



DEEP SEA MINERALS

1B

Manganese Nodules

A physical, biological, environmental, and technical review



Edited by Elaine Baker and Yannick Beaudoin



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Jan Steffen IUCN
Arthur Webb Secretariat of the Pacific Community/SOPAC Division

Editors

Elaine Baker and Yannick Beaudoin

Authors

Malcolm R. Clark National Institute of Water & Atmospheric Research Ltd (NIWA)
Robert Heydon Offshore Council
James R. Hein United States Geological Survey (USGS)
Samantha Smith Nautilus Minerals Inc.
Craig Smith University of Hawai'i
Sven Petersen GEOMAR
Elaine Baker GRID-Arendal at the University of Sydney
Yannick Beaudoin GRID-Arendal

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Cartography

Kristina Thygesen GRID-Arendal
Riccardo Pravettoni GRID-Arendal

Front Cover

Alex Mathers

Technical Editors

Claire Eamer
Patrick Daley

Production

GRID-Arendal

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Introduction

The presence of polymetallic nodules, commonly referred to as manganese nodules, on the abyssal plains has been known for more than a century. The nodules – rocky lumps made up of iron and manganese hydroxides – contain a variety of metals of commercial interest. In the 1970s, a number of national governments and mineral exploration companies sponsored efforts to investigate the recovery of manganese nodules discovered on the seabed underlying international waters.

At the time, however, there was no international regulatory regime governing the international seabed. Consequently, security of tenure and legal certainty of ownership could not be guaranteed. This lack of certainty affected the commercial development of polymetallic nodules (Derkmann *et al* 1981). At the same time, major land deposits of nickel and copper, the metals then driving interest in nodules, were discovered. That pushed metal prices downward and made the potential economic return on manganese nodules uncertain. These factors combined to halt the full-scale development of the industry.

Today, there is renewed interest in manganese nodules. Governments and investors see them as a potential source of nickel, copper, and a number of rare-earth elements. Initially, the growing interest in nodules focused on Areas Beyond National Jurisdiction – often simply called the Area – especially a region of the equatorial North Pacific east of Kiribati and Hawaii, known as the Clarion-Clipperton Zone (CCZ). In 2010, the International Seabed Authority (ISA), the organization responsible for administering the resources in the Area, published a technical report (ISA 2010), which contains a geological model of nodule deposits in the CCZ. More recently, there has been increased interest in nodules located within the Exclusive Economic Zones (EEZs) of Pacific Island states.

To support Pacific Islands in governing and developing these natural resources, the Applied Geoscience and Technology (SOPAC) Division of the Secretariat of the Pacific Community (SPC) is providing a range of information products, technical and policy support, and capacity-building activities through a project called Deep Sea Minerals in the Pacific Islands Region: a Legal and Fiscal Framework for Sustainable Resource Management (Figure 1). This publication, created as part of that project, brings together expert knowledge on the geology and biology of manganese nodules and information about best practices related to the environmental management and technical aspects of mineral exploration and extraction.



Figure 1. The Pacific ACP States (i.e., Africa-Caribbean-Pacific Group of States) participating in the European-Union-funded SPC Deep Sea Minerals Project

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1.0

The Geology of Manganese Nodules

James R. Hein¹ and Sven Petersen²

¹ U.S. Geological Survey, 400 Natural Bridges Dr., Santa Cruz, CA, 95060, USA

² Helmholtz Centre for Ocean Research Kiel (GEOMAR), 24148 Kiel, Germany



1.1

The formation and occurrence of manganese nodules

Manganese nodules are mineral concretions made up of manganese and iron oxides. They can be as small as golf balls or as big as large potatoes. The nodules occur over extensive areas of the vast, sediment-covered, abyssal plains of the global ocean in water depths of 4 000 to 6 500 metres, where temperatures are just above freezing, pressures are high, and no sunlight reaches (Figure 2).

The manganese and iron minerals in these concretions precipitate (form a solid) from the ambient, or surrounding, water in two ways (Figure 3):

- hydrogenetically, in which the minerals precipitate from cold ambient seawater; and
- diagenetically, in which minerals precipitate from sediment pore waters – that is, seawater that has been modified by chemical reactions within the sediment.

The metal oxides that make up the precipitate attach to a nucleus – perhaps something as small and common as a bit of shell or a shark’s tooth – and very slowly build up around the nucleus in layers. Their mineralogy is simple: vernadite (a form of manganese oxide) precipitates from seawater; todorokite (another manganese oxide) precipitates from pore waters; and birnessite (a third manganese oxide) forms from the todorokite.

Depth region of potential nodule development

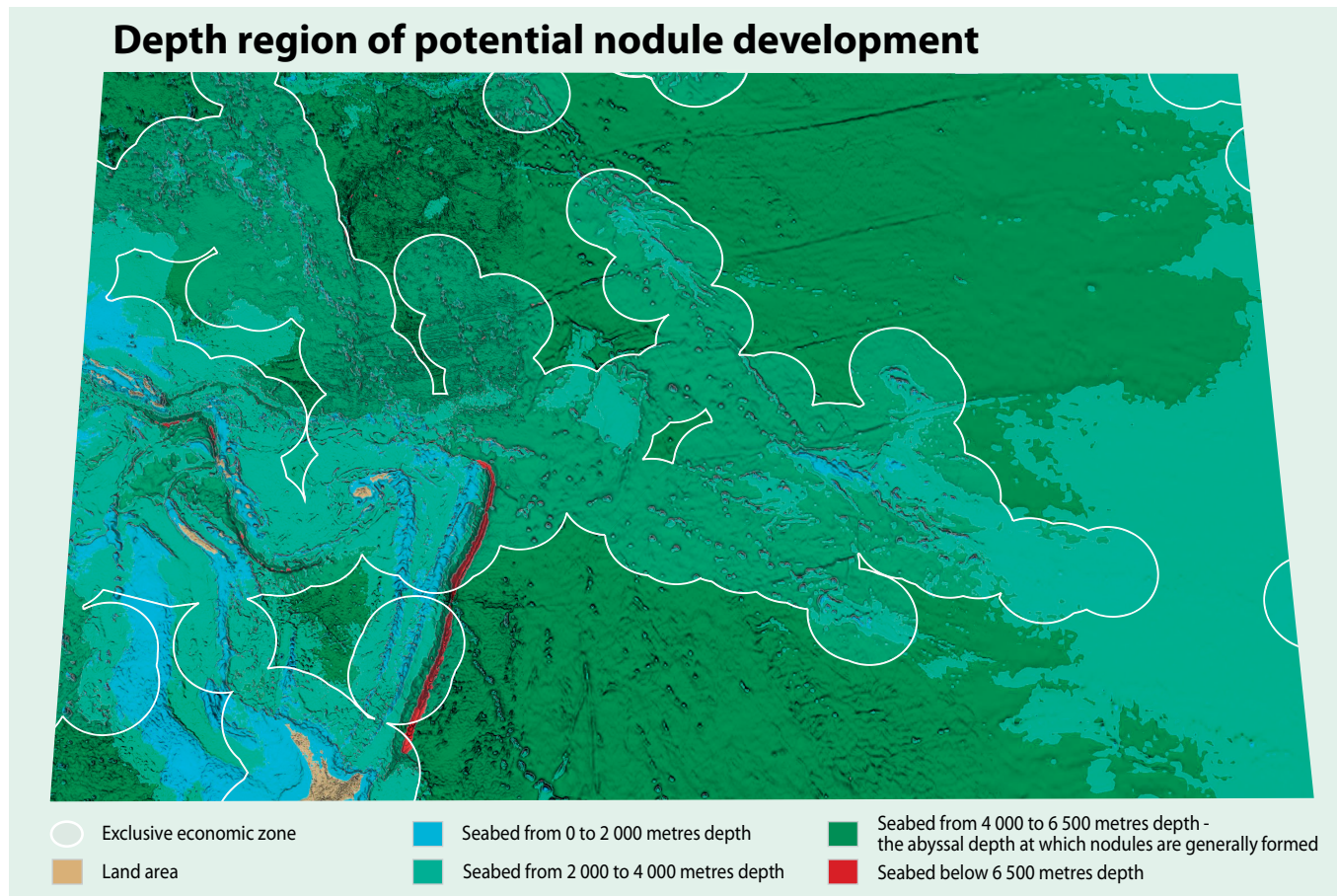


Figure 2. Sea-floor bathymetric map showing where manganese nodules might occur in the Pacific ACP States region. Manganese nodules occur at depths of 4 000 to 6 500 m, indicated by dark green in this map.

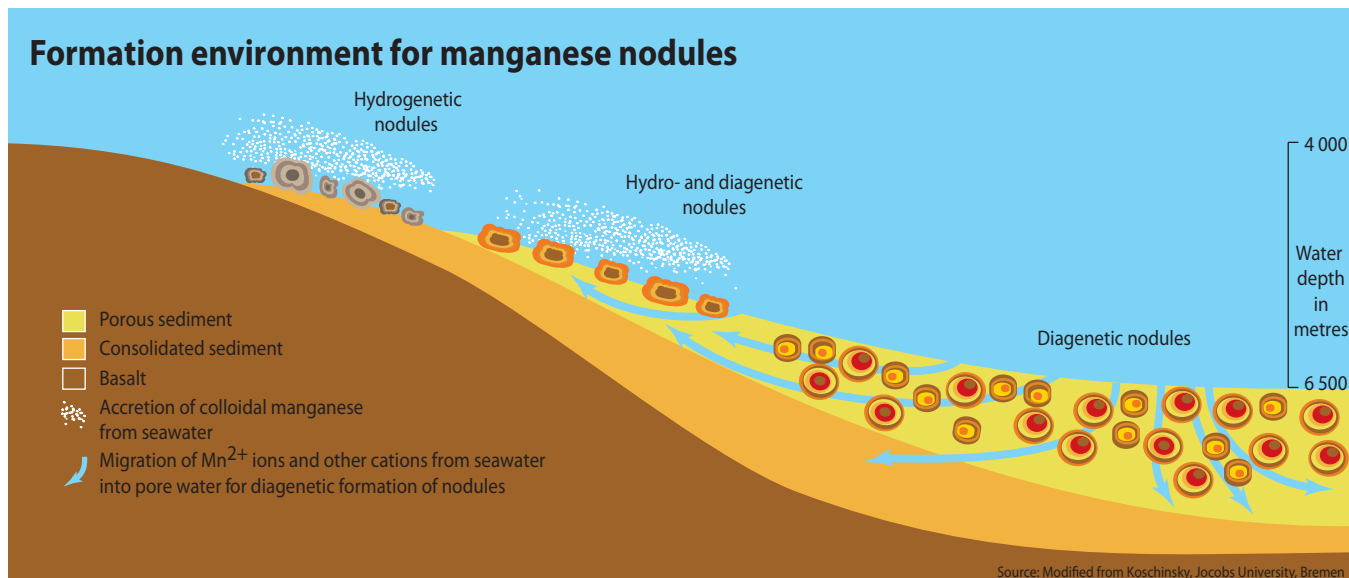


Figure 3. Formation of manganese nodules. This process takes place in water depths of 4 000 to 6 500 metres.

Hydrogenetic nodules grow extremely slowly, at a rate of about 1 to 10 mm per million years, while diagenetic nodules grow at rates of several hundred mm per million years. Most nodules

form by both hydrogenetic and diagenetic precipitation and, therefore, grow at intermediate rates of several tens of mm per million years (Figure 4).

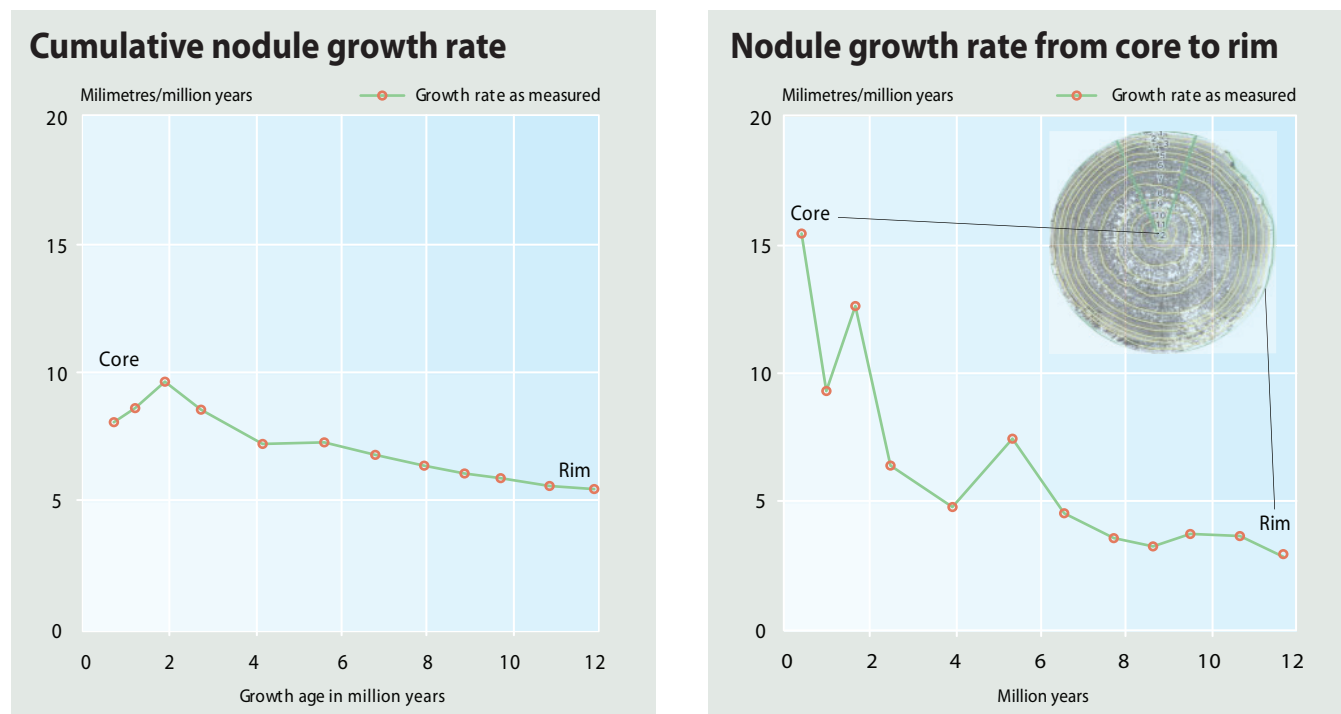


Figure 4. Growth age and growth rate of nodules. Growth age versus cumulative growth rate (left) and growth rate versus model age (right) in nodules from the Campbell Nodule Field, New Zealand. Extrapolated ages are based on measured $^{10}Be/^{9}Be$ ratios and the extrapolated $^{10}Be/^{9}Be$ ratio of the rim. Model ages are based on measured $^{10}Be/^{9}Be$ ratios and an assumed initial $^{10}Be/^{9}Be$ ratio. Growth ages (in m.y.) are based on the elapsed time from initiation of growth (i.e., core to rim). Graham et al. 2004.



Cross-section of large, 13.6-cm diameter seamount nodule from Lomilik seamount within the Marshall Islands EEZ. The complex growth histories of manganese nodules are revealed by the tree-ring-like texture of the nodule interior. Photo courtesy of Jim Hein, USGS.

The role of bacteria and organic matter in the formation of nodules is not well understood. The presence of bacteria could indicate a biological role in the formation of the nodules, but the bacteria could also be bystanders caught up in the process of mineralization. The very slow growth rates of nodules suggest that reactions linked with bacteria are not the major mechanisms of manganese and iron accretion. However, bacteria are the major players in sediment diagenesis, the process that releases manganese, nickel, copper, and lithium to the pore fluids, which then take part in forming the nodules (Hein and Koschinsky 2013). Bacterial activity and precipitation of organic matter may also play some role in the mineralization process.

The greatest concentrations of metal-rich nodules occur in the Clarion-Clipperton Zone (CCZ; ISA 2010, Figure 5), which extends from off the west coast of Mexico to as far west as Hawaii. Nodules are also concentrated in the Peru Basin, in the Penrhyn Basin near the Cook Islands (Figure 5), and at abyssal depths in the Indian and Atlantic oceans. In the CCZ, the man-

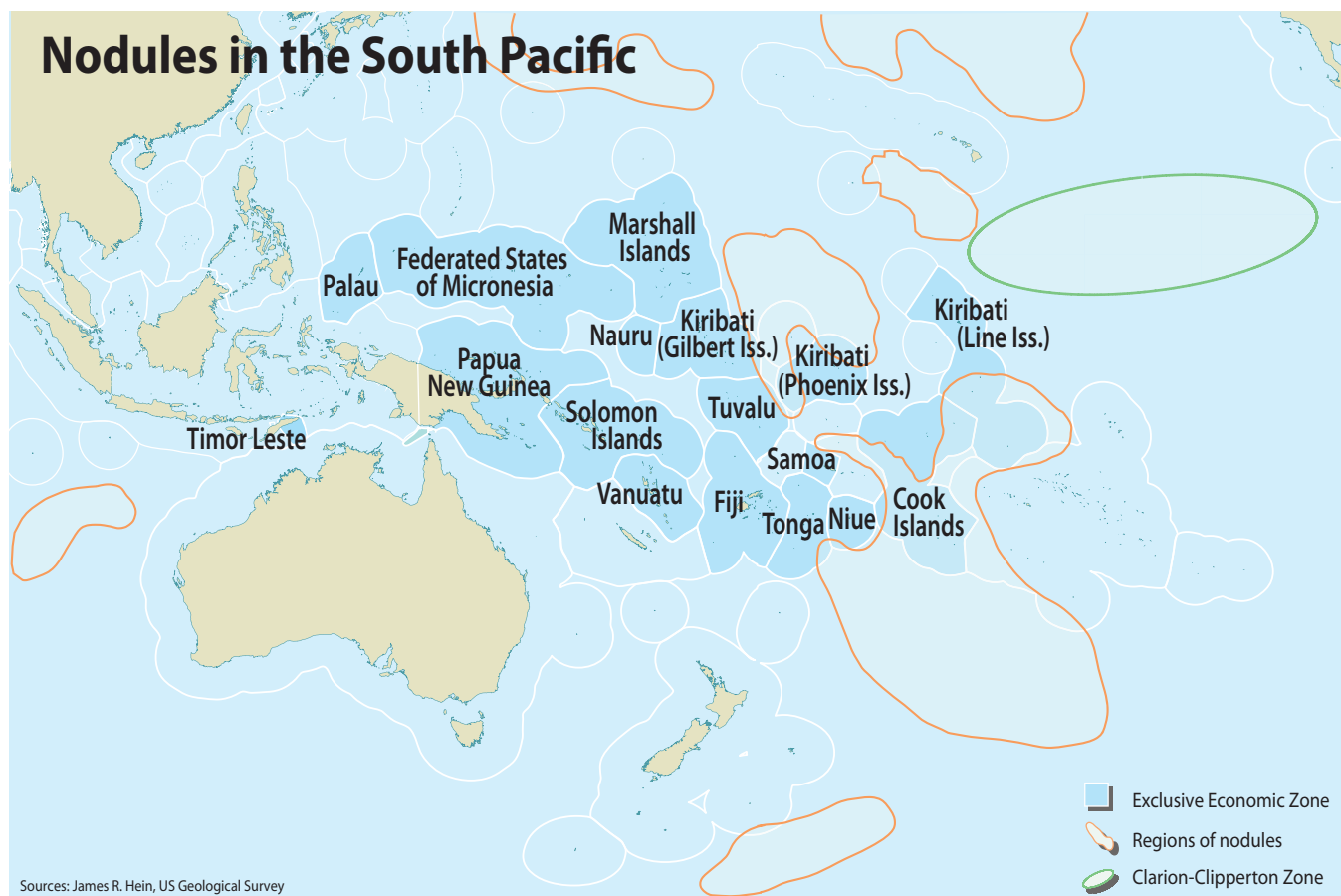


Figure 5. Location of nodule zones in Oceania.

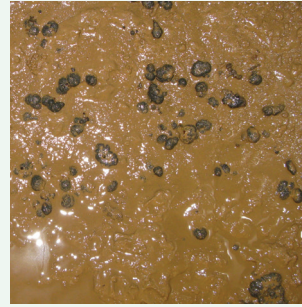
Variability in nodule abundance within the Clarion-Clipperton Zone



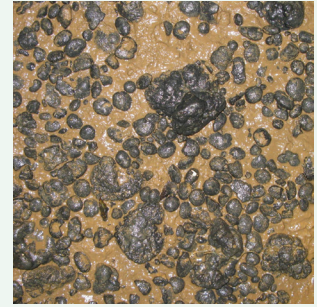
Small nodules of high abundance



Large nodules of high abundance



Small nodules of low abundance



Bi-modal nodules of high abundance

Photo: Micheal Wiedicke-Hombach, BGR

Average abundance of nodules

Kilograms per square metre



Source: James R. Hein, US Geological Survey

Figure 6. Current estimates of average nodule abundance in four major locations.

ganese nodules lie on abyssal sediments covering an area of at least 9 million square kilometres. Nodule densities can be as high as 75 kg per m² of seabed within this area, but more commonly average less than 15 kg per m² (Figure 6).

The high abundance of nodules in the CCZ is attributed to a number of factors. The combination of slow rates of sedimentation and abundant sediment infauna (animals living within the sediment itself), which cause bioturbation and the uplifting of the nodules, helps to keep them on the surface of the seabed. The

flow of Antarctic Bottom Water through the CCZ erodes and removes fine sediments, leaving abundant materials (such as fragments of broken nodules, mineral grains, and plankton shells) for the manganese and iron to nucleate around. This flow also keeps the bottom waters well oxygenated. The moderate surface-water productivity of the region provides the organic matter that the bacteria in the sediment use in diagenetic reactions, yet is not high enough to increase sedimentation rates. Finally, a semi-liquid bottom sediment layer provides abundant pore water to contribution to diagenetic nodule formation.

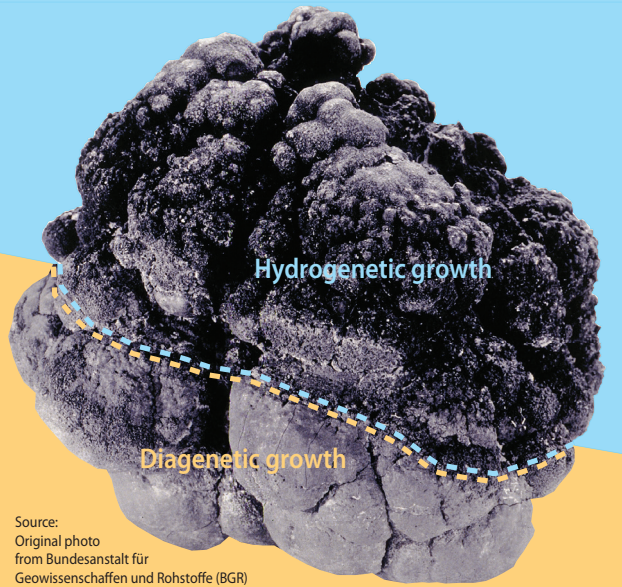


Physical characteristics of manganese nodules

Manganese nodules come in many shapes and sizes. They can be round, oblong, composite, or flat. Their shape can be influenced by the shape of the nucleus, the water content of the surrounding sediment, growth rates, and how often they are turned by infauna or moved by epifauna. As a general rule, smaller nodules tend to be more symmetrical. As nodules grow, they are less easily moved about by currents and animals, which leads to asymmetric growth resulting from faster diagenetic growth on the bottom and slower hydrogenetic growth on the top.

The surface texture of nodules depends partly on the dominant mechanism of formation. Other factors that influence texture include the size of the nodules, the strength of bottom currents, sediment on the surface of the nodules, and how often the nodules are turned (Figure 7). Diagenetic nodules tend to be rougher. Hydrogenetic nodules, in their most pure form, have a botryoidal surface (shaped like a bunch of grapes) that can be smooth or rough, but usually falls somewhere between those two extremes. If the surface is very smooth, it was likely worn down by bottom currents (Hein *et al.* 2000; Hayes *et al.* 1985).

A mixed manganese nodule - Differences in surface texture



Source:
Original photo
from Bundesanstalt für
Geowissenschaften und Rohstoffe (BGR)

Figure 7. Hydrogenetic and diagenetic manganese nodule growth.

1.2 Metal concentrations and tonnages

Manganese and iron are the principal metals in manganese nodules (Figure 8). The metals of greatest economic interest, however, are nickel, copper, cobalt, and manganese. In addition, there are traces of other valuable metals – such as molybdenum, rare-earth elements, and lithium – that have industrial importance in many high-tech and green-tech applications and can be recovered as by-products (Figure 9).

The abundance of nodules and, therefore, the quantities of associated metals are moderately well known for the CCZ, the Central Indian Ocean Basin and the Cook Islands EEZ, but

poorly known for other areas of the global ocean. A conservative calculation for the CCZ estimates there are about 21 100 million dry metric tonnes of nodules in the region. That would yield nearly 6 000 million tonnes of manganese, more than the entire land-based reserve base of manganese (Hein and Koschinsky 2013). Similarly, the amount of nickel and cobalt in those nodules would be two and three times greater than the entire land-based nickel and cobalt reserve bases, respectively. The amount of copper in the CCZ nodules is about 20 per cent the size of the global land-based reserve base (Hein and Koschinsky 2013).

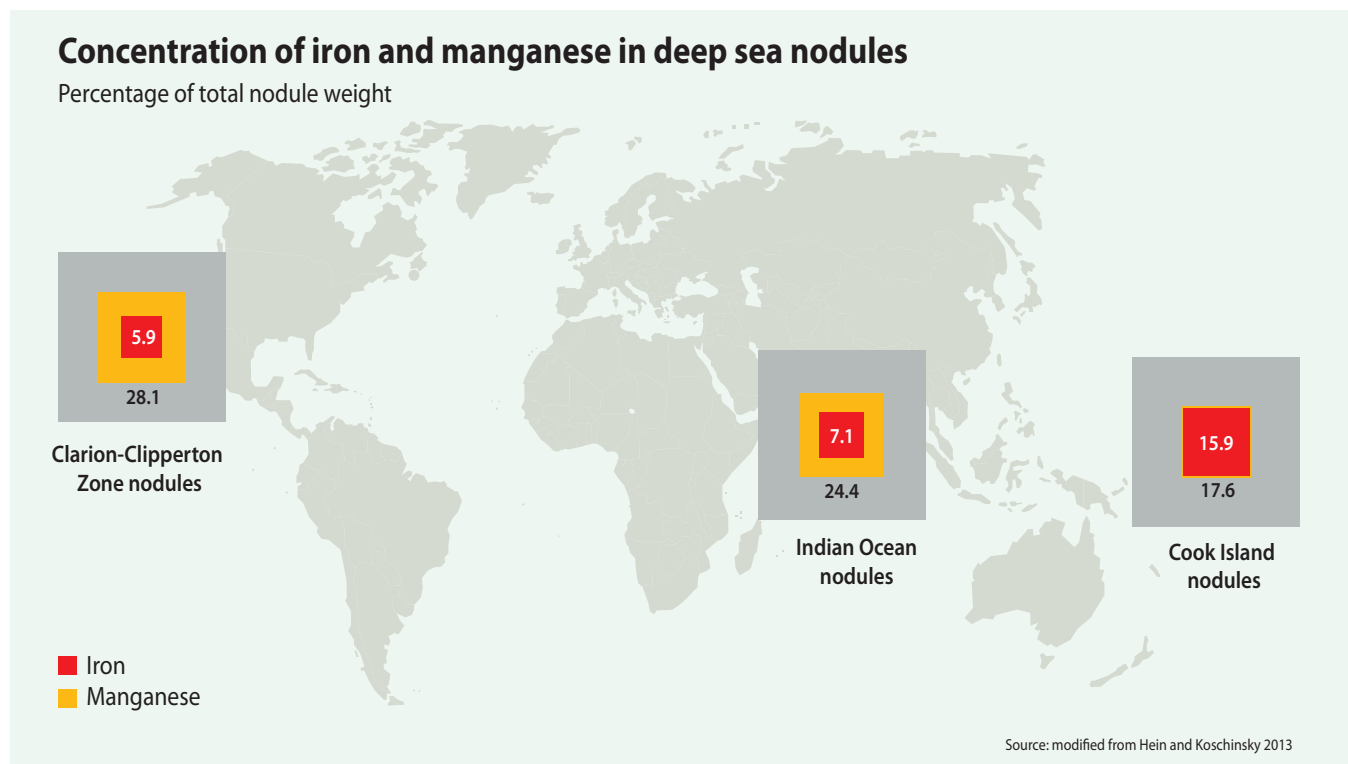
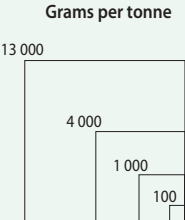
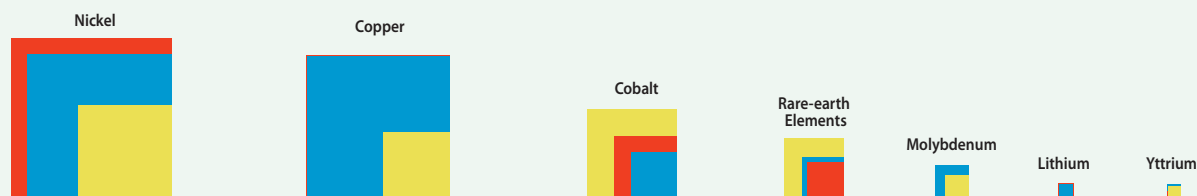


Figure 8. Varying percentages of iron and manganese in nodules from different environments. The iron/manganese ratio is controlled by the ratio of hydrogenetic/diagenetic input and whether or not the sediments involved in diagenesis are oxic, containing measurable amounts of oxygen. The Cook Islands nodules are almost solely hydrogenetic.

Concentration of nickel and other metals of potential economic importance in deep sea nodules



Note: the area of the squares is proportional to the grams per tonne value for each mineral. For comparison purposes, the area of the entire page represents proportionally one tonne.

Source: modified from Hein and Koschinsky 2013

Figure 9. Concentrations of metals other than iron and manganese. Concentrations are shown in gm/t in nodules from three different nodule regions. For iron and manganese, see Figure 8.

Cook Islands manganese nodules

Characteristics of Cook Islands EEZ Nodule Resource	
Water depth:	~5 000 m
Area of EEZ:	1 830 000 km ² (see Fig. 1)
Area of nodules ≥5 kg/m ² :	750 000 km ²
Target metal:	Cobalt
Potential by products:	Nickel, copper, manganese, niobium, zirconium, rare-earth elements
Tonnage of nodules (dry):	5 130 000 000 tonnes
Cobalt grade:	0.41%
Tonnage of in-place cobalt:	21 033 000 tonnes
Global cobalt reserves (2012):	7 500 000 tonnes
Global cobalt reserve base (2009):	13 000 000 tonnes
Global cobalt production (2011):	98 000 tonnes
Cobalt in 2x10 ⁶ dry tonnes nodules:	8 200 tonnes; ~8.4% of global production
Current cobalt price:	\$14–25/lb USD (\$31–55/kg)
35-years cobalt prices:	(see Figure 12)
Current profitable cobalt price:	≥\$25/lb
Projected cobalt price:	Steady for several years
Distance to Rarotonga:	Variable, <1160 km (from Manihiki)
Distance to processing plant:	~3 200 km (NZ) to ~5 700 km (Australia)

The parameters listed above, combined with average concentrations of 0.45 per cent for nickel, 0.23 per cent for copper, and 16 per cent for manganese, suggest in-place resources of 23 085 000 tonnes of nickel, 11 799 000 tonnes of copper, and 820 800 000 tonnes of manganese. These in-place tonnages are significantly greater than those that will be obtained after collection and processing of the nodules, since not all nodules in an area will be mined and some are lost in processing. Small areas (in the range of thousands of km²) with abundant (≥25 kg/m²), high-grade (~0.5 per cent cobalt) nodules will be the initial targets for mining operations, should such operations take place.

The Cook Island nodules are characterized by their high cobalt content (Figure 10 and Figure 11). Cobalt is becoming increasingly important, especially in the energy sector, due to its role in the production of rechargeable batteries. Cobalt is also used in a diverse range of industrial, hi-tech, medical, and military applications. The global cobalt market has historically

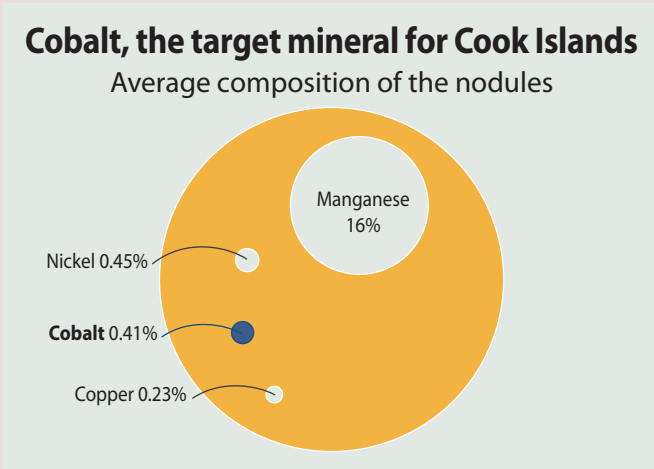


Figure 10. Current estimated average concentration of various metals in nodules from the Cook Islands. Data compiled by James R. Hein, USGS.

been very volatile (Figure 12). However, in recognition of the growing demand (Figure 13) and in an effort to provide greater price transparency, the London Minerals Exchange introduced cobalt futures trading at the beginning of 2010. Cobalt is traditionally produced as a by-product of the extraction of oth-

er metals, such as copper or nickel (Figure 14). The economic potential of the Cook Island nodules may increase if they are found to contain significant concentrations of rare metals and rare-earth elements. Determining this will require further geo-chemical analyses.

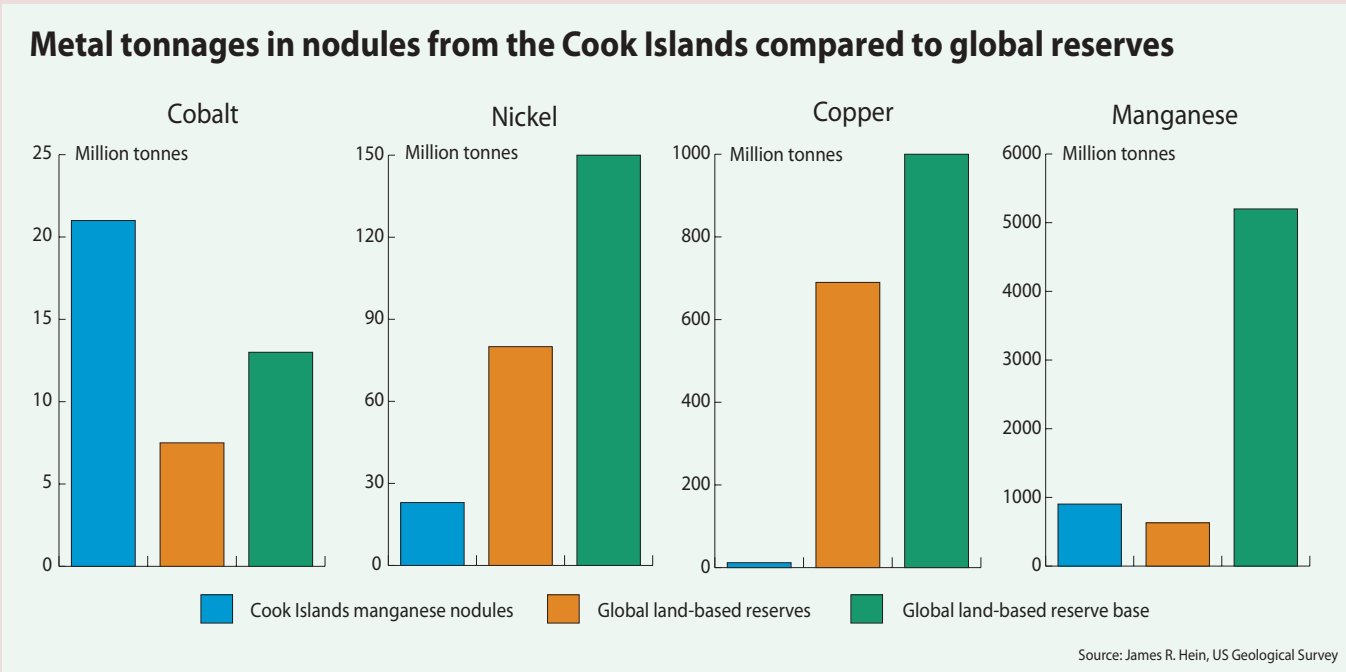


Figure 11. Current estimates of Cook Islands manganese nodules compared to global reserves. In-place tonnage of cobalt, nickel, copper, and manganese in Cook Islands nodules and a comparison with global land-based reserves and global land-based reserve base.

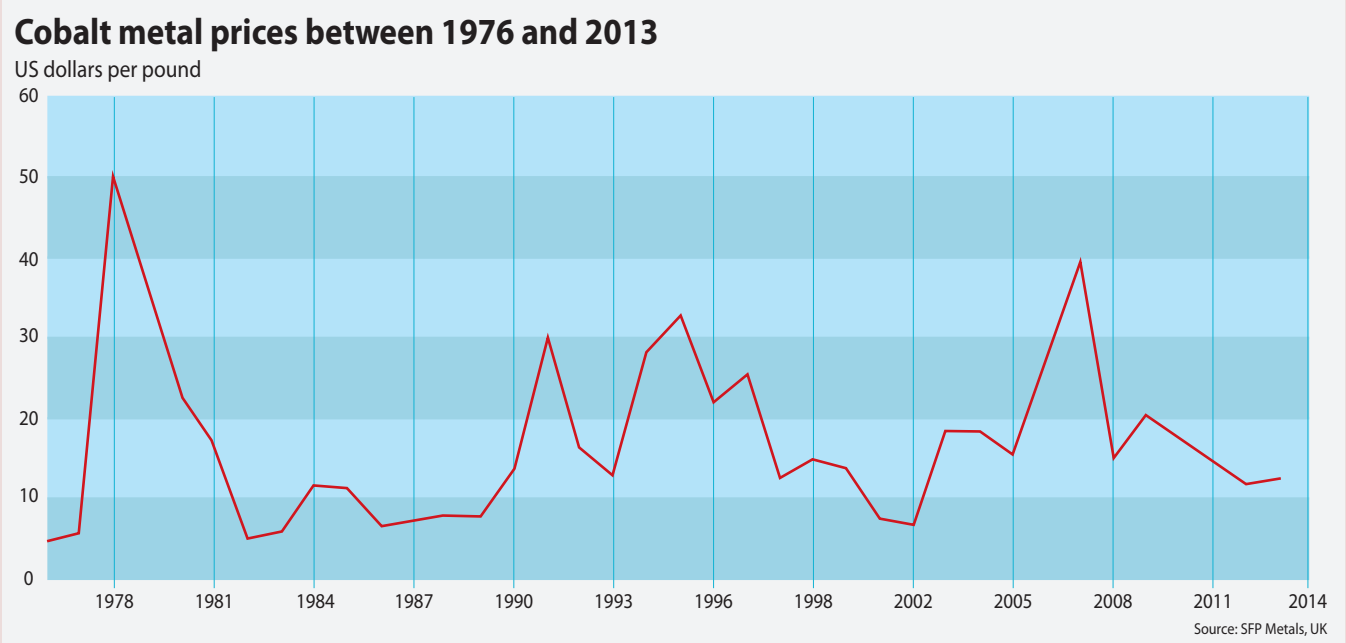


Figure 12. Global cobalt prices 1976-2011. Source SFP metals UK, <http://www.sfp-cobalt.co.uk>.

Increasing land-based cobalt production

Recoverable cobalt in tonnes

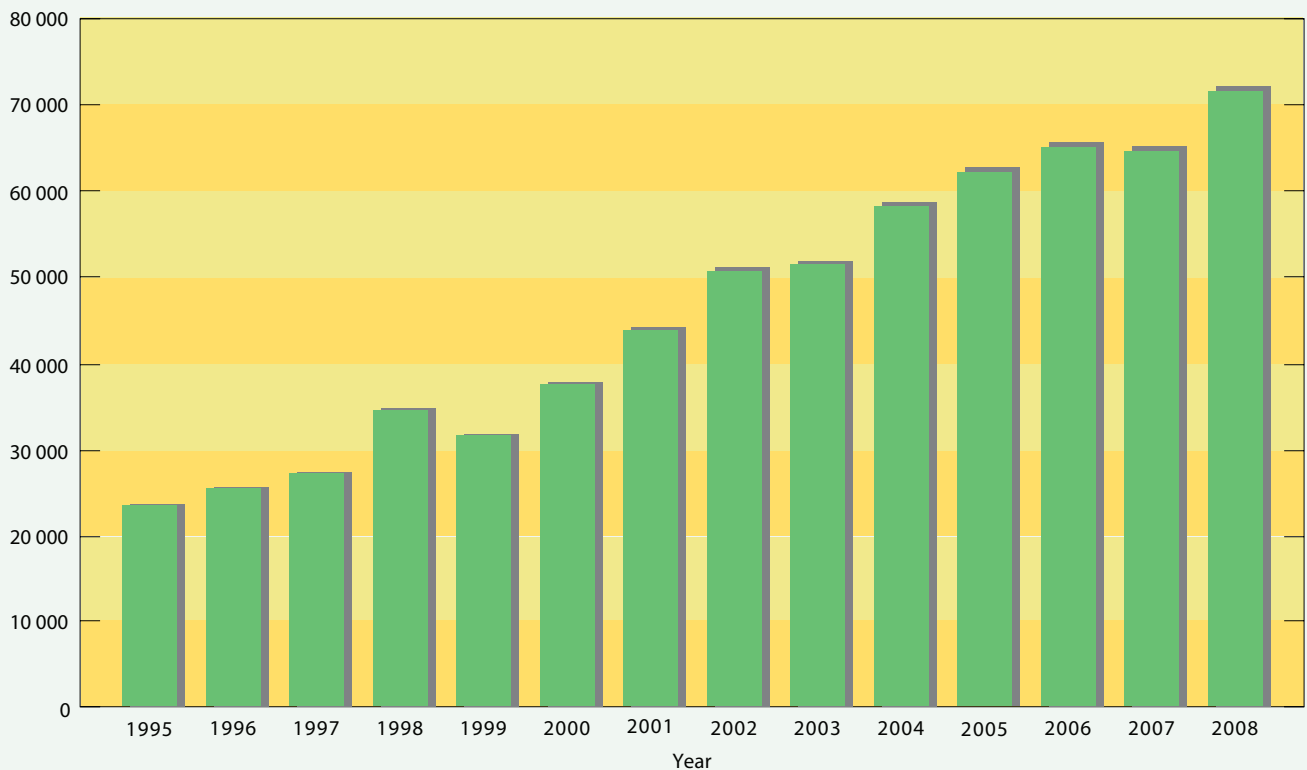


Figure 13. Increase in cobalt production. (Wilburn 2012).

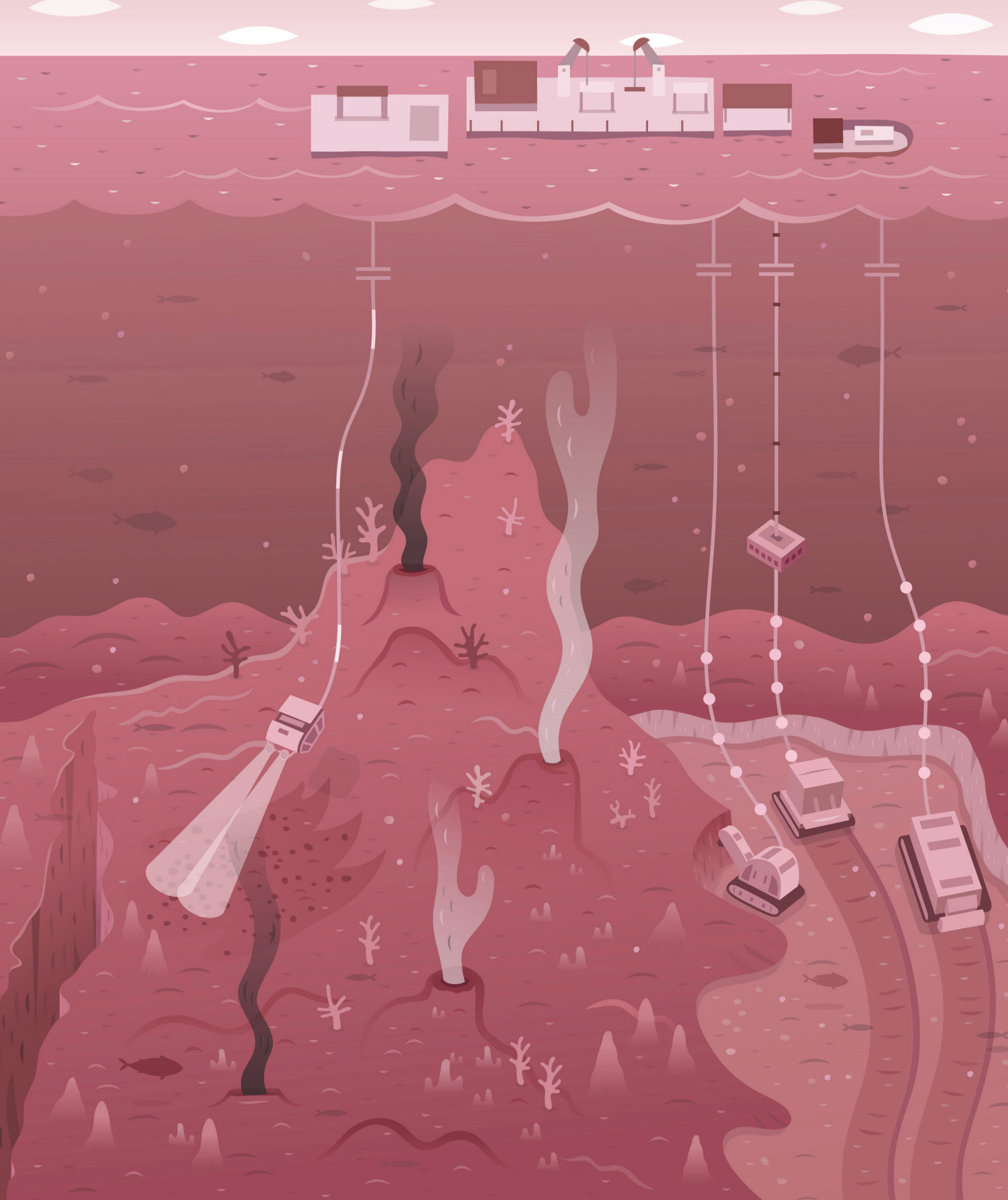
Sources of cobalt production



Figure 14. Current sources of cobalt. After Wilburn 2012.

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2.1 Habitats and biodiversity in manganese nodule regions

Manganese nodules occur widely on the vast, sediment-covered, rolling plains of the abyssal ocean (an environment that occupies more than half of Earth's surface) at depths of about 4 000 to 6 500 m. The nodules are especially widespread in the North and South Pacific basins at latitudes greater than 10° N and S (McMurtry 2001). Where nodules occur, they are typically the predominant hard substrate, covering up to 75 per cent of the sea floor. Manganese nodules vary in size, abundance, and

surface texture, producing habitat heterogeneity, or diversity, at the sea floor on landscape (km) scales for both hard-bottom and soft-sediment biotas, or life forms. This habitat heterogeneity leads to variations in faunal (animal) abundance and community structure. Different communities live in sediments with heavy and light nodule cover, and distinct groups of animals live on the nodules themselves (Mullineaux 1987; Veillette *et al.* 2007a and b; Miljutina *et al.* 2010).

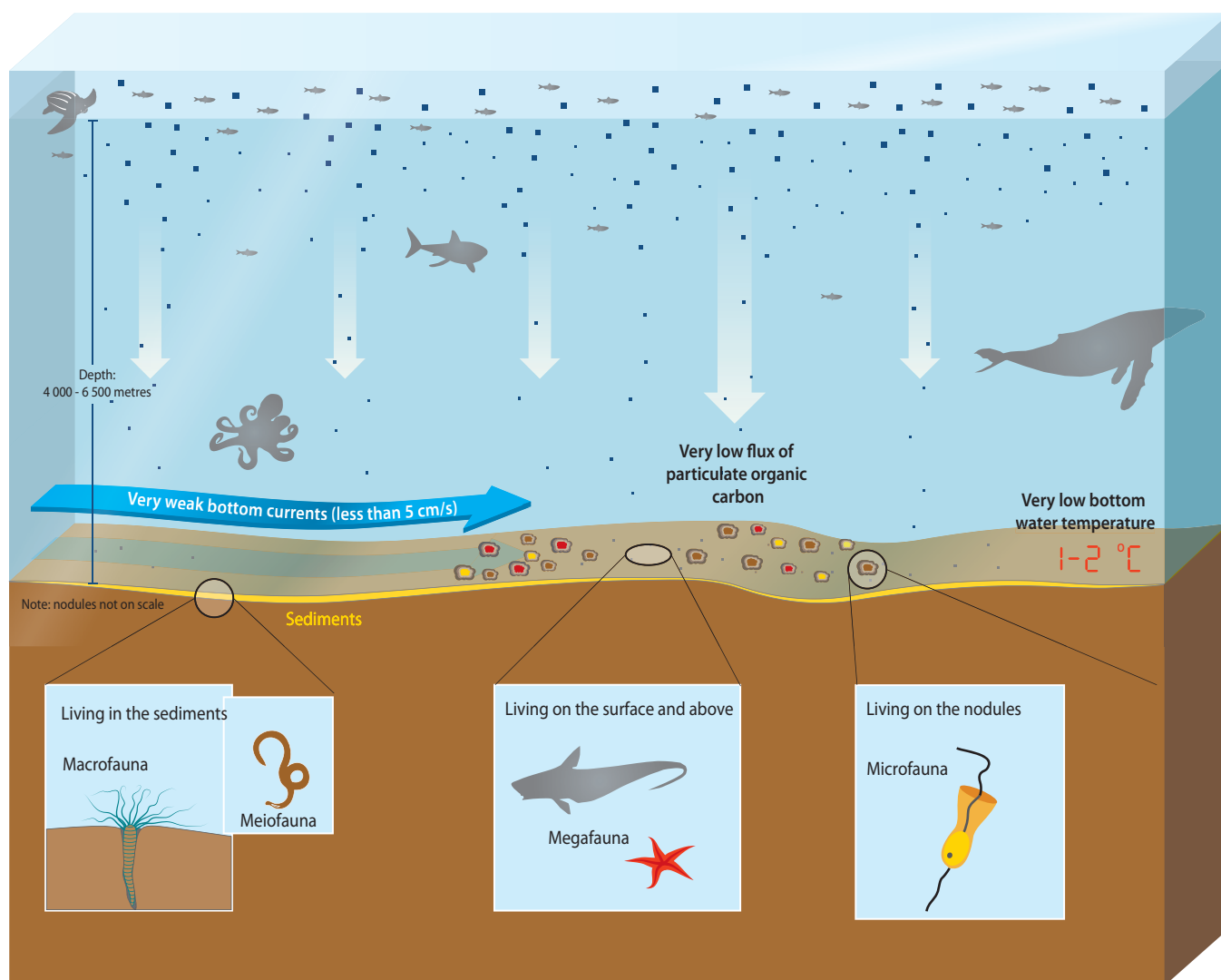


Figure 15. Habitats and biodiversity in nodule regions. Source GRID-Arendal.



Large foraminifera growing on manganese nodule from abyssal depths in the CCZ. Photo courtesy of C. Smith.

In general, deep sea habitats are influenced by a number of key ecosystem parameters including hydrodynamic regime, bottom-water temperatures, and the flux or flow of sinking food material (particulate organic carbon) from the zone, far above, where enough light penetrates to enable photosynthesis (Smith and Demopoulos 2003; Smith *et al.* 2008a). The abyssal regions experience relative extremes in all of these influences, with typically very slow bottom currents (and, therefore, high physical stability), low bottom-water temperatures (around 2°C), and very low annual fluxes of particulate organic carbon. Because animals in the abyssal regions rely on the organic material sinking from above, abyssal ecosystems are among the most food-limited on the planet (Smith *et al.* 2008a), and ecosystem structure and function vary regionally, largely in response to the flux of particulate organic carbon (Smith *et al.* 2008a; Figure 15).

Species diversity is often high in abyssal habitats, compared to more food-rich, shallow-water settings (Snelgrove and Smith 2002). For example, hundreds of species of polychaete worms and isopod crustaceans, such as shrimp, are typically found at single abyssal sampling sites (Glover *et al.* 2002; Brandt *et al.*

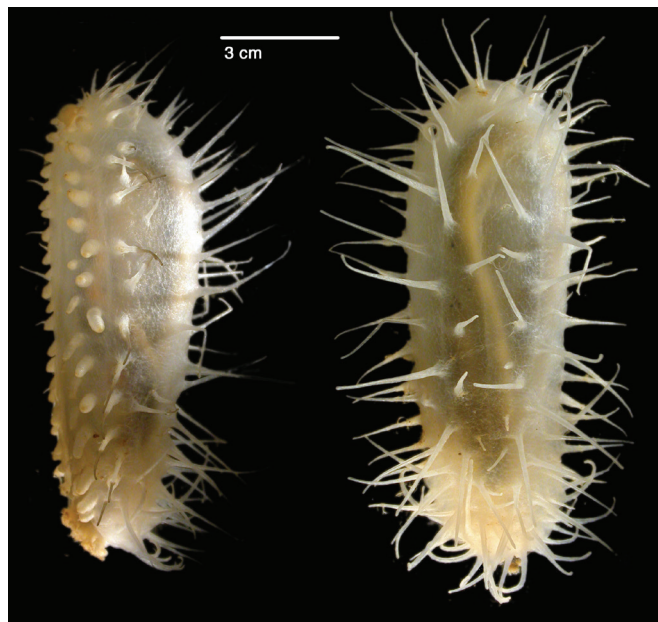
2005; Ebbe *et al.* 2010). High diversity is also common among relatively large animals, especially echinoderms such as sea stars and sea cucumbers, and among much smaller animals, including nematode worms and the tiny single-cell, shell-clad protozoan foraminiferans. For example, more than 500 species of nematodes and over 200 species of foraminiferans have been found in single study areas of about 20 x 20 km (Nozawa *et al.* 2006; Smith *et al.* 2008b; Miljutina *et al.* 2010). At regional scales, diversity is less well quantified but is thought to be high, with many thousands of species inhabiting abyssal basins (Snelgrove and Smith 2002; Ebbe *et al.* 2010).

Some of these abyssal species – especially fish, sea cucumbers, and some foraminiferans – are widely distributed. However, many species have been collected, sometimes in very high abundance, in single localities only (Mullineaux 1987; Glover *et al.* 2002; Brandt *et al.* 2005; Nozawa *et al.* 2006; Smith *et al.* 2008b; Ebbe *et al.* 2010). Thus, there is likely no characteristic scale of distribution for abyssal species. Some species may be very widely distributed at abyssal depths across ocean basins, while others appear to have very restricted ranges spanning only 100 to 1 000 km.

2.2 Global geographic context



Abyssal sea cucumber wrestling – *Psychropotes* versus Adrian Glover. Photo courtesy of C. Smith.



Tiny holothurians that live on the spines of sea urchins at abyssal depths in the CCZ. Photo courtesy of Adrian Glover.

Nodule regions sustaining different levels of particulate organic carbon flux appear to have different levels of species diversity and substantially different faunal communities, both in the soft sediments and on the nodules themselves. (Figure 16; Mullineux 1987; Veillette *et al.* 2007a; UNESCO 2009; Ebbe *et al.* 2010). The CCZ, the area of most intense interest for manganese nodule mining in the Pacific, experiences substantial east-west and south-north gradients in overlying primary production and the flux of food to the abyssal sea floor (UNESCO *et al.* 2009; Watling *et al.* submitted). Based on these gradients, as well as on patterns of faunal turnover, the CCZ is expected to harbour distinct faunas and levels of biodiversity in different subregions. The CCZ is also thought to straddle a major biogeographic provincial boundary in the abyssal Pacific (UNESCO 2009; Watling *et al.* in press).

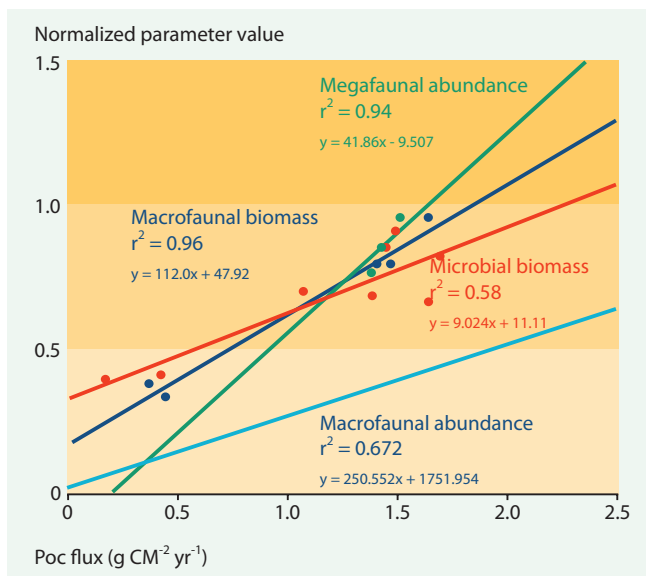


Figure 16. Links between abyssal benthic ecosystems and particulate organic matter. Regression relationships demonstrating the strong dependence of abyssal benthic ecosystem structure and function on the level of particulate organic matter (expressed as carbon) flux to the sea floor. All relationships are statistically significant ($p < 0.05$). Bioturbation intensity is based on ^{210}Pb Db SCOC = sediment community oxygen consumption. Modified from Smith *et al.* (2008a).

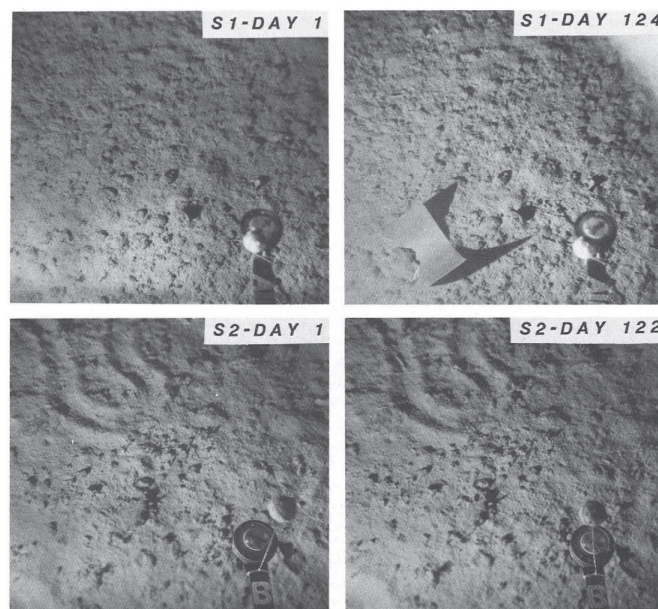
2.3 Composition of sea-floor communities

The biology associated with manganese nodules has been studied most intensively in the CCZ. However, the environmental conditions and factors affecting faunal communities are likely to be generally applicable to other abyssal plain habitats and, hence, relevant for the southwestern Pacific.

Sea-floor communities in the CCZ exist in what is called the mesotrophic abyss, a region of moderate particulate organic carbon flux and food availability by abyssal standards. The sea floor in this region is heavily modified by the activities of animals. Xenophyophores (giant foraminifera ranging from 3 to 10 cm in width) are abundant, with furrows formed by burrowing sea urchins and spoke-like feeding traces and faecal mounds from spoon worms appearing occasionally (Smith and Demopoulos 2003). These sea-floor animal traces are remarkably persistent, due to the physical stability of the sediment. In the CCZ, animal tracks and trails ranging in size from millimetres to centimetres last longer than 12 months before they are erased by biological or physical processes (Gardner *et al.* 1984).

Mega fauna are the largest animals in CCZ benthic (sea-bottom) ecosystems. These are animals large enough to be recognized in bottom photographs and range from about 2 cm to more than 100 cm in length. Mega fauna include omnivorous fishes (especially

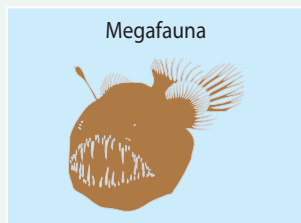
rattails), cephalopods (such as octopus and squid), scavenging amphipods and deep sea shrimp, large deposit feeders such as sea cucumbers and starfish, and suspension-feeding glass sponges, anemones, and other cnidarians. More than 20 megafaunal species can occur in seemingly homogeneous areas of 1-2 km². Xenophyophores are typically the most abundant megafauna in this region (Smith *et al.* 1997; Smith and Demopoulos 2003).



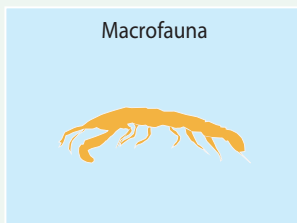
Photographs of animal tracks and faecal mounds on the sea floor in the CCZ, taken with a time-lapse camera (Gardner *et al.* 1984)

Deep sea communities are generally divided into four body-size classes for study and description: megafauna, macrofauna, meiofauna, and microfauna (Figure 17).

Size of life in the deep oceans



Animals identifiable from bottom photographs and videos



Animals retained on a 0.3 to 0.5 millimetre sieve

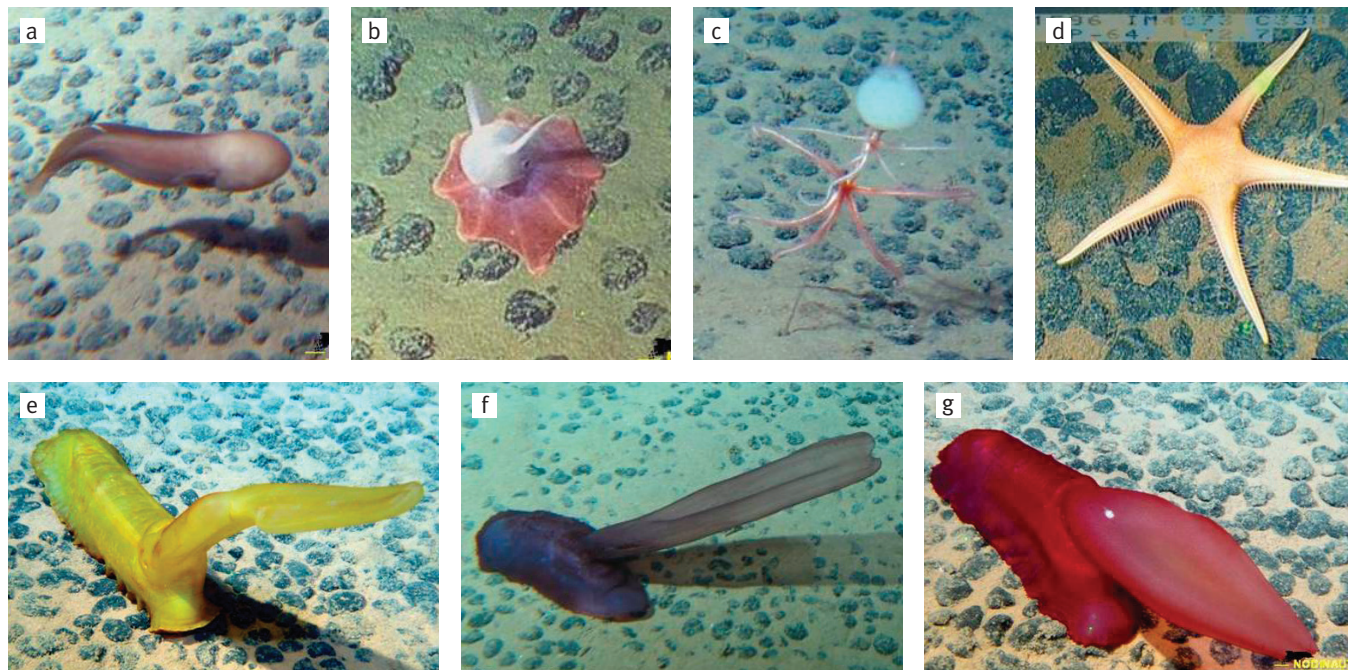


Animals passing through a 0.3 millimetre sieve and retained on 0.032 to 0.063 millimetre sieves



Organisms passing through a 0.32 millimetre sieve

Figure 17. Faunal size classes routinely found on the abyssal plain.



Mega fauna of the CCZ nodule province including (a) small-eyed omnivorous fish, (b) a predacious cirrate octopod, (c) suspension-feeding sponge and brisingid asteroids, (d) a deposit-feeding starfish (*Hyphalaster*), (e) a 50-cm long, deposit-feeding sea cucumber (*Psychropodes longicauda*), (f) a suspension-feeding anemone attached to a nodule, and (g) another large (50 cm) deposit-feeding sea cucumber (*Psychropodes semperiana*).

The macrofauna are the size class below the megafauna. These are animals large enough to be retained on a 300- to 500-micrometre sieve. The macrofauna of the CCZ are a variety of sediment-dwelling animals, including polychaete worms, crustaceans, and bivalve molluscs (Borowski and Thiel 1998; Smith and Demopoulos 2003). The polychaetes dominate, accounting for about 50 to 65 per cent of both abundance and biomass in nodule regions (Borowski and Thiel 1998; Smith and Demopoulos 2003). The level of macrofaunal abundance is relatively low in abyssal nodule regions, compared to most of the deep sea. The body size of the CCZ macrofauna is also relatively small, compared to those found on the continental margins. Most animals are only a few millimetres to 1 centimetre in length, with a median wet weight of about 0.4 mg (Smith and Demopoulos 2003).

Most macrofaunal species appear to feed on surface deposits (Paterson *et al.* 1998; Smith and Demopoulos 2003; Smith *et al.* 2008b). Subsurface deposit feeders (such as the paranoid polychaetes) may also be abundant. Other trophic types, including predators and omnivores, make up a small percentage of the total macrofaunal community (Smith *et al.* 2008b). At least 95 per cent of macrofaunal abundance in abyssal sediments in nodule regions is concentrated in the top 5 cm of sediment.

The size class below the macrofauna is called the meiofauna. These are animals that pass through a 300-micrometre sieve, but are retained on sieve sizes ranging from 32 to 63 micrometres, depending on the type of organisms studied. This very small size class is comprised primarily of the tiny, shell-clad foraminiferans, nematode worms, and shrimp-like harpacticoid copepods. The foraminiferans appear to be the dominant and most species-rich group in the CCZ (Nozawa *et al.* 2006). These poorly understood protozoans appear to feed on sedimentary organic matter and sediment bacteria and, because of their abundance, may play a role in carbon cycling over the Pacific abyss, including the CCZ. The nematode worms are also numerous in nodule-province sediments (Lambshhead *et al.* 2002; Miljutina *et al.* 2010). Nematode abundance is linked with bacterial biomass, so many of these worms may graze on sediment bacteria (Brown *et al.* 2002).

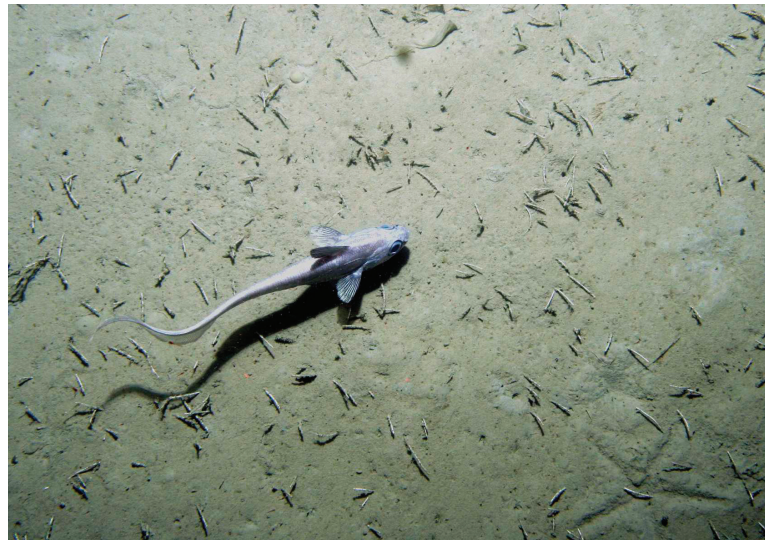
The microfauna, mainly bacteria, constitutes the smallest size class of organisms in abyssal sediments. The estimated microbial biomass in CCZ sediments (Smith *et al.* 1997) appears to be 10-fold larger than that of the macrofauna and 100-fold greater than that of the nematode worms (Smith and Demopoulos 2003). Although much of the bacterial biomass in abyssal sediments may consist of inactive cells sinking out of the wa-

ter column (Novitsky 1987), the high microbial biomass relative to other size classes suggests that microbes may account for a large proportion of the respiration of the sediment community, playing a major role in the functioning of the sea-floor ecosystem (Smith and Demopoulos 2003).

In the CCZ, the manganese nodules themselves harbour a biota distinct from the surrounding sediments. In one CCZ locality, roughly 10 per cent of exposed nodule surfaces were recorded as being covered by sessile, eukaryotic organisms. Of these, foraminiferan protozoans accounted for over 98 per cent of both the surface cover and number of individuals (Mullineaux 1987), although this may not necessarily be representative of the entire CCZ. Animals found attached to nodules include small sponges, molluscs, polychaetes, and encrusting bryozoans, with the vast majority of the nodule species not found in surrounding sediments (Mullineaux 1987; Veillette *et al.* 2007a). The nodule fauna varies with the surface texture of nodules, as well as with regional variability in the flux of particulate organic carbon to the sea floor (Veillette *et al.* 2007a and b).

In addition to manganese nodules, the giant, single-cell xenophyophores may provide habitat variety on the sea floor in abyssal nodule regions (Smith and Demopoulos 2003). Although the ecology of xenophyophores in the equatorial abyss has not been explicitly studied, in other areas (such as on seamounts) the shell-like tests of these organisms provide shelter and/or food resources for a specialized community of macrofaunal invertebrates (Levin and Gooday 1992). Because of their abundance, xenophyophores very likely contribute fundamentally to macrofaunal and meiofaunal community structure in nodule regions.

Studies of sea-floor communities in the CCZ and other abyssal Pacific regions suggest that there is a characteristic fauna of

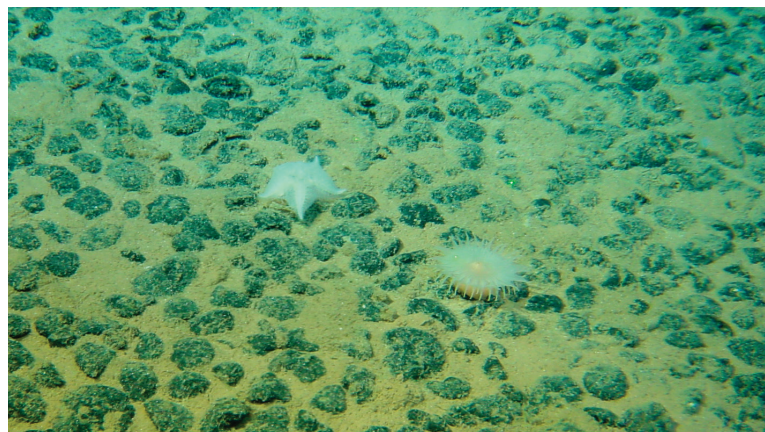


A macrourid rattail, *Coryphaenoides serrulatus*, photographed at 2 000 m on soft-sediment sea floor with many quill worm tubes, off the coast of New Zealand. Photo courtesy of M. Clark.

the abyss, distinct from populations at the ocean margins. In addition, there is evidence that the community structure of many components of the fauna differs substantially over scales of 1 000 to 3 000 km across the CCZ, driven in part by gradients in the flux of particulate organic carbon (Smith and Demopoulos 2003; Veillette *et al.* 2007a; Smith *et al.* 2008a and b). Many aspects of species function are also controlled by, or at least correlated with, this flux, so community composition is expected to change across the region. Rates of change will vary with dispersal abilities and life histories of the fauna, which are generally very poorly known. For recommendations on environmental management strategies to conserve biodiversity and ecosystems of the abyssal plains, see section 4.



A penaeid shrimp and a sea urchin belonging to the genus *Plesiodyadema* on a nodule field. Photo courtesy of Ifremer/Nautil, Nodinaut.



A pterasterid sea star and a sea anemone on a nodule field. Photo courtesy of Ifremer/Nautil, Nodinaut.

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The background of the page is a stylized illustration of an underwater mining operation. At the top, a large white mining vessel with two cranes is on the surface. Several vertical cables or pipes extend from the vessel down into the water. In the middle ground, there are some small fish and a few pieces of coral. At the bottom, there is a dark, rocky seabed with a hydrothermal vent emitting a white plume. To the right, a small white mining vehicle is on the seabed, connected to a larger white vehicle by a cable. Another cable with a small white vehicle is visible on the left. The overall color scheme is a monochromatic reddish-pink.

3.0

Environmental Management Considerations

Malcolm Clark¹ and Samantha Smith²

¹ National Institute of Water & Atmospheric Research, NIWA, Wellington 6021, New Zealand

² Nautilus Minerals Inc. Level 7, 303 Coronation Drive, Milton, Queensland 4064, Australia

Human activities invariably have some impact on any ecosystem, and activities in the deep sea are no exception. Sea-floor ecosystems are increasingly affected by human activities, such as bottom fishing, oil drilling, and waste disposal (Polunin *et al.* 2008; Smith *et al.* 2008). With the emerging industry of deep sea mineral extraction, there is a need for appropriate and responsible management strategies with an aim to maintain overall biodiversity and ecosystem health and function.

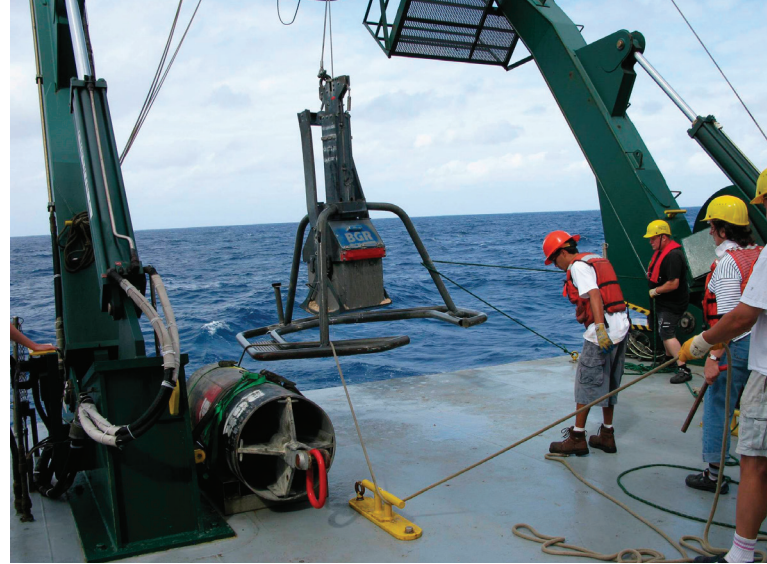
In this section, we describe the likely environmental effects of deep sea nodule extraction, with a particular emphasis on the specific characteristics of abyssal and manganese-nodule biological communities. Management options are discussed, and recommendations are made on options that could balance the impacts of extraction with conservation of the wider environment and faunal communities.

3.1 Environmental management objectives

A key issue at the outset, before any exploration or extraction occurs, is the clear definition of environmental objectives that will guide the management of any future operations. These will vary regionally and nationally, but are typically directed at two broad goals:

- to maintain overall biodiversity and ecosystem health and function; and
- to reduce, mitigate, and, where possible, prevent adverse effects of mining and pollution that can affect wider habitats and ecosystems.

A further key consideration is integrating environmental management strategies with other, related efforts and agreements aimed at the conservation and sustainable use of the marine environment. This includes national and regional initiatives, as well as such global frameworks as the Convention on Biological Diversity's process to identify ecologically or biologically significant areas and the UN General Assembly Resolutions to protect vulnerable marine ecosystems.



Sampling manganese nodules. Photo courtesy BGR.

3.2 General environmental management approaches and principles

Responsible environmental management objectives involve balancing resource use with the maintenance of deep-ocean ecosystem biodiversity. Thus, management should include consideration of any functional linkages between the ecosystem and the subsurface biosphere, the water column, the atmosphere, and the coasts. Consideration should also be given to the full range of goods and services that the ecosystem provides (Armstrong *et al.* 2010).

The 1992 United Nations Convention on Biological Diversity defines the Ecosystem Approach as: “*Ecosystem and natural habitats management...to meet human requirements to use natural resources, whilst maintaining the biological richness and ecological processes necessary to sustain the composition, structure and function of the habitats or ecosystems concerned.*”

Environmental impact assessment and environmental permitting process considerations: an example from Papua New Guinea

One approach to determining whether a project requires an environmental impact assessment (EIA) is a phased system of licences. In Papua New Guinea (PNG), the Environment Act (2000) outlines three levels of activity based on impact severity. Each has different permitting requirements.

Level 1 includes activities such as exploration, which may be similar in some cases to scientific research. Exploration includes drilling to a cumulative depth of up to 2 500 m. Level 2 includes activities such as drilling greater than a cumulative depth of 2 500 m. Mining is a Level 3 activity. A Level 1 activity does not require an EIA or an environment permit. A Level 2 activity requires an environment permit, which involves an application process, but not an EIA. Any Level 3 activity requires an EIA, which culminates in an environmental impact statement (EIS) that must be approved in order to obtain an environment permit. The permit, in turn, must be in place before development proceeds. In PNG, the environmental permitting responsibilities lie with the Department of Environment and Conservation (DEC), while the mining licensing

It is generally a legal requirement (e.g. UNCLOS Article 206) for a process of prior environmental impact assessment (EIA) and a resulting report to be undertaken before any activities likely to cause significant harm to the environment are permitted to proceed. An EIA should identify the likely environmental and social impacts of an activity, and how these would be monitored, prevented, mitigated and/or compensated for, to enable the relevant government to decide whether or not to permit the activity to proceed.

responsibilities are separate, falling to the Mineral Resources Authority (MRA).

Key stages of work involved in obtaining an environment permit in PNG potentially serve as a useful guide for more general application within the southwest Pacific. These are described, in sequence, below:

1. Environmental Inception Report (EIR): The completion of an EIR is the first step in developing an environmental impact statement. The EIR outlines the project description and the studies that will be conducted during the environmental impact assessment process.
2. Environmental Impact Assessment (EIA): The International Association for Impact Assessment (IAIA) defines an EIA as “the process of identifying, predicting, evaluating and mitigating the biophysical, social, and other relevant effects of development proposals prior to major decisions being taken and commitments made.” The EIA process will involve conducting various studies (see below).
3. Environmental Impact Statement (EIS): The EIS is the report that compiles all the information gathered during the EIA process and forms the statutory basis for environmental assessment of the project. The EIS usually sets out a development proposal intended to enable engineering, cost, environmental, and commercial implications to be assessed by the project proponent, the public, and relevant government agencies. The EIS characterizes the project’s beneficial and adverse impacts and risks, based, where necessary, on external scientific studies, and sets out measures to mitigate and monitor those impacts and risks. The

Management approaches can focus on a single sector (such as one geographical area or one human activity) or a single species, but there is increasing recognition of the importance of an Ecosystem Approach to Management (EAM).

Inherent in EAM is the application of ecological, economic, and social information, and the underlying acceptance that humans

are an integral part of many ecosystems. The approach requires integration of information from a wide range of disciplines, across different levels of ecological and socio-economic organization, and on a range of temporal and spatial scales.

A second important concept in the exploitation of any resource is the precautionary approach. One of the primary foundations of

EIS provides the information that allows interested parties to develop an informed view on the merits of the project. The statutory function of the EIS process is to enable the appropriate regulatory authority to decide whether or not to approve the development and, if so, under what conditions. The EIS is assessed by the relevant government agencies and/or reviewed externally. A workshop held by the International Seabed Authority in collaboration with SPC and the Fiji Government in Nadi Fiji in 2011 developed a draft template for an EIS (ISA 2011).

4. Public Hearings: The public hearings process involves a series of meetings that allow the public and local communities a

chance to provide comments and raise concerns regarding the EIS and the development proposal.

5. EIS Review: The results of the assessment, along with the outcome of the public hearings, allow the relevant authorities to make a recommendation on the EIS.

6. Environment Permit: Following the EIS approval and submission of an environment permit application, an environment permit is awarded if successful. Note that a common condition of the permit is for an environmental management plan (including monitoring plans) to be approved prior to the commencement of operations.

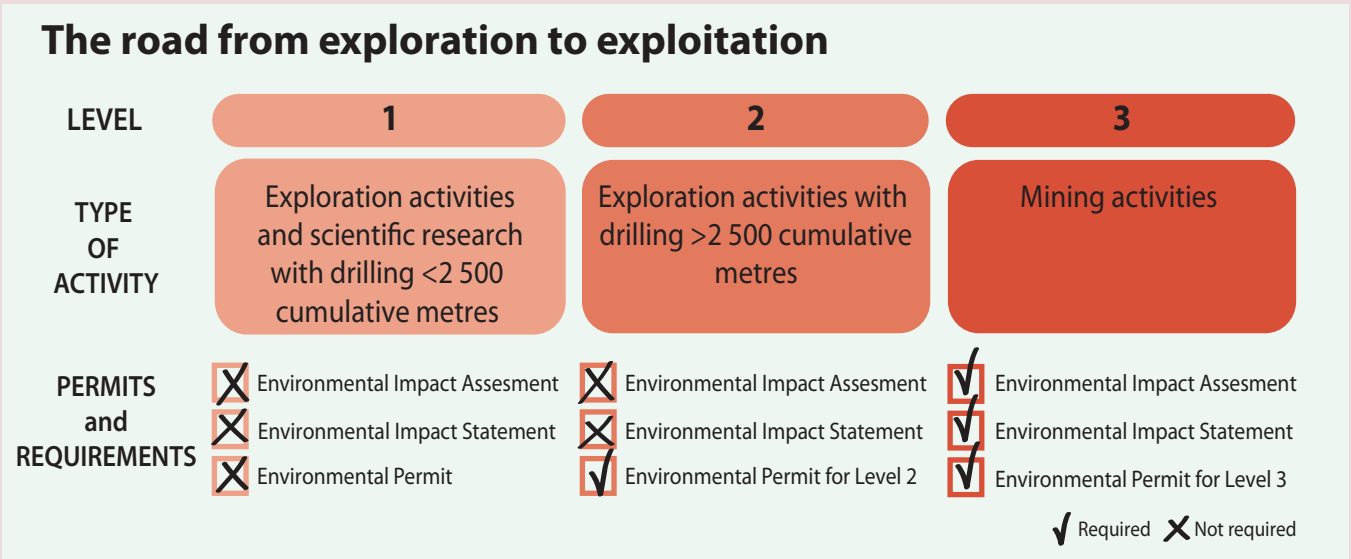


Figure 18. Permitting process - note these requirements are used as an example of the permitting process. Manganese nodule exploration and exploitation would require a different permitting process, which could also be multi leveled.

the precautionary approach, and globally accepted definitions, results from the work of the Rio Conference, or Earth Summit, in 1992. Principle 15 of the Rio Declaration states: “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; see also DSM Project Information Brochure 13 available at www.sopac.org/dsm, for discussion on the Precautionary Approach as it relates to DSM).

A management method that is frequently applied in support of the precautionary approach is adaptive management, which attempts to reduce uncertainties over time in a structured process of “learning by doing” (Walters & Hilborn 1978). Management actions continue to be informed and adapted as more is learned about the ecosystem, at the same time as it is being exploited and managed. An integral part of the process involves allowing managers the flexibility to make rapid management decisions in order to ensure that conservation objectives are being met.

Marine spatial planning (MSP) is a tool being embraced by a number of countries to manage multiple uses of their territorial seas. MSP maps which activities can be undertaken where, manages conflicts between competing marine activities, and reduces environmental impact by analyzing current and anticipated uses of the ocean. It is a practical way to balance demands for development with conservation goals and to achieve social and economic objectives in an open and planned way. The principal output of MSP is a comprehensive spatial management plan for a marine area or ecosystem.

There are many papers and reports that provide general guidance and advice to help commercial operators, scientists, and managers plan sound environmental management of mining and maritime activities. Several are particularly important for the deep sea, including:

- International Seabed Authority: Deep-seabed polymetallic nodule exploration: development of environmental guidelines (ISA 1999)
- Madang Guidelines of the South Pacific Applied Geoscience Commission (SOPAC 1999)
- International Marine Minerals Society: Code for environmental management of marine mining, Revised edition (IMMS 2011)

3.3 Environmental studies

Part of the EIA process involves carrying out environmental studies to define the existing environment before development occurs. These studies allow an assessment of impacts and an evaluation of effective mitigation and management measures.

A description of the existing environment will be needed, including habitat, animals present, meteorology, air quality, oceanography, water and sediment quality, midwater and surface water biology, other uses of the area, and occurrence of large marine mammals and turtles, etc. For examples of some studies that might be relevant to assessing the environment prior to deep sea mineral extraction, see Figure 19.

If the proposed project is close to shore, other considerations could include effects on near-shore ecosystems, such as coral reefs and estuaries. The effects on local human communities will also need to be considered. Social awareness and acceptance of the project will be important.

Effective monitoring of any impact will depend upon detailed baseline studies that establish a benchmark prior to exploitation. Ideally, this will include an evaluation of natural variability in the

structure and function of communities, so that changes caused by mining can be separated from natural fluctuations in species distribution and densities and so that changes to the environment due to mining can be discussed within the context of natural conditions. The nature and extent of baseline studies required to support adequate management of a particular mining operation will vary with management objectives, site characteristics, the size of the proposed mining area, the techniques to be used in mining, and available equipment and resources for carrying out environmental studies. General guidelines for deep sea sampling, as well as advice on survey design, sampling gear, and data analysis, can be found in Eletheriou and McIntyre (2005) and Clark *et al.* (in prep).

The amount of research possible, as well as its cost-effectiveness, can be enhanced through national or international collaboration between commercial companies and professional researchers or research institutes. Examples in the southwest Pacific of highly effective collaborative research include Nautilus Minerals’ collaboration with a consortium of international experts (including deep sea scientists) in PNG, and Neptune Minerals’ collaboration with the National Institute of Water and Atmospheric Research in New Zealand.

Physical assessment	Oceanographic assessment	Biological assessment	Existing activities assessment
Air quality	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

Figure 19. Studies that may be required to define the environment prior to development. Note that this is not an exhaustive list.

3.4 **Defining characteristics of nodule biodiversity**

The faunal communities associated with nodules have been described in detail in the preceding section on nodule habitats and ecosystems. There are several key characteristics to be considered specifically for this environment when evaluating potential impacts. These considerations, and others, are summarized below.

Sea-floor habitats in abyssal nodule regions are believed to be physically stable, especially when compared to the more dynamic physical setting of actively venting sea-floor massive sulphide deposits. Animals associated with nodules are unlikely to be well adapted to cope with disturbance.

The faunal composition differs between the nodules and the surrounding and intervening soft sediment. The biological characteristics of nodule and non-nodule communities differ, which

needs to be considered when evaluating effectiveness of management options. Abundance and density of epifauna (animals living on the surface of the sea floor) in abyssal habitats is generally low, whereas infauna (animals living within the sediment) can be highly diverse and abundant.

Many of the 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. Sedimentation rates and particulate organic carbon flux are therefore important drivers of abyssal ecosystems.

Recolonization rates of fauna are low, and hence recovery from impacts is expected to be slow. It is probably not practical to expect visible recolonization of animals within the tenure of a mining licence.

3.5 Environmental impacts

As with any mining activity, the main impacts of deep sea mineral extraction will involve removal or destruction of material, habitat, and associated fauna. Where mineral extraction is planned to occur, therefore, the practical management objective will not be to preserve all the habitat and local animal communities, but to ensure the impacts of exploitation do not jeopardize such conservation objectives as maintaining biodiversity and ecosystem integrity. Impacts on the social and economic status of human populations will also need to be considered and will be discussed in Volume 2 of this series.

When evaluating the potential impacts of sea-floor mineral extraction, there are two general categories to consider: those impacts

associated with normal operations, and those impacts associated with potential accidental events (which may or may not be related to natural hazards). Each is dealt with separately below.

Impacts associated with normal operations

As discussed in more detail in the following section on mining manganese nodules, there are four key components to deep sea mineral extraction:

- disaggregating mineralized material from the sea floor;
- transporting the material from the sea floor to the surface;
- dewatering the material; and
- transporting the material to market.

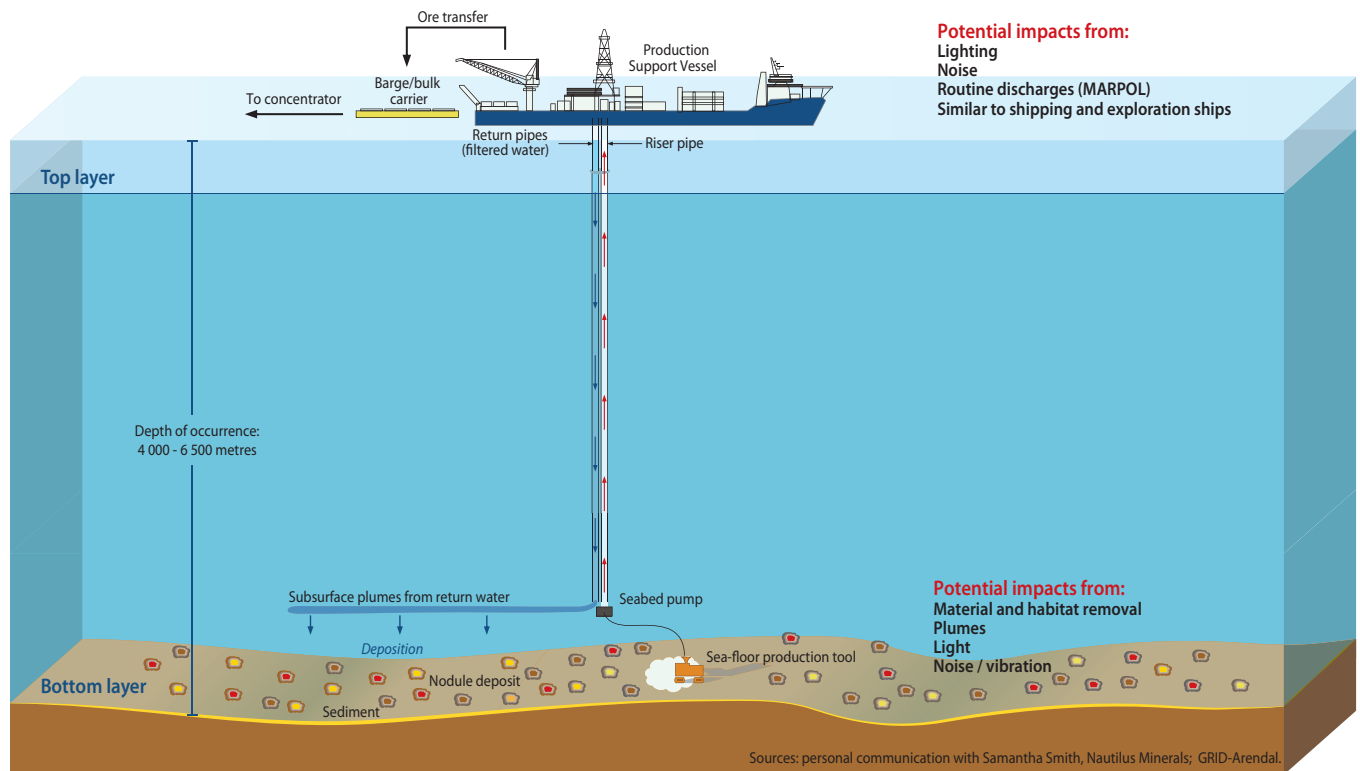


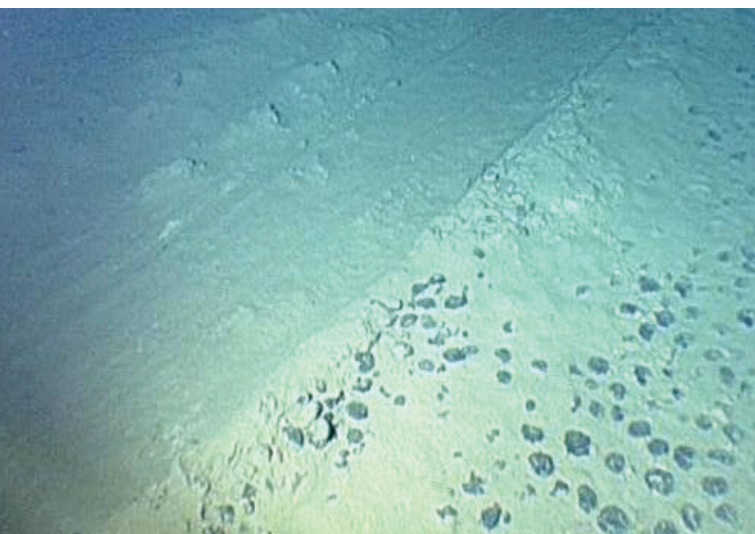
Figure 20. Example of a sea-floor manganese nodule mining system and related sources of potential environmental impact. Note that while mineral processing (concentrating) is part of the minerals life cycle, it is not specific to deep sea minerals. Thus, here we focus on issues related to deep sea mineral extraction and associated processes only. It should also be noted that an offshore, vessel-based mineral processing facility is not currently considered viable.

While each of the above steps can be carried out in a number of different ways, there are some general impacts that are expected to occur, no matter which method is chosen. Below, we discuss potential impacts as they may relate to the sea floor, the midwater column, and the surface of the sea.

Sea floor

During the extraction phase, disaggregating the minerals on the sea floor will result in the physical removal of habitat and animals. Retrieving the nodules will involve suction, digging, or scraping of the top section of the sea-floor substrate, and surface and near-surface animals will inevitably be affected. The nodules are generally between 5 and 10 cm in diameter, but can be up to 20 cm. They lie half-buried in the sediment, so any extractor will dig to some depth into the substrate. Suggestions vary from 5 to 50 cm (Cronan 1999; Weisheng 2007; Smith *et al.* 2008).

Mobile swimming or crawling animals may be able to move aside, but most sessile benthic fauna in the path of the mining operation will be affected. The foraminifera that dominate nodule-specific fauna will be picked up with the nodules, as will the sessile megafaunal sponges. Polychaetes, nematodes, and holothurians are slow-moving and will not be able to move out of the way of equipment. Impacts will differ between sites.



In 1978, experimental dredging to recover nodules was carried out in the Clarion Clipperton Zone. The dredging removed the upper 4.5-cm layer of sediment and left behind a track approximately 1.5 m wide. In 2004, a team of researchers returned to the area, where the original disturbance is still clearly visible more than 20 years later. Photo courtesy of Ifremer, Nodinaut 2004, Nautille.

Disturbance of the sea floor will increase mixing of sediments and overlying water. Where the sea floor is being mined, there could be alteration of the chemical makeup of the overlying water. The greatest changes will occur when oxic sediments are removed and suboxic sediments become suspended, releasing their pore waters. There will potentially be release of metal from lower sections of the sediment and an increase in manganese flux (Cronan 1999).

In areas of sea floor with soft sediment, much of the biodiversity is to be found in the top 8 cm of the sediment (Giere 1993). Gear that digs into the sediment can have an impact through direct crushing of buried infauna and by compacting the substrate through the weight of machinery or equipment. Mining operations will stir up the sediment, dislodge animals, and leave a suspended sediment cloud that will eventually settle on the underlying sea floor. Effects of this are likely to be site-specific and will depend strongly on the fraction of seabed covered by nodules, seabed composition, the type of technology used, the nature of the fauna, and oceanographic conditions in the area. However, filter-feeding animals, such as deep octocorals, anemones, and sponges, depend upon a flow of clean water containing the small animals and particles that are their food. The feeding efficiency of such filter feeders may also be affected through clogging of the small pores. Yamazaki *et al.* (1997) recorded decreases in most components of the biological communities by an increase in sedimentation of only 1 cm. Disturbance of the sediment surface also has implications for surface-deposit feeders, which rely upon recently settled particulate matter from the water column. The flux dynamics are likely to change in directly mined areas, with alteration of the sediment composition.

Physical removal of benthic animals on a large scale will almost certainly cause a reduction in habitat complexity and associated invertebrate biodiversity. In general, abyssal environments with manganese nodules host a high proportion of small-bodied species, dominated by foraminifera, and the polychaete and nematode worms (Mullineaux 1987; Smith 1999; Smith *et al.* 2006; Veillette *et al.* 2007; Smith *et al.* 2008). The same higher taxa extensively researched in the eastern Pacific at the Clarion Clipperton Fracture Zone, are found in the southwest Pacific, based on Japan-SOPAC voyages in the 1990s (Fukushima 2007) and surveys by German researchers (Bluhm 1994). Physical disturbance of these communities can cause established communities to decline and, in the short term, become dominated by motile, fast-growing, opportunistic and scavenger species (Bluhm 2001).

Recovery of disturbed habitat and benthic communities will likely take a long time. Experimental impact-recovery time-series research has been carried out under several programs such as DISCOL (Disturbance and Recolonisation Experiment) in the Peru Basin, and JET (Japan Deepsea Impact Experiment) in the CCZ. These studies produced similar results: there is initially a dramatic decrease in most benthic fauna, and, while after several years the abundance of mobile species increases, sessile species remain depressed (Kaneko *et al.* 1997, ISA 1999, Thiel *et al.* 2001, Bluhm 2001). Even at the conclusion of DISCOL (after seven years), the density of sessile megafauna had shown very little recovery.

Other impacts from mining include noise, vibration, and light from vessel or underwater vehicle operations, all of which may attract or cause avoidance by fauna.

Midwater column

Potential impacts to the water column also need to be considered. Water-column activities may include transport of ore from the sea floor to the surface, transit of tools/remotely operated vehicles (ROVs), and potential input of discharge water from the dewatering plant (if discharged midwater).

Any impacts associated with transporting the material from the sea floor to the production support vessel will be related to the presence and nature of the lifting system, which may or may not be fully enclosed. Interactions between the mineralized material and the water column might need to be considered more carefully if the ore delivery system is not fully enclosed.

Accidental direct contact with the lifting system or transitting equipment could cause physical damage to individual fish and free-swimming invertebrates. However, given the wide geographical distribution of most midwater-column animals, any localized mortality is likely to have a very minor impact on populations or stocks. Additional consideration of this issue might be warranted if the proposed development site is within an area of animal aggregation for spawning or feeding, or if it serves as a nursery ground for juvenile stages.

Dewatering involves the separation of the seawater from the mineralized material (ore). This activity will likely occur immediately above or near to the extraction site, either on the production platform or on associated barges. While the mineralized material will be transported for temporary storage or directly to a concentrator facility, the seawater that has been separated from the ore will likely be discharged back to the sea. This discharge could occur at the surface, somewhere within the water column, or near the sea floor.

The feasibility of various alternatives, especially return to near the bottom, will depend on factors such as the water depth of the operation, cost, and local currents. The discharge water will likely contain some fine material, primarily unwanted sediments that were brought up with the nodules. Most developers will seek solutions that minimize the amount of unwanted material transported from the sea floor to the surface as it wastes time and energy. Besides potential turbidity issues, discharge water could have different physical properties (e.g., temperature, salinity) than the ambient seawater to which it is returned. Hydrodynamic modeling will be needed to estimate the fate of the discharge and to inform discharge equipment design (e.g., diffusers, appropriate depth and direction of discharge, etc.). Understanding the extent of this impact is important because discharge plumes could extend beyond the area where actual mineral extraction occurs.

Surface

Surface impacts will depend upon the type and size of vessels and/or platforms deployed at the mine site. There will be normal impacts associated with surface vessel operations, which are not exclusive to mining. These include noise and lighting from the main vessel operation, as well as from support vessels and bulk carriers moving in and out of the area. There is also air pollution and routine discharge associated with these vessels. These impacts are governed by existing international legislation such as MARPOL.

If the dewatering plant discharge water is released within the upper 200 m of the water column (the depth to which light generally penetrates in the open ocean), it could affect primary productivity and flux to the sea floor on a local scale. If there is a significant plume near the surface, localized oxygen depletion could occur as a result of reduced penetration of sunlight and depressed phytoplanktonic production. Conversely, if the deep bottom waters are nutrient-rich (through nutrient release from the seabed), growth of phytoplankton might be enhanced. If there is a reduction in water clarity through sediment release, there could also be an effect on deep-diving marine mammals, which are visual predators. The complex interplay of factors governing the effects of bottom-water discharges makes it important to monitor surface changes.

It will be up to individual jurisdictions to determine whether surface discharge of dewatering process water should be permitted. Decision making may include considerations such as international law and standards, distance from shore/reefs, productivity and biodiversity of the surface waters, and other uses of the surface waters, such as fisheries.

3.6 The potential extent of impacts

The footprint or spatial scale of extraction will vary with each site. Whether a site is likely to be mined, and the extent of a commercial mining operation, will depend on the region, nodule distribution and density, ore grade, and topography/bathymetry. Initial estimates from the CCZ suggest extraction could be on the order of several hundred square kilometres per year and tens of thousands of square kilometres over the commercial life of an operation (Smith *et al.* 2008). The area to be mined, com-

Accidental Events and Natural Hazards

In addition to the potential impacts from normal operation, it is important to consider accidental events and natural hazards. These include possible spills and oil leaks on the vessel/platform, which then enter the sea, and leaks from the sea-floor-to-vessel lifting equipment or from the sea-floor equipment (e.g., hydraulic oil leaks). Although unlikely, extreme events – such as a ship sinking or collisions between vessels or with marine mammals – are possible. Commercial operators and national management agencies must reduce the risk of such events occurring in the first instance, and they must be prepared to respond if they do happen. Such precautions are generally covered under national and/or international (including maritime) regulations and are not detailed here.

pared to the area that will be untouched, may be an important consideration when developing management strategies.

There is little doubt that some amount of sediment plume will be created by the extraction of nodules. Because of dispersal by currents, the plume may have a larger footprint than the physical mining area. There is also potential for such plumes to extend into the bottom parts of the water column. Several direct measurements of actual plumes generated by ploughing the sea-floor in the CCZ showed the plumes visibly lasting up to six hours (Bluhm 1994). Modelling indicates that dispersal and resettlement rates could be very low (Rolinski *et al.* 2001) and result in coverage of the surrounding 100 km by a layer of fine sediment that can have a smothering effect on the benthic ecosystem, even if the layer is less than 1 cm deep (Glover and Smith 2003). The area affected by discharge of the wastewater and fine sediments will need to be considered. Discharge plumes in the water column will disperse with distance, and this progressive dilution will mean there is a gradient of impact, with effects lessening as distance from the mining site increases.

The likelihood that resedimentation could extend over a considerable area adjacent to the physical operation means that care is needed when defining conservation sites. Such areas will have to be far enough away from mining operations to avoid any potential “downstream” effect.

3.7 Mitigation and management measures

Mitigation and management measures will need to be developed in consultation with a broad range of stakeholders, including persons who consider that they are likely to be affected by the activities, scientists, and engineers, to determine what is technically and economically feasible. Once these measures are developed, a review of the potential impacts will be required in order to determine the residual impacts of the development. Criteria for assessing residual impacts in the marine environment are based (wherever practicable) on likely extent, duration, and severity. Extent refers to whether the impact will occur on a site, local, or regional scale. Duration may be either prolonged or short. Severity can be classed as negligible, low, moderate, or high. Once these conditions have been defined, they can inform a cost-benefit analysis to assess mining feasibility and whether it is determined (by government, in consultation with concerned citizens) that the impacts that cannot be prevented or mitigated are deemed acceptable. There are a number of ways to mitigate and minimize impacts, and several can be considered in the context of nodule extraction. They can be grouped into three key responses: operational, spatial, and temporal.

Operational: these measures reduce environmental impacts at the start and are incorporated into the mining operation. Every component of the operation should be examined to ensure that no unnecessary environmental risks are posed. Measures might include using an enclosed, rather than semi-enclosed, lifting mechanism and, if practical, pumping the discharge fluid back to near the sea floor, rather than releasing it at the surface. Responsible management will include:

- development and implementation of environmental management plans that will cover waste minimization and loss prevention to minimize impacts on water quality. These plans should address, among other things, deck drainage, non-dewatering-process wastewater discharges, waste management, and ballast water. A working example of a management plan has been produced by the International Seabed Authority (2012);
- the development and implementation of emergency response procedures in the event of accidents leading to spills to the environment;
- effective mitigation measures to minimize the risk of injury to marine animals from ship strike or collision;



Shipboard dynamic probing core-sampling equipment. Photo courtesy Malcolm Clark.

- an approved sewage treatment plant, certified to meet relevant international standards and/or other relevant regulations, to treat normal ship discharges, such as sewage; and
- development and implementation of safety, health, and environmental policies and plans for all offshore operations.

Spatial: these management measures introduce a separation of activities and generally include aspects of protected areas and exploitable areas. Options include:

- setting areas aside for conservation, possibly within mine site/mine lease areas. Depending on the site, it may not be possible to find an appropriate site within the mining lease that will not be impacted by mining (e.g., by plumes), in which case a similar site nearby may be nominated as the conservation area instead. Attention should be given to the representativeness, adequacy, resilience, and connectivity of a network of areas (UNEP-WCMC 2008; PISCO 2007).
- establishing marine management areas, which involves zoning of different areas for different uses or intensities of use. Such an approach may designate areas that are acceptable for total mining, areas that can only be partially mined, or areas

set aside for conservation. This approach should take into account all different marine uses (e.g., extractive industries, fisheries, navigation, cabling, tourism) and will enable associated impacts to be considered and managed cumulatively.

- evaluating the location of discharges to ensure minimal impact on ecosystems. Discharging at depth reduces the risk to surface or pelagic animals, but may have effects on benthic fauna if discharges spread over a wider area than the mining sediment plume. In very deep water, discharging near the sea-floor may not be technologically or economically feasible. The use of diffusers can aid dispersal, and oceanographic considerations are important regarding the direction of flow and the direction of discharge.
- considering animal relocation, if there are populations of rare, endemic (found nowhere else), or highly endangered species. Experience from the CCZ indicates that there can be high diversity and abundance at individual sites and considerable variability in species distributions over hundreds of kilometres (Smith *et al.* 2008). However, such an approach might be less conservation-effective and less cost-efficient than designating Marine Protected Areas (MPAs).
- employing reserve networks, such as Marine Protected Areas. These networks are recommended by many scientists and managers as effective means of protecting fauna from impacts of fishing or mining. This approach is often adopted at a na-

tional level and sometimes at a much larger spatial scale than a single mining operation. Inter-governmental involvement might be required. Whether or not an MPA network approach is warranted may depend on the proportion of sites that are considered commercially viable in relation to the total number of sites present, and whether or not the remaining untouched sites are representative of the sites to be mined. Ideally, the design of MPAs and MPA networks should follow four sequential steps: (1) evaluation of conservation needs; (2) definition of the objectives for establishing the MPAs; (3) integration of information on the biological characteristics (e.g., life histories, dispersal patterns, species distributions) and habitat distribution of the managed ecosystem; and (4) selection of suitable sites to serve as MPAs.

The key design elements of marine reserves listed by the Partnership for Interdisciplinary Studies of Coastal Oceans (PISCO 2007) provide a useful starting point for considering marine spatial planning and MPA planning (Figure 21).

Temporal measures: the time scales of nodule growth and faunal recovery in the abyssal deep sea almost certainly make consideration of short-time-scale measures impractical. Measures to rehabilitate degraded areas or encourage longer-term faunal recruitment are much less likely to be effective than spatial management approaches.

Key elements of marine reserve design

Biodiversity	Ensure maintenance of the ecosystems
Connectivity	Ensure ecological connectivity between sites
Replication	Conserve multiple sites, not just one
Viability	Ensure the size and spacing of reserves is adequate
Representivity	Multiple sites must contain a wide range of species and functions to allow for uncertainty or natural variation in populations
Sustainable use	Include other potential uses in designing the areas (e.g, fishing)

Figure 21. Key elements of marine reserve design (ISA 2008).

Key messages for environmental management

Ecosystems of the abyssal plains are generally diverse and have high infaunal densities but typically low abundance of larger epifauna. The animals are likely characterized by very high sensitivity and very low resilience to disturbance.

Scientific knowledge is limited in deep sea nodule environments in the western Pacific, but sufficient information exists from the eastern Pacific to guide initial environmental management decisions.

Baseline studies of animal composition, distribution, abundance, and environmental impact assessment are necessary before exploitation begins, and they must be followed by regular monitoring programs.

Multidisciplinary science is needed and will involve collaboration among industry, academia, relevant communities or interest groups, and government agencies.

Nodule mining in the deep sea will have impacts on affected species and habitats. Impacts should be mitigated by effective management strategies that reflect both the ecosystem approach and the precautionary approach.

Environmental management plans will be situation-specific, but should include a combination of best-practice mining operation to reduce environmental impacts and spatial management that protects similar areas and communities from impact.

Successful management of deep sea mining is reliant on a cooperative and integrated approach among all stakeholders.

Continuation of the wide-ranging involvement from mining companies, policy makers, lawyers, managers, economists, scientists, conservation agencies, non-government organizations, and societal representatives will be an important element in successful management of the deep sea minerals sector in the Pacific Island region (see Volume 2 in this series).

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The background of the page features a stylized illustration of marine mining. At the top, a large white mining vessel with two cranes is on the surface. Below it, several vertical cables or pipes extend into the water. The bottom of the illustration shows a deep-sea environment with a dark, rocky seabed, some coral-like structures, and small fish. On the left, a mining vehicle is shown with a large, conical discharge of material. On the right, another mining vehicle is shown with a conveyor belt system. The overall color scheme is a mix of light and dark blues, with white for the vessels and some seabed features.

4.0

Processes Related to the Technical Development of Marine Mining

Samantha Smith¹ and Robert Heydon²

¹ Nautilus Minerals Inc. Level 7, 303 Coronation Drive, Milton, Queensland 4064, Australia

² Offshore Council (<http://offshorecouncil.org>)

Deep sea mineral exploration and mining technology is aimed at the efficient identification and economic extraction of sea-floor mineral resources. To date, no actual mining of nodules (or other deep sea minerals) has taken place. There have recently been significant advances made in offshore technology, engineering, and equipment, predominantly fuelled by the offshore oil and gas, dredging, and telecommunications industries. Much of this technology, especially the trenching technology for laying pipelines, can be applied to deep sea mineral extraction, bringing the deep sea mining industry closer to commercialization.

4.1 Exploration

Exploration involves the identification, delineation, and evaluation of deep sea mineral resources and generally requires sophisticated, multipurpose research vessels using advanced technologies such as deep sea mapping equipment, remotely operated vehicles, photographic and video systems, and sampling devices.

Manganese nodule exploration typically involves:

- mapping the bathymetry and sea-floor topography to determine areas that are suitable for nodule occurrence and future mining operations;
- determining nodule coverage using high-resolution imagery;
- nodule sampling to determine grade and confirm nodule abundance;

- bulk nodule sampling to obtain sufficient quantities for mineral processing studies;
- geotechnical studies to feed into engineering design for mining technology;
- calculating the size and grade of the resource; and
- carrying out environmental baseline studies and impact assessments.

Manganese nodules occur over areas of thousands of square kilometres. To date, the most effective method of exploration has involved a staged exploration strategy, starting with large broad-scale acoustic surveys and followed by finer-scale sampling.

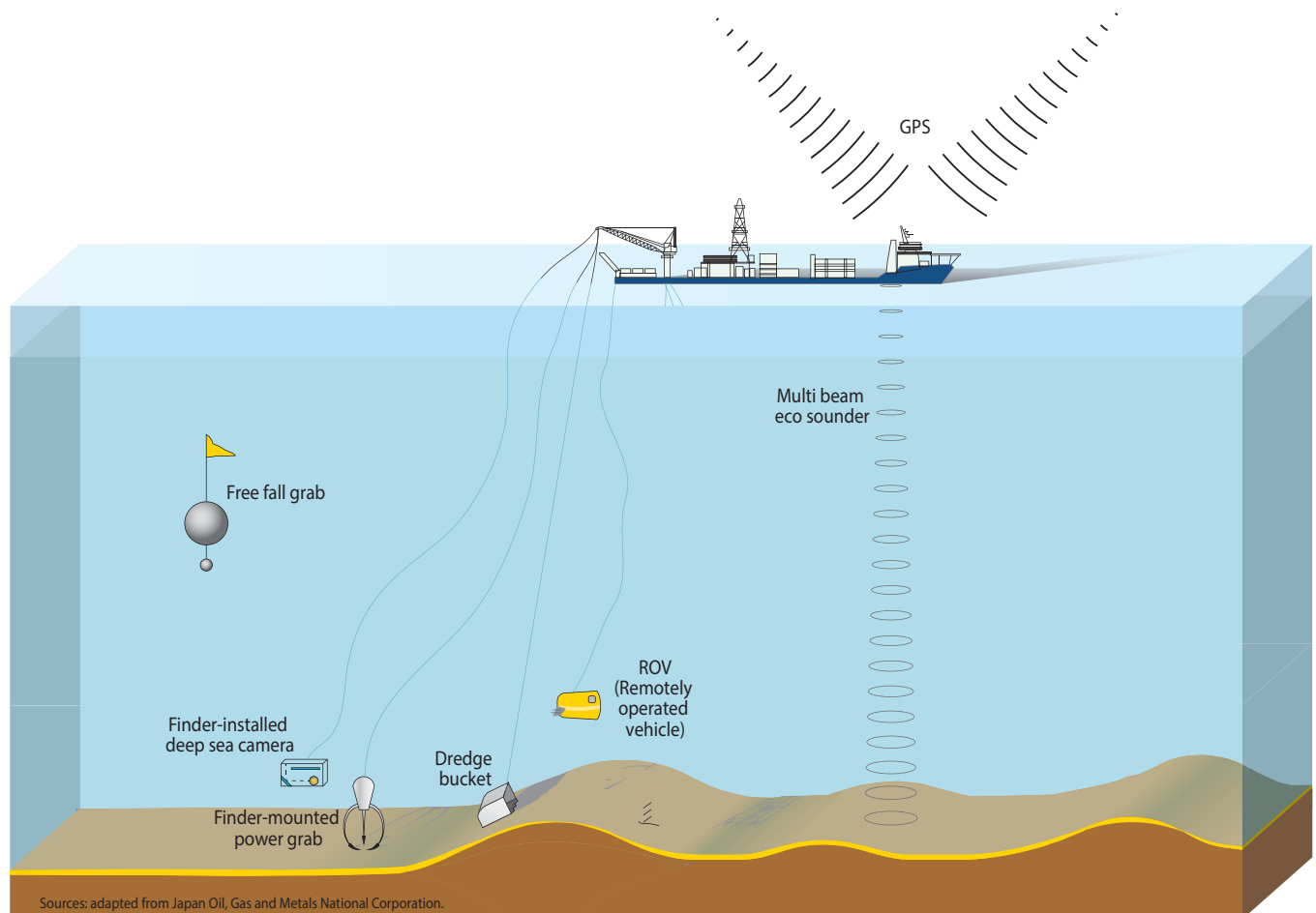
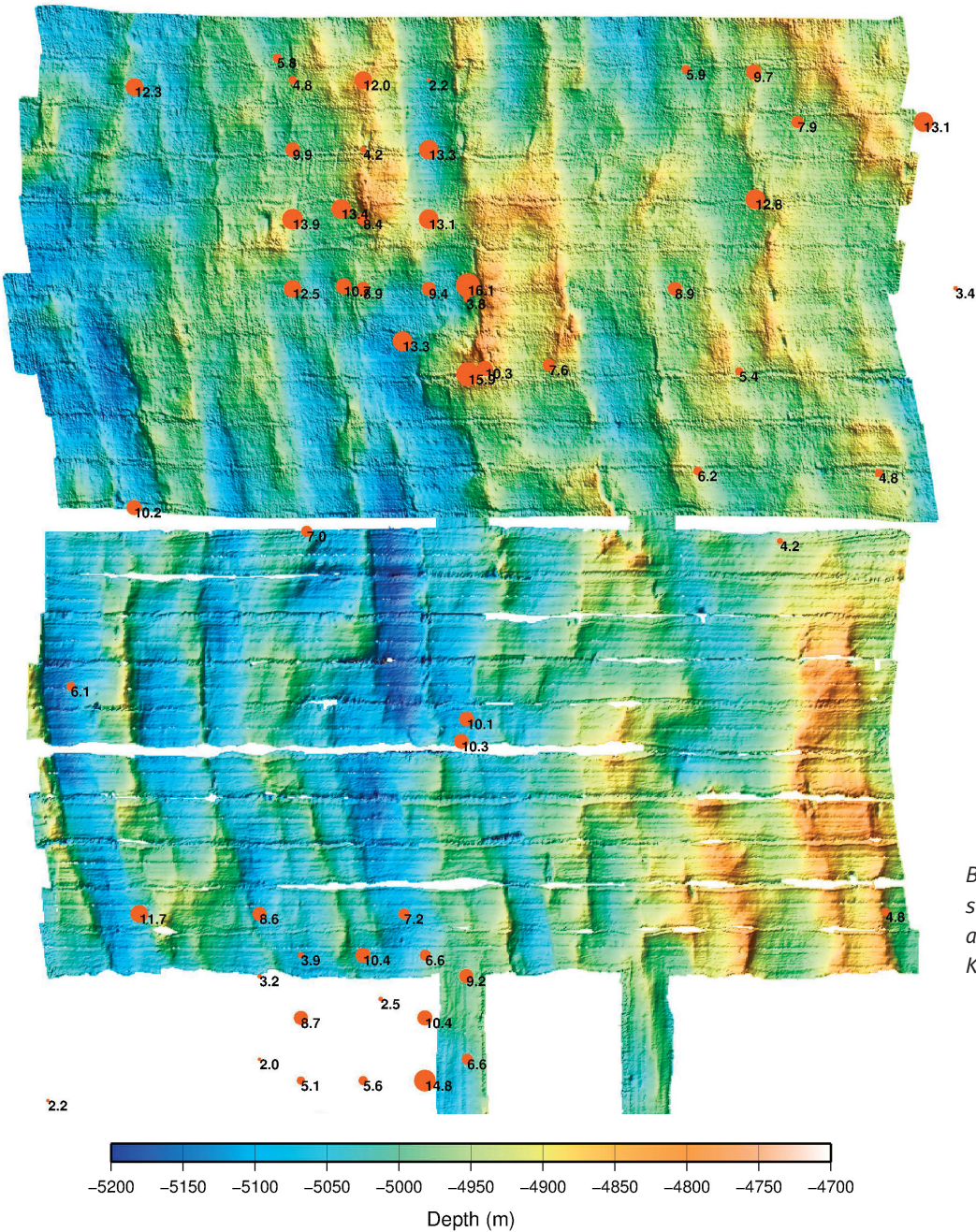


Figure 22. Examples of exploration tools.

4.1.1 Acoustic survey

The first phase of manganese-nodule acoustic surveying involves large-scale reconnaissance grid surveys with spacing of several tens of square kilometres. This is carried out using wide-swath multibeam echo sounder systems to produce bathymetric maps of the region, which permit elimination of those areas not suited to mining (such as seamounts, troughs, cliffs, steep or rugged terrain, etc.).

The second phase of acoustic surveying involves more detailed imagery within a prospective area, with the aim of producing a complete bathymetric map and a map of estimated nodule abundance. This typically involves using deep-towed sidescan sonar to generate high-resolution sea-floor images of the flat areas that are more favourable for mining. The deep-towed systems are also able to detect small-scale features and variations in nodule abundance.



Bathymetric map of pilot area showing observed nodule abundance. Photo courtesy of KIOST.

4.1.2 Sampling and visual observation

Nodule samples are recovered from the sea floor to determine their abundance and metal grade. Nodule abundance can be determined using a combination of bottom sampling, photo/video surveys of the sea floor, and acoustic backscatter. Bottom sampling by means of box coring or grab sampling (see box) can give definitive information on nodule abundance at a specific location on the sea floor. Photo/video tows in close proximity to the bottom can extend this information along restricted corridors within visual range of the tow path.



Sampling with a video

A video grab typically samples 1 square metre with each deployment (samples are generally taken every 30 square kilometres). These are untethered devices, usually fitted with flash cameras, which descend to the sea floor. A suspended weight triggers the camera at a set height above the bottom, followed by the grab jaws collecting a sample of the material shown in the camera photo. As the grab jaws close, weights are dropped and the now-buoyant device floats to the surface for recovery. On its appearance at the surface, it is located by the presence of a flag and night flash, as well as a radio beacon. After recovery of the video grabs, nodules are described, photographed, sampled, measured, weighed, and prepared for analysis onboard the vessel and at land-based laboratories. Preliminary metal grade analysis can be carried out onboard the vessel using handheld X-Ray Fluorescence (XRF) analysis.

4.1.3. Geotechnical studies

Geotechnical studies are carried out to describe the physical, chemical, and mechanical properties of the sediments. The results feed into both the environmental baseline studies and the engineering design studies for mining technology development.



Comparison of nodule abundance. (a) few, small; (b) many, small; (c) many, large; (d) many, bimodal. Photo courtesy of BGR.

4.2 : Mining

Deep sea mineral extraction is expected to involve the following basic processes:

- recovery of minerals from the sea floor using remotely operated sea-floor production equipment;
- transport of a slurry (ore and seawater) vertically from the sea floor to a vessel or platform on the sea surface;
- dewatering of the ore onboard a vessel or platform;
- transfer of the ore from the vessel to a transport barge or bulk carrier/storage facility (land-based or an offshore silo vessel) and disposal of the separated seawater; and
- transport of the ore to land for treatment and/or processing.

4.2.1 Production support vessel

At the centre of a deep sea mining operation is the production support vessel (PSV), which supports the surface and subsea mining operations. Operationally, the PSV is similar to many of the vessels involved in oil and gas, dredging, or transportation industries. Its purpose is to supply a large deck space and a stable platform from which the mining operations are controlled.

The PSV maintains its position over the deposit on the sea floor, using either dynamic positioning or anchoring. Dynamic positioning systems consist of several electric or diesel powered thruster propellers that are controlled by a computer system that uses global positioning system technology as a reference. The computer system varies the output from each thruster to hold a vessel to within a few metres of the required location. Once the ore is pumped from the sea floor to the PSV, it will be transferred to a transportation barge or bulk carrier.

4.2.2 Manganese nodule collecting systems

While various groups have successfully tested trial nodule-mining systems (Heath 1981 and UNIDO 1992), production-scale technology and methodology for mining nodules have yet to be determined. The collector system needs to be operational in a high pressure (~400 bar) and low-temperature (1-20 C) environment. It will likely operate on substrate of poor strength and, therefore, needs to be lightweight. Due to the distance of most known nodule sites from major engineering bases, the collector system needs to be highly reliable and able to function with a minimum of maintenance.

Three basic design concepts for manganese nodule mining technology have been pursued to date. They are:

- picking up nodules with a hydraulic, mechanical, or hybrid collector and lifting them through a pipe (the hydraulic mining system);
- picking up nodules with a bucket-type collector and dragging up the bucket with a rope or cable (the continuous line bucket mining system); and
- picking up nodules with a dredge-type collector and having the collector ascend by the force of its own buoyancy (the modular or shuttle mining system). (ISA 2008):

The hydraulic mining system has received the most attention among deep seabed mining technology developers. The system envisaged and developed in part includes the collection of nodules by either a towed or a self-propelled collector.

If a hydraulic mining system is used, it is likely that remote-controlled, fully manoeuvrable collectors will harvest the sea-floor nodules in much the same way as a combine harvester operates on land. The harvesters will traverse the sea floor and pick up the nodules, separating the nodules from the mud and then pumping the nodules to the surface platform, where they will be transferred to transport vessels for delivery to an onshore processing facility. These sea-floor harvester vehicles will travel along depth contour lines at a speed of approximately 2 knots, sweeping the sea-floor in nearly abutting swaths approximately 10 metres wide.



Manganese nodule collector. Photo courtesy COMRA.

4.2.3 Lifting system

A number of methods have been investigated for transporting the ore from the sea floor to the surface. To date, the majority of work has focused on a fully enclosed riser and lifting system (RALS), technology from the oil and gas industry. The purpose of the RALS is to:

- receive the mineral ore particles (mined slurry) excavated from sea-floor deposits by the sea-floor production tool/collector;
- lift the mined slurry vertically to the dewatering plant inlet on the deck of the PSV, using a subsea lift pump or an airlift system and a vertical riser system suspended from the PSV; and
- send the return water back to the sea.

4.2.4 Dewatering plant

The dewatering plant, situated on the PSV, will dewater the slurry to achieve a transportable moisture level, while min-

imizing any material losses. The seawater, which has been separated from the ore, will likely be discharged back to sea. The location of the discharge (that is, near the sea floor or within the midwater column) will depend on a number of factors, including the total water depth, environmental conditions, and cost.

4.2.5 Onshore logistics / ore handling

Ore may either be transported directly from the PSV to market or, alternatively, taken to a port closer to the mine site. The port would likely be used for onshore ore handling, stockpiling, and load-out operations, as well as for storage of spares, equipment, and supplies. If a port is used for unloading and stockpiling, ore will be transferred to bulk carriers for transportation to a concentrator site or direct delivery to smelters. Ore transportation, handling, offloading, and stockpiling are well-established and well-understood operations.

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Glossary

Abyss – the deep ocean, usually considered to be depths of 2 000 to 6 000 metres, a region of low temperatures, high pressure, and an absence of sunlight.

Abyssal Plain – an extensive, flat, gently sloping or nearly level region at abyssal depths.

Algae – the simplest plants; may be single-cell (such as diatoms) or quite large (such as seaweeds).

Antarctic Bottom Water – AABW, a water mass with temperatures ranging from -0.8 to 2 °C. The AABW can be found at the very bottom of the ocean, directly overlying the sea floor. This cold, salty, and therefore dense water spreads across the very deep, abyssal plains of the global ocean and can be found as far north as the equator.

Assemblage – a neutral substitute for “community” but implying no necessary interrelationships among species; also called species assemblage.

Bathymetry – mapping of elevations and the variations in water depth; the topography of the sea floor.

Beneficiation – in mining, crushing and separating the ore to recover the target metals.

Benthic – associated with the sea floor.

Benthos – the collection of organisms living on or within the seabed.

Biodiversity – biological diversity; used by marine conservationists most commonly with respect to species diversity. Biodiversity can also encompass habitat or community diversity and genetic diversity within a species.

Biogenic – in geology, sediments or sedimentary rocks of biological origin, including, in particular calcium carbonate and biogenic silica (opal).

Bioregionalization – a spatial representation depicting the boundaries of areas represented by each level in a hierarchical classification of habitat types (provinces, biomes, habitat complexes, etc.)

Biurbation – stirring or mixing of sediment by organisms, especially burrowing or boring organisms.

Botryoidal surface – like a bunch of grapes

CBD – (United Nations) Convention on Biological Diversity. <http://www.cbd.int>

Community – a group of species that generally are assumed to be interdependent (though this is often not demonstrated). The term can be used in a variety of hierarchies. Communities at larger scales can be progressively subdivided, such as spatially, taxonomically, and, trophically to finer scales.

Clarion Clipperton Zone – an area of manganese nodule prospectivity, located in the eastern central Pacific, to the south and southeast of the Hawaiian Islands. The geographical limits of the area have been taken to be the area beyond national jurisdiction contained within a box approximately 0°-23°30'N x 115°W-160°W. The Zone is bounded to the north and south by the ENE-WNW trending Clarion and Clipperton Fracture Zones.

Crustaceans – large group of arthropods that include familiar animals such as crabs, prawns, and barnacles.

Demersal species – a fish (also called groundfish), cephalopod, or crustacean that lives on or near the seabed.

Diagenetic – when referring to the formation of manganese nodules, indicates the precipitation of colloidal metal particles from interstitial water.

Ecosystem – short for ecological system. Functional unit that results from the interactions of abiotic and biotic components; a combination of interacting, interrelated parts that forms a unitary whole. All ecosystems are “open” systems in the sense that energy and matter are transferred in and out. Earth, as a single ecosystem, constantly converts solar energy into myriad organic products and has increased in biological complexity over geologic time.

Ecosystem based management – place-based management that integrates the scientific knowledge of ecological relationships with environmental, social, and economic values, with the goal of protecting entire ecosystems over the long term.

Endemic – species only known to occur in one location.

Environmental impact assessment – is a necessary process contributing to the management of ecologically sustainable development. It is one of the main tools used to minimize environmental degradation associated with human activities. The EIA process is complex and involves input from numerous disciplines, including science, engineering, social sciences, and economics. In addition to the collection and analysis of data, EIA requires the effective communication of information, public consultation, and an appreciation of human needs and values.

Environmental impact statement – a comprehensive document that describes the positive and negative effects of a proposed action.

Epibenthic – belonging to the community of organisms living on top of the sediment surface of the sea floor.

Epifauna – animals that live on the surface of the seabed or upon other benthic animals or plants.

Eukaryotic – organisms whose cells contain a nucleus.

Foraminifera – single-celled planktonic organisms. They typically produce a shell or test, which can have an elaborate structure. These shells are made of calcium carbonate or small pieces of sediment cemented together (agglutinated forams).

Filter feeding – in zoology, a form of food procurement in which food particles or small organisms are randomly strained from water. Passive filter feeding (sessile animals that rely on currents for food delivery) is found primarily among the small- to medium-sized invertebrates, and active filter feeding (mobile animals) occurs in a few large vertebrates (e.g., flamingos, baleen whales).

GOODS – Global Open Ocean and Deep Sea-habitats classification developed by the United Nations Convention on Biological Diversity.

Habitat – physically distinct areas of seabed associated with suites of species (communities or assemblages) that consistently occur together.

Hydrodynamic modelling – a hydrodynamic model is a tool able to describe or represent in some way the motion of water.

Hydrodynamic regime – pattern of water movement.

Hydrogenetic – when referring to manganese nodule formation, indicates precipitation of colloidal metal particles from near-bottom seawater.

Infauna – animals that live within sediments.

Invertebrate – an animal without a backbone or spinal column (i.e., not vertebrate).

Macrofauna – benthic organisms retained on a 0.3 mm (or larger) sieve.

Marine protected area (MPA) – defined by the IUCN as “any area of intertidal or subtidal terrain, together with its overlying water and associated flora, fauna, historical and cultural features, which has been reserved by law or other effective means to protect part or all of the enclosed environment.”

Marine spatial planning – a process that brings together multiple users of the ocean – including energy, industry, government, conservation, and recreation – to make informed and coordinated decisions about how to use marine resources sustainably, based on a spatial framework (maps). Marine protected areas and fisheries reserves are examples of marine spatial planning devices.

Meiofauna – animals pass through a 300 µm sieve and are retained on sieve sizes ranging from 32 to 63 µm, depending on the taxon studied.

Megabenthic community – community comprising megafauna, which are benthic organisms that can be seen by the naked eye, or which can be detected in underwater photographs.

Megafauna – animals that can be seen by the naked eye; also defined as animals larger than 45 kg in weight.

Mineral reserves – part of the mineral resource that can be economically mined.

Mineral reserve base – includes the mineral reserves, plus sub-economic reserves (i.e. not mineable at a profit). The development of new process technologies generally results in the conversion of some of the mineral reserve base into proven mineral reserves.

Microalgae – phytoplankton; small plants visible under a microscope, such as diatoms. The definition includes benthic algae.

Microfauna – small, mostly microscopic animals (less 0.063 mm), such as protozoa, nematodes, small arthropods, etc.

Motile – organisms with an ability to move.

Mud – sediment grains smaller than 0.0625 mm in size. Includes silt (between 0.0625 and 0.004 mm) and clay (<0.004 mm).

Nematode – or roundworms; are simple unsegmented worms that can be free-living or parasitic.

Oxic sediments – sediments containing measurable amounts of dissolved oxygen. The oxic zone is an important redox boundary in sediment-pore water systems. It is regulated by organic carbon degradation and the transport of oxygen from bottom water into the sediment.

Pelagic – of, relating to, or living in the water column of seas and oceans (as distinct from benthic).

Paranoid polychaetes – a family of small slender polychaete worms

Precautionary principle – the guiding ecological principle that maintains that, when considering which activities to permit, only those that have been demonstrated not to damage ecological resources be permitted.

Phytoplankton – microscopic free-floating algae that drift in sunlit surface waters.

Plankton – small or microscopic aquatic plants and animals that are suspended freely in the water column; they drift passively and cannot move against the horizontal motion of the water (contrast with “nekton” that are capable of horizontal movement). Planktic animals (zooplankton) include small protozoans and the eggs and larvae of larger animals and some migrate vertically in the water column each day. Planktic plants are phytoplankton and include diatoms, cyanobacteria, dinoflagellates, and coccolithophores.

Pore water – water occupying the spaces between sediment particles.

Precipitate – to separate in solid form from a solution: e.g., manganese ions precipitate from seawater onto the surface of another solid, such as a grain of sand.

Primary production – synthesis of organic compounds through photosynthesis or chemosynthesis. The organisms responsible for primary production are known as primary producers or autotrophs and form the base of the food chain

Protozoans – a diverse group of generally motile single-cell organisms.

Recruitment – the influx of new members into a population by either reproduction or immigration.

Sand – sediment grains between 0.0625 mm and 2 mm in size.

Seascape – the marine version of “landscape”; comprised of suites of habitats that consistently occur together.

Sessile – an organism fixed in one place, immobile.

Substrate – the surface a plant or animal lives upon. The substrate can include biotic or abiotic materials. For example, encrusting algae that live on a rock can be substrate for another animal that lives on top of the algae.

Trophic level – position an organism occupies in the food chain.

Xenophyophores – single cell protozoans, abundant on the abyssal plains. They can grow to a surprisingly large size (up to 20 cm) and have a diverse range of appearance. They are filter feeders that continually turn over the sediment, an activity that seems to encourage biodiversity.

Zooplankton – small, sometimes microscopic, animals that drift in the ocean; protozoa, crustaceans, jellyfish, and other invertebrates that drift at various depths in the water column are zooplankton.

