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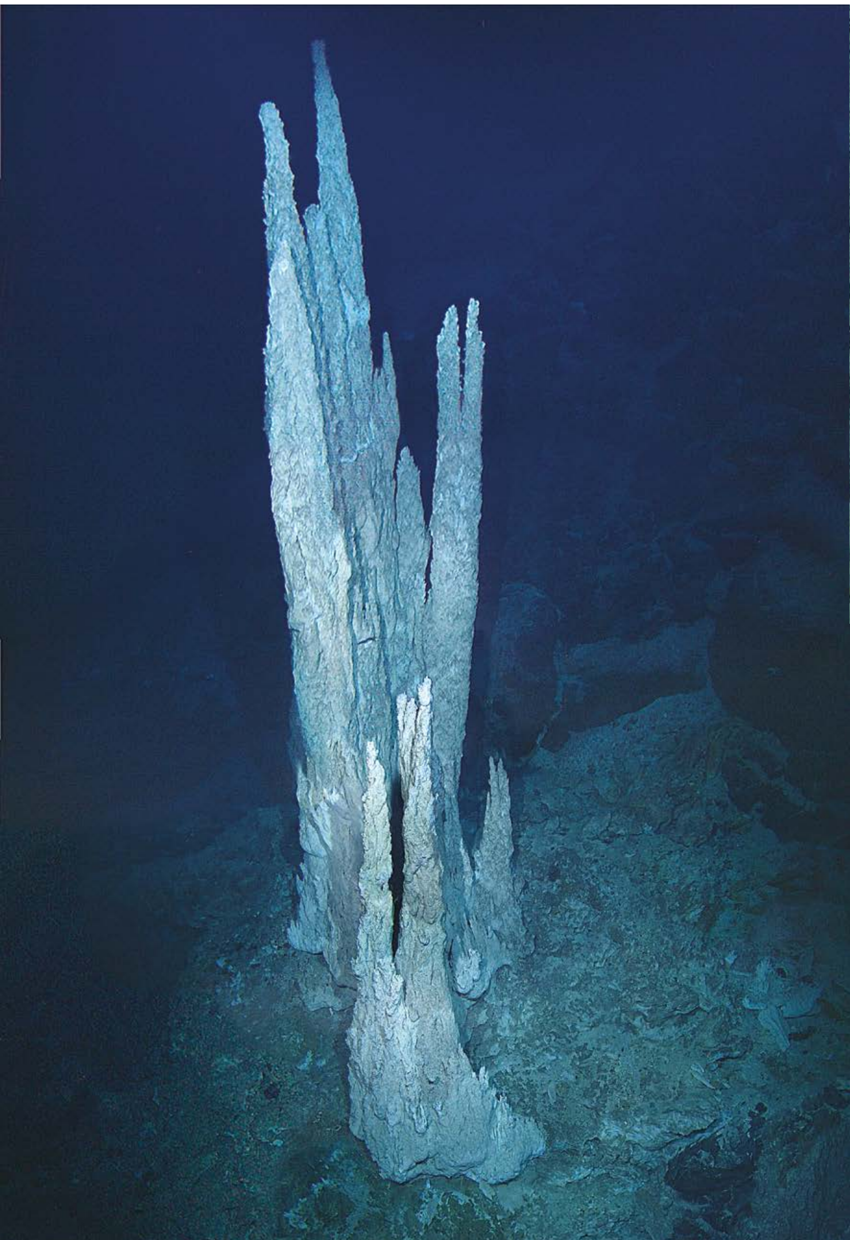
Deep seabed mining

A rising environmental challenge

Luc Cuyvers, Whitney Berry, Kristina Gjerde,
Torsten Thiele and Caroline Wilhem



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Published by: IUCN, Gland Switzerland, in collaboration with Gallifrey Foundation.

Citation: Cuyvers, L., Berry, W., Gjerde, K., Thiele, T. and Wilhem, C. (2018). *Deep seabed mining: a rising environmental challenge*. Gland, Switzerland: IUCN and Gallifrey Foundation. x + 74pp.

Cover photo: Left: Lost City pinnacle. See p. 46. Courtesy D. Kelley and M. Elend, University of Washington,
Upper Right: A deep-sea lizardfish (*Bathysaurus*) at a depth of just over 2,000m. Courtesy NOAA.
Lower right: Giant tube worms (*Riftia pachyptila*), East Pacific Rise. See p. 18. Courtesy NOAA.

ISBN: 978-2-8317-1921-4 (PDF)
978-2-8317-1922-1 (print version)

DOI: https://doi.org/10.2305/IUCN.CH.2018.16.en

Executive Editor: John Vermilye, Gallifrey Foundation

Project Manager: Alexis McGivern, IUCN & Gallifrey Foundation

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Layout by: Imre Sebestyén Jr. / Unit Graphics

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ACKNOWLEDGEMENTS

Pulling together a report like this with so many sources is a herculean task. Our thanks and appreciation for this goes to Alexis McGivern, IUCN & Gallifrey Foundation.

The authors of this report would like to thank Kris Van Nijen (Faculty of Applied Economics, Department of Engineering Management, University of Antwerp, Belgium and Global Sea Mineral Resources NV, Ostend, Belgium) and Phil Weaver (Seascape Consultants Ltd National Oceanography Centre) for the time and advice provided in the course of reviewing this report. There is no question that it benefited greatly from the expertise and perspective they so generously shared.

Sandor Mulsow at the ISA provided much-needed maps for this publication, for which we are grateful.

We also would like to thank NOAA for making a photographic record of its many deep-sea expeditions publicly available and to all the others who allowed us to use their photographs and/or illustrations: Claire Armstrong, Geomar, Global Sea Mineral Resources NV (GSR); Royal IHC Mining; the International Seabed Authority (ISA); Jamstec; the Japan, Oil, Gas and Metals National Corporation (JOGMEC); Nautilus Minerals, Inc.; MIT Materials Research Laboratory; Ocean Networks Canada; the Schmidt Ocean Institute; Stratfor and the University of Washington.

A big thank you to Carl Gustaf Lundin, Director of the Global Marine & Polar Programme at IUCN who provided valuable comments and without whom and his staff many of these initiatives would never see the light of day. We would also like to extend our gratitude to James Oliver for continued guidance and support on this publication. At IUCN we are also indebted to Michael Vollmar for his excellent maps of resource areas and potential mining zones. We would also like to thank Aurélie Spadone from IUCN's Global Marine and Polar Programme for her contributions to the conclusions of this report.

Thank you to the Gallifrey Foundation for its support and collaboration in producing this report.

FOREWORD

When we ask ourselves to consider if we have been good stewards of our natural resources we must admit we have not always lived up to our potential.

When we look at the oceans these failures are manifest; 90% of the large fish and whales have been fished or killed. Our fishing fleets have scoured vast parts of the seabed and destroyed vital habitats and ecosystems, we are dumping an estimated eight million tons of plastic into the oceans every year creating enormous gyres of plastic waste, fish, birds and other marine animals are being choked and suffocated by this waste. No, we have to admit we have not done a good job.

There is, however, one area where it is not too late and where we have the chance to get it right – the deep sea. The sea below 200 meters depth accounts for 95% of the volume of the ocean, making it the largest habitat for life on Earth. Though it is perpetually cold, generally dark, and subject to extreme pressures, the deep sea contains a wealth of unique and unusual species, habitats and ecosystems.

The deep seabed also contains valuable mineral deposits. There is growing commercial interest in mining the ocean floor for these minerals. We might be entering into a gold rush to get to these resources and there is a growing competition between countries and companies to exploit these minerals with limited consideration for the effects on nature.

The International Seabed Authority (ISA) is operating with the dual mandate of promoting the development of the deep sea bed whilst ensuring that this development is not harmful to the environment. This challenging and conflicting dual mandate will require improved oversight by the international community to make sure that the broader interests and welfare of the oceans are adequately addressed. It is our desire that this publication assists in shedding light on the issues that need to be addressed to achieve these goals and ensure that, if the deep seabed is to be developed, it is done in a manner that is sustainable both economically as well as environmentally. Using subsidies to develop seabed mining is a bad investment for people and the planet.

This report, produced by the Global Marine and Polar Programme of the International Union for the Conservation of Nature (IUCN) with the support of the Gallifrey Foundation, aims to provide policy makers, industry and the public at large, a comprehensive overview of the opportunities and threats posed by deep sea mining.

The findings in this report challenge all concerned to collaborate to ensure that before commercial deep sea mining commences that the environmental risks have been understood, what the acceptable limits of impact shall be and how such shall be monitored, controlled and mitigated. Many of the assumptions made when UNCLOS was drafted, such as the growth rate of polymetallic nodules or the lack of fauna at depth, have been overturned. This demands that together we reassess how best to balance the dual mandate of the ISA based on science and fact.

Carl Gustaf Lundin
Director, IUCN Global Marine and Polar Programme

Summary

The sea below 200 meters depth accounts for 95% of the volume of the ocean, making it the largest habitat for life on Earth. Though it is perpetually cold, generally dark, and subject to extreme pressures, the deep sea contains a wealth of unique and unusual species, habitats and ecosystems.

It also contains a wealth of mineral resources, some of them in unique or highly enriched concentrations. Attempts to recover these resources during the 1970s and 1980s were impaired by legal uncertainties and technical constraints, along with metal prices that did not justify the enormous investments required. Today, the legal uncertainties have been largely resolved, marine mining and environmental monitoring technology has advanced rapidly, and every rise in metal rates—real and projected—increases the commercial appeal of deep-sea mining. Yet while the technological and commercial challenges are being met, little is known about the environmental implications. Deep-sea mining may well be within commercial reach and some operations may even have a lower footprint than their terrestrial counterpart, but assessing how this activity would affect the deep seabed, and possibly other parts of the ocean, remains largely unknown.

This report aims to stimulate interest in the deep ocean and the discussions surrounding its potential development, with a specific focus on deep-sea mining of hard metal-bearing minerals. It first outlines the geology of deep seabed metal-bearing minerals, explaining the formation and global distribution of polymetallic nodules on abyssal plains, polymetallic crusts on tops and flanks of seamounts and sulphide deposits in active and inactive hydrothermal vent fields. It next describes the ecosystems associated with these areas, revealing that in spite of harsh conditions, the deep sea hosts an astonishing variety of specially adapted life forms.

To better understand the challenges faced by deep-sea mining companies, the report reviews some of the mining technologies. Deep seabed mineral extraction will take place with equipment operated remotely under extreme physical conditions. Technical challenges include designing machinery to excavate, collect, grind and lift to the surface minerals from 1,000-6,000 m depths, while withstanding considerable differences in pressure, temperature, density, salinity and acidity.

The laws that govern deep seabed mining are briefly reviewed as well. The 1982 United Nations Convention on the Law of the Sea (UNCLOS) sets forth specific rules, rights and responsibilities regarding the use of the deep sea and its natural resources. A key component stipulates that the deep seabed beyond national jurisdiction is the common heritage of mankind, requiring its development to benefit mankind as a whole. UNCLOS thus details responsibilities to share the benefits of deep seabed exploration and exploitation, including

monetary benefits, access to technology and capacity building; a task it delegated to the International Seabed Authority (ISA). At the same time, UNCLOS calls for high environmental safeguards to ensure the effective protection of the marine environment from the harmful effects of any mining operations.

As the economics of mining will determine its appeal to investors and its potential for delivering financial benefits to mankind, the report summarizes the costs of deep-sea mining operations. These comprise the financial costs associated with the mining process, including innovation costs and upfront capital expenditures on design, construction, testing, maintenance and processing; intangible costs such as the potential long-term impacts resulting from the degradation of marine ecosystems; and costs associated with developing and enforcing regulations as well as environmental mitigation. Current deep-sea mining activities both within and beyond national jurisdiction are reviewed, using information provided by industry and regulatory agencies.

Although at present there is little, if any, empirical information on the impacts of deep seabed mining, the report identifies potential adverse environmental effects. These include the actual removal of minerals, some of which have formed over millions of years and host a diverse array of species; physical disturbances that can alter or destroy deep-sea habitats; and the disturbance of seafloor sediment, which could create plumes of suspended particles that will take time to settle and affect the marine environment beyond the mining area. The report asserts that effective environmental management will need to be based on a far better understanding of the deep sea than currently exists. Improving this understanding requires comprehensive baseline studies that cover ecosystem functioning, the nature of ecosystem regeneration within mined areas, the life history of local species, connectivity between these species and communities outside the mined areas, and how these various parameters change over clearly defined spatial and temporal parameters and in response to other stressors.

The report concludes with a number of recommendations designed to safeguard the health of the deep-sea and to ensure that its development will be carried out for the benefit of mankind.

Long thought to be sparsely inhabited, the deep sea actually harbors an astonishing diversity of life. Here large bathymodiolin mussels and tiny brittlestars coexist near a cold seep more than 3000 m beneath the Gulf of Mexico. Courtesy Expedition to the Deep Slope 2007, NOAA-OE.

1. INTRODUCTION

Comprising the seabed and water column below 200 m depths, the deep-sea is often referred to as Earth's final frontier. It is a proper description because more than any other part of the planet, the deep-sea remains largely unexplored. But the little we know reveals a variety of habitats with a rich and unique biodiversity, as well as ecosystems we had not even imagined until they were discovered some 40 years ago. It also reveals an abundance of mineral resources, some of which are rare on land (or, if not rare, located in politically sensitive regions); others of which are considered essential to high-tech applications and the switch to a greener economy.

Final frontiers are not destined to remain final forever. The desire to know what it is there and how it affects the planet, coupled with the notion that some of it may be valuable to the economy, has stimulated the development of the technology to access the deep-sea. As long as science and industry explore, they can cooperate and help expand our knowledge and understanding of the deep-sea. Yet once industry shifts from exploration to exploitation, their objectives diverge. Ensuring that these diverging paths will not harm the health of the ocean will require a regulatory framework that accurately anticipates, mitigates and monitors the entire impact of industrial deep-sea mining operations.

A brief history

During the 19th century there was a strong interest in determining what forms of life existed in the ocean's deepest reaches. To find out, nets and dredges were lowered several kilometres, some of which returned not only with interesting organisms but also with seafloor deposits. Dark, potato-sized nodules, for instance, regularly showed up in deep-sea samples aboard HMS *Challenger*, the first ship to complete a circumnavigation for oceanographic research during the 1870s. Like other deep-sea mineral deposits, the nodules were measured, analysed and properly described as manganese nodules by the scientists aboard, before being stored away as a mineralogical curiosity.

The International Geophysical Year (IGY) made clear that the deep-sea held more than strange life-forms and mineralogical curiosities. Implemented to gain a better understanding of the planet, the IGY stimulated interest in the deep ocean floor, the assumption being that it held clues to the planet's geophysical characteristics. To confirm their theories, scientists not only systematically dredged the deep seafloor, but also photographed it. What they saw was astonishing. Immense areas of the deep-sea were found to be covered with manganese nodules. American geologists found them throughout the entire eastern Pacific basin. Other teams discovered and photographed massive deposits in the deep reaches of the western Pacific, the Indian Ocean and the Atlantic.

Figure 1.1
One hundred years after HMS *Challenger* discovered manganese nodules in the Pacific, mining companies returned to explore their extent. Courtesy Ocean Mining Associates (OMA).

By the early 1960s, manganese nodules had been studied in more detail, revealing that, aside from manganese, they contained high concentrations of nickel, copper and cobalt: essential ingredients of high-performance alloys. Although not exactly scarce on land, the principal land-based reserves of these metals were located in developing countries and what was then still the Soviet Union. If the estimates of the quantities of nodules in the deep sea were correct, it seemed that the ocean could provide an alternative, and perhaps more reliable, source of these vital metals. That, in turn, caught the attention of the mining industry.

In response, several companies began exploring the potential of deep-sea mining. To share risk, capital and know-how, they formed consortia. By the mid-1970s, several of these were operating. They included all of the world's leading mining companies: Kennecott Copper, U.S. Steel, Standard Oil, Sun Company, SEDCO, Lockheed, and Tenneco from the U.S.; the International Nickel Corporation (INCO) and Noranda Mines from Canada, Preussag and Metallgesellschaft from Germany; Shell and Boskalis from the Netherlands; Union Minière from Belgium; Rio Tinto Zinc, British Petroleum (BP) and Consolidated Goldfields from the United Kingdom; and Mitsubishi and Sumitomo from Japan.

The consortia spent millions of dollars in developing prototype mining systems. They were tested at sea, and during the late 1970s a few hundred tons of nodules were brought up. That was a far cry from the millions of tons needed to make mining operations commercially feasible, but it proved that the system worked and that, with the right incentives, the technology to mine the deep seafloor could be developed. But by that time, the glowing projections of a few years earlier were no longer valid. For one thing, metal prices had collapsed. Starting a deep-sea mining operation required an estimated investment of as much as a billion dollars and to make such a venture profitable the prices of cobalt, nickel, copper and manganese had to rise, not drop.

The industry was also concerned about the legal status of the deep ocean floor. When the mining consortia began looking into nodule mining, it was argued that the deep sea did not belong to anyone, making its resources available to whoever made the effort to recover them. By the end of the 1960s that was no longer the case. Assuming that nodules represented a potential fortune, there were calls for a determination of ownership – a demand that would lead to a revision of the law of the sea and a legal regime that, from a commercial point of view, raised all kinds of uncertainties. The would-be miners pulled out their ships and equipment. Aside from a few tracks left by their dredges, the deep sea and its resources would be left undisturbed, at least for the time being.

Deep-sea mining plans were shelved, but not necessarily abandoned. Some companies pulled out of the industry altogether; others waited for more favourable conditions before taking further steps. By the beginning of the current millennium, the time seemed ripe to give deep-sea mining another chance. Metal prices, though never entirely predictable, had stabilized, in no small part as a result of strong growth in emerging economies. The legal situation had also been clarified, with a newly established intergovernmental organization empowered to grant licenses for deep-sea mining in international waters. Deep-sea technology had advanced rapidly as well, driven in no small part by the needs of the offshore oil and gas industry, which was breaking one offshore drilling record after another. And perhaps most important, in the intervening years, other interesting deep-sea hard mineral deposits had been discovered, some of them located nearer to shore and at lower depths than nodules.

And so, deep-sea mining is about to enter its second phase. The first small-scale recovery of deep-sea deposits took place in nationally controlled waters in 2017, and more are scheduled in the next few years. Mining in international waters is not expected until several years from now, but already 29 exploration contracts, covering more than a million km^2 of deep ocean, have been issued. To help ensure that these operations indeed benefit mankind as a whole, the costs of deep-sea mining - financial as well as environmental - need to be weighed fairly and objectively against its potential benefits.

Challenges

Deep-sea mineral extraction may have some economic and environmental advantages over its land-based counterpart (Hoagland, et al., 2010). There is, for instance, no need to construct permanent physical mine and transport infrastructures. The overburden is limited and, unlike terrestrial mining, does not include communities and rainforests. Assets like surface vessels and platforms are reusable. There is no use or pollution of fresh water sources; limited or no effect on local communities (depending on the distance from shore); and metal grades and quantities are often higher than terrestrial ores (Hein et al., 2013). On the other hand, developing the extraction technology to mine several kilometres below the surface will require major investments, as will mitigation strategies to ensure effective protection and avoid serious harm of the marine environment (MIDAS, 2017).

Table 1.1
Knowledge of Ecosystems, Habitats and Their Value. Cell colours indicate the state of natural science knowledge on the contribution of these ecosystems and habitats to the provision of goods and services.

Services	Ecosystems and Habitats	Cold Water Corals	Open Slopes and Basins	Canyons	Sea-mounts	Chemo-synthetic	Water Column	Sub-seabed
Supporting Services	Nutrient cycling	?	+	?	?	+	+	0
	Habitat	+	+	+	+	+	+	0
	Resilience	?	?	?	?	?	?	0
	Primary production	?	?	?	?	+	+	0
	Biodiversity	+	+	+	+	+	+	?
	Water circulation and exchange	0	+	+	?	0	+	0
Provisioning Services	Carbon capture and storage (artificial)	0	0	0	0	0	+	€
	Finfish, shellfish, marine mammals	+	+	+	+	+	€	0
	Energy: Oil, gas, minerals	?	?	0	?	?	0	€
	Chemicals compounds – industrial/ pharmaceutical	+	?	?	?	+	?	?
	Waste disposal sites	0	+	+	0	0	0	+
Regulating Service	Gas & climate regulation	0	?	+	0	+	+	+
	Waste absorption and detoxification	0	+	+	0	0	+	0
	Biological regulation	?	+	?	?	+	+	0
Cultural Services	Educational	+	+	+	+	+	+	+
	Scientific	+	+	+	+	+	+	+
	Aesthetic	+	?	?	?	+	+	0
	Existence / Bequest	+	?	?	?	?	+	?

As illustrated by Armstrong et al., (2012), the contribution of the various deep-sea habitats to goods and services remains poorly mapped (Table 1.1). Precisely assessing the value of the potential damage to deep-sea ecosystems and biodiversity is one of the major challenges associated with deep-sea mining (Glover, 2003; MIDAS, 2017). "The benefit of mankind as a whole" can arguably no longer merely be seen from a purely financial perspective with proceeds that are to be partly redistributed, as it did when the phrase was coined half a century ago. There are also benefits associated with safeguarding one of the few untouched places on the planet, especially to those generations that are yet to follow and thus have no say in what is being decided now (Halfar & Fujita, 2007; Hoagland et al., 2010; Van Dover et al., 2018).

Key:
Blue = solid knowledge;
Green = some knowledge;
Yellow = little knowledge;
Grey – no knowledge;
White = not applicable.
Value is defined as being: present (+); not present (0); unknown (?); monetarily known (€). From Armstrong et al. (2012) – Services from the deep: Steps towards valuation of deep sea goods and services.

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2. THE GEOLOGY OF DEEP-SEA MINERALS

Geological, geophysical and geochemical factors affect the formation and distribution of the principal types of deep seabed mineral deposits of commercial interest. Polymetallic nodules, which caught the attention of mining companies already half a century ago, take millions of years to grow to recoverable size, and hence require stable environments for their formation. Polymetallic (or ferromanganese) crusts occur as pavements on seamounts, ridges and plateau, and, like nodules, take millions of years to form. The third deep seabed mineral eyed by mining interests goes by a variety of names: polymetallic sulphides, seafloor massive sulphides or hydrothermal sulphides. Unlike nodules and crusts, polymetallic sulphides form in tectonically active areas associated with hydrothermalism. Some can accumulate rapidly; others may take thousands of years to develop significant deposits.

The deep sea contains five major physiographic zones: continental slopes, abyssal plains, mid-ocean ridges, seamounts, and deep ocean trenches (Fig. 2.1). Along the continental slope the seafloor rapidly descends to depths of between 4,000 and 6,000 m, to level off into immense, sediment-covered areas known as abyssal plains. These, in turn, are interrupted by mid-oceanic ridges, which encircle the entire globe, and seamounts, undersea extinct volcanoes that rise high above the seafloor. Trenches, in contrast, are deep ocean depressions generally reaching depths beyond 6,000 m. The Challenger Deep in the Marianas Trench, named after H.M.S. *Challenger*, extends to a depth just shy of 11,000 m in the western North Pacific - the greatest depth registered anywhere in the ocean.

Understanding the formation of these zones and its effect on the distribution of their mineral deposits requires an understanding of the process of plate tectonics.

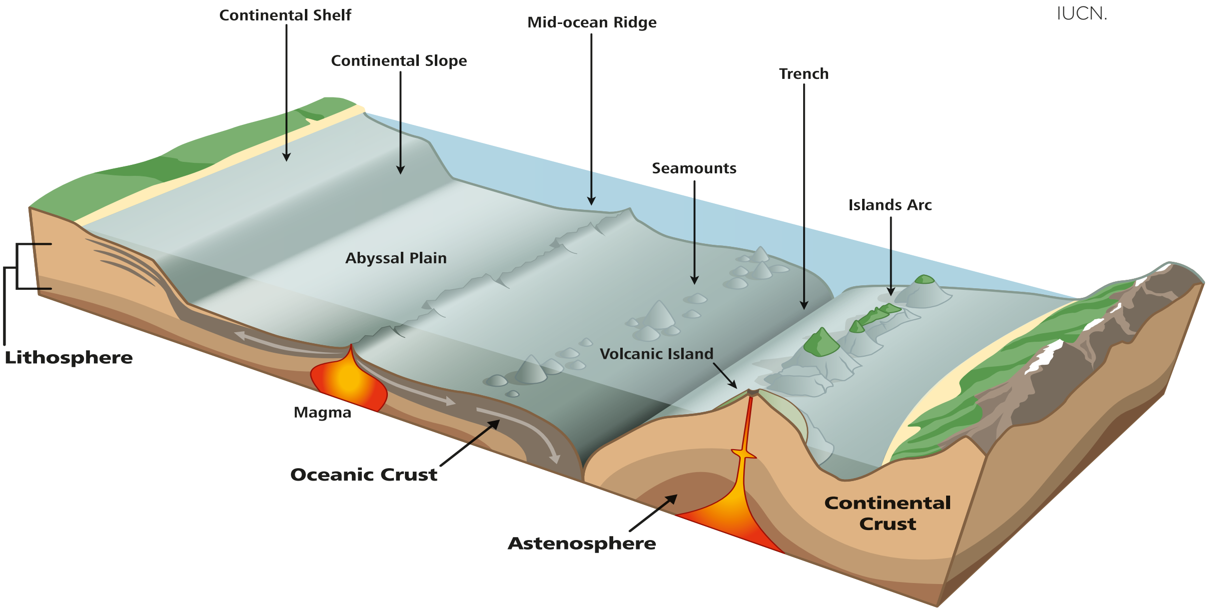

Figure 2.1
A simplified representation of the seafloor's topography. Abyssal plains are by far the predominant feature, covering some 70 percent of the seafloor. The area from the abyssal plain to the coast, including the continental shelf and slope, totals about 27 percent, leaving only a small portion of seafloor for ridges and trenches. Source: Global Marine and Polar Programme, IUCN.

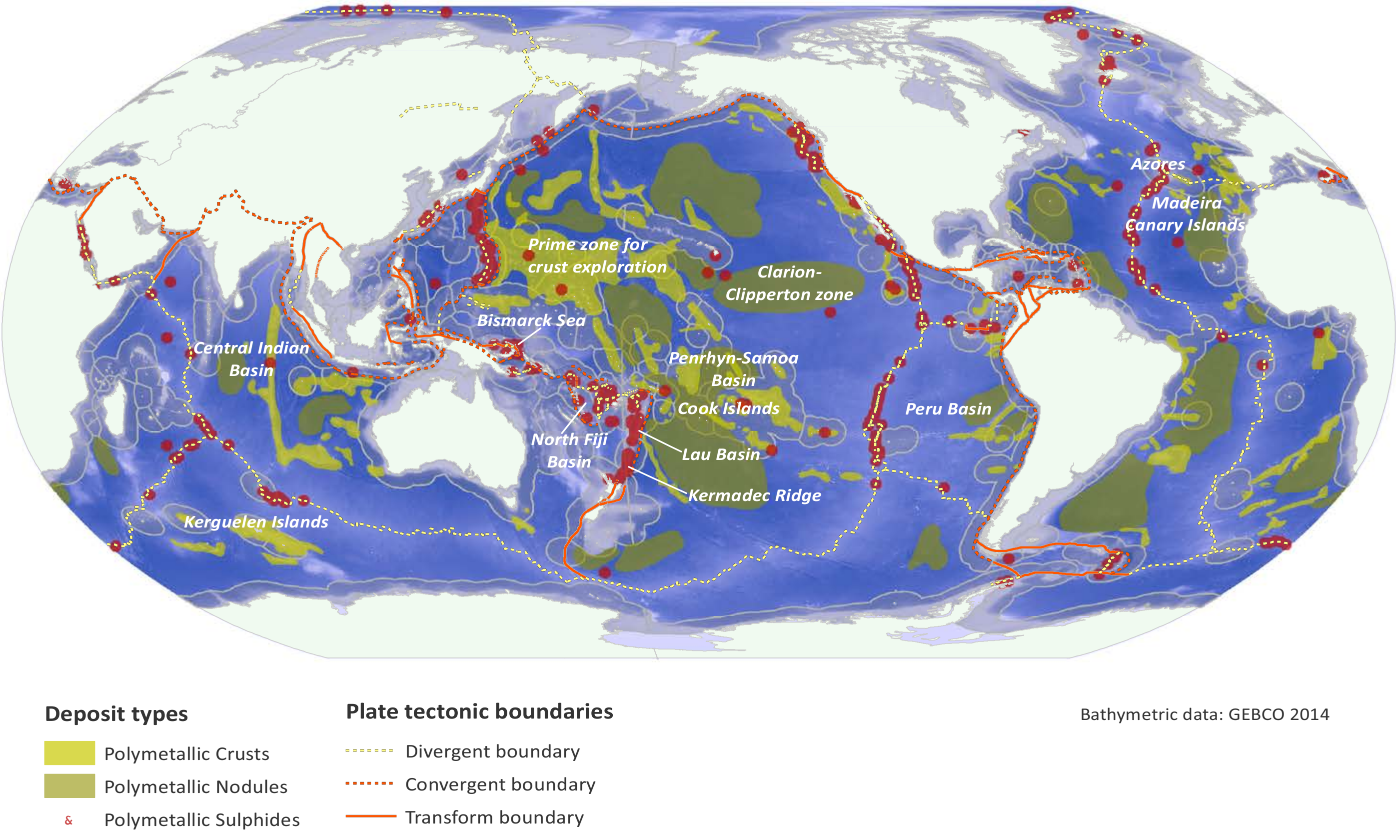

Figure 2.2
Major occurrences of deep-sea metal-bearing minerals within a plate tectonic context.

Data: polymetallic nodules and crusts Hein & Petersen (2013); Fouquet (2012); Major Hydrothermal Vents – Sulphides deposits (Fouquet 2012; and International Seabed Authority (ISA). Coordinate System: World Robinson centred on 200 degree meridian; Bathymetric data GEBCO 2014; Plate tectonic boundaries: simplified from the Neftex Geodynamic Earth Model (© Neftex Petroleum Consultants Ltd) Map created by Caroline Wilhem; updated and re-coloured by Michael Vollmar.

Principles of plate tectonics

The theory of plate tectonics confirms that the Earth's rigid outer layer (the lithosphere) is divided into several plates that move across the partially molten upper layer of the planet's mantle (the asthenosphere). There are three major ways in which the plates interact with one another: they can move away from each other - a process known as spreading; they can collide – a process which, in the ocean, usually entails one plate being forced under the other – a process known as subduction; or they can grind against one another, creating fault lines.

Spreading occurs when hot magma, fuelled by upwelling in the mantle, rises and cools to form new oceanic crust. As it continues to move away from the spreading axis, it sinks deeper into the asthenosphere (Figure 2.1) leaving the ridge axis as an elongated deep-sea mountain range. Actively spreading ridges can be located in the middle of the ocean, as is the case in the Atlantic, or away from its centre, as seen in the eastern Pacific (Fig. 2.2). On either side of the ridge axis abyssal plains usually form. Spreading zones create divergent boundaries and are generally characterized by active volcanism. The intensity of volcanic activity and the topography of ridges varies according to the spreading rate.

When oceanic plates collide, the denser plate will be forced under the lighter one to create a convergent plate boundary. In the process, deep-sea trenches are formed, descending anywhere from 7,000 to more than 10,000 m below the surface. Subduction zones are geologically complex because tectonic, sedimentary and magmatic processes vary from one zone to another, greatly influencing the composition of the associated rocks and minerals. Subduction zones are generally characterized by high amounts of volcanism with a wide variety of geochemical and geological components.

Another geological feature associated with subduction zones can be found in the Western Pacific Ocean, where the subducting plate can create geological rifting features known as back-arc basins. The spreading ridges of these basins can be dormant, as in the Japan Sea, or active, as in the Lau Basin and North Fiji Basin (Fig. 2.2). Due to their magmatic activity, geochemical composition and accessibility (i.e. their proximity to land and their relatively shallow depth), back-arc basins may offer attractive commercial prospects for deep-sea mining.

A third type of oceanic plate boundary is the transform fault, which is caused by differences in plate motion at divergent boundaries, thereby offsetting the mid-oceanic ridge and creating fractures in the ocean floor that can continue for hundreds of kilometres. The Clarion-Clipperton Fracture Zone (Fig. 2.2) is one of several Pacific fracture zones, extending more than 7,000 km across the northern portion of the East Pacific Rise. It is characterized by major canyons and vast abyssal plains with high concentrations of polymetallic nodules. The Atlantic Ocean contains many fracture zones as well, all of which are associated with the Mid-Atlantic Ridge, while the seafloor of Indian Ocean is characterized by relatively few fracture zones.

Polymetallic nodules

Polymetallic nodules, also called manganese or ferromanganese nodules (Fig. 2.3), consist of spherical mineral concretions typically ranging from 5 to 10 cm in diameter. Although composed principally of manganese and iron hydroxides, they also contain nickel, copper and cobalt, along with traces of lithium, molybdenum and various rare-earth elements (Table 2.1). Manganese nodules were discovered throughout the deep sea by scientists aboard HMS *Challenger*, which undertook the first full-scale investigation of the ocean during the 1870s. In the 150 years since, polymetallic nodules have been found by various expeditions in all of the world's oceans.

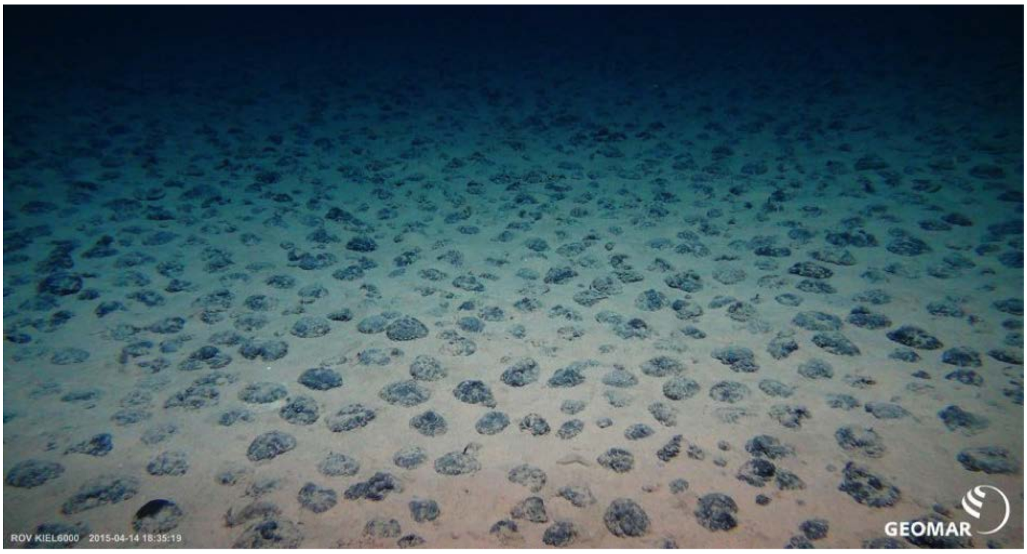

Figure 2.3
Half-buried polymetallic nodules on the seafloor in the Eastern Pacific's Clarion-Clipperton Zone (CCZ) at a depth of some 4,500 m. Nodule concentrations of this nature are found over extensive areas in the CCZ, making it one of the most interesting targets for deep-sea mining operations. Photo ROV Kiel6000, Courtesy GEOMAR.

The formation of polymetallic nodules

Polymetallic nodules originate from specific sedimentary and chemical processes that typically take place in abyssal environments. This environment is characterized by slow sedimentation rates, caused in part by distance from land and low primary productivity, which reduces the quantity of material available for settlement to the seafloor. Under productive waters, skeletons of calcareous and siliceous plankton provide much of the sediment supply, but in waters below 4,000 meters calcareous material usually dissolves, reducing sedimentation rates.

The nodules are formed when dissolved metal compounds precipitate around a small nucleus, typically some debris or a fossilized bone, shark tooth or shell fragment. Growth is concentric and extremely slow, ranging from 1 to a few hundred mm per million years, depending on location and the precipitation process (Hein et al., 2013). There are two types of growth process: hydrogenetic and diagenetic. The hydrogenetic process involves precipitation of metallic compounds from the surrounding water and can occur at any latitude and depth, but the nodules require the specific environmental conditions of abyssal plains for their formation (Fig. 2.4). Diagenetic nodules, in contrast, form within the sediments and use metal-enriched water in pores within the sediments as a source of metallic compounds. Most nodule growth occurs from a combination of the two processes, with the relative influence from each process depending on location.

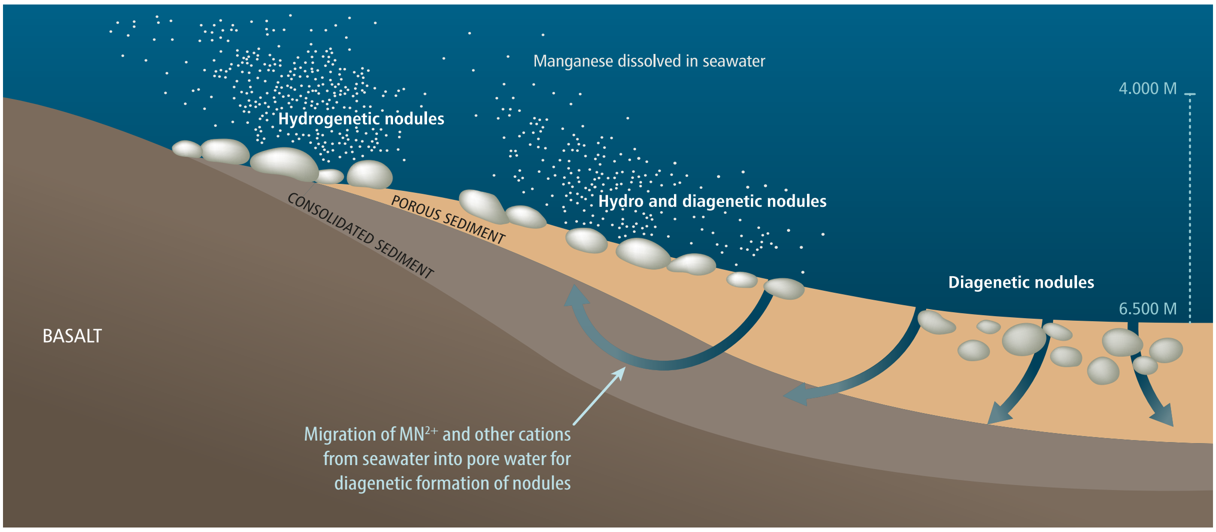

Figure 2.4 The formation of polymetallic nodules. Adapted from Hein & Petersen (2013a) and World Ocean Review (2014).

High-grade nodules generally form below the Calcium Carbonate Compensation Depth (CCD), i.e., the depth at which carbonates dissolve as a result of low temperatures and high pressure, resulting in lower sedimentation rates. They also tend to be more abundant in areas with oxygenated bottom waters that favour bacterial activity (Hein et al., 2013). Because the growth rate of nodules is much lower than the accumulation of sediments, it is not entirely clear how the nodules remain at or near the seabed surface. Aside from very slow sedimentation rates, active bioturbation and bottom current processes have been suggested as possible contributions to this process.

Distribution

Nodule composition, growth, distribution and abundance are influenced by various factors, including topography, local and regional hydrodynamic conditions, bioturbation, primary productivity of the overlying surface water, sedimentation rates, and bacterial activity (Fouquet, 2012; Morgan, 2012; Hein & Petersen, 2013a). The most extensive field of nodules is located in the Clarion-Clipperton Fracture Zone (CCZ) in the central Pacific (Fig. 2.2), a region that has been of interest to mining companies since the first nodule recovery efforts in the 1970s. Other major nodule fields occur in the Peru and Penrhyn Basins, in the Central Indian Basin (Hein et al., 2013), and on both sides of the Mid-Atlantic Ridge.

Additional nodule fields may yet be discovered, but the above regions currently attract most commercial interest. In the CCZ alone, for instance, manganese, nickel and cobalt deposits are estimated to amount to more than the total known land-based reserves (Hein & Petersen, 2013a). Nodules found within the CCZ also contain promising concentrations of rare earth elements (REEs) used in high-tech applications.

Polymetallic crusts

Polymetallic (or ferromanganese) crusts occur as pavements and coatings on sediment-free rocks at the surface of geologically stable seamounts, ridges and plateaus (Fig. 2.5). They are found throughout the entire ocean at depths ranging from 400 to 7,000 m, and can reach a thickness of 25 cm. Like polymetallic nodules, they contain high concentrations of iron and manganese hydroxides, cobalt, copper and nickel, along with trace concentrations of other metals and rare earth elements (Table 2.1). These metals are used in high-tech and green-technology applications, making polymetallic crusts, and especially those located in depths above 2,500 m, a potential candidate for deep-sea mining operations (Hein et al., 2010).

The formation of polymetallic crusts

Seamount reliefs create conditions that favour the hydrogenous processes needed for the formation of ferromanganese crusts. Ocean currents create upwelling and turbulent mixing along the flanks and over the summits of seamounts, preventing and reducing the deposition of sediments. Upwelling also fosters hydro- and geochemical conditions that favour the precipitation of metals and other elements (Hein et al., 2013). Growth is hydrogenetic and very slow: no more than 1 to 5 mm per million years (Hein & Petersen, 2013b).

Figure 2.5
Though most polymetallic crusts are located on seamounts at depths between 1,500 and 2,500 m, they can be found much deeper as well. These crusts were discovered at a depth of 4,500 m on the southern slope of the Takuyo Daigo seamount, located 1,800 km southeast of Japan. Courtesy Japan Agency for Marine-Earth Science and Technology (JAMSTEC).

Distribution

Although seamounts occur throughout the oceans, they are most abundant in the Western Pacific. Ferromanganese crust thickness increases with time and is thus directly related to the age of the ocean floor. The oldest Pacific oceanic crust is around 160 million years old and is found in the northwest Pacific, where many seamounts are located. High metal concentrations have been detected in polymetallic crusts in this region, causing it to be designated the Prime Zone for Crust exploration (PCZ) (Hein et al., 2013) (Fig 2.2). A mine-site model based on geological and geomorphological criteria indicated potential deposits at depths from 1,500 to 2,500 m as a result of the distribution of the crusts and the characteristics of the seamounts in the region (Hein et al., 2009).

Ferromanganese crusts on seamounts in the central Pacific are estimated to contain about four times the cobalt, three and a half times more yttrium, and nine times more tellurium than the entire known land-based reserves of these metals (see a review of metal concentration and tonnages in Hein & Petersen, 2013b). Although fewer seamounts occur in the Atlantic, deep-sea ferromanganese crusts with potential commercial appeal have been identified on the Rio Grande Rise in the South Atlantic (Fig. 2.2).

Seafloor massive sulphide deposits

Seafloor massive sulphides are the only metal-bearing deposits of (current) commercial significance that form at active plate boundaries. Though they are mostly located in association with oceanic ridges, massive sulphide deposits can also be found near volcanic island sites and in island arc systems (Figure 2.1), at depths ranging from 800 to 5,000 m. More than 300 high-temperature hydrothermal venting sites have been identified; 165 of these present significant massive sulphide accumulation. The deposits contain high concentrations of copper, zinc, lead, arsenic, cobalt, silver, gold and other metals (Table 2.1), depending on their tectonic context, but not all are of economic interest (Petersen et al., 2016). Additional field and laboratory studies on grades and tonnages of specific sites are required to test their economic viability.

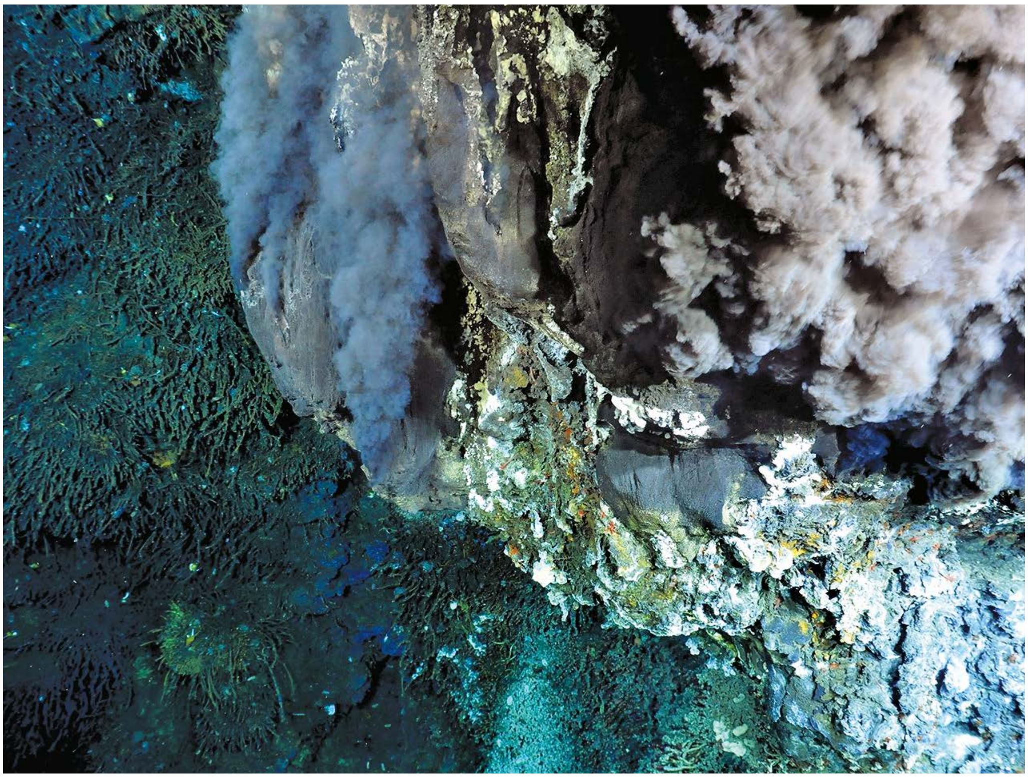

Figure 2.6
Clouds of hot vent fluid pour out of the 45m-tall Godzilla hydrothermal vent in the Endeavour Ridge rift valley, near the northern end of the Juan de Fuca Ridge. The site, located off the Pacific Northwest coast, lies at a depth of more than 2000m and features several high-temperature hydrothermal vent systems. The superheated fluid, which can reach temperatures of several hundred degrees C, contains high concentrations of minerals, some of which precipitate below or above the surface to form the vent structures (aka black smokers). Courtesy Ocean Networks Canada.

The formation of sea-floor massive sulphides

Massive sulphide deposits are the result of seawater circulation within the oceanic crust. High pressure forces cold seawater deep into the seafloor, causing the water to superheat and accumulate metal sulphides from the surrounding rock. The resulting hot fluid decreases in density and is pushed upwards to the seafloor where it is expelled from hydrothermal vents (Fig. 2.7). A portion of the minerals may precipitate to form chimneys and mounds; the majority is transported as a plume and deposited as particulate debris.

Hydrothermal fields have been observed to group around as many as fifty chimneys and can remain active for tens of thousands of years. For commercially significant deposits to form, specific geological conditions are required, including sediment input to trap metallic compounds and to stimulate metal precipitation. An example of this process can be seen at the Middle Valley Site of the Juan de Fuca Ridge, where an estimated 15 million tons of ore deposits can be found, making it one of the largest sulphide deposits known (Fouquet, 2012).

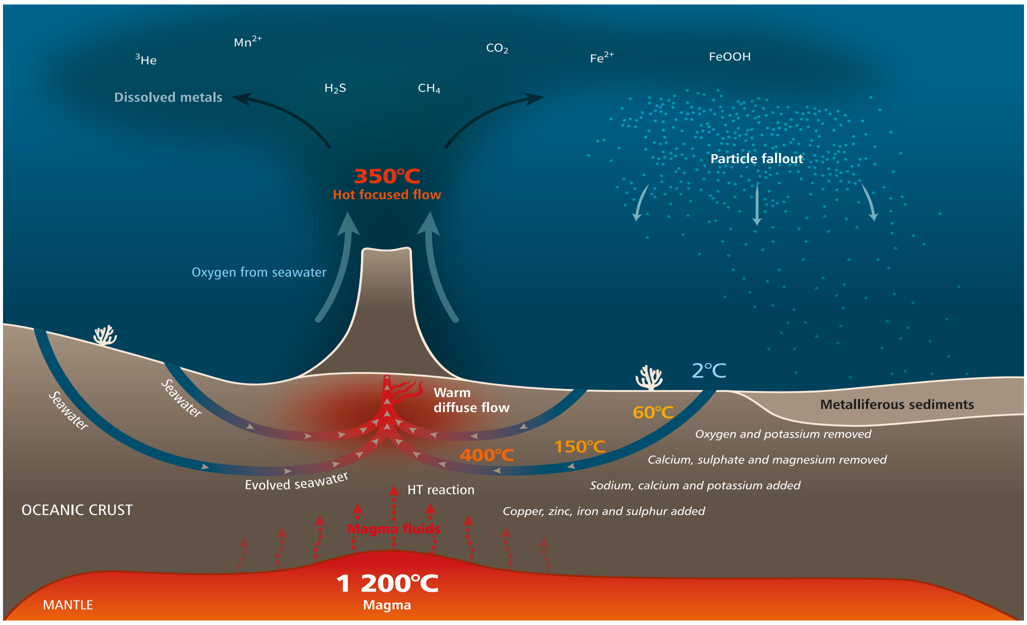

Figure 2.7
The formation of polymetallic chimneys (smokers) and seafloor massive sulphide deposits. Adapted from Hein & Petersen (2013c).

Hydrothermal vents that occur in ridge-spreading settings are classified into three distinct geological environments: slow (<4cm/year), medium (4-10cm/year) and fast or even ultra-fast (> 10cm/year) spreading ridges. Slow-spreading ridges like the Mid-Atlantic Ridge generate extensive hydrothermal vent fields that can remain active for thousands of years, creating conditions that are favourable for the formation of massive sulphide deposits. The intensive tectonic activity associated with rapid-spreading settings along the East Pacific Rise and some back-arc basins, in contrast, creates unstable hydrothermal fields. Some of these may be active for no more than a few decades, their fluid flow having been altered or shut down because of seismic activity. The process can be reversed, with inactive sites reactivating within similarly short time spans as a result of nearby volcanic or earthquake activity. Short cycles of activity generally preclude the accumulation of vast mineral deposits, though their proximity to land and relatively shallow depths can still generate commercial interest.

Aside from the type of plate boundary, the composition of hydrothermal sulphides varies in accordance with the physicochemical conditions of the water and the nature of the underlying rocks from which the metals are leached. Deposits generally contain around 8% zinc, with a noted increase in concentrations at ridge axes and back-arc basins. Silver and gold are also found within seafloor massive sulphides. Back-arc settings favour the inclusion of silver and gold; proximity to land and the associated supply of sediments increase lead and arsenic concentrations (Fouquet, 2012). Deposits with high concentrations of copper, gold and cobalt have also been identified at the Northern Equatorial Mid-Atlantic Ridge (Cherkashov et al., 2010).

Type	Description	Volume	Metals	Principal deposits
Seafloor Massive Sulphides (SMS)	Concentrated deposits of sulphidic minerals (>50-60%) resulting from hydro-thermal activity on the seabed	Up to several km^2; up to tens of metres thick	Pb, Zn, Cu, Co +/- Au, Ag, As, Al, Si, REEs	Red Sea, back-arc basins, mid-oceanic ridges and other plate boundaries, oceanic hotspots (intra-plate volcanoes)
Polymetallic nodules	Concretions of layered iron and manganese oxides with associated metals from the water column or sediment	Nodules: average 5-10cm; deposits: up to thousands of km^2	Mn, Ni, Cu, Co +/- Mo, Zn, Zr, Li, Pt, Ti, Ge, Y, REEs	Clarion-Clipperton Zone, Peru Basin, Central Indian Ocean and Penrhyn Basin
Ferromanganese crusts	Layered manganese and iron oxides with associated metals on hard substrate rock of subsea mountains and ridges	Up to several km^2; <0.3m thick	Mn, Co, Ni, Cu, Te, Mo, Zr, Ti, Bi, Ni, Pt, W, REEs	Equatorial Pacific Ocean and Central Atlantic Ocean

Table 2.1
Types of metal deposits in the deep sea. Adapted from Analysis of the EconomicBenefits of Developing Commercial Deep-sea Mining Operations in Regions where Germany has Exploration Licenses of the International Seabed Authority. Adapted from Study on Behalf of the Federal Ministry for Economic Affairs and Energy Division I C 4, Project No. 59/15

Distribution

According to our current understanding of the development of seafloor massive sulphides, two major regions have been identified as being favourable for the development of commercially attractive deposits. They include the western Pacific, with its numerous back-arc basins, and the slow-spreading Mid-Atlantic Ridge. Both regions have been explored intensively for their mining potential.

The mid-ocean ridges in the Indian Ocean are characterized by slow and ultra-slow spreading, which makes them a third potential site for commercially significant quantities of seafloor massive sulphide deposits. The Red Sea is considered an area of particular interest due to a slow-spreading tectonic setting in which metal-bearing muds are deposited directly on the seafloor. It is one of the most important hydrothermal deposit sites known and contains millions of tons of ores with commercially significant quantities of zinc, copper and silver.

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Much of the deep-sea floor consist of relatively flat, sediment-covered areas, but there are sediment-free outcrops which support uniquely adapted life-forms, including an astonishing variety of deep-sea corals. Unlike their shallow-water counterparts, the corals manage to build large reefs without the help of photosynthetic organisms, surviving by trapping small organisms from passing currents. So do the brittle stars that perched themselves on this *Hemicorallium* coral, deep beneath the Phoenix Islands Protected Area, one of the largest Marine Protected Areas (MPA) in the world. Courtesy of the NOAA Office of Ocean Exploration and Research.

3. DEEP-SEA ECOSYSTEMS AND BIODIVERSITY

The deep sea, usually defined as that area of the ocean below a depth of 200 m, covers about 65 percent of the planet's surface. Its seafloor exhibits an extensive array of geological features, from immense abyssal plains to towering mountain chains and deep trenches. Life here faces harsh conditions: no sunlight (and hence no photosynthesis), immense pressures, low but generally consistent temperatures and varying oxygen levels. Food is often scarce and, with few exceptions, limited to organic material that slowly trickles down from more productive regions near the surface or to other deep-sea organisms. In spite of these challenging conditions, the deep sea supports a rich and often unique biodiversity.

Deep-sea mining will affect the communities of living organisms near the mining sites; ecosystems which, because of their remoteness, remain poorly studied and understood. The habitats most likely to be affected are those near polymetallic nodule fields on the abyssal plains, on polymetallic crust-covered seamounts, and near hydrothermal vents and seeps.

Abyssal plain ecosystems

Abyssal plain ecosystems are influenced by depth, hydrodynamic regimes, latitude, surface productivity, and changes in climate (Smith, 2013; Galéron, 2012). They are predominantly covered by fine-grained sediments, consisting of silt, clay and the remains of microorganisms. Although abyssal plains appear to be a relatively simple habitat, with large expanses of relatively smooth "mud" supporting a low level of biomass, they are now known to host high levels of species diversity. The Census of Diversity of Abyssal Marine Life (CeDAMar), a field project of the Census of Marine Life, revealed a variety of species of protozoans, bacteria and invertebrates - many of them new to science - in deep abyssal plain ecosystems. The invertebrates include worms, crustaceans, sponges, mollusks and echinoderms like sea cucumbers, starfish, brittle stars and sea urchins. Vertebrates include various species of deep-sea pelagic and demersal fish, including gulper eels, anglerfish, viperfish, and rattails.

By far the largest share of the biomass in and on abyssal plains consists of bacteria, which play an essential role in recycling organic matter (Galéron, 2012). This can be seen when the carcass of a large animal settles on the seafloor, after drifting down from above. Bacteria and scavengers quickly populate the site and will feed on it for months, even years. Apart from these "pop-up" feeding communities, our current understanding of abyssal plains ecosystems suggests no particular pattern of distribution. Some fish, echinoderms, crustaceans and micro-organisms appear to be widely distributed, but other species appear to remain restricted to certain zones (Smith, 2013).

The occurrence on abyssal plains of hard substrates like polymetallic nodules influences life - and the associated ecosystems - on and in abyssal plains as well. The variability in both nodule size and abundance produces heterogeneous habitats that host diverse communities (Smith, 2013). Video transects of the seafloor in the Clarion-Clipperton Zone

(CCZ) nodule fields, which have long been of interest to the deep-sea mining community, reveals species not usually found in sediment-covered areas, including octopuses, fish, crinoids and corals (Vanreusel et al., 2016). This suggests that the fauna associated with polymetallic nodules is more abundant and diverse than that of areas without or low nodule concentrations.

Figure 3.1
A small sponge clings on to life by attaching itself to a polymetallic nodule. As they attract animals that need a hard substrate to settle onto, nodule fields exhibit a larger biodiversity than those parts of the abyssal plains that contain few or no nodules. Photo: ROV Kiel6000, Courtesy GEOMAR.

In spite of these sporadic insights, the inaccessibility of abyssal plains in combination with a lack of funding has constrained scientific exploration, resulting in a poor understanding of their ecosystems. That lack of knowledge, along with the fact that many organisms collected from these depths were previously unknown, invites a precautionary approach to polymetallic nodule mining.

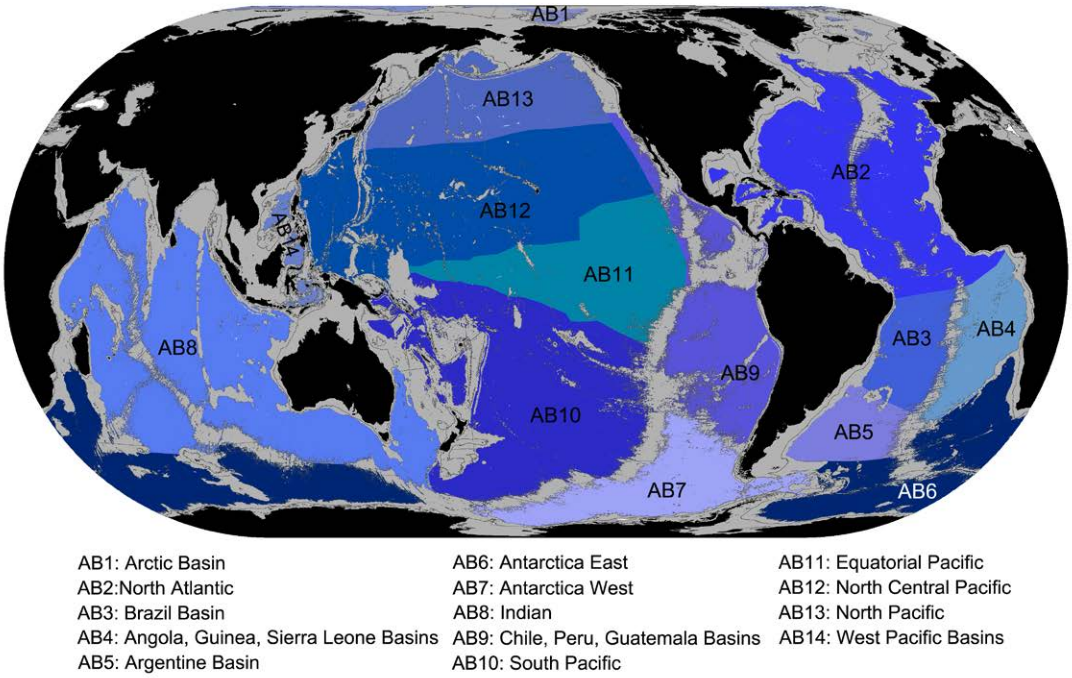

Figure 3.2
A designation of abyssal provinces, based on the deep basin(s) in which they occur. Depth range 800 to 6500 m. From Courtesy of Watling et al., 2013.

Seamount ecosystems

Seamounts exhibit a wide variety of features and characteristics, including size, shape, location, hydrodynamics and climatic setting, creating conditions that often favour an abundance of deep marine fauna. There is evidence that seamounts are biodiversity hotspots, with roughly 800 species of fish identified as specifically associated with seamounts, alongside frequent pelagic visitors like tuna, sharks, cetaceans and sea turtles (Morato et al., 2010).

The seamount surface is typically dominated by filter feeders like corals and sponges fixed onto hard substrates (Fig. 3.3). These organisms influence the existing ecosystem structure by forming reefs and "gardens" that attract more organisms, including crustaceans, mollusks and echinoderms (Rogers, 2012). Cavities and craters may accumulate fine sediment and accommodate fauna similar to that found on abyssal plains.

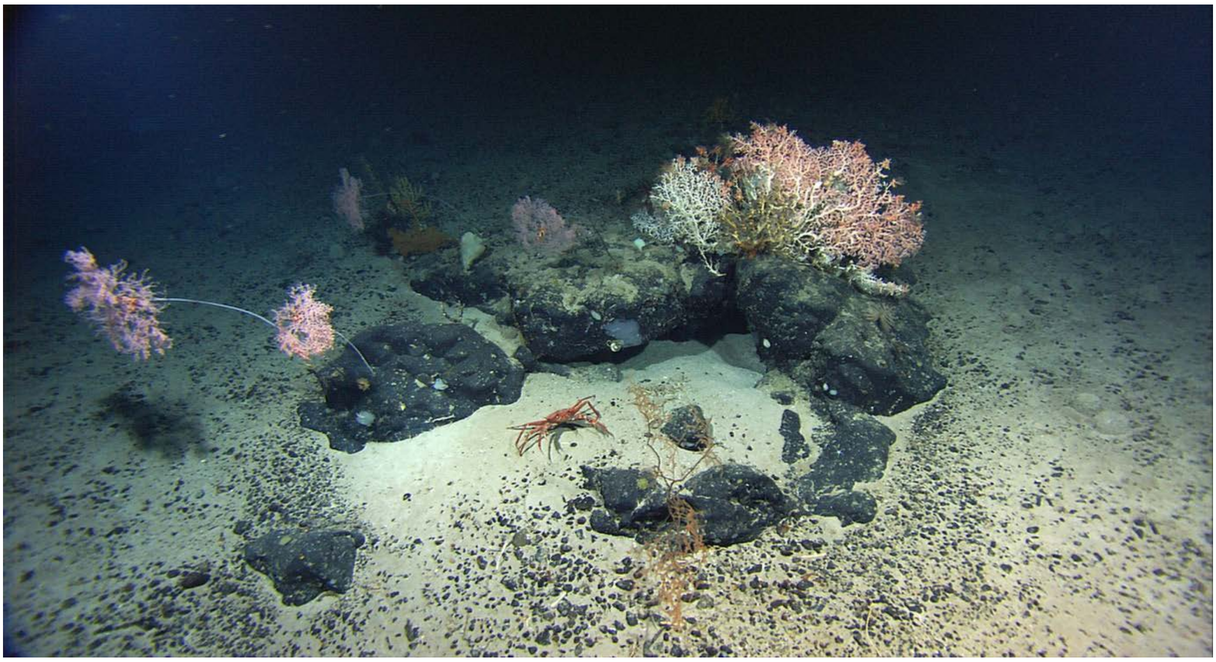

Figure 3.3
A crab defends its territory on a seamount in the North Atlantic. Seamounts host a very rich biodiversity, with corals, crustaceans, sponges and echinoderms among the most frequently found organisms. Courtesy Mountains in the Sea Research Team, NOAA.

This rich biodiversity appears to be made possible by hydrodynamic conditions: seamounts are often subject to strong ocean currents resulting from their steep and exposed profiles, generating residual currents and internal waves. This, in turn, enhances vertical mixing and upwelling of nutrient-rich deep water to the surface, leading to an increase in primary productivity above the seamounts (Rogers, 2012). There is considerable uncertainty about to what extent seamount fauna is endemic. Some studies suggest that as much as 80 percent of sedentary species can be endemic to specific sites, even with short distances separating them from nearby seamounts; others propose a level of long-distance transoceanic dispersal for some species, strongly influencing the evolution of global marine fauna (Rogers, 2012)

Like much of the deep sea, seamount environments remain underexplored and inadequately studied, leaving many questions unanswered. It would make sense to obtain as many answers as possible prior to any mining operations because polymetallic crust removal would unquestionably have a very severe impact on anything living on or within its vicinity.

Hydrothermal vent ecosystems

First observed in 1977 by scientists exploring the Galápagos Rift, deep-sea hydrothermal vents have since been found all along the mid-ocean ridge and island arcs, ancient plate boundaries, and in association with volcanoes. The deep-sea equivalent of geysers on land, hydrothermal vents form when water is forced into seafloor fissures near seismically active sites and is subsequently heated by the underlying magma (Fig. 2.7). In the process the water becomes acidic, enabling it to leach minerals from the surrounding rock on its way back to the seafloor surface. When the mineral-rich superheated fluid is ejected there, it reacts with the cold and oxygenated seawater, causing some of the dissolved material to precipitate, forming hydrothermal vent chimneys and mineral deposits on the seafloor.

Despite the extreme temperatures (up to 400° C) of the superheated water ejected from the vents, the immense pressure near the seafloor, and near total darkness, many hydrothermal vents are home to unique ecosystems with a rich array of life. As there is no light for conventional chlorophyll-based photosynthesis, its primary producers rely on chemosynthesis to create organic matter on which other organisms can feed (Galéron, 2012). Over 500 species, virtually all of them new to science, have been identified in deep-sea hydrothermal vent ecosystems, including bacteria, polychaetes, gastropods, crustaceans and fish.

Because there can be major differences in temperature, chemicals and plume flow from one hydrothermal vent system to another, the biodiversity they support usually differs as well. Hydrothermal vent systems in the Eastern Pacific (Fig. 3.4), for instance, support very different ecosystems from those of the Atlantic (Fig. 3.5) and from those in back-arc basins of the Western Pacific (Fig. 3.6). There can even be major differences in species composition in systems located near one another, suggesting very high levels of endemism (Galéron, 2012).

Figure 3.4
Giant tube worms (*Riftia pachyptila*) are frequently found at hydrothermal vent sites along the East Pacific Rise, but not in the Atlantic or Indian Ocean. The worms can grow to a length of 1.5 m in less than two years. Courtesy NOAA Okeanos Explorer Program, Galapagos Rift Expedition 2011.

Events like submarine earthquakes or shifts in volcanic activity can also have a major impact on the development of these ecosystems. Fundamental differences exist between hydrothermal vent habitats that are found in slow-spreading seafloor zones and those found in fast-spreading settings, including their spacing and longevity, which are determined by tectonic or volcanic activity (Van Dover et al., 2018).

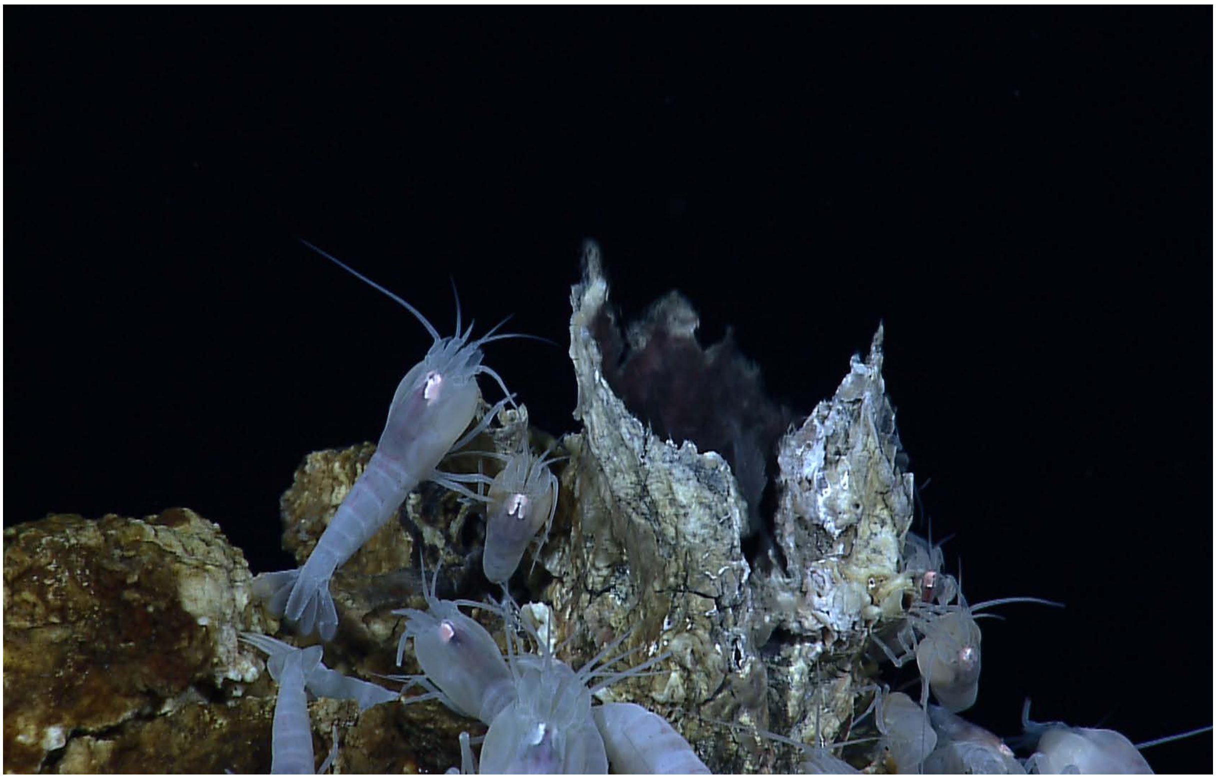

Figure 3.5
Deepsea shrimp (*Rimicaris exoculata*) crawl atop a deep-sea vent in the Mid-Atlantic Ridge to feed on microorganisms that grow along the sides of the chimney. This unique shrimp thrives in warm sulfide-rich water at depths up to 3600 m. Courtesy NOAA.

Inactive hydrothermal vent fields and inactive chimneys in active sites have lost their chemosynthetically-based communities but provide large surfaces of hard substrate on which benthic suspension-feeding animals like corals and sea urchins can be found. These species are often slow-growing and long-lived (Fisher et al., 2013) and would obviously be affected if the site were mined and levelled. Inactive vent systems in fast-spreading zones like the East Pacific Rise and some back-arc basins can reactivate as a result of seismic or volcanic disturbance, dramatically changing biodiversity over short time spans. Like their counterparts on active sites, ecosystems found at inactive hydrothermal vent sites need much additional research to be fully understood (Levin et al., 2009; Van Dover, 2011).

Figure 3.6
Shrimp and crabs cover a hydrothermal vent releasing extremely hot fluid (up to 365°C) at a depth of 3,500 m in the Mariana back-arc basin. Others fauna nearby includes mussels, limpets, anemones and bristle worms, some of which unique to back-arc basins. Courtesy Schmidt Ocean Institute.

Back-arc basin ecosystems

As mentioned in Section 2, the western rim of the Pacific Ocean is fringed by a complex arrangement of relatively young basins formed by back-arc extensions (Fig. 2.2). The basins favour the development of unique fauna and, in part as a result of their relative accessibility (i.e., their proximity to land and relatively shallow depth), have proved to be a superb natural laboratory for the study of hydrothermal vent ecosystems. That accessibility also appeals to mining companies, with some the deposits likely to be developed before other deep-sea minerals. For this reason, it is important that industry and the scientific community cooperate to conduct a thorough investigation of back-arc hydrothermal vent systems prior to the onset of large-scale mining operations.

Recovery rates of deep-sea fauna

Vent fauna

There are major differences in the fauna observed at active and inactive vent sites. Active vent fauna that is associated with volcanic activity appears able to recover relatively rapidly from major disturbances like volcanic eruptions, as has been noticed on the Juan de Fuca Ridge, the East Pacific Rise and in the Mariana Arc. There also is evidence that active vent fauna can adapt to higher concentrations of heavy metals; conditions that would probably be toxic for organisms located at inactive sites (Boschen et al., 2013, Van Dover, 2011). However, recovery time for slower growing and long-established vent communities on mid-ocean ridges, where large ore deposits may be located and where major disturbances are infrequent, remains largely unknown. Though long-lasting active vent sites may be recolonized after mining, there is no certainty about which species would be involved, how species interactions might change or how long recovery might take (Van Dover et al., 2018).

Abyssal fauna

Many abyssal animals are surface-deposit feeders, relying upon recently-settled particulate matter from the water column, or suspension feeders that trap particles before they settle on the sea-floor. Sea-floor habitats in abyssal nodule regions are believed to be physically stable. Organisms living in nodule fields hence are unlikely to be able to cope with disturbance (Baker & Beaudoin, 2013b); an observation confirmed by studies analyzing life within the test mining tracks created in the 1970s in the Clarion-Clipperton Zone (Miljutin et al., 2011, Vanreusel et al., 2016).

Seamount fauna

The dominant benthic fauna on seamounts consist of sessile organisms like corals and sponges. These may include species that are widely distributed as well as organisms that are endemic or specific to a small region. Their slow growth rates and high longevity make recovery from disturbance either unlikely or very long-term, especially on isolated seamounts (Clark et al., 2010).

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Deep-sea mining will affect different species differently. The octopus, seen here at a depth of 2422 m on a seamount, would be able to move in time; sessile organisms like the orange stalked crinoid next to it will not. Courtesy NOAA/Monterey Bay Aquarium Research Institute.

4. DEEP-SEA MINERAL EXTRACTION

Whether at sea or on land, there are four basic ways to mine for a mineral deposit: scraping it from the surface; excavating it by digging a hole, tunneling to a deposit beneath the surface; or directly drilling into it. Once the resource is obtained through one of these methods, it must then be transported, processed, and refined into a marketable product. As refinement usually calls for the raw material to be reduced in size multiple times, the remaining unneeded materials need to be disposed of or, if possible, used for other purposes.

Deep-sea mining poses new challenges as it must be conducted deep beneath the ocean's surface in extreme environmental conditions using remote technology. To meet these challenges, modern deep-sea mining methods are being designed in consultation and cooperation with other sectors involved in deep ocean activities, including ocean cable-laying, offshore diamond mining, dredging, and offshore oil and gas extraction. All are contributing, directly and indirectly, to developing the technology needed to extract the deposits of most interest: polymetallic nodules and polymetallic sulphides and, possibly at a later stage, polymetallic crusts.

Polymetallic nodule recovery

When mining companies first sought to extract nodules from the Clarion-Clipperton Fracture Zone in the 1970s, they relied on two different types of recovery systems. The Continuous Line Bucket (or CLB) method adapted the principle of the traditional bucket ladder dredge, which was widely used at the time for channel dredging and for the recovery of marine aggregates like sand and gravel. When the CLB system proved impractical in greater depths, the mining consortia focused on hydraulic systems instead, using either pumps or compressed air injected into a pipe string to draw the nodules to the surface. Though hindered by technical constraints and, in comparison to today, relatively primitive positioning technology, three consortia managed to bring up several hundred tons of nodules from the seafloor far below, proving that the hydraulic system worked in a test setting, though not necessarily for the far greater amounts that would need to be recovered in a commercial context.

Since those pioneering efforts, mining companies have made massive progress in terms of mapping the resource and refining the hydraulic mining system, at least on paper. Although their specific plans are proprietary, they all include a (horizontal) seafloor component that moves along the seafloor to collect the nodules; a vertical transport component that lifts the nodules to the surface, and a surface (ship-based) component to handle the continuous flow of nodules and separate them from the transport slurry.

The seafloor component consists of a remotely operated collector that is steered along the seafloor to collect nodules and funnel them towards the vertical transport component, consisting of the pipe string or riser. The equipment needs to be designed to minimize the disturbance of very fine bottom sediments that have settled on the abyssal plains for millions of years. It also will need to be able to contend with the potential clogging capacity of these sediments, and with the immense pressure and increased acidity found at depths between 4 and 6 km. The system will have to remain on site for long periods of time since retrieval and redeployment are time-consuming and costly.

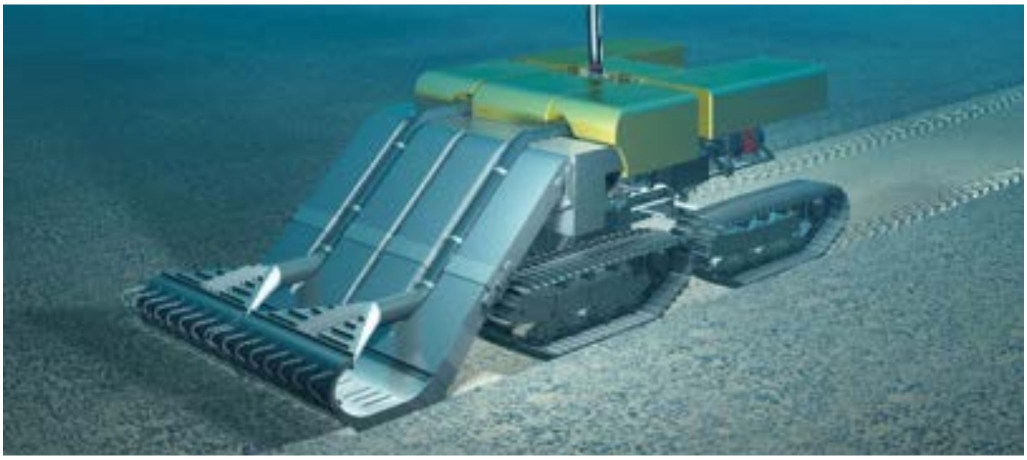

Figure 4.1
Artist impression of a scaled-down seafloor nodule collector (or crawler). In a commercial setting, a collector would need to lift several thousand tons of nodules per day. A full-scale collector would have a width of some 16 m (50 feet). Courtesy IHC Mining.

The vertical transport component consists of a pipe string (riser), which extends for several kilometres from the surface vessel or platform to the collector on the seafloor. A pipe string of that length was deployed successfully on several occasions during test mining operations in the late 1970s, creating confidence that this can be done on a larger scale. Deploying a pipe that long is a costly and time-consuming procedure; hence here too it is essential that the equipment can stay in place and without any malfunctions for long periods of time. Although breakdowns cannot be ruled out when deploying new technology, especially in harsh environmental conditions, the industry anticipates and addresses potential problems by testing and deploying scaled-down versions of the equipment that will be used in commercial operations.

The surface component needs sufficient space to store the nodules and a mechanism to transfer them to storage vessels. It also needs to generate considerable power to pull up the slurry containing nodules, sediment and water from several kilometres below. In addition, there is a need for equipment to separate and clean the nodules, along with space to store and, as appropriate, properly dispose of the fluid portion of the slurry. Unlike offshore platforms, which remain stationary much of the time, the surface component will be mobile, slowly following the track made by the collector(s) below. This requires state-of-the art dynamic positioning equipment to reduce the strain on the pipe string and the seafloor component.

Not including the potential costs added by environmental compliance, polymetallic nodule mining will require major investments, explaining in part why no recovery has taken place since the first mining tests more than 40 years ago. This will require long-term commitments, not only by the operators and their investors, but also by the agencies and organizations that monitor and regulate their operations.

Polymetallic crust recovery from seamounts

Although the concentrations of metals in polymetallic crusts are of economic interest, removing crusts that are cemented to hard substrates is technologically complex, currently very expensive and most likely environmentally destructive (Hein et al., 2009). In comparison to other deep-sea deposits, only a limited amount of research has been devoted to the development of extraction technologies. One possible method of crust mining consists of a bottom-crawling vehicle to remove and fragment the crust and send the pieces to a surface vessel by a hydraulic-pipe lift system. Other systems propose sonic separation of the crust from its substrate followed by in-situ water-jet stripping and chemical leaching (ISA, 2010). Most of the engineering data related to crust mining are proprietary and therefore not publicly accessible (Smith & Heydon, 2013c).

Polymetallic sulphide recovery

In late Summer 2017, the Japan Oil, Gas and Metals National Corporation (JOGMEC) and the Japanese Ministry of Economy, Trade and Industry (METI) reported the successful retrieval of a small quantity of polymetallic sulphides from a depth of 1,600 m in waters off Okinawa. Though both organizations have long shown an interest in deep-sea deposits, the announcement came as somewhat of a surprise, because the first mining operations were expected to be conducted further south, in waters off Papua New Guinea (PNG). But unlike commercial companies that must seek funding, investors, and licenses, JOGMEC was able to plan and develop the operation without comparable restrictions, enabling Japan to become the first country to successfully recover massive sulphide deposits using continuous ore lifting technology.

The announcement brought more information about the technology used in the pilot operation, including an excavator to disaggregate the deposits on the seafloor (Fig. 4.2), a lifting system to bring the ore to the surface, and a surface vessel to store the material and provide support and power to the equipment on the seafloor. The excavator crushed the deposits to the proper size to prevent malfunctioning of the pumps needed to lift the slurry to the surface vessel. No information was provided on the quantity of material that was obtained, although METI reported the amount of zinc in the targeted deposit to be equivalent to Japan's annual consumption, suggesting the area may see more mining in the years to come.

In contrast to Japan's efforts, plans to mine polymetallic sulphides in the Bismarck Sea off Papua New Guinea (PNG) are much more in the limelight, partly due to the cost of the operation and growing local

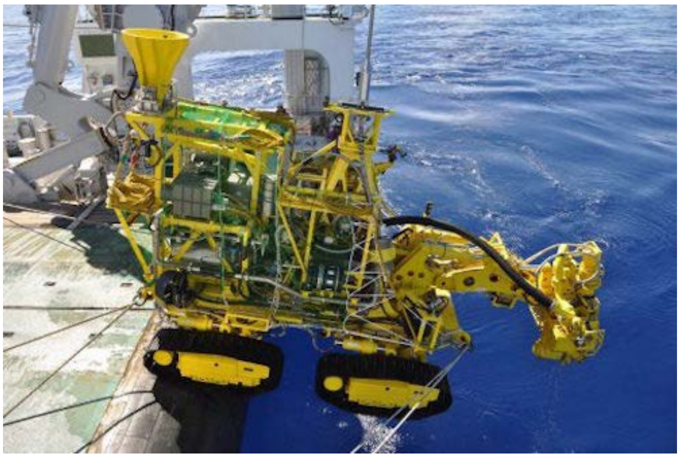

Figure 4.2
JOGMEC's experimental ore collector is launched from the deck of the organization's research vessel *Hakurei*. The equipment collected crushed polymetallic sulphides at a depth of 1,600 m. These were subsequently lifted to a support vessel using submersible pumps and a riser pipe. Courtesy METI/JOGMEC.

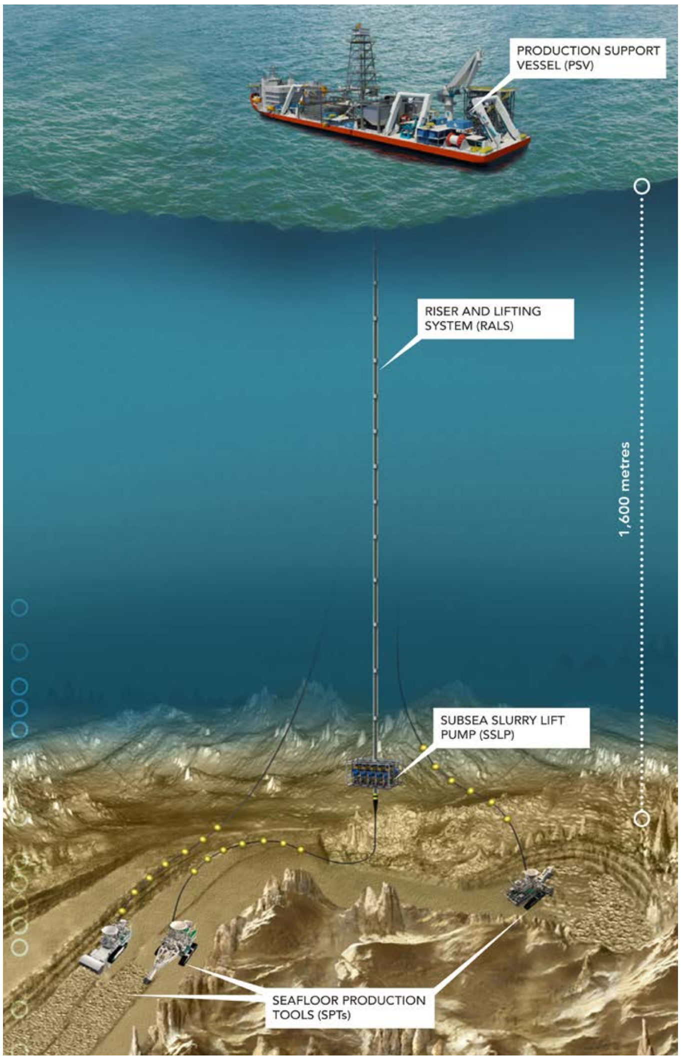

Figure 4.3
Artist impression of the Nautilus Minerals mining system in operation. Unlike polymetallic nodules, which can be gathered by a single seafloor collector, polymetallic sulphide mining will involve several components to excavate and crush the material to the proper size before it can be lifted to the surface. Courtesy Nautilus Minerals, Inc.

opposition. At the centre of the controversy is Canadian company Nautilus Minerals Inc., which was granted several licenses by the PNG government (see section 7). The company has focused most of its efforts on the development of the Solwara 1 site, located some 30 km from the coast at a depth of 1,600 m. Solwara 1 is one of several hydrothermal sites in PNG waters holding high-grade massive sulphide deposits containing copper, zinc, gold and silver. Though its production schedule has encountered considerable delays, the company hopes to deploy its mining system (Fig. 4.3) by late 2019 or or early 2020. A comprehensive overview of other deep-sea technologies for the recovery of polymetallic sulphides is presented in Egorov et al., 2012.

The Nautilus mining system

The current mining approach for the Solwara site is based on remotely operated equipment to crush and excavate the targeted deposits using a continuous cutting process, not unlike bulk mining equipment used on land. Because of the topography of the site, with relatively steep slopes and numerous chimney-like structures, three different excavating machines will be used: the auxiliary cutter, a bulk cutter and a collector (Fig. 4.4).

The Auxiliary Cutter (AC) consists of a boom-mounted cutting head designed to disaggregate the rocks on rough terrain. Once it has done so, the material is further disaggregated by the Bulk Cutter (BC), which has a much higher cutting capacity but is restricted to areas which have been levelled by the AC. The crushed deposits are then gathered by the Collecting Machine (CM), which mixes the ore fragments with seawater and sends the slurry to the Riser and Lifting System.

Figure 4.4
A line-up of nautilus minerals seafloor production tools (SPTs). From left to right the Auxiliary Cutter, the Bulk Cutter and the Collecting Machine. Courtesy Nautilus Minerals, Inc.

The Riser and Lifting system is designed to transport the slurry to the surface using a subsea lift pump attached to its base and a vertical riser system linked to the surface vessel. Once the slurry reaches the ship it passes through a dewatering process, with the solids subsequently transferred to a transport barge for shipment to shore and the remainder pumped back to the subsea lift pump for discharge near the seafloor, the assumption being that this would mitigate the environmental impact.

None of this equipment was tested in a scaled-down version or otherwise derisked at operating depth, which will make for interesting times if and when it finally reaches the mining site. Whether Nautilus' gamble paid off will not be known until 2020 at the earliest.

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A squat lobster settled itself inside a glass sponge at a depth of 845 m off the Sangihe Talaud archipelago, North Sulawesi, Indonesia. A yellow feather star crinoid attached itself to the sponge as well. Courtesy NOAA Okeanos Explorer Program, INDEX-SATAL 2010

5. THE LEGAL FRAMEWORK

Law can be defined as a body of rules, so the legal framework for deep-sea mining covers the rules that relate to the exploitation of the deep sea. The rules for mineral resource recovery are usually drafted and enacted by whomever holds ownership or title over them, and in the case of the deep sea this is simple: it is either a national government entity or the International Seabed Authority (ISA) that does so, depending on whether the deposits are located under national or international jurisdiction. What complicates this seemingly simple setting is that national and international entities are accountable to a wide variety of stakeholders, from environmental organizations which may oppose development to mining companies that seek to unlock the deep sea's mineral wealth. Rule-making thus turns into a balancing act and, like any such act, requires time and caution to succeed.

A brief history

The legal framework for the regulation of deep-sea mining depends on whether the deposits are located within national or international jurisdiction. The boundary between the two is established in the 1982 United Nations Convention on the Law of the Sea (UNCLOS) – a major international treaty that provides rules, principles and guidelines for virtually every ocean use. The long negotiations preceding UNCLOS were triggered by the need to determine to whom the deep sea and its resources belonged.

The issue was first officially raised on 1 November 1967. On the agenda of the 1515th meeting of the First Committee of the General Assembly that morning was Item 92, described as an "*Examination of the question of the reservation exclusively for peaceful purposes of the sea-bed and the ocean floor, and the subsoil thereof, underlying the high seas beyond the limits of present national jurisdiction, and the use of their resources in the interests of mankind.*" As its title indicated, the debate would focus on the ocean floor beyond the limits of national jurisdiction or, to put it simply, that part of it not owned or controlled by nations (and hence unclaimed). By 1967 it had become clear that there were vast mineral resources there, so it made sense to start discussing their legal status and how they should or could be used.

Before the question could be addressed in earnest, there was a need to determine the boundary between the sea under "national jurisdiction" and whatever lay "beyond." That was a problem: a precise division between the two no longer existed. It had until 25 years earlier, when the sea was essentially divided into two major legal zones, both covering the sea from its surface all the way to the bottom and subsoil. On one hand, there was the territorial sea – a narrow belt of ocean adjacent to the coast that was regarded as part of a nation's territory. Beyond that were high seas – a region of ocean not owned nor claimed by any nation and thus free and open to all. The legal picture was relatively simple in those days: just two major zones and all that was needed to separate them was a boundary. Nations didn't necessarily use the same distance to mark that boundary, but it was easily drawn on a map.

Shortly after the Second World War, that clear division became blurred by a new concept of ocean jurisdiction. In a 1945 proclamation, President Truman asserted U.S. jurisdiction over the seafloor not just under its territorial sea, but much further out, all the way to the edge of the continental shelf. To clarify what was meant by that, a press release explained that the continental shelf was "generally" considered to consist of "submerged land contiguous to the coast and covered by no more than 100 fathoms (600 feet or about 183 m) of water," a description largely in line with the geological definition. The motivation behind the claim was clear: securing offshore oil. There was no doubt that the U.S. owned the oil under its three-mile territorial sea, but beyond that the question of ownership had not been addressed. To pre-empt others from suggesting answers, Washington simply informed the rest of the world that, in its view, nothing in international law prevented a state from claiming the mineral resources of its continental shelf.

Figure 5.1
By the early 20th century, American oil companies had already moved offshore, drilling first from piers, later from platforms. As they moved further out to sea, legal questions arose about ownership of the seabed (and its oil) beyond the territorial sea. Courtesy Standard Oil Co (California)

Looking back, the Truman Proclamation was the first major national claim over large tracts of ocean in modern history. Though it ran counter to the way nations treated the ocean at the time, it could be argued that it made sense. Geologically speaking, the continental shelf did form part of the continent, so it was not entirely unreasonable to propose that its resources belonged to the coastal state. But it soon became clear that the American claim created complex problems. A month after the Truman Proclamation, Mexico also decided to claim its continental shelf, but it added "superjacent" resources, a legal term meant to include the fish that swam above it. Other Latin American nations went even further, extending not only their jurisdiction but their sovereignty over the sea and the seafloor. Before long there was so much confusion over who supposedly owned what at sea that the US State Department's geographer was forced to admit in his 1949 Report to Congress that "never have national claims in adjacent seas been so numerous, so varied, or so inconsistent."

To prevent that inconsistency from leading to conflict, the United Nations appointed a body of lawyers and set them to work on drafting a set of uniform rules. Their preparations resulted in four 1958 conventions; two of them dealing with the zones that had existed since times immemorial: the territorial sea and the high seas; a third addressing the legal status of the continental shelf, and a final one dealing with conservation and fisheries. The conventions entered into force during the early 1960s, giving the world its first internationally accepted set of rules for the oceans.

Unfortunately, a few important provisions were not clear. To arrive at consensus, compromises were made, some of which ruled out agreement on the boundaries the conventions were supposed to establish. The Convention on the Territorial Sea, for instance, failed to come up with a width that everyone could accept, but the treaty was approved anyway. And the important Convention on the Continental Shelf codified coastal state jurisdiction over the shelf into international law but rather than stopping its extent at 100 fathoms or some other reasonable depth, it included a phrase so vague one still wonders how it ever got included. According to the assembled lawyers and diplomats, the continental shelf was the seabed adjacent to the coast to a depth of 200 meters or “beyond that limit, to where the depth of the superjacent waters admits of the exploitation” of its natural resources.

That sentence, more than anything else, was central to the debate facing the General Assembly on 1 November 1967. The agenda proposed a discussion on peaceful uses and potential resources of the ocean floor beyond national jurisdiction, but then-existing international law failed to define where that area began. When a definition of the continental shelf was negotiated in 1958, some nations possibly did not anticipate mining or exploiting the sea beyond the 200-meter depth but by 1967 they knew better. Including exploitability in the legal definition of the continental shelf was a clear invitation for technologically advanced countries to claim as much of the ocean floor as their industry (or military) managed to reach.

Some of those technologically advanced nations, the U.S. among them, preferred to keep it that way, but others started questioning its inclusion. Not only that, by 1967 the United Nations numbered far more members than in 1958, including a group of African countries that had become independent in the intervening years. Gradually a desire grew among them and other member states to review some aspects of the law of the sea, or at least figure out where national jurisdiction was supposed to end. Working tirelessly behind the scenes was Arvid Pardo, the Ambassador of Malta, a small Mediterranean island nation that had become a U.N member just three years earlier. It was the 53-year-old diplomat who had requested the topic to be placed on the morning’s agenda and it was he who had now been scheduled to open the debate.

As it turned out, there would be no debate, at least not that day. Pardo spoke for more than three hours, not only taking up all of the 1515th meeting but continuing straight on into the 1516th. By the time he finished, there was no time left for a debate, or much energy from those who attended the entire session. Pardo indeed delivered not a speech but a full-blown lecture, covering the scientific, military, technological, economic and legal aspects of the oceans in considerable detail, prior to coming up with a plea to declare the seafloor beyond the continental shelf the “common heritage of mankind”; to ensure that the immense resources of the deep sea would be exploited with “harm to none and benefit to all.”

Reaction to the speech was mixed. Developing nations were intrigued by the reference Pardo made to what had happened to Africa in the 19th century, when the Great Powers carved up much of the continent to mine and exploit it for their own benefit. The implication was clear: do nothing and the deep sea would befall the same fate. Pardo’s calculations of the billions of dollars that were up for grabs also intrigued them. No wonder they supported a mechanism that would entitle them to a share of it. Pardo also found support among some Eastern Bloc countries, which were averse to any capitalist claims on the seafloor, and even managed to get backing from some West European nations.

The technologically advanced and military powers Pardo had indirectly rallied against were less enamored. Even before Pardo’s speech the topic was described as premature;

a sentiment that was repeated in even stronger terms upon its completion. But Pardo had played this very intelligently. Unlike the ocean and the seafloor, where the rich and powerful might dictate some rules, the General Assembly was a level playing field where strength in numbers counted. And with developing nations in favour of a mechanism that designated the seafloor under more than half of the planet as belonging to all of humankind, the votes stacked up in his favour. Whether the great powers liked it or not, they had been outmanoeuvred. Jurisdiction over all of the seafloor had now been firmly placed on the U.N. agenda. Next up was a discussion to determine to what extent Pardo's proposals ought to be implemented.

Figure 5.2
It took nearly 10 years of negotiations, but in 1982 the UN finally reached consensus on a new Law of the Sea Convention, including a first set of rules and regulations for the deep sea. Courtesy United Nations.

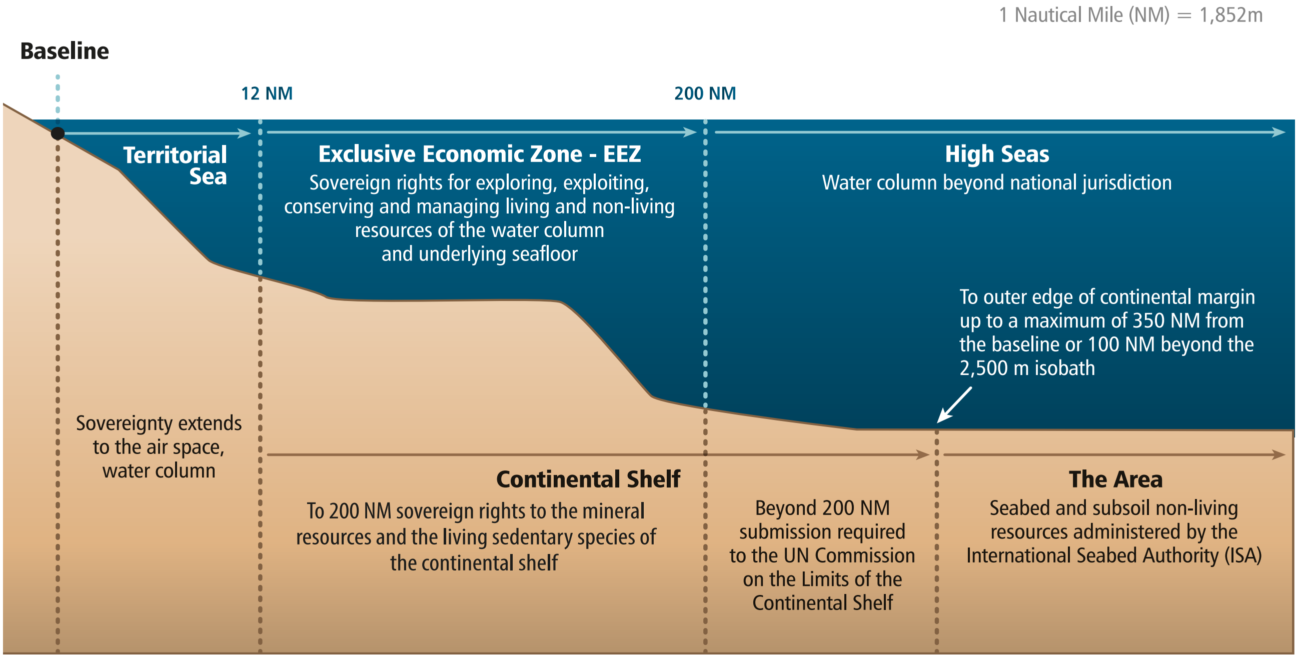
As it turned out, that discussion wouldn't be concluded until 15 years later, when the U.N. adopted its 1982 Convention on the Law of the Sea (UNCLOS). The agreement replaced the four conventions that had been adopted in 1958 and remains the backbone of international ocean law to this day. Like its predecessors, UNCLOS divides the ocean into different jurisdictional zones (Fig. 5.3), three of which relevant to mineral development: the Exclusive Economic Zone (EEZ) and the Continental Shelf, both of which fall under jurisdiction of the coastal state, and the seafloor beyond these zones, which is known as the International Seabed Area (or simply" the Area"). That part, still covering nearly half of the surface of the planet, is designated as the common heritage of mankind (CHM), just as Arvid Pardo proposed more than 50 years ago.

The Exclusive Economic Zone (EEZ)

UNCLOS precisely defines the EEZ: it extends 200 nautical miles (nm) from the baseline from which the breadth of the territorial sea is measured (PART V, Article 57). The EEZs of opposite countries can overlap, in which case the EEZ's extent will be less than 200 nm, depending on the location and configuration of the coast. The countries involved need to figure out a boundary in this instance, preferably by mutual agreement, much the same way adjacent countries should delineate their maritime zones as well.

UNCLOS assigns sovereign rights over all mineral deposits found in the EEZ to the coastal state. In most EEZs this relates to marine aggregates like sand and gravel, or offshore oil and gas deposits, but if an EEZ extends past the continental margin into the deep sea, its resources, whether polymetallic nodules, ferromanganese crusts or massive sulphide deposits, also belong to the coastal state. Ownership and jurisdiction implies the right to grant licenses and exploit these resources. National regulations are subject to the requirement that they shall be no less effective than international rules, standards and recommended practices and procedures, though these have yet to be set. In the interim, applicable requirements include the general obligation to "protect and preserve the marine environment" (Article 192) and a more detailed requirement to minimize "pollution from installations and devices used in exploration or exploitation of the natural resources of the seabed and subsoil" (Article 194.3.c). UNCLOS further calls on states to take measures to "protect and preserve rare or fragile ecosystems as well as the habitat of depleted, threated or endangered species and other forms of marine life" (Article 194.5). This obligation is reinforced by other international agreements, including the Climate Change and Biodiversity Conventions and the 1992 Rio Declaration on Environment and Development.

Figure 5.3
UNCLOS divides the sea into several zones. Coastal states own the mineral resources of the EEZ and Continental Shelf, the Area beyond is the Common Heritage of Mankind (CHM)



The continental shelf

The Continental Shelf as defined by UNCLOS is a legal construct, which broadens the geological definition of the continental shelf to include the outer edge of the continental margin (including the shelf, the slope and the rise - see section 2) and extends it 200 nautical miles regardless of whether there is a (geological) continental shelf of that length adjacent to the coast. As in the case of the EEZ, the coastal state possesses sovereign rights over its continental shelf "for the purpose of exploring it and exploiting its natural resources".

Unlike the EEZ with its clearly defined maximum extent, the continental shelf as defined by UNCLOS can extend beyond 200 nm. To accommodate legitimate extensions, the convention enables nations with wide (geological) continental shelves to claim a portion beyond 200 nm using a number of criteria that limit its extent to 350 nm or a line drawn 100 nm from the 2,500 m depth contour. This so-called extended continental shelf requires approval by a specialized Commission on the Limits of the Continental Shelf (CLCS). As the "deep ocean floor with its oceanic ridges" is specifically excluded from the definition of the continental margin, extended continental shelf claims should not affect deep seabed resources. However, the many applications submitted to the CLCS, each one of which with a specific set of approved or yet-to-be approved outer limits, still create uncertainty about the precise boundary between the seabed under national jurisdiction and that part of it considered Common Heritage of Mankind, a full 50 years after the issue was raised.

National regulation of deep-sea mining

In contrast to nations with wide (geological) continental shelves, there are nations with no or very narrow shelf areas, including volcanic islands or countries located near subduction zones (see section 2). These countries are likely to have extensive areas of deep sea within their EEZ, giving them the exclusive right to explore and exploit deep-sea deposits. Examples include several Pacific island nations, New Zealand and Japan, but also archipelagos like the Azores (belonging to Portugal) and countries that include sections of the mid-oceanic ridge like Iceland.

National legislation regarding the potential development of deep-sea resources within the EEZ is currently under development in a number of countries. The Cook Islands government, for instance, has enacted a national regulatory framework to regulate EEZ mining activities. The principal legislation is the Seabed Minerals Act 2009, which came into force 1 March 2013, as amended by the Seabed Minerals Amendment Act (2015). Environmental considerations are currently covered by the Environment Act 2003, with further regulations planned in order to align it with deep seabed mining. (Lynch, 2011; Pacific Islands Report, 2016). Papua New Guinea's deep-sea mining leases, on the other hand, are based on the Mining Act 1992, as amended to include offshore activities, and the Environment Act of 2000, to be amended by an Environmental Policy on Offshore Mining. Environmental groups have voiced concerns that amendments to existing terrestrial mining legislation may not provide sufficient safeguards for deep-sea mining, given the differences between terrestrial and seabed environments.

To assist Pacific countries with the regulatory process, the Deep-sea Minerals Project of the European Union and the Secretariat of the Pacific Community Applied Geosciences and Technology Division (SPC-SOPAC) produced guidance on regulating deep-sea mining activities in accordance with international law. The project, now completed, supplements an earlier report covering principles for the development of national offshore mineral policies, known as the Madang Guidelines (SOPAC, 1999).

UNCLOS requires national regulations to demonstrate a commitment to marine protection, although the lack of knowledge and expertise about deep-sea environments at government levels in some countries may delay the development and implementation of suitable management and mitigation strategies (Boschen et al., 2013). As emphasized by marine scientists, lawyers and decision-makers, a global approach paired with inter-disciplinary collaboration will be essential to resolving deep-sea mining issues in national as well as international waters.

International regulation of deep-sea mining

UNCLOS designates the sea-bed and ocean floor and subsoil thereof, beyond the limits of national jurisdiction (i.e., beyond the EEZ and the (extended) continental shelf), as "the Area", and states that the Area and its resources are the common heritage of mankind. UNCLOS and the 1994 Agreement relating to the Implementation of Part XI of the United Nations Convention on the Law of the Sea (the 1994 Implementation Agreement), are the fundamental governing instruments for the Area and activities related to its resources

UNCLOS established the International Seabed Authority (ISA) to organize and control activities in the Area. Financial and other economic benefits derived from activities in the Area must be equitably shared, taking into particular consideration the interests and needs of developing countries. Entities that are interested in carrying out activities in the Area must apply to the ISA, following the detailed procedures set out in UNCLOS and the 1994 Implementation Agreement. States Parties (and relevant international organizations) must ensure that activities in the Area are carried in accordance with UNCLOS Part XI. (Article 139).

ISA: REGULATOR AND PROMOTER?

UNCLOS saddled the ISA with a dual mandate: to develop the resources of the Area (for the benefit of humankind) AND to make sure that this development proceeds without harming the environment. It is a somewhat uncomfortable mix of tasks because one mandate implies promoting development to generate revenue whilst the other calls on the organization to draft regulations that could stifle that development.

As long as commercial deep-sea mining remained no more than a remote possibility, this dual mandate wasn't heavily questioned. The organization operated in relative obscurity from Kingston, Jamaica and seldom made the news, except to point out, more for curiosity's sake than anything else, that an entity "controlling" half of the planet's physical surface was staffed by no more than a handful of people.

Now that deep-sea mining is approaching the transition from exploration to exploitation, the ISA will need to get adjusted to considerably more scrutiny. More people and more governments are questioning whether it is a good idea to have an organization that promotes deep-sea development also write the rules that are meant to protect its environment. At the centre of the debate is the mining code which mirrors the ISA's dual mandate to develop and to protect, along with determining how any benefits are to be shared. It can be done, but it is forcing the ISA to contemplate environmental considerations more seriously than it did in the past, when commercial mining remained a distant (and even unrealistic) prospect.

The main driver behind this shift in focus are national delegations, which insist that the ISA strengthens the mining code's environmental requirements. European and other nations, many of which actually interested in the deep sea as a potential source of metals, are driven by environmental concerns; other countries may be motivated by a desire to protect land-based mining. Some Asian nations, on the other hand, are calling for a balance between environmental and commercial considerations that does not unduly delay the publication of the mining code (and along with it the plans of their mining companies).

Aside from environmental considerations, the ISA will also need to draft and implement operational requirements, including safety and inspection standards. As mining in the Area is still years away, there is time to do so but it may make sense to consider transferring some authority to an autonomous or semi-autonomous entity. Promotion and regulation seldom make good bedfellows, especially when something goes wrong. Though a malfunction of deep-sea mining equipment is unlikely to cause the havoc caused by deep water oil drilling or even shipping accidents, it is important to avoid conflicts of interest by ensuring that the promoter is not in charge of enforcement.

Deep-sea mining's (re)appearance on the public radar screen is thus forcing the ISA to live up to its logo and balance its dual mandate – a step that is necessary to ensure that the benefits of any deep-sea mining will also accrue to future generations.

In addition to entering into contracts, the ISA must establish rules, regulations and procedures to ensure effective protection of the marine environment from harmful effects that may arise from activities in the Area (Article 145); this task UNCLOS assigns to the ISA's Legal and Technical Commission. The Commission, which consists of 30 experts nominated by ISA Member States, has a broad list of responsibilities, including reviewing applications for exploration contracts, evaluating annual reports from contractors, setting guidelines for reporting on environmental baseline studies, preparing assessments of the environmental implications of activities in the Area, and drafting rules, regulations and procedures for adoption by the ISA Council.

To date, the Authority has issued Regulations on Prospecting and Exploration for Polymetallic Nodules in the Area (the "Nodules Regulations" - adopted 13 July 2000 and updated 25 July 2013); and similar sets of regulations for Polymetallic Sulphides (the "Sulphides Regulations" - adopted 7 May 2010) and Cobalt-Rich Crusts (adopted 27 July 2012). In conjunction with Commission recommendations for the guidance of contractors, including guidelines for the assessment of possible environmental impacts, these regulations form the so-called 'Mining Code'. The next phase in the development of the regulatory framework is the introduction of regulations governing exploitation. This phase is ongoing and provides an opportunity for public comment and input.

To effectively protect the marine environment from potentially harmful effects associated with deep-sea mining, the Mining Code will need to take into account a variety of factors. This will require regulations and procedures for the protection and conservation of deep-sea biodiversity; the prevention, reduction and control of pollution and other hazards to the marine environment; and the prevention of interference with the ecological balance of the marine environment. Reaching these objectives will require well-defined environmental goals and measurable indicators, along with a high level of transparency with regard to all activities, commercial as well as regulatory (Jaeckel, 2017).

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A close-up of barnacles with tentacles (or cirri) extended to catch micro-organism from the passing vent water on Kawio Barat volcano, Indonesia. Deep-sea mining could affect organisms like these. That impact needs to be included in cost estimates. Courtesy NOAA Okeanos Explorer Program, INDEX-SATAL 2010.

6. THE ECONOMICS OF DEEP-SEA MINING

Advances in technology may permit deep-sea mineral resource extraction, but the high level of required investments raises questions about its economic viability. When all costs - financial, social, economic and environmental - are taken into account, does deep-sea mining still make sense?

This is not a recent question - it was raised nearly half a century ago, when governments and mining companies began eyeing the deep sea as a potential source of strategic minerals and revenue. Since then, financial and economic evaluations have been completed to address the profitability of the sector, identifying the direct financial costs associated with the mining process. There are indirect costs as well, including the potential impact on society and the environment. Although often more difficult to assess, these too need to be included in any economic assessment of deep-sea mining.

The financial cost of deep-sea mining

Estimating the total cost of deep-sea mining involves a range of assumptions and estimates. Terrestrial mining can provide no more than limited guidance, as the technologies and operations required for deep-sea excavation differ in many ways from land-based operations. Successful mining in the deep sea necessitates technologies that must be able to withstand immense pressures, low temperatures and function flawlessly in seawater. In addition, a solid understanding of affected ecosystems is needed to assess the environmental impact of the operations.

Before deep-sea minerals can be lifted from the international deep seabed to the surface, potential operators face considerable costs. First there are expenses associated with applying to the International Seabed Authority (ISA) for an exploration and exploitation contract, including the preparation of Environmental Impact Assessments, obtaining legal and technical advice, and procuring an Economic Feasibility Assessment. Once permission has been obtained from regulatory agencies and investors, capital expenditures (CAPEX) are needed for the design, construction, testing, repair, maintenance and full-scale manufacturing of deep-sea mining machinery (Seafloor Production Tools, Riser and Lifting System, Production Support Vessel - see section 4).

During the exploitation phase, sufficient capital will be needed to cover regulatory costs and operating expenditures (OPEX), including the labour costs of running a mining operation and its infrastructure, fuel for ships and machines at each site, utilities, transport, spare parts, and consumables amongst others. Post-excavation expenses include stripping waste material, processing raw minerals, hauling and treating ore and waste offsite, and producing a market-ready product.

Industry and academia have completed several cost-estimates. One of the first evaluations was conducted in 1976 at the Massachusetts Institute of Technology (MIT), envisaging a 30-year project consisting of a five-year preparatory phase (research & development, mine-site assessment and the construction of a commercial mining system) and a 25-year exploitation phase, recovering 3 million tons of nodules annually in the Clarion-Clipperton Zone. The study revealed a required investment of at least US$560 million, of which US$65 million for R&D and US$496.5 million for equipment, physical facilities and working capital. To convert 1976 dollars to their equivalent today, multiply by a factor of 4.44, yielding a total of nearly US$2,500 million. At the time, the MIT study was considered to be on the conservative side, with other (though less complete) assessments envisaging considerably higher capital and operational expenses.

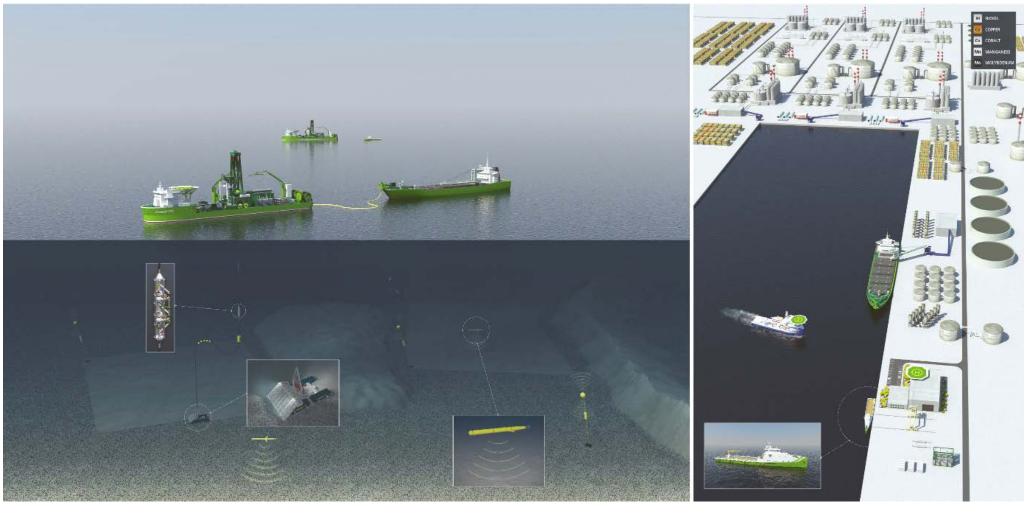

Figure 6.1
Artist impression of a full-scale polymetallic nodule mining and processing operation. To meet the three-million-ton annual target, some 11,000 tons of nodules would have to be brought up every day on average: a production rate that would require two specially-built mining ships along with several bulk carriers to transport the nodules to shore. Processing facilities would require considerable investments as well – a full-scale metallurgical plant could add several billion dollars in capital expenditures (CAPEX). Total annual operating expenditures (OPEX) are estimated at USD1,000 million/year. Courtesy GSR.

In comparison, a recent contractor estimate (Van Nijen, 2018) for an operation envisaging similar annual recovery (i.e., 3 million tons of nodules) but including processing (an activity that is outside the remit of the ISA) estimates some US$360 million spent on R&D (pre-feasibility and feasibility); US$584 million of capital expenditures on the collection system; US$692 million on surface vessels; and US$2,415 million in capital expenditures for the processing plant(s). Operating expenditures would add another US$995 million annually. MIT's latest estimates follow similar lines, projecting CAPEX to amount from US$3,000 million to US$4,000 million and OPEX to range between US$600 million and US$1,100 million (Roth et al., 2018).

Recent cost estimates for seafloor massive sulphide (SMS) deposits reveal capital expenditures, including exploration costs, to be in the vicinity of US$1,000 million - considerably higher than initial estimates. Costs estimates for polymetallic crust mining, in contrast, tend to be based on nodule recovery, with capital and operating expenditures estimated at approximately 50 percent of nodule mining operations. Estimated production volumes are lower than those of the nodule model, however, resulting in higher CAPEX and OPEX per ton recovered and making polymetallic crust mining at present a less attractive commercial option (Rozemeijer et al, 2017).

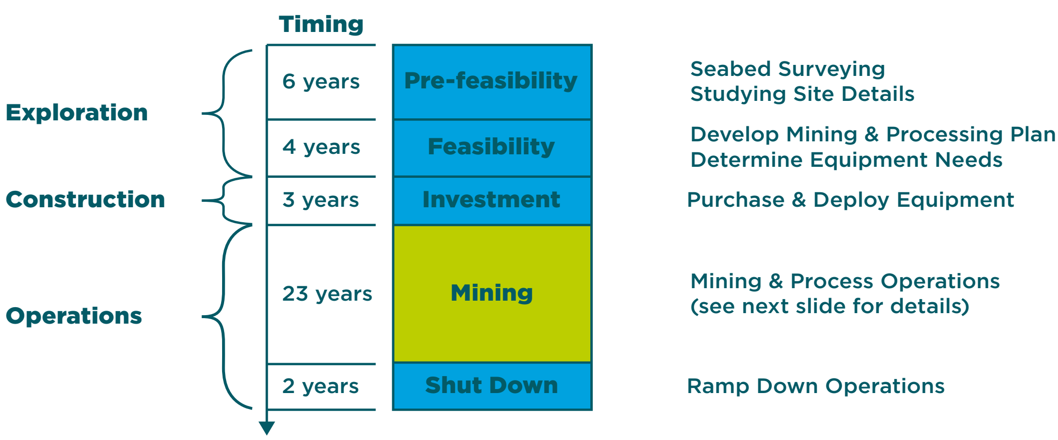

Figure 6.2
A deep-sea mining project schedule typically envisages about ten years of R&D (pre-feasibility and feasibility) and several years of construction and production ramp-up before mining can start. Concessions are expected to last 25- 30 years. Courtesy MIT Materials Research Laboratory.

Figure 6.3
Nautilus Minerals' production support vessel (PSV) after its launch in late March 2018. The ship, along with the three seafloor production tools (SPTs) represent a considerable share of Nautilus' upfront costs. It is expected to be delivered Spring 2019. Courtesy Nautilus Minerals, Inc.

These estimates do not include an assessment of financial costs incurred at the governmental level, including a robustly structured regulatory regime; scientific, technical and environmental advice sought by regulatory agencies; funding for insurance and liability structures; or the cost for public consultation and other transparency measures. Environmental mitigation and restoration efforts will also be required as part of the exploitation license, adding a yet-to-be determined additional cost.

The societal cost of deep seabed mining

The economic and societal costs of deep-sea mining, and in particular the impact on the natural capital of the deep sea, need to be considered as well. These costs are difficult to ascertain, given gaps in knowledge and understanding of the deep sea, including such aspects as ecosystem functioning, connectivity, vulnerable species, recovery rates, and spatial and temporal variations (section 3). A range of methods (direct use, non-use, bequest value) have been utilized for the economic valuation of ecosystem services, all of which could be considered.

The potential for losses in the form of impacts on this biodiversity and ecosystems services are incompletely known and will require further analysis. The degradation of water quality and ecosystems resulting from deep-seabed mining will likely result in loss of biodiversity and other effects at a local level, and may affect adjacent areas as well. It is not possible to assign an accurate value to the existence of any particular species, but the interconnectivity of ocean biodiversity leads to the assumption that the extinction of a species, or the destruction of an ecosystem, could have severe repercussions. In addition, the deep ocean and seabed are responsible for large amounts of carbon sequestration. Whether that capacity would be affected by deep-sea mining has not been established but is important to evaluate.

Given the near-inevitability of environmental degradation resulting from deep seabed mining, a number of environmental mitigation and pollution reduction strategies have been proposed. Due to the special nature of deep-sea ecosystems and their low (and slow) prospects for recovery, there is little, if any, opportunity for offsetting the environmental degradation by protecting an equivalent ecosystem elsewhere (Van Dover et al., 2017; Niner et al., 2018). Some have suggested that marine mining companies should invest a percentage of their profit into a sustainability fund for the protection and study of the deep sea, but as profits depend on lots of factors and may not materialize for a long time anyway, it is probably more realistic to include that contribution in the financial payment plan administered by the ISA. The ongoing development of the draft Exploitation Regulations provides an important opportunity for public consultation and engagement to ensure that seabed mining is regulated in a way that is economically sound, equitable to present and future generations, ensures effective protection of the marine environment and prepared to address, financially or otherwise, any damage inflicted.

The economic benefits of deep-sea mining

In order to assess the commercial viability of deep-sea mining, financial models are required. Potential miners and contractors are costing out their plans, but regulators and other stakeholders need access to financial information as well in order to develop a payment regime whereby some of the economic and financial benefits derived from deep-sea mining can be shared equitably with humankind.

Investors provide funding based on an assessment of the potential risks and returns. "Hurdle rates," or the minimum rate of return on an investment required by the investor, denote the appropriate compensation for the level of risk associated with a project. When the anticipated rate of return is above the hurdle rate, the project is likely to go ahead. The common hurdle rate for a terrestrial mining investment is around 15 percent. Given that deep-sea mining is still in its earliest stage, with higher risks and uncertainties, its hurdle rate is expected to be higher, with some suggesting 18 percent or more, depending on the operation.

While it is impossible to predict future metal prices, a recent contractor analysis (Van Nijen, 2018) suggests that the required hurdle rates may be attainable, depending on the level of duties and/or royalties assessed by the ISA. Its estimates are based on the annual production of approximately 37,000 tons of nickel; 32,400 tons of copper; 6,375 tons of cobalt and nearly 770,000 tons of manganese obtained from the 3 million tons of nodules recovered. These annual totals are based on the actual metal content of nodules samples from the contractor's license area in the Clarion-Clipperton Zone.

As indicated in section 4, polymetallic sulphide mining in national waters may commence before nodule mining in international waters though seafloor massive sulphide deposits, being relatively limited in size, would not sustain mining for long periods of time. Nautilus Minerals Inc.'s Solwara 1 Project, for instance, appears to contain deposits for two years of mining, requiring operators to mine other sites during the 15-years needed to generate returns. Few revenue estimates have been made for polymetallic crust mining, the current assumption being that under current market conditions the operations are not commercially feasible.

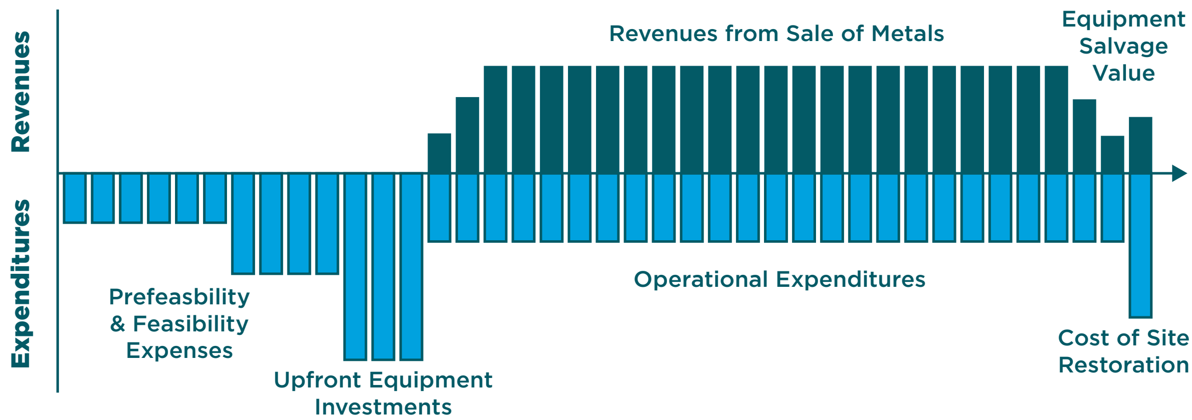

Figure 6.4
Deep-sea mining's considerable upfront costs and operational expenditures need to be offset by revenues obtained through the sale of metals to make the operation economically viable. To attract funding, discounted future revenues must be large enough to provide a Return on Investment (ROI) competitive with other investment opportunities. Courtesy MIT Materials Research Laboratory.

Aside from return on investment to the mining companies, there also are opportunities for other partners in the value chain, such as equipment manufacturers and metal processing plants. If the participating companies make a profit, they will contribute to the tax base in their country of taxation. This contribution can come in the form of royalties on mineral production, taxation on profits, access fees from foreign countries, and from direct and indirect employment. This, in turn, has the potential to spur growth in some sponsoring countries, especially Pacific island states (Baker & Beaudoin, 2013a-d).

The societal benefits of deep-sea mining

Once the ISA receives payments beyond those required to cover the administrative cost of regulating the industry and managing environmental impacts, it will be able to distribute the surplus as envisaged in the common heritage of mankind (CHM) principle included in UNCLOS (Lodge et al., 2018). It is anticipated that the Authority will collect the funds through an ad-valorem royalty, as proposed by draft regulations published in August 2017 (Fig. 6.5). The level of this royalty and its alternative, a profit tax or hybrid regime, remain a matter of considerable debate since the various stakeholders hold different opinions on what percentage is required to comply with UNCLOS' goal of equitably sharing the financial and economic benefits of deep-sea mining.

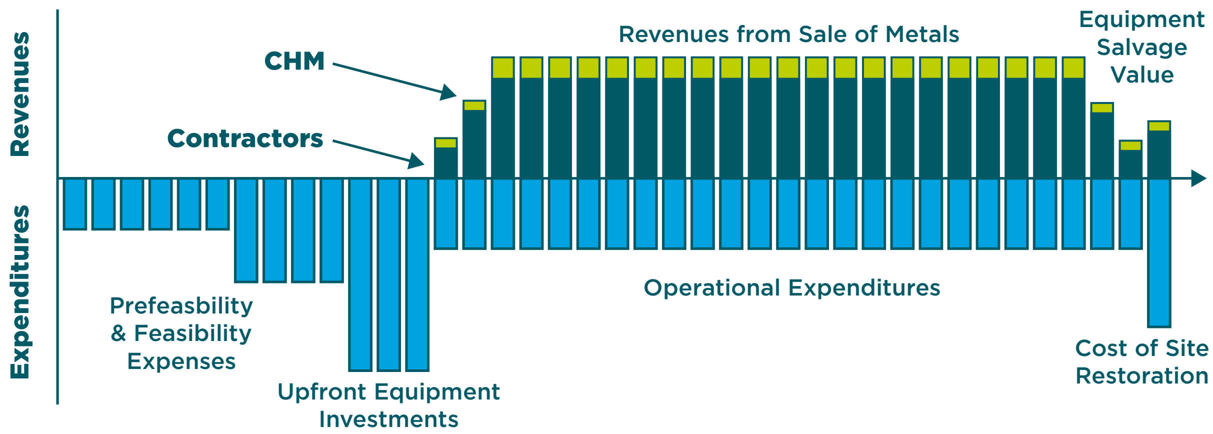

Figure 6.5
The share of revenues to be contributed via the International Seabed Authority (ISA) for the benefit of humankind (CHM) must be factored into financial models. It is expected this share will be collected through an ad-valorem duty, the percentage of which has yet to be determined. Courtesy MIT Materials Research Laboratory.

Should global metal prices go down as a result of an increase in the global supply, this could benefit metal users and ultimately consumers. At the same time, any such price drop would affect not only deep-sea miners but also land-based suppliers, and especially those in developing countries, the economies of some of which rely heavily on mining. UNCLOS provides for the establishment of an economic assistance fund in cases where the economies of developing countries been determined to be seriously affected by the production of minerals from the deep seabed and sets out conditions for receiving assistance from the fund.

In addition to direct market benefits, there is potential for non-market benefits. The exploration of potential mining sites has already led to the discovery of new species, while providing considerable new insight on previously unknown biological processes in the deep ocean. As is true with much ocean research, and deep-sea research in particular, these discoveries often raise more questions, some of which need to be addressed as well. Doing so will benefit from further collaboration. While industry-driven science focuses on what needs to be done to comply with specific environmental requirements, providing access to research platforms, even for studies not directly related to deep-sea mining, and widely sharing data and information will help improve our understanding of this fascinating part of the planet and benefit all who live on it.

Another potential benefit centres around the notion that deep-sea mining will help supply the growing demand for metals like cobalt and nickel which are essential for the transition to renewable energy and other green technologies. Not everyone agrees, a recent report countering that the transition towards a 100% renewable energy supply can take place without deep-sea mining, "even assuming very aggressive growth rates under the most ambitious future energy scenarios" (Teske et al., 2016). While it is often countered that terrestrial mining comes at an environmental cost as well, with some of the worst offenders precisely the metals targeted from deep-sea deposits, this still doesn't address to what extent deep-sea mining could or should supplement terrestrial mining, and the larger issue of reducing the human and environmental costs throughout the supply chain.

Either way, it is unlikely that the transition to a low-carbon future can be met, at least initially, by recycling and alternative technologies that reduce or eliminate the use of supply-constrained metals. More metals will be needed (Arrobas et al., 2017; Ali et al., 2017). Whether they are obtained from land or from the deep sea is a question that the economics of either operation can only partially answer.

Civil society reaction to deep-sea mining

With the exception of the Solwara 1 project 30 km off the coast of Papua New Guinea (PNG), most planned deep-sea mining will take place far from inhabited areas. As such, the impact on local communities will be minimal. However, for potential mining projects near the coast, the impact could be significant and needs to be understood.

There is a potential positive effect from meaningful employment, but if this is short-lived, the negative impacts could outweigh the positive. If there is onshore processing of mined materials, waste water or other elements, this could lead to environmental strains with a concurrent impact on civil society.

In this respect, Nautilus Minerals' Solwara 1 project has stirred up controversy on several fronts. Groups of affected communities, represented by the Centre for Environmental Law and Community Rights Inc (Celcor), claim that they were not adequately consulted by Nautilus Minerals and accuse the PNG Government of withholding key information prior to approving the project. The company, in contrast, insists that due consultation did take place, stating that it reached more than 30,000 people across the affected area and published detailed environmental impact statements online.

As deep-sea mining makes the transition from possibility to reality, it is likely to galvanise more civil society groups. The Deep Sea Mining (DSM) Campaign (www.deepseaminingoutofourdepth.org), an association of NGOs and citizens concerned about the impacts of deep-sea mining on marine and coastal ecosystems, is one such group, aiming to develop a holistic and informed civil society response to this new industry.

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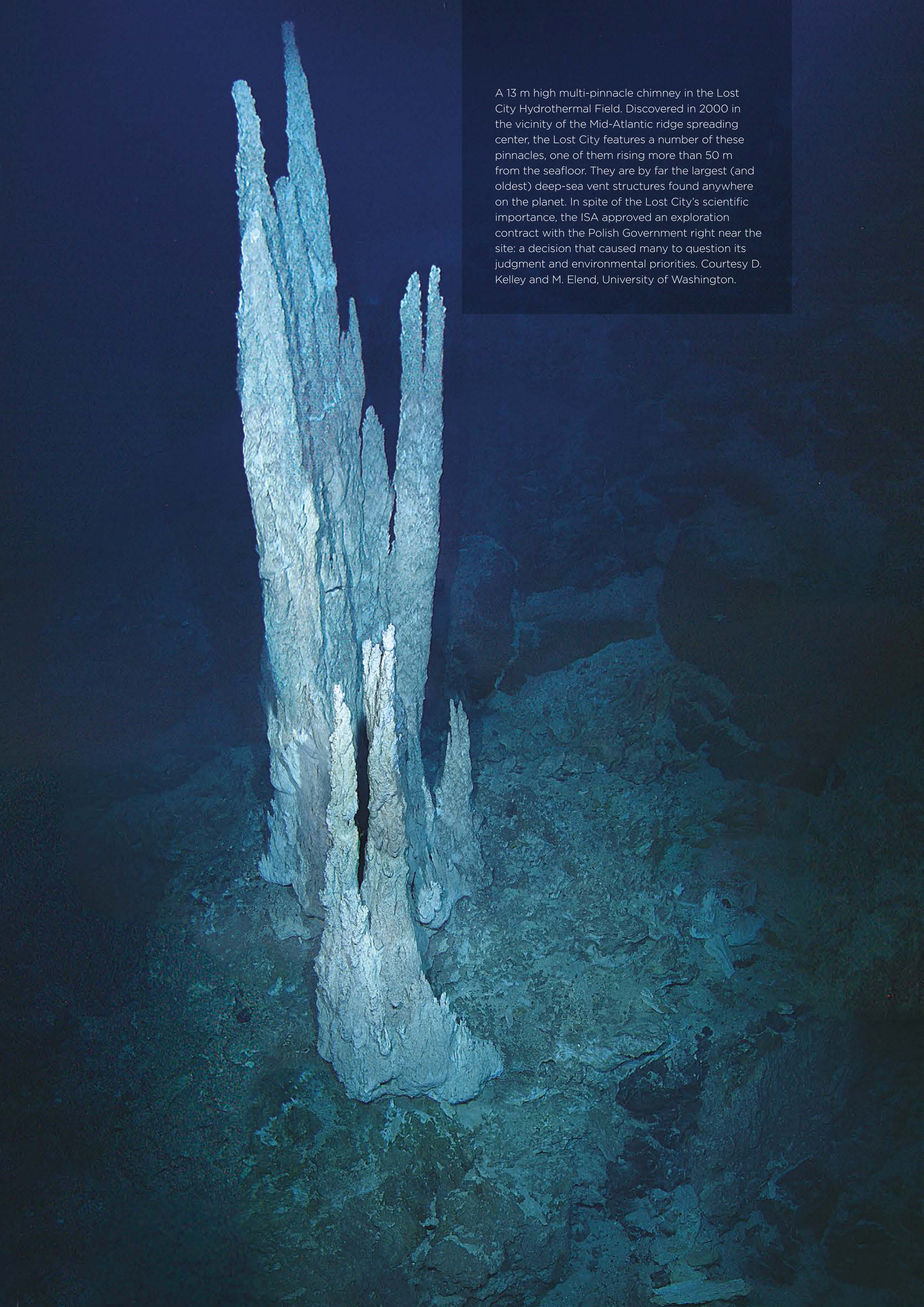


A 13 m high multi-pinnacle chimney in the Lost City Hydrothermal Field. Discovered in 2000 in the vicinity of the Mid-Atlantic ridge spreading center, the Lost City features a number of these pinnacles, one of them rising more than 50 m from the seafloor. They are by far the largest (and oldest) deep-sea vent structures found anywhere on the planet. In spite of the Lost City's scientific importance, the ISA approved an exploration contract with the Polish Government right near the site: a decision that caused many to question its judgment and environmental priorities. Courtesy D. Kelley and M. Elend, University of Washington.

7. POTENTIAL MINING ACTIVITIES

Mining activities are typically divided into three stages: prospecting, exploration and exploitation. Prospecting includes searching for deposits and estimating their size, distribution, composition, grade and economic value. Exploration follows up through further analysis of the deposits, testing equipment and facilities, and completing environmental, technical, economic and commercial assessments. Exploitation involves the commercial recovery of deposits and the extraction of the desired minerals, and includes the construction and operation of mining, processing and transportation systems.

Deep seabed exploration activities are currently operating in both national and international waters (Fig. 7.1). The first deep-sea mining operation in national waters using continuous ore lifting technology was undertaken by the Japan Oil, Gas and Metals National Corporation (JOGMEC) and the Japanese Ministry of Economy, Trade and Industry (METI) in the Summer of 2017. It recovered polymetallic sulphides from a depth of 1,600 m in waters off Okinawa. Next in line may be commercial mining in the Exclusive Economic Zone (EEZ) of Papua New Guinea (PNG) by Canadian contractor Nautilus Minerals, Inc., though its plans may encounter further delays as a result of legal and financial constraints. Another perpetual deep-sea mining hopeful is the Atlantis II project in the Red Sea, though it too has faced legal and political uncertainties.

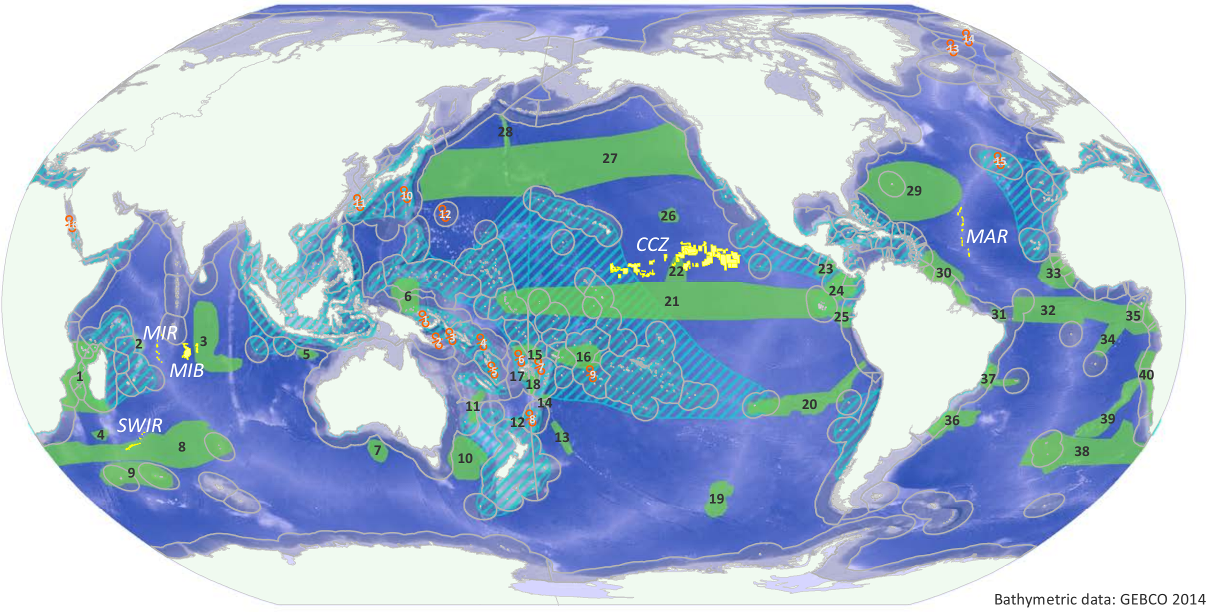
In the Area all seabed mining-related activities are currently in the exploratory stage; actual mining is not expected before 2025. As a general rule, information on who is doing what in the Area is accessible, much of it available from the ISA and the contractors' websites.

Mining activities within the area

By May 2018, the ISA had issued 29 contracts for the exploration of deep-sea mineral deposits (Table 7.1). Seventeen of these were issued for polymetallic nodules, all but one in the Clarion-Clipperton Fracture Zone (Fig. 7.1); seven for polymetallic sulphides in the South West Indian Ridge, Central Indian Ridge and the Mid-Atlantic Ridge; and five for cobalt-rich crusts in the Western Pacific and South Atlantic Ocean. Exploration contracts for polymetallic nodules cover large areas, ranging from 58,000 to 75,000 km^2. Given the more limited extent of the deposits, exploration contracts for polymetallic sulphides are limited to 10,000 km^2, consisting of a maximum 100 blocks no larger than 100 km^2. For cobalt-rich ferromanganese crusts, the exploration areas are set at 3,000 km^2, consisting of 150 blocks no larger than 20 km^2.

The contractors

Current exploration contract holders are a select club, in part due to the price of admission (a US$500,000 application fee plus a US$47,000 annual exploration fee), and the extensive (and costly) legal and technical requirements. Each contractor must also have a sponsoring state, which must be a party to UNCLOS.



Ecologically or biologically significant areas (EBSA)
Biodiversity Hotspots
Exclusive Economic Zones (EEZ)
Exploration activities within EEZ
ISA contract zones
MAR Abbreviation for ISA contract zone

Exploration activities within EEZ:
1 - Papua New Guinea ñ Bismarck Sea
2 - Papua New Guinea - Solomon Sea
3 - Solomon Islands - Western Province
4 - Solomon Islands - Temotu Province
5 - Vanuatu
6 - Fiji
7 - Kingdom of Tonga
8 - New Zealand - Kermadec arc
9 - Cook Islands
10 - Japan - Izu-Ogasawara sea
11 - Japan - Okinawa Trough
12 - Japan - Minami-Tori-shima
13 - Norway - Jan Mayen
14 - Norway - Norwegian Atlantic Ridge
15 - Portugal - Azores
16 - Sudan/Saudi Arabia - Red Sea

Figure 7.1
Mining Activities within EEZs and The Area. Abbreviations for ISA contracts zones: MIB - Mid-Indian Basin, MIR - Mid-Indian Ridge, SWIR - Southwest Indian Ridge, CCZ - Clarion-Clipperton Zone, MAR - Mid-Atlantic Zone. In legend: EBSA: Ecologically or biologically significant areas (CBD-Convention of biological Diversity), EEZs: Exclusive Economic Zones, MPA: Marine Protected Areas. Data sources: Contract zones (ISA), CBD-EBSA (Marine Geospatial Ecology Lab, Duke University - 2013), Biodiversity Hotspots (Conservation International), EEZs (Marine Regions), MPA (Protected Planet - IUCN/WCMC). Coordinate system: World Robinson centred on 200° meridian; ocean background: NaturalEarth (1:10m) Map created by Caroline Wilhem; updated and re-done by Michael Vollmar. For list of ESBAs see Table 7.2.

YUZHMORGEOLOGIYA

ymg.rosgeo.com

Administered by the Federal Agency of Mineral Resources of the Russian Ministry of Natural Resources and Environment, JSC YUZHMORGEOLOGIYA carries out activities related to the exploration and development of marine mineral resources. It has a long-standing interest in polymetallic nodule mining in the Clarion-Clipperton Fracture Zone (CCZ), where it obtained a 75,000 km^2 area (Fig. 7.2). The organization also cooperates in the exploration of polymetallic nodules in the Indian Ocean with a variety of international partners and along the Mid-Atlantic Ridge, where the Government of the Russian Federation obtained a contract to investigate hydrothermal sulphides (Fig. 7.4). In 2015, the Ministry of Natural Resources and Environment of the Russian Federation became a contractor to explore for ferromanganese crusts in the Magellan Seamount chain in the Central Pacific (Fig. 7.5).

CONTRACTOR	SPONSORING STATE	LOCATION	START DATE
POLYMETALLIC NODULES			
Yuzhmorgeologiya	Russian Federation	Clarion-Clipperton Fracture Zone	29 March 2001
Interoceanmetal Joint Organization	Bulgaria, Cuba, Czech Republic, Poland, Russian Federation and Slovakia	Clarion-Clipperton Fracture Zone	29 March 2001
Government of the Republic of Korea	Korea	Clarion-Clipperton Fracture Zone	27 April 2001
China Ocean Mineral Resources Research and Development Association	China	Clarion-Clipperton Fracture Zone	22 May 2001
Institut Français de Recherche pour l'Exploitation de la Mer	France	Clarion-Clipperton Fracture Zone	20 June 2001
Deep Ocean Resources Development Co. Ltd.	Japan	Clarion-Clipperton Fracture Zone	20 June 2001
Government of India	India	Indian Ocean	25 March 2002
Federal Institute for Geosciences and Natural Resources of Germany	Germany	Clarion-Clipperton Fracture Zone	19 July 2006
Nauru Ocean Resources Inc.	Nauru	Clarion-Clipperton Fracture Zone	22 July 2011
Tonga Offshore Mining Limited	Tonga	Clarion-Clipperton Fracture Zone	11 January 2012
Global Sea Mineral Resources NV	Belgium	Clarion-Clipperton Fracture Zone	14 January 2013
UK Seabed Resources Ltd.	United Kingdom	Clarion-Clipperton Fracture Zone	8 February 2013
Marawa Research and Exploration Ltd.	Kiribati	Clarion-Clipperton Fracture Zone	19 January 2015
Ocean Mineral Singapore Pte Ltd.	Singapore	Clarion-Clipperton Fracture Zone	22 January 2015
UK Seabed Resources Ltd	United Kingdom	Clarion-Clipperton Fracture Zone (2)	29 March 2016
Cook Islands Investment Corporation	Cook Islands	Clarion-Clipperton Fracture Zone	15 July 2016
China Minmetals Corporation	China	Clarion-Clipperton Fracture Zone	12 May 2017

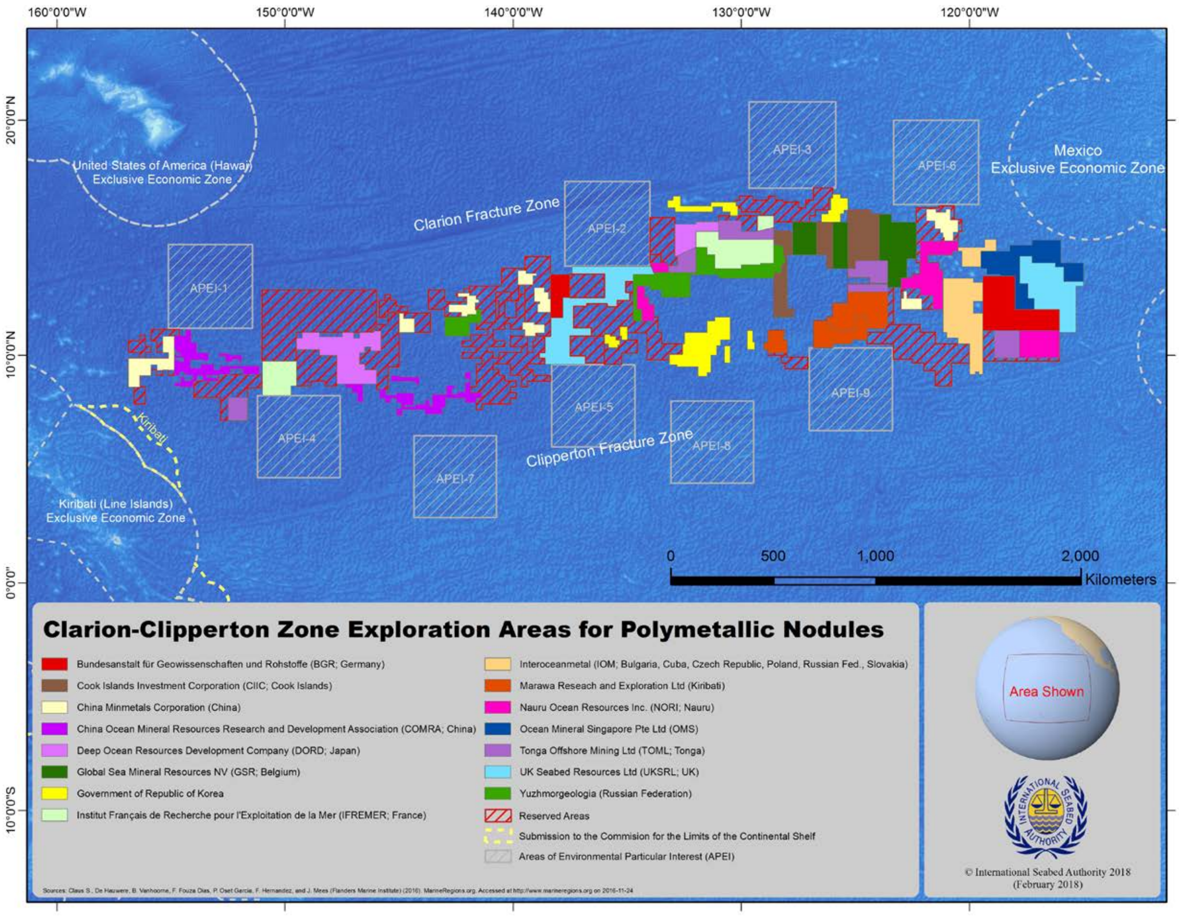
POLYMETALLIC SULPHIDES			
China Ocean Mineral Resources Research and Development Association	China	Southwest Indian Ridge	18 November 2011
Government of the Russian Federation	Russia	Mid-Atlantic Ridge	29 October 2012
Government of the Republic of Korea	Korea	Central Indian Ridge	24 June 2014
Institut Français de Recherché pour l'Exploitation de la Mer	France	Mid-Atlantic Ridge	18 November 2014
Federal Institute for Geosciences and Natural Resources of the Federal Republic of Germany	Germany	Central Indian Ocean	6 May 2015
The Government of India	India	Central Indian Ocean	26 September 2016
The Government of the Republic of Poland	Poland	Mid-Atlantic Ridge	12 February 2018
POLYMETALLIC CRUSTS			
Japan Oil, Gas and Metals National Corporation (JOGMEC)	Japan	Western Pacific Ocean	27 January 2014
China Ocean Mineral Resources Research and Development Association (COMRA)	China	Western Pacific Ocean	29 April 2014
Ministry of Natural Resources and Environment of the Russian Federation	Russian Federation	Magellan Mountain, Pacific Ocean	10 March 2015
Companhia De Pesquisa de Recursos Minerais	Brazil	Rio Grande Rise, South Atlantic Ocean	9 November 2015
Government of the Republic of Korea	Korea	Western Pacific Ocean	27 March 2018

Table 7.1
29 contractors have signed 15-year exploration contracts with the ISA. Contracts that would have expired in 2016 and 2017 were renewed for an additional 5-year period.

INTEROCEANMETAL JOINT ORGANIZATION

www.iom.gov.pl

The Interoceanmetal Joint Organization (IOM) is a scientific international organization established by Bulgaria, Cuba, the Czech Republic, Poland, Russia and Slovakia with the objective of conducting the exploration, prospecting and exploitation of polymetallic nodules. The organization was registered as a pioneer investor from 1992 to 2001 and on 29 March 2001 became one of the first approved ISA contractors. The organization holds a 75,000 km^2 contract in the Clarion-Clipperton Fracture Zone (Fig. 7.2) which was extended in 2016 for a five-year period.



RESERVED AREAS and APEIs

At the heart of the regime for the Area established by Part XI of the United Nations Convention on the Law of the Sea and the 1994 Implementation Agreement is the so-called *parallel system*, elaborated in article 153 of the Convention. An essential element of this parallel system prescribes applications for nodule mining to be sufficiently large and of sufficient value to accommodate two mining operations of "equal estimated commercial value". One of these is to be allocated to the applicant and the other is to become the reserved area. The reserved areas are set aside for activities by developing States or by the Authority through its Enterprise. Though the ISA's Enterprise has not yet been established, a number of reserved areas have been assigned to Pacific island states. The parallel system is further detailed in annex III, article 8, of the Convention, in the Agreement (annex, section 3, para. 11 (b), and in the Regulations on Prospecting and Exploration for Polymetallic Nodules in the Area (the "Nodules Regulations" 15 to 17).

Areas of Particular Environmental Interest (APEIs), in contrast, are no-mining areas, each one of which measuring 400 km x 400 km. Nine of these were designated in the ISA's 2011 environmental management plan for the Clarion Clipperton Zone. To avoid conflict with exploration contracts, the 9 APEIs surround the 16 existing contract areas (Fig. 7.2). The nine APEIs protect 1,4440,000 km^2 of the CCZ – more than the areas assigned to the various contractors.

Figure 7.2
Aside from the 16 contract area, there are also Reserved Areas (see text box) and Areas of Particular Environmental Interest (APEIs) in the CCZ. Courtesy International Seabed Authority.

REPUBLIC OF SOUTH KOREA

www.kiost.ac.kr

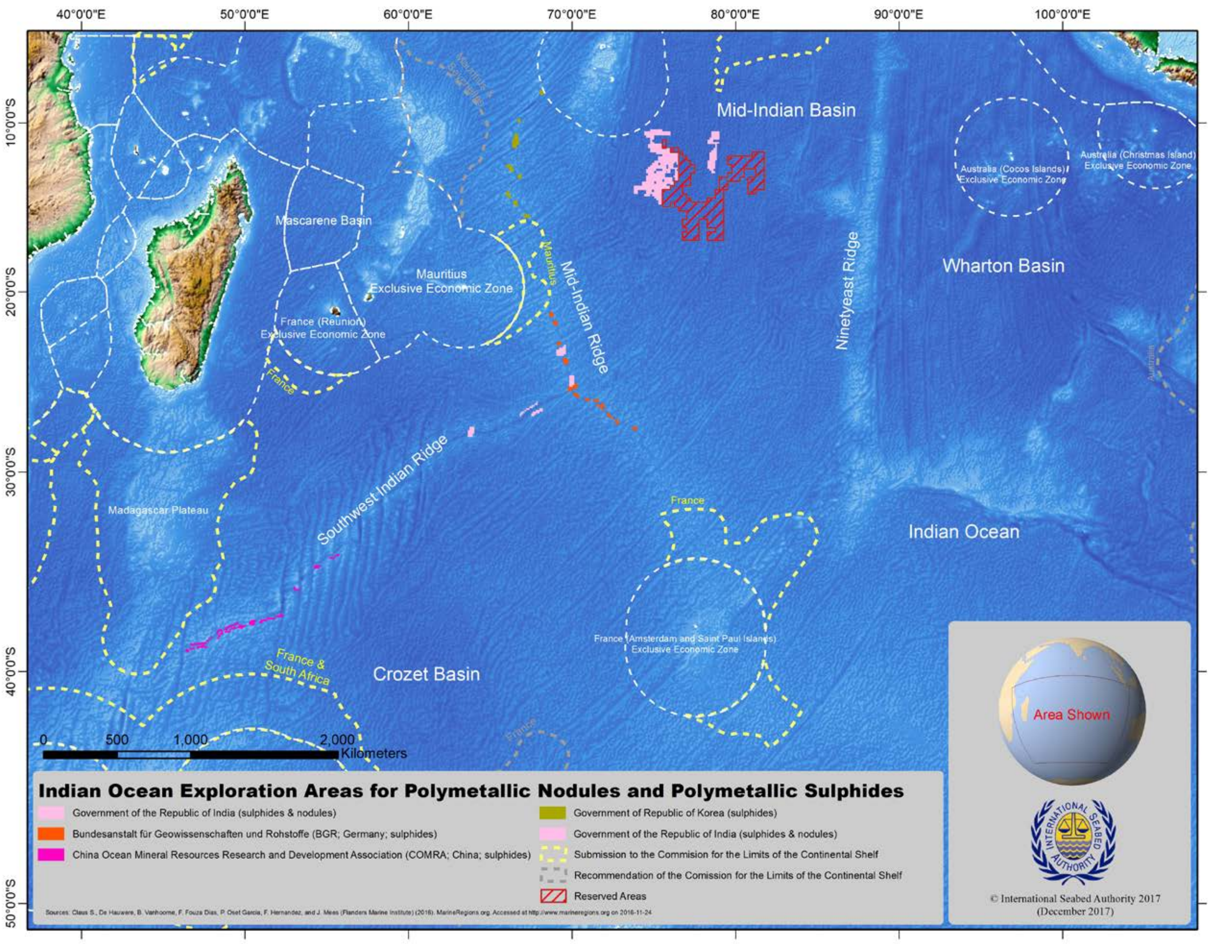
A major metal importer, South Korea has long been interested in polymetallic nodules, and obtained a 75,000 km^2 contract area in the Clarion-Clipperton Fracture Zone in 2002 (Fig. 7.2). Its Ministry of Fisheries and Oceans has conducted extensive exploration and test mining operations in its assigned area, estimating a resource potential of 560 million tons of nodules. The Government of the Republic of Korea also signed a contract in 2014 to explore hydrothermal vents along the Central Indian Ridge (Fig. 7.3) and did so four years later to explore ferromanganese crusts in the Western Pacific Ocean.

CHINA OCEAN MINERAL RESOURCES RESEARCH AND DEVELOPMENT ASSOCIATION

www.comra.org

China Ocean Mineral Resource R&D Association (COMRA) was established in 1990 to undertake and investigate deep-sea exploration and exploitation in the Area. The organization signed its first exploration contract for polymetallic nodules with the Authority in 2001, gaining exploration rights in the Clarion-Clipperton Fracture Zone (Fig. 7.2). It expanded its activities in 2011 with an exploration contract for polymetallic sulphides in the Southwest Indian Ridge (Fig. 7.3) and three years later with the first exploration contract for cobalt-rich ferromanganese crusts in the Western Pacific (Fig. 7.5).

Figure 7.3
The ISA has approved five exploration contracts in the Indian Ocean: 4 for polymetallic sulphides along the Mid-Indian Ridge and one for polymetallic nodules in the Mid-Indian Basin. Courtesy International Seabed Authority.



IFREMER

wwz.ifremer.fr

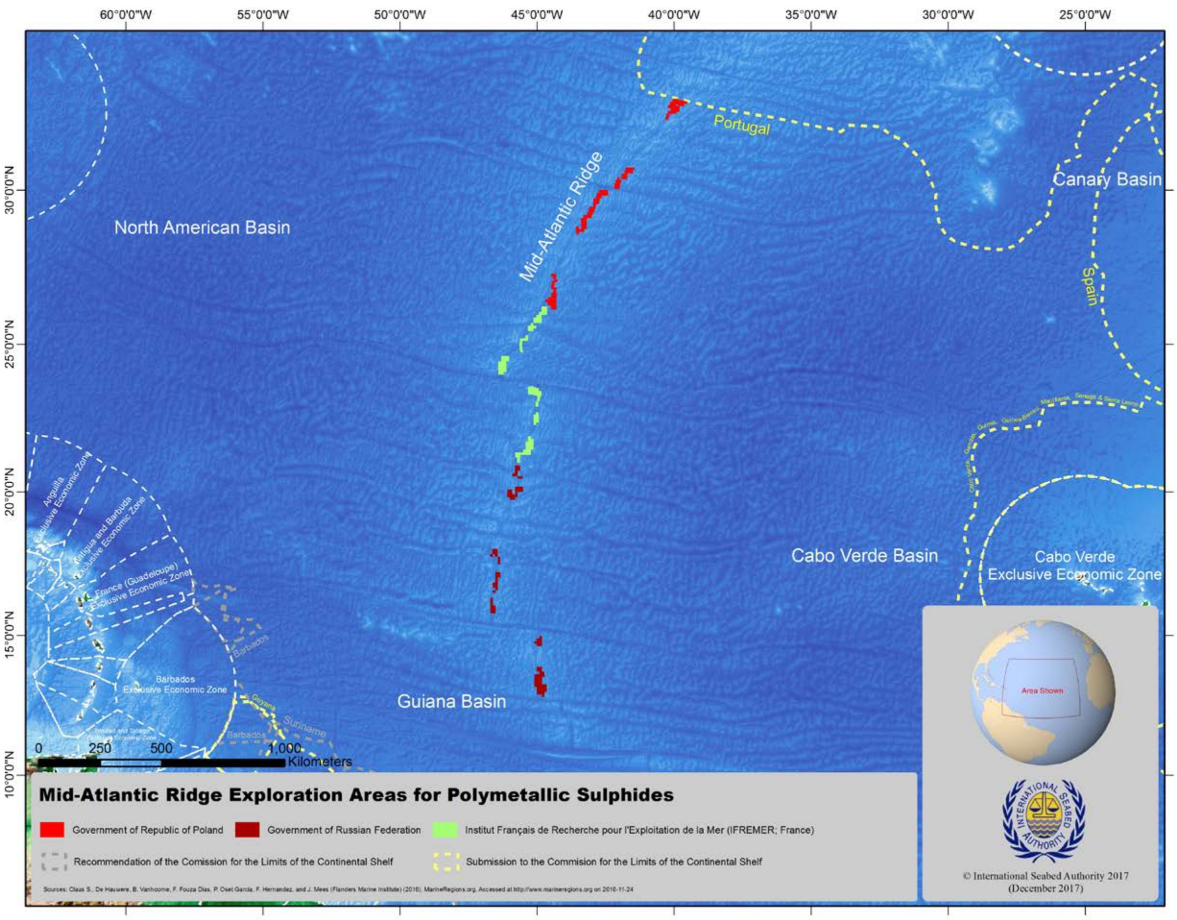
French research organization IFREMER (Institut Français de Recherche pour l'Exploitation de la Mer) in late 2001 entered into a 15-year contract for exploration for polymetallic nodules in the Clarion-Clipperton Fracture Zone (Fig. 7.2). The organization has since obtained an extension of the contract and continues its investigations in both the resource base and deep-sea ecosystems. In late 2014 IFREMER also signed an exploration contract to examine polymetallic sulphides on the Mid-Atlantic Ridge (Fig. 7.4).

DEEP OCEAN RESOURCES DEVELOPMENT CO. LTD

www.dord.co.jp

Japan's Deep Ocean Resources Development Company (DORD) was established in 1982, shortly after the first wave of interest in deep-sea mining and signed one of the first contracts for polymetallic nodule exploration in the Clarion-Clipperton Fracture Zone (Fig. 7.2). A state-private joint venture, the company's principal investor is the Japan Oil, Gas and Metals National Corporation (JOGMEC), which is also involved in polymetallic sulphide mining and in 2014 signed an ISA contract for ferromanganese crusts (see below). DORD has completed extensive surveys of its assigned area and developed technology to not only recover manganese nodules, but other deep-sea resources as well.

Figure 7.4 Three contractors obtained contracts to explore polymetallic sulphides along the Mid-Atlantic Ridge. Courtesy International Seabed Authority.



INDIAN GOVERNMENT

www.niot.res.in

With its economy rapidly expanding, India has long taken an interest in deep-sea minerals, the exploration for which is currently conducted by the National Institute of Ocean Technology (NIOT), an autonomous research organization under the Indian Ministry of Earth Sciences. India holds two ISA contracts, one to explore for polymetallic nodules in the Mid-Indian Basin; the other to do so for polymetallic sulphides along the Southwest Indian Ridge (Fig. 7.3).

FEDERAL INSTITUTE FOR GEOSCIENCES AND NATURAL RESOURCES

www.bgr.bund.de

Germany was involved in polymetallic nodule mining from the early days; several German companies participated in the first deep-sea mining consortia and R&D was conducted by its research institutions, with the Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) playing a leading role. BGR's Marine Resource Exploration sub-department has conducted several in situ scientific tests in two contract areas: one for polymetallic nodules in the Clarion-Clipperton Zone (Fig. 7.2); the other for polymetallic sulphides in the Indian Ocean (Fig. 7.3). The department examines mining technologies as well as their environmental impact.

NAURU OCEAN RESOURCES INC.

www.nauruoceanresources.com

Nauru Ocean Resources Inc. ("NORI") was granted an ISA contract to explore for polymetallic nodules in 2011 (Fig. 7.2). Based on the small island of Nauru, the company is a wholly-owned subsidiary of Canadian company DeepGreen Resources, Inc., which gained access to the NORI license area in the Clarion-Clipperton Zone through the acquisition. DeepGreen Resources has committed to conducting precise resource and environmental impact assessments in the Nauru-sponsored area in the coming years.

TONGA OFFSHORE MINING LIMITED

Tonga Offshore Mining Limited (TOML) is a subsidiary of Canadian company Nautilus Minerals, Inc., known for its plans to mine hydrothermal sulphides in Papua New Guinean (PNG) waters. With TOML, Nautilus obtained access to an area of approximately 75,000 km^2 in the Clarion Clipperton Zone (CCZ) (Fig. 7.2). The license area was examined and sampled during a 2013 research cruise, revealing nodule densities of approximately 10 kg/m^2. Since then, Nautilus's main focus has been on its PNG operations, due to commence in 2019 (see below).

GLOBAL SEA MINERAL RESOURCES NV

www.deme-group.com/gsr

Global Sea Mineral Resources NV (GSR) is a subsidiary of the Belgian DEME Group, which is best known for its worldwide dredging and marine construction activities. In early 2013 the company signed a 15-year exploration contract with the ISA, granting access to

76,728 km² in the eastern part of the Clarion Clipperton Zone (Fig. 7.2). GSR and DEME have extensively explored, mapped and photographed their contract area, and plan to test their nodule collector component in 2019.

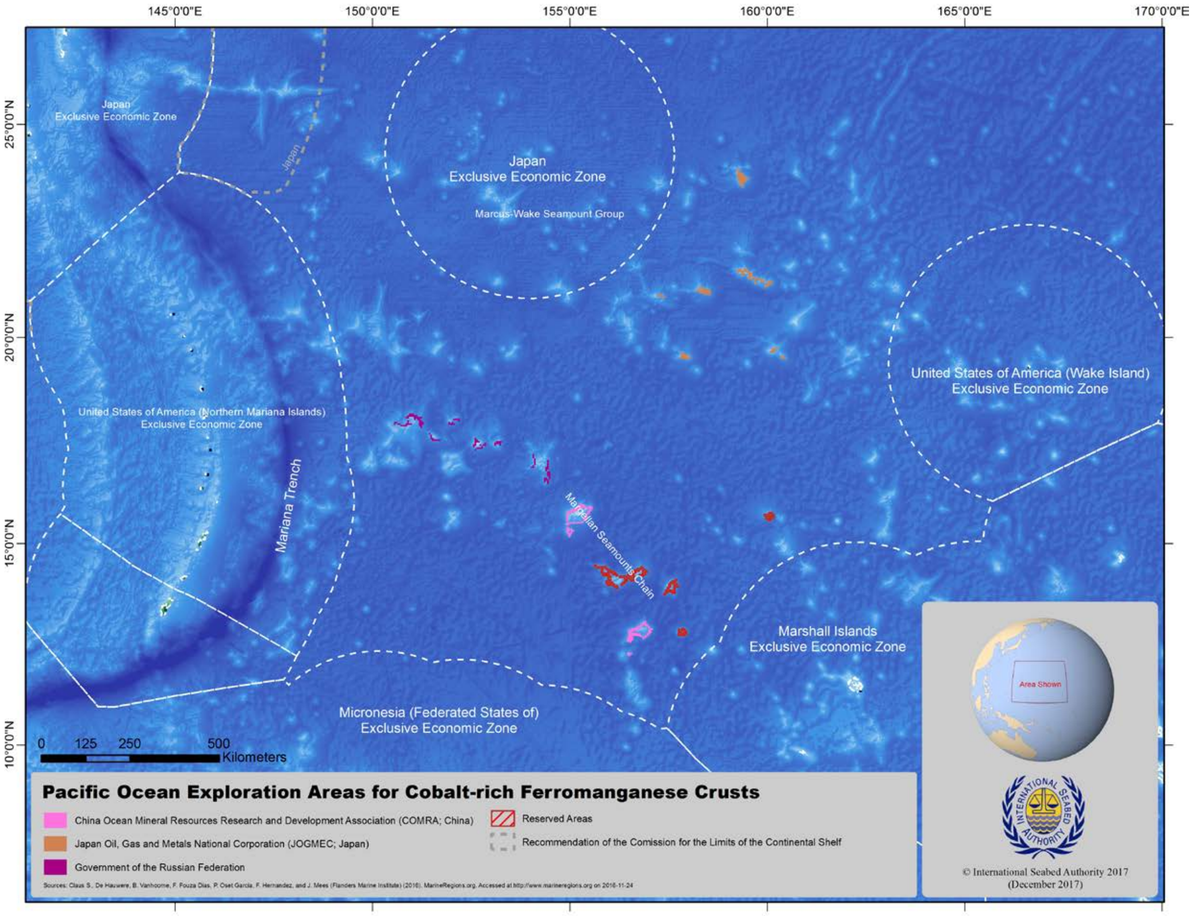


Figure 7.5
Though considered to have less commercial appeal, ferromanganese crust exploration contracts have been signed with Chinese, Japanese, Korean and Russian entities. Courtesy International Seabed Authority.

UK SEABED RESOURCES LTD

www.lockheedmartin.com/en-gb/products/uk-seabed-resources.html

UK Seabed Resources Ltd. Is a wholly owned subsidiary of Lockheed Martin UK Limited. It signed a first ISA contract in 2013 to explore a 58,000 km² area in the Clarion Clipperton Zone for polymetallic nodules and a second in 2016, giving Lockheed Martin access to parts of the Pacific it had already explored during the very first mining tests 40 years ago (Fig. 7.2). US-based parent company Lockheed Martin must operate in the CCZ through its British subsidiary because the US is not a party to UNCLOS.

JAPAN OIL, GAS AND METALS NATIONAL CORPORATION

www.jogmec.go.jp

The Japan Oil, Gas and Metals National Corporation (JOGMEC), established in 2004, integrates the functions of the former Japan National Oil Corporation and the former Metal Mining Agency of Japan, both of which were tasked to ensuring a stable supply of critical mineral resources for Japan. JOGMEC received the first ISA contract to explore ferromanganese crusts on seamounts in the Western Pacific (Fig 7.6). The company is also involved in hydrothermal sulphide assessment and test-mining in Japanese waters (see below).

MARAWA RESEARCH AND EXPLORATION LTD

www.marawaresearch.com

Marawa Research and Exploration Ltd., a State-owned enterprise of the Republic of Kiribati, signed a contract to explore for polymetallic nodules in the Clarion-Clipperton Zone in early 2015. Its block is located just 150 km from Kiribati's EEZ boundary (Fig. 7.2). The CCZ manganese nodule belt extends into the country's EEZ, making Kiribati one of a few countries with commercially interesting polymetallic nodule deposits under national jurisdiction.

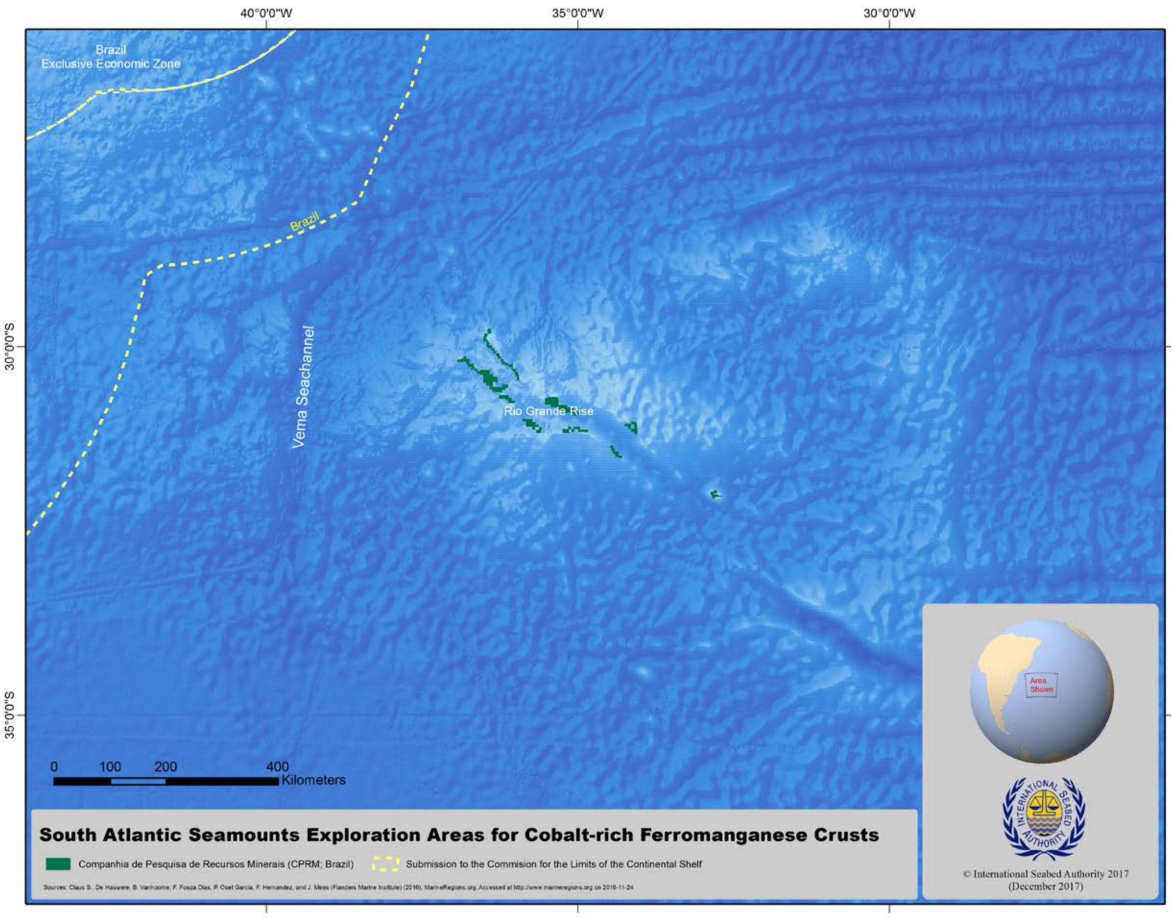


Figure 7.6 Brazil's Geological Survey is the sole contractor in the South Atlantic. Its contract permits exploration of seamounts along the Rio Grande Rise. Courtesy International Seabed Authority.

OCEAN MINERAL SINGAPORE PTE LTD

www.kepcorp.com

Ocean Mineral Singapore Pte Ltd. (OMS) is a subsidiary of Singapore-based Keppel Corporation, which also owns offshore rig and ship builder Keppel Offshore & Marine. It obtained a 15-year exploration contract for polymetallic nodules within the Clarion-Clipperton Fracture Zone in 2014 (Fig. 7.2), the first Singaporean company to do so. OMS cooperates with the Keppel-NUS Corporate Laboratory to conduct environmental studies and surveys within the 58,000 km^2 block.

COMPANHIA DE PESQUISA DE RECURSOS MINERAIS

www.cprm.gov.br

As Brazil's Geological Survey, the Companhia De Pesquisa de Recursos Minerais (CPRM) is tasked with gathering data and information on Brazilian geology, minerals and water resources; a task which was extended to include the ISA exploration contract on the Rio Grande Rise which the organization signed in late 2015. Located some 1,500 km southeast of Rio de Janeiro (Fig. 7.6), the Rio Grande Rise consists of a chain of seamounts, many of which CPRM exploration revealed to be covered with ferromanganese crusts.

COOK ISLANDS INVESTMENT CORPORATION

www.ciiconline.com

Cook Islands Investment Corporation (CIIC), a statutory Corporation of the Cook Islands Government, was established in 1998 to manage Crown assets, including land and offshore areas. In July 2016 CIIC signed an exploration contract with the ISA, granting the Cook Islands a block of 75,000 km^2 in the Clarion Clipperton Fracture Zone (Fig. 7.2). At the same time, CIIC also signed a Joint Venture Agreement with Global Sea Mineral Resources (GSR), which holds adjoining blocks, to jointly explore and possibly develop the CIIC license area.

CHINA MINMETALS CORPORATION (CMC)

www.minmetals.com

China Minmetals Corporation (CMC) is China's largest metals and minerals conglomerate and a world leader in the production and trading of many of the metals found in deep-sea deposits. The company is active in more than 60 countries, and in 2017 added a deep-sea tract as well, signing an ISA exploration contract for a 72,740 km^2 block in the Clarion-Clipperton Zone (Fig. 7.2). Aside from exploring and assessing the resource, CMC intends to build its own deep-sea mining system, using technology developed by two of its research subsidiaries.

GOVERNMENT OF THE REPUBLIC OF POLAND

In early 2017, the Polish government applied for a contract to explore for polymetallic sulphides in the Mid-Atlantic Ridge. Its application area is located between Hayes, Atlantis and Kane transform fault zones and consists of 100 exploration blocks, each with an area of 10 x 10 kilometres. Although the blocks are located near what the UN Convention on Biological Diversity has identified as an "Ecologically or Biologically Significant Area", the ISA approved the application in August 2017 for a contract starting in February 2018. Poland is also one of the Sponsoring States for the exploration contract for polymetallic nodules signed by the Interoceanmetal Joint Organization (IOM).

Mining Activities within EEZs

Acquiring precise information on the status of deep seabed mining activities in national waters can be more difficult because governments and/or individual companies may not be willing to share it publicly. According to the Study to Investigate State of Knowledge of Deep-seabed Mining (2014), prepared on behalf of the Directorate-General for Maritime Affairs and Fisheries of the European Commission (DG MARE), the total area licensed or under application in areas under coastal state jurisdiction totals approximately one million km^2, most of which to explore or exploit seafloor massive sulphide deposits (Ecorys, 2014).

Pacific Region

Nautilus Minerals Inc. (Canada) holds more than 290,000 km^2 of granted tenements and a further 240,000 km^2 under application in the Exclusive Economic Zones (EEZs) of Papua New Guinea, Tonga, the Solomon Islands, Fiji and Vanuatu. By far the most relevant of these claims is the Solwara 1 lease, located some 30 km off the coast of New Ireland in Papua New Guinea (see Section 4). As of early 2018 Nautilus was testing its mining equipment, with deployments and mining slated to start late 2019.

Red Sea

The Atlantis II Deep mining site, located along the Red Sea Ridge between Sudan and Saudi Arabia, has long been considered one of the most promising deep-sea mining sites in the world. During the 1970s, the site was explored for its economic potential by German company A.G. Preussag. Its work pinpointed the most promising deposits in a series of deep basins along the central rift valley, of which Atlantis II, at a depth of 1,900-2,200 m and covering an area of 62 km^2 (Fig. 7.7), was determined to be the largest. The upper 10 m of sediments were estimated to contain about 2.9 million tons of zinc, 1 million tons of copper, 0.8 million tons of lead, 45,000 tons of silver and 45 tons of gold.

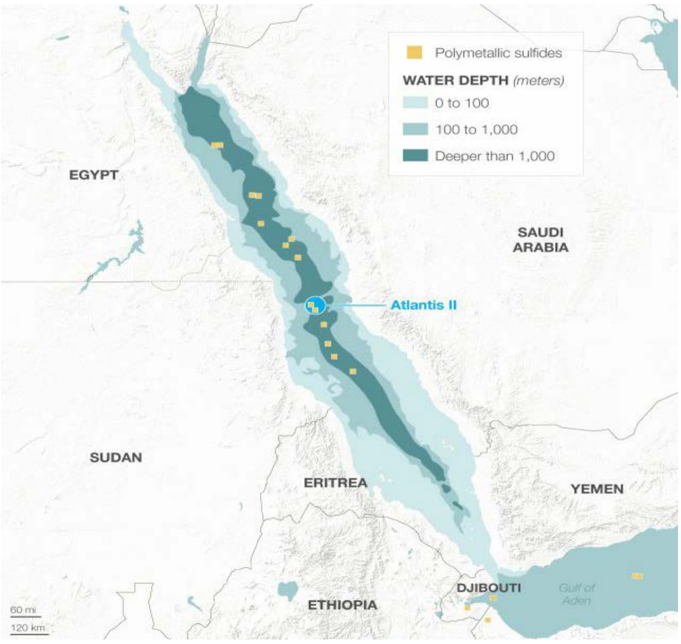


Figure 7.7
The Atlantis II Deep is located in the middle of the Red Sea, approximately equidistant from the coast of Saudi Arabia and Sudan. It is believed to be the largest sulphide deposit in the world. Courtesy Stratfor.

In 2010 Manafai International of Saudi Arabia and Canadian partner Diamond Fields International received a 30-year license to mine copper, manganese, zinc, cobalt, silver and gold from metalliferous sediments in the Atlantis II Deep. Work was started on a pre-feasibility study, including final technical and geological assessments revealing 89 million tons of Dry Salt-Free (DSF) ore with 4 million tons of manganese; 500-740,000 tons of copper; 5,000 tons of cobalt; 6,500 tons of silver and 47 tons of gold.

Though the project's exploration phase was scheduled to start in 2014, it has since been held up by contractual disputes. Both Saudi Arabia and Sudan are committed to breathe new life into the venture, though the legal, economic and technical constraints on drilling in the Red Sea, not to mention the environmental implications, have not changed in any notable way.

SHALLOW SEABED MINING

Most marine mining under national jurisdiction takes place in shallow water on the (geological) continental shelf. Oil and gas are by far the most valuable minerals mined offshore, but there are other resources. Most abundant are sand and gravel, used extensively in construction as well as for beach replenishment. The deposits are recovered using dredging equipment, which allows for quick transport from mining site to port.

Marine detrital minerals are heavy minerals of economic value which are concentrated in placer deposits by physical processes like waves, wind and currents. Iron sands, rich in minerals like ilmenite, rutile, zircon and monazite occur in beach deposits and shallow waters in India, Egypt, Brazil, Australia, New Zealand and Southeast Asia. Cassiterite, an important tin ore, is a residual mineral of the weathering of granites. It has been mined offshore in the Southeast Asian Tin Belt since the early 1900s. The increased demand for tin in high-tech applications has revitalized the offshore mining sector, with appalling environmental effects on coastal waters in some of the Indonesian tin islands.

Diamonds can also be found in offshore placer deposits. During the 1970s and 1980s they were mined off the Namibian coast with smaller vessels at depths of up to 40m. In the past few years, specially-built vessels have entered the industry, capable of operating to depths up to 300 m – the greatest depth reached by any shallow seabed mining operation. These are expensive operations with a considerable environmental footprint but concerns about the effects tend to be eclipsed by the profits: deposits off the Namibian coast are estimated at over 1,500 million carats.

Most shallow-water seabed mining employs dredging systems to recover the targeted materials. These include bucket (ladder) dredges, suction dredges that basically vacuum up unconsolidated materials, and cutter dredges to dislodge consolidated materials. All cause serious environmental effects, from the removal of the top layer of sediments (and the associated loss of benthic communities) to turbidity plumes (which can affect areas well beyond the mining site), noise, and changes in seabed geomorphology – all of which similar to the effects expected from deep-sea mining.

The record of addressing and mitigating the environmental effects of shallow seabed mining is mixed. The operations are regulated at the national or regional level, with terrestrial mining legislation often applied to the sector (Baker et al., 2016). Some countries apply strict requirements; others hardly bother, causing considerable deterioration of coastal environments. Though some of the experience gained in shallow water operations may be of use in the deep sea, its regulation is not the place to look for exemplary environmental management. Deep-sea mining in national waters will be better served by taking cues from the regulations that are being drafted at the international level.

Japan

In September 2017 the Japan Oil, Gas and Metals National Corporation (JOGMEC) and the Japanese Ministry of Economy, Trade and Industry (METI) reported the first successful retrieval of polymetallic sulphides using continuous ore lifting technology from a depth of 1,600 m in waters off Okinawa (see also section 4). Both organizations have long shown an interest in deep-sea deposits to supply Japan's growing mineral needs and, as government organizations, can explore and develop without commercial constraints.

No information was provided on the precise quantity of material that was brought to the surface, though newspaper reports quoted METI as stating that the quantity of zinc in the targeted deposit was equivalent to Japan's annual consumption of approximately 500,000 tons. METI expects more commercially interesting ore deposits to be found in the area and predicts these could be mined in the early 2020s.

Ecologically or Biologically Significant Areas (EBSAs)

1	Mozambique Channel	21	Equatorial High-Productivity Zone
2	Saya de Malha Bank	22	Clipperton Fracture Zone
3	Central Indian Ocean Basin	23	Thermal Dome Eastern Tropical Pacific
4	Walters Shoals	24	Marine Corridor Eastern Tropical Pacific
5	South of Java Island	25	Carnegie Ridge - Equatorial Front
6	Remetau group	26	Northeast Pacific White Shark Area
7	Due South of Great Australian Bight	27	North Pacific Transition Zone
8	Agulhas Front	28	Emperor Seamount Chain
9	Coral Seamount and Fracture Zone Feature	29	Sargasso Sea
10	South Tasman Sea	30	Amazonia-Orinoco Influence Zone
11	Seamounts of West Norfolk Ridge	31	Fernando de Noronha
12	Northern New Zealand-South Fiji Basin	32	Atlantic Equatorial Fracture zone
13	Central Louisville Seamount Chain	33	Canary Current Convergence Zone
14	Kermadec - Tonga - Louisville Junction	34	East Central Atlantic Seamounts
15	South of Tuvalu/Wallis and Fortuna	35	Equatorial High-Productivity Zone
16	Western South Pacific	36	Southern Brazilian Sea
17	Kadavu	37	Subtropical Convergence Zone
18	Southern Lau Region	39	Walvis Ridge
19	Grey Petrel feeding area South East Pacific	39	Benguela Upwelling System
20	Salas y Gomez and Nazca Ridges		

Table 7.2
List of Ecologically or Biologically Significant Areas (EBSAs) shown in Fig. 7.1

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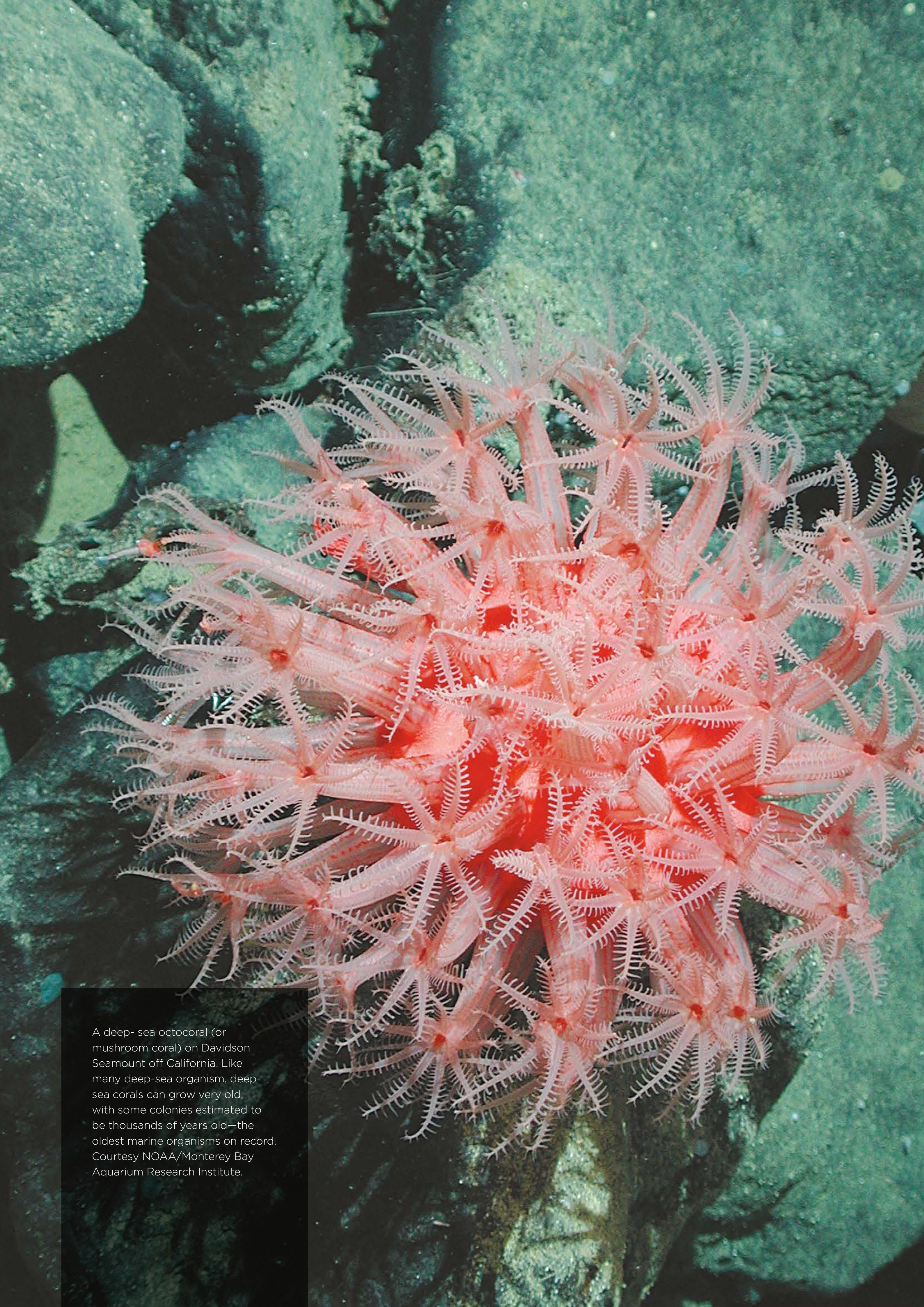

A deep- sea octocoral (or mushroom coral) on Davidson Seamount off California. Like many deep-sea organism, deep-sea corals can grow very old, with some colonies estimated to be thousands of years old—the oldest marine organisms on record. Courtesy NOAA/Monterey Bay Aquarium Research Institute.

8. ENVIRONMENTAL MANAGEMENT

More than 1.3 million km^2 of international seabed have been set aside for mineral exploration in the Pacific and Indian Ocean and along the Mid-Atlantic Ridge. Another 1,000,000 km^2 of deep seabed has been licensed or applied for in waters under national jurisdiction. Before any of these areas can be exploited, state parties to UNCLOS must make sure that any development does not take place at the expense of the deep-sea environment. In the case of the international seabed, the International Seabed Authority (ISA) is charged with taking whatever measures are needed to ensure the proper level of protection and conservation; any exploitation in waters under national jurisdiction needs to be regulated equally strictly by national authorities.

Though the commitment to protect the deep sea is indispensable, its actual implementation is hindered by a lack of information. The many gaps in our understanding of deep-sea biodiversity, ecology and ecosystem functioning make it difficult to thoroughly assess the potential threats and impacts of deep seabed mining. To comply with UNCLOS' directive to ensure protection for the marine environment from deep-sea mining and provide regulators with the information they need to do so, these threats and effects must now be clearly identified and assessed: a task that requires additional research, collaboration between science and industry, and the best environmental management tools.

The principal direct impacts from mining deep seabed hard mineral resources are broadly similar and include the loss of substrate, the compaction of the sea floor, turbidity plumes, re-sedimentation, and discharge plumes which, depending on the depth of the discharge, could affect both pelagic and benthic fauna (MIDAS, 2016). The actual impact on each mining site will differ, depending on the type of deposit, the physical conditions of the site, and the type and scale of operations (Levin et al., 2016).

Identification and assessment of environmental impacts

Seafloor disturbance is one of the most important environmental impacts resulting from deep seabed mining because it causes the direct loss of habitats and the possible loss of a variety of organisms. It is also not clear to what extent and under what conditions the affected areas will be recolonized. Some studies (Vanreusel et al., 2016) noted the apparent lack of faunal recovery in experimental mining tracks created in the Clarion-Clipperton Fracture Zone nearly 40 years ago, suggesting that the effects of nodule recovery on benthic fauna in the mining area are long-lasting and possibly irreversible on time-scales relevant to proper environmental management. Similar uncertainty exists for polymetallic deposits on and near vent sites or on seamounts.

During mining, seafloor sediments will be stirred up, resulting in a plume of suspended particles (MIDAS, 2016). Depending on the deposit type and local hydrodynamic conditions, these sediment plumes will differ in nature and disperse over different distances. When the plumes resettle, they could affect sessile fauna, clog filter-feeding mechanisms and, depending on the spatial and temporal scales of the plume and its nature, cause changes in ecosystems and habitats. The severity and spatial scales of plumes remains a controversial issue, with environmentalists fearing plumes could travel hundreds of kilometres and mining companies anticipating the impact to extend no further than 10 km from the mining site. Resolving these widely diverging views will require additional in situ data collection in combination with hydrodynamic sediment plume forecasting, even though a precise impact may only become clear during on-site operations as a result of fluctuations that are influenced by sediment size and hydrodynamic conditions specific to each site.

At the other end of the water column, surface water could be affected by secondary plumes generated by the rising systems and dewatering processes on board the surface ship or platform, prior to the transfer to storage vessels. These plumes may pose threats from metal leaching, mine tailings, and micro-particles. Furthermore, waste-water containing a sediment-water mix after the nodules have been removed could create plumes as well. If these are released at depth but at a higher temperature than the ambient water, they could rise, thereby impacting the water column over a wider area.

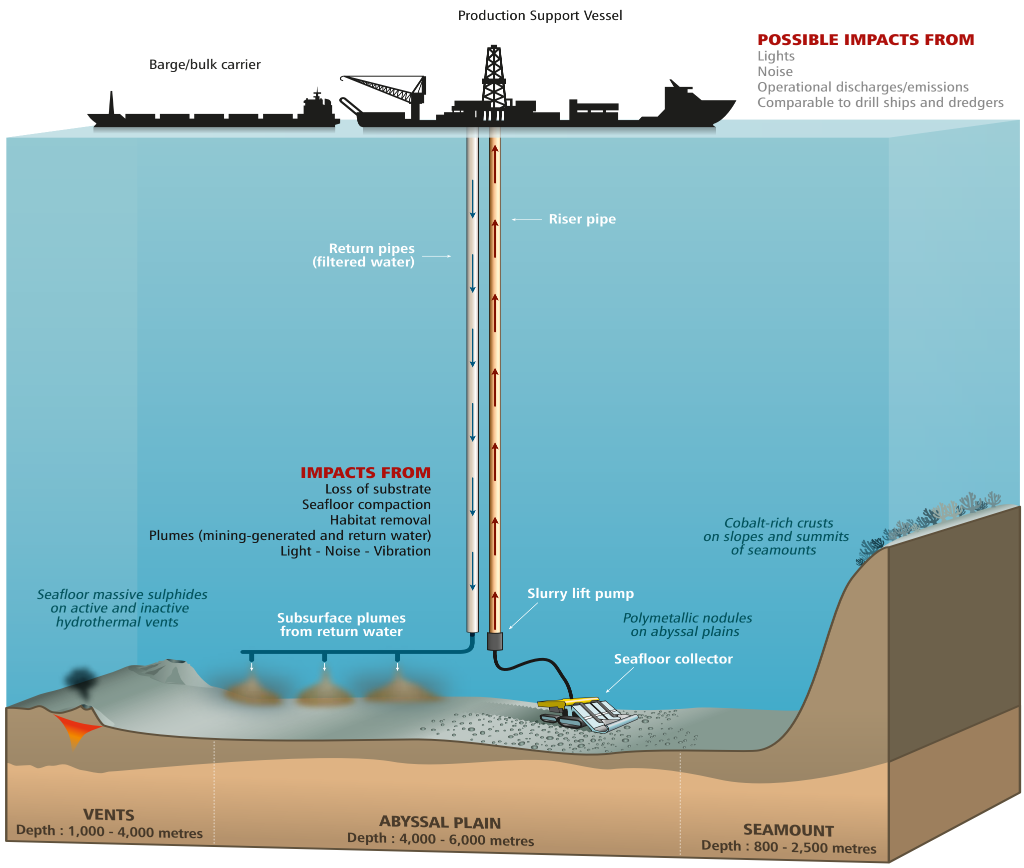

Figure 8.1
A schematic diagram showing some of the potential effects of deep-sea mining. Only one operation is shown – polymetallic nodule mining. Mining may also take place for seafloor massive sulphides near hydrothermal vents and, at a later stage, for polymetallic (cobalt-rich) crusts on seamounts. On the surface the impact of the production support vessel(s) would be similar and comparable to drill or dredging vessels. Near the seafloor, the impact would depend on the type of mining, though in all three instances the impact and size of sediment plumes and the effects on deep-sea biodiversity remain among the issues of most concern. Source: Global Marine and Polar Programme, IUCN.

Secondary impacts are also poorly understood and hence difficult to predict or assess. These can include noise and light pollution caused by the mining equipment and surface vessels, electromagnetic disturbances, increased shipping activity and vibrations, and a risk of leaks and spills of fuel and toxic products. A variety of organisms could be affected, including pelagic fish and marine mammals as well as benthic invertebrates. It also should be noted that the consequences and impacts of deep seabed mining activities could intensify other anthropogenic impacts impacting the marine environment.

Environmental Management

UNCLOS clearly directs deep-sea mining, in national as well in international waters, to proceed with minimal impact on the marine environment. To do so, effective environmental management strategies and recommendations need to be included within the relevant legal frameworks and guidelines. This will require the development and application of the best available scientific information, sound scientific principles and effective mitigation measures.

Baseline Studies

Baseline studies or assessments offer information on the status and condition of the deep seabed prior to any development. They provide a critical reference point for assessing any changes and impacts, as they establish a benchmark for comparing the situation before, during and after mining. Detailed baseline assessments are a crucial first step in proper environmental management.

The Precautionary Approach

In order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation (UNCED, 1992, Principle 15)

The precautionary approach emerged during the onset of the environmental movement in the 1970s to provide decision-makers guidelines when scientific evidence about environmental or human health hazards was uncertain. As Principle 15 of the 1992 Rio Declaration on the Environment and Development, the precautionary approach became enshrined at a global level and in the quarter century since has been incorporated in many legal instruments, from major international agreements like the Convention on Biological Diversity and the Convention on Climate Change to regional agreements and national environmental laws.

The precautionary principle also applies to deep-sea mining, as was confirmed by the International Tribunal for the Law of the Sea's (ITLOS) Advisory Opinion on "Responsibilities and Obligations of States Sponsoring Persons and Entities with Respect to Activities in the Area." In its opinion, released on 1 February 2011, the Tribunal unanimously agreed that Sponsoring States have *the obligation to apply a precautionary approach as reflected in Principle 15 of the Rio Declaration and set out in the Nodules Regulations and the Sulphides Regulations; this obligation is also to be considered an integral part of the "due diligence" obligation of the sponsoring State and applicable beyond the scope of the two Regulations*. In addition, the Tribunal declared Sponsoring States to have *the obligation to apply the "best environmental practices" set out in the Sulphides Regulations but equally applicable in the context of the Nodules Regulations* and *the obligation to adopt measures to ensure the provision of guarantees in the event of an emergency order by the Authority for protection of the marine environment*.

There are a number of conservation strategies that can be applied as part of a precautionary approach on deep-sea mining. These include the establishment of natural resource conservation units on a regional scale as well as within the contractor's license area (e.g., through preservation reference areas) and the development of mitigation and restoration strategies. A properly implemented precautionary approach also establishes criteria under which mining would be disallowed or strictly limited. Completing that part of the process requires additional data and research along with scaled test mining to study and predict all impacts before the onset of large-scale operations.

The growing interest in commercializing the deep sea in combination with a general desire to apply a precautionary approach has revealed a multitude of knowledge gaps regarding the deep ocean. There is a need for additional baseline data on deep ocean biodiversity (species richness, abundance, biomass and habitat mapping), connectivity and life cycles of local species, temporal dynamics of deep-sea ecosystems, bentho-pelagic coupling via food webs, ecotoxicology associated with exposure to re-suspended metals and materials, modelling of deep ocean currents and associated dispersal of sediment plumes and chemical elements contained therein (Rogers et al., 2015).

The nature and extent of baseline studies required to support proper management of a particular mining operation will vary with its management objectives, site characteristics, the size of the proposed mining area, the mining techniques and available equipment and resources for carrying out environmental studies (Figure 8.2).

Figure 8.2
Deep-sea baseline studies require an analysis and description of the existing environment, including assessments of the aspects shown here. Environmental and Social Impact Statements will also address the effects on local communities and/or other marine activities. Adapted from Baker & Beaudoin (2013a).

PHYSICAL ASSESSMENT	OCEANOGRAPHIC ASSESSMENT	BIOLOGICAL ASSESSMENT	EXISTING ACTIVITIES ASSESSMENT
Geology	Current regime	Pelagic biodiversity	Fishing
Bathymetry	Hydrodynamic modelling	Benthic biodiversity	Tourism
Sediment characteristics	Water quality	Ecosystem structure	Shipping
Sedimentation rates	Visual characteristics	Ecosystem function	Cultural

Baseline assessments need to be followed up by long-term monitoring and sampling to track any changes and to understand and quantify the pressures and impacts facing the deep sea. In addition, data collected during baseline studies can help identify special areas for conservation or networks of no-mining areas and contribute to the improvement of Environmental Impact Assessment (EIA) procedures (Rogers et al., 2015).

Environmental Impact Assessment

An Environmental Impact Assessment (EIA) evaluates the probable impacts of a proposed project or development on the associated environment. It is a necessary tool that typically considers the environmental, social and economic impacts prior to making final decisions so that adverse impacts can be reduced. It also evaluates any risks and proposes mitigation strategies to reduce them. A properly conducted EIA forms the basis of an Environmental Impact Statement (EIS), which proposes measures to minimize environmental impacts and maximize legislative compliance.

As they are essential in determining the potential impact of deep seabed mining activities, EIAs are required by the ISA prior to the commencement of exploration and exploitation activities. To assist with the development of EIAs and EISs, the ISA has released technical guidelines that will be regularly updated to reflect new scientific insights and new information on the environmental effects of exploitation. Prior to exploitation, contractors will also be required to submit an Environmental Management and Monitoring Plan, setting out management and mitigation measures and detailing all monitoring and reporting actions that will be taken to comply with the EIS (Boschen et al., 2013).

Mitigation strategies

Mitigation strategies are closely linked with EIAs, as their purpose is to reduce the likelihood of the events identified in the EIA from occurring or to lessen their potential effects. The strategies typically follow a hierarchy: first by attempts to avoid the effects, then by minimization strategies and finally by remediation efforts. The extent to which the various components can be effectively applied depends on the nature and range of the expected impacts as well as the type of environment that is to be protected.

In the case of deep-seabed mining, mitigation measures may be restricted to the site of the deposits or they may be applied on a much larger scale (Boschen et al., 2013). The ISA, following the guidance of the International Marine Minerals Society Code (IMMS, 2011a), recommended the creation of "impact reference zones" and "preservation reference zones" to be used exclusively for scientific observation and monitoring (ISA, 2010). Following the release of a technical study on these zones in vent sites, a series of networks of chemosynthetic ecosystem reserves (CERs) have been proposed to protect vent ecosystems throughout the deep sea (International Seabed Authority, 2011b; Van Dover et al., 2012).

SOCIAL IMPACT ASSESSMENT

Much the same way Environmental Impact Assessments determine the impacts of certain activities on the environment, Social Impact Assessments (SIA) do so for the impacts of a project or infrastructure development on society. Like EIAs, SIAs originated during the 1970s, initially to address the impact of planned projects on indigenous peoples in the United States, Canada and Australia. They are now legally required in many other countries, usually in combination with Environmental Impact Assessments.

A widely used definition calls on SAIs to include "the processes of analyzing, monitoring and managing the intended and unintended social consequences, both positive and negative, of planned interventions (policies, programs, plans, projects) and any social change processes invoked by those interventions. Its primary purpose is to bring about a more sustainable and equitable biophysical and human environment."

Given the distance of ISA contract sites from coastal communities, the ISA does not require SIAs to be submitted. Deep-sea mining projects in EEZs nearer to the coast, on the other hand, can have a major impact on coastal communities, both positive (e.g., by generating financial resources and employment in poorly developed areas) and negative (e.g., when affecting other ocean users like fishermen). For this reason, deep sea mining projects in national waters should include an assessment of social impacts, either as a separate SIA or combined with the environmental aspects in an integrated Environmental Social Impact Assessment (ESIA).

The greatest social impact of deep-sea mining will probably not relate to mining as much as to the processing of the raw materials – an activity that will take place onshore and, like most large-scale metal processing, can be accompanied by considerable social costs and benefits. As any EIA, a proper SIA not only summarizes potential impacts but also suggests ways to mitigate or remediate the consequences.

In addition to the establishment of protected areas and reserves, other potential mitigation strategies include mining patterns that leave large, adjoining areas undisturbed by direct mining (avoidance); the continual improvement of mining equipment to reduce sediment plume dispersion or seafloor compaction along with modifications in waste disposal techniques to reduce their impact (minimization); and the development of artificial substrate to help with the re-colonization process or the development and implementation of emergency response procedures (remediation). Other potential (though untested) mitigation strategies are presented and explored in the SPC-UNEP GRID/Arendal Deep-sea Minerals report series (Baker & Beaudoin, 2013a, b, c). The likelihood of these mitigation and remediation strategies being successful has been questioned in recent reports (Van Dover et al., 2017; Niner et al, 2018).

Marine Spatial Planning (MSP)

The ocean-equivalent of land-use planning, marine spatial planning seeks to make informed and coordinated decisions on out how to best use a specific marine zone or its resources. Depending on the number of users that seek to use a specific marine area, it can be a complicated process involving many stakeholders with conflicting interests.

As many of the potential mining sites are located far from shore in areas that are neither intensively navigated or fished, spatial planning for deep-sea mining is mostly a matter of designating which areas can be mined versus those that should be protected. The more areas that are declared off limits, the greater the chances of meeting the requirement to protect and conserve the marine environment. Spatial management through the designation of no-mining areas will thus undoubtedly contribute to ensuring site-specific and regional-scale conservation of ecosystems and biodiversity (Boschen et al., 2013).

There are several ways to declare certain areas off limits. Marine Protected Areas (MPAs) can be designated to protect parts of the deep sea from the environmental impacts of marine mining. The Convention on Biological Diversity (CBD) has taken steps to help support the development of MPAs and other area-based management tools in areas beyond national jurisdiction, including guidelines for describing ecologically or biologically significant areas in need of protection (Gjerde & Rulska-Domino, 2012). Several studies have investigated the scientific basis for a systematic and practical approach to the establishment of protected areas (Van Dover et al., 2012, Wedding et al., 2013; Ban et al., 2014). This systematic approach to deep-sea spatial management and environmental zoning envisages a framework that balances socio-economic interests with the protection of the marine environment, including the conservation of marine biodiversity and ecosystems.

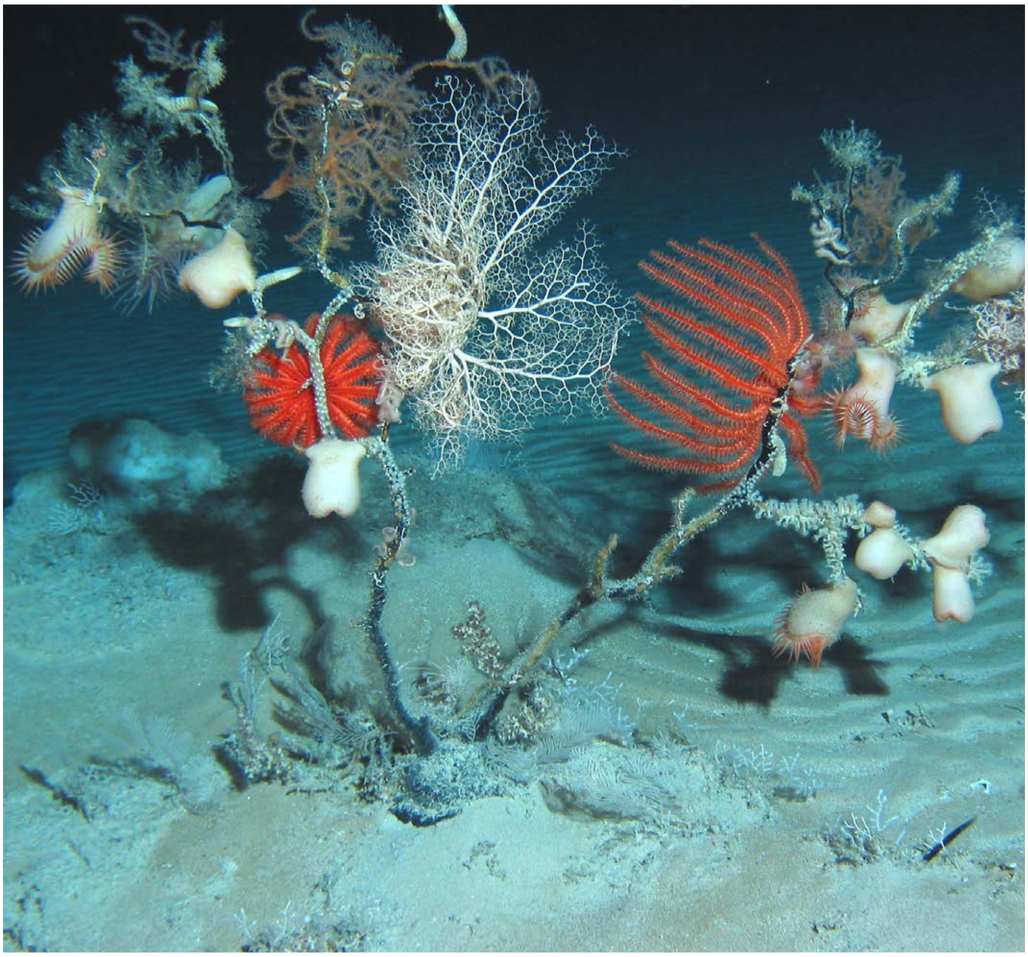

Figure 8.3
A deep-sea coral on the seafloor near the Bahamas provides a place to hang out for variety of creatures. Dangling from its branches are several flytrap anemones, two brisingid sea stars, a few holothurians high in the branches, brittle stars and at least one basket star amongst other creatures. The ripple pattern on the seafloor indicates a brisk current to provide a continuous stream of small organisms on which they all can feed. Every trip to the deep sea yields new insights and often species previously unknown, and this creates one of the key dilemmas related to deep-sea mining: are we in danger of losing any of this before we even knew it existed. To prevent this from happening there is a need to set aside large no-mining areas and to apply and enforce sound environmental practices. In instances where, in spite of all precautions, biodiversity cannot be protected or preserved, deep-sea mining operations should be prohibited or strictly limited. Doing otherwise would run counter to one of UNCLOS' principal objectives: ensuring that deep-sea development takes place not only for the benefit of our generation, but also for all those generations that are yet to come. Courtesy Bioluminescence 2009 Expedition, NOAA/OER.

The establishment of networks of clearly delineated no-mining areas as part of regional environmental management plans provides another way to keep part of the deep seabed undisturbed. No-mining areas provide a buffer against existing threats to the marine environment and can help mitigate future threats. In this respect, the network of Areas of Particular Interest (APEIs) established by the ISA for the Clarion-Clipperton Fracture Zone (Fig. 7.2) can develop into a significant example of deep-sea environmental management. An MPA network of sorts, the APEI system seeks to maintain healthy marine populations, account for regional ecological gradients, protect a full range of habitats, and create sufficiently large buffer zones against external anthropogenic impacts like sediment plumes. The nine APEIs measure the same 400 km by 400 km and, unlike contract zones, consists of straight-line boundaries to facilitate rapid recognition and compliance. There have been calls to establish even more APEIs, positioned nearer to one another to avoid excessive spacing (which limits population connectivity).

Monitoring Programs

Monitoring programs enable regulatory authorities to regularly check, review and assess the environmental effects of mining activities. They are essential to developing and testing additional prevention, reduction and mitigation methods. The programs rely on completed baseline studies to identify and track any changes, thereby enabling the measurement of potential and actual changes at a mining site. Long-term monitoring programs are required by the ISA, as recommended by the International Marine Minerals Society Code for Environmental Management of Deep-Sea Mining. They need to be adapted to suitable spatial and temporal scales in accordance with the precautionary management approach (Boschen et al., 2013; Clark & Smith, 2013).

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9 THE WAY FORWARD

This overview of deep-sea mineral resources and their potential development reveals issues that warrant further consideration.

The facts:

- The deep sea consists of the seabed and water column below a depth of 200 m. It accounts for 95% of the volume of the oceans, making it the largest habitat for life on Earth.
- The deep seabed contains valuable mineral deposits. Due to the growing demand for metals and the depletion of some terrestrial reserves, three of those are of increasing commercial and strategic interest: polymetallic nodules, ferromanganese crusts and seafloor massive sulphides.
- Though deep-sea mineral deposits are often mentioned in the same breath, they are very different in terms of formation, composition, and extent. These differences require different mining technologies and strategies, which are currently being tested and developed. Commercial mining in national waters could start in 2020; in international waters no earlier than 2025.
- Deep-sea mining will affect the diverse communities of living organisms in the vicinity of mining sites; ecosystems which, because of their remoteness, remain poorly understood. There may be ways to limit and perhaps contain the impact, but deep-sea mining without environmental effects is impossible.
- UNCLOS directs the deep seabed beyond national jurisdiction to be developed for the benefit of humankind. That benefit was implied to include a financial component derived from resource development along with an obligation to ensure effective protection of the marine environment from its potentially harmful effects: a challenging dual mandate UNCLOS assigned to the International Seabed Authority (ISA).

Key findings:

- Deep-sea mining will impact the deep-sea environment. The nature and extent of the potential environmental effects remain incompletely known, justifying a precautionary approach to the deep sea's development.
- Unlike existing ocean uses, deep-sea mining is a new marine activity, which allows the precautionary approach to be integrated into the regulatory framework prior to the onset of commercial operations. At present there is broad support among all stakeholders to do so, creating a powerful precedent for the management and exploitation of natural resources.
- An effective regulatory framework is deposit- and/or site-specific and is based on high-quality environmental assessments at multiple scales. This calls for comprehensive, interdisciplinary baseline studies, regional scale and site-specific spatial planning and monitoring programmes, as well as an advanced mitigations strategy that ensures effective protection through avoidance, minimization and, where needed and appropriate, remediation.

Suggested action:

- Organizations tasked with developing, implementing and enforcing the regulatory framework, whether at the national or international level, should be provided the proper financial means, infrastructure and expertise to accomplish *and* report on their task. This is particularly relevant to the ISA, an organization entrusted with the development and conservation of nearly half of the surface of the planet and therefore subject to the highest levels of transparency.

- The ISA's mandate to regulate both the development and the protection of the deep sea will become more difficult to balance as deep-sea mining makes the the transition from exploration to exploitation. To avoid possible conflicts of interest, it is appropriate for the ISA to consider divesting some responsibilities to autonomous review, inspection and/or enforcement entities.

- Given the vital importance of the deep sea to the planet, it is recommended that a significant part of the revenues collected by the ISA for the benefit of mankind is to be re-invested in the deep sea through training, education, marine science and conservation programs, thereby ensuring that those benefits also accrue to future generations.

- Alternatives to metals derived from deep seabed and land mining should be considered as part of a strategic and complimentary approach. These include enhancing product design to reduce demand for scarce resources, encouraging repair and reuse, improving recycling and metal retention within the circular economy, and developing alternative materials.

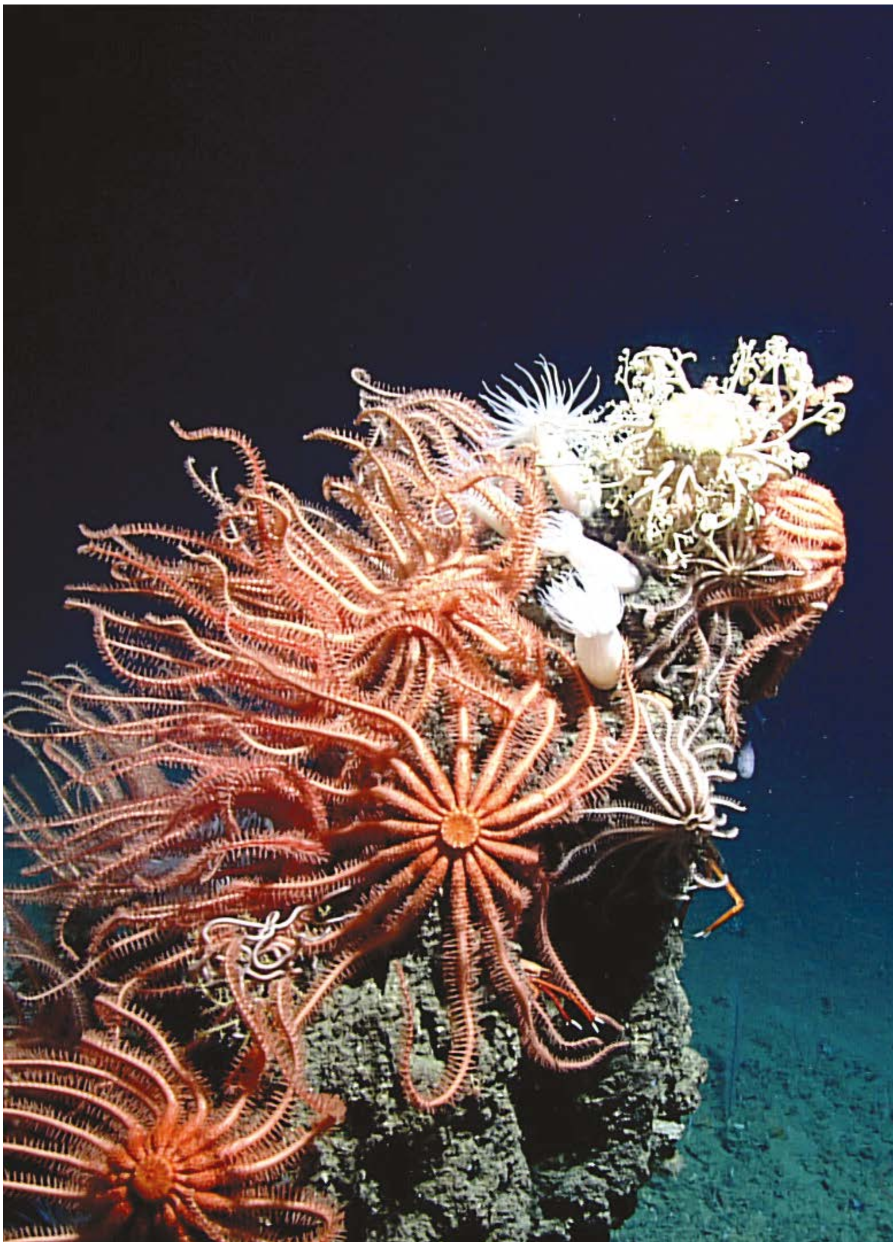
Some final thoughts:

- Resolving deep-sea mining issues requires cooperation, clear communication and mutual respect among the various stakeholders. Diverging views must be clearly communicated and discussed in an atmosphere of mutual respect in search of balanced solutions.

- Research that benefits humanity through a better understanding of the deep sea can and should be publicly funded or supported; research that focuses on the direct effects or the efficiency of deep-sea mining technology, in contrast, should be privately funded.

- UNCLOS's directive to develop *and* protect the deep seabed from any mining-related harmful effects implies the option of not proceeding with development if adequate protection cannot be guaranteed. While the data and information to do so may not yet be available, there will be a need to establish clear deposit- and/or site-specific criteria under which deep-sea mining would be disallowed or strictly limited.

- The *benefit of mankind* concept can be construed more broadly now than it was when coined half a century ago. At that time, exaggerated estimates on the value of deep-sea minerals projected a massive redistribution of wealth, while the environmental implications of their exploitation were hardly considered. Since then, the potential financial returns have been lowered whilst environmental issues (and costs) have expanded. In view of this adjustment, deep-sea development for the benefit of humankind should be considered less of an obligation than an opportunity, the economic and social costs of which need to be carefully weighed against the economic and social benefits.



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