeed, pending the establishment of all mechanisms to truly implement the status of the Area and its mineral resources as the common heritage of mankind, developing states are not on an equal footing and provisional corrections, subject to specific conditions,[91] should thus not be condemned.[92]

6 Conclusion

In this chapter, the link between the fundamental principle of the international deep seabed regime—the common heritage of mankind—and the interests of developing states was explained. Several mechanisms were conceived to achieve the intended objectives: a payment and equitable distribution system will be set up, the Enterprise will be able to generate direct revenue for mankind as a whole and can be a suitable partner, reserved areas were introduced to be set aside for the Enterprise and developing states, and international cooperation with regard to capacity building, scientific research and technology transfer is promoted. However, only a few of these measures have currently been implemented, and the recent trend of deep-sea mining partnerships between private foreign companies and developing states might jeopardize the foundations of the international deep seabed regime. Indeed, while it is true that the aforementioned collaborations might be beneficial to developing states and could be viewed as the type of cooperation that is encouraged by the Law of the Sea Convention, it should not be neglected that access to reserved areas for private

as a whole and would simply result in reduced taxes for deep-sea mining contractors. Consequently, in order to ensure that national taxation is effectively replaced by international taxation, it is crucial to combine the suggested adjustments with synchronized changes to the forthcoming ISA payment system, for example by linking the financial model and related contractual terms to certain threshold values regarding the accumulated tax rates imposed by sponsoring states. After all, revisions of the payment system and the applicable tariffs can only be introduced in existing contracts at the election of the contractor (K Willaert (n 83); Implementation Agreement 1994 (n 5), Annex Section 8(1)(e); Draft Exploitation Regulations (n 8), Articles 81–82).

[90] LOSC (n 1), Article 140(2).

[91] For example, recovery fees or high corporate income taxes could be deemed legitimate when applied by developing states for as long as the ISA has not adopted suitable payment and distribution systems, on condition that the fees are paid into a specific fund dedicated to adequate and sustainable management of deep-sea mining activities and provided that recovery fees and corporate tax tariffs exceeding the mean among sponsoring states are not cumulated.

[92] K Willaert (n 83).

foreign companies based in developed nations might undermine the status of the Area and its mineral resources as the common heritage of mankind, so caution should be exercised.

An effective solution to prevent easy forum shopping and subsequent access to reserved areas for private deep-sea mining companies based in developed states is a more thoughtful interpretation of the concept of "effective control." If economic control factors would be integrated in the definition of this important criterion, choosing a "sponsoring state of convenience" through foreign subsidiaries would be precluded, entailing that some of the current partnership arrangements between developing states and foreign enterprises would require additional sponsorships. However, this can only be accomplished if the ISA is prepared to duly investigate the ownership structures and partnership arrangements of applicants and contractors. Full disclosure of all information relevant to assessing the effective control criterion should be demanded, and the ISA must be willing to look beyond what the applicant has submitted in order to verify this. Moreover, taking into account that a more advanced interpretation of effective control will not prevent every possible form of forum shopping, it might be appropriate to impose certain standards in terms of distribution of financial proceeds when developing states are involved as sponsoring states, in order to ensure that they receive their fair share.

Apart from the introduction of corrections on the international level, developing states might also try to protect their national interests through specific provisions in domestic legislation. Although the legitimacy of such creeping national interests can be considered questionable, taking into account the duty to carry out activities in the Area for the benefit of mankind as a whole, developing states should enjoy more leeway here and may to a certain extent—and under specific conditions—integrate national interests in their legislation. Imposing a condition that the proposed deep-sea mining activities must be in the public interest of the sponsoring state can preclude one-sided partnerships with foreign enterprises, while recovery fees or corporate income taxes—which should in other situations be avoided and are ideally replaced by international taxation for the benefit of mankind as a whole—can ensure that developing states receive their fair share, pending the establishment of a system that provides for the equitable distribution of financial benefits derived from activities in the Area.

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