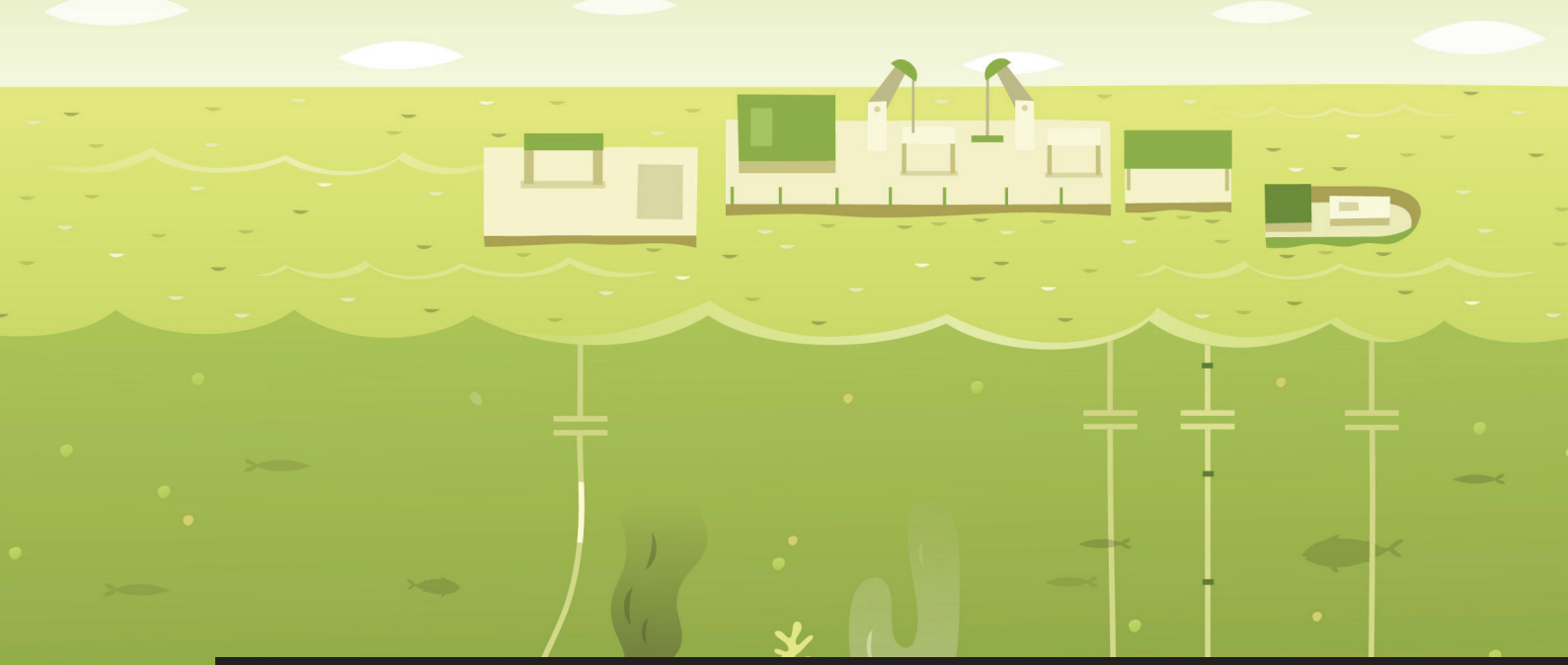

DEEP SEA MINERALS

1C

Cobalt-rich Ferromanganese Crusts

A physical, biological, environmental, and technical review

Edited by Elaine Baker and Yannick Beaudoin

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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)
Sven Petersen GEOMAR
Ashley Rowden National Institute of Water & Atmospheric Research Ltd (NIWA)
Samantha Smith Nautilus Minerals Inc.
Elaine Baker GRID-Arendal at the University of Sydney
Yannick Beaudoin GRID-Arendal

Reviewers
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DEEP SEA MINERALS

1C Cobalt-rich Ferromanganese Crusts

A physical, biological, environmental, and technical review

CONTENTS

Introduction

On the slopes of submarine mountains around the world, minerals precipitate out of the seawater to form thin crusts on rocky surfaces. The crusts are commonly called ferromanganese crusts, reflecting the fact that their major constituents are iron (Fe) and manganese (Mn), although a host of other minerals occur in them in smaller amounts, including cobalt – which is why they are also often called cobalt-rich crusts or cobalt-rich ferromanganese crusts. Many of these minerals have potential economic value.

The ferromanganese crusts of the Pacific have been of interest for some time. During the 20-year period from 1980 to 2000, more than 40 research cruises investigated aspects of the formation and character of ferromanganese crusts (Cronan 1984; Hodkinson and Cronan 1991; Hein *et al* 2000). Ferromanganese crusts are partially made up of valuable cobalt, nickel, and manganese. Additionally, crusts are seen as a potential source of the rare-earth elements and other in-demand metals that are increasingly used in high technology and green technology industries. However, mining the crusts has been considered more technically challenging than mining other deep sea deposits, such as manganese nodules or sea-floor massive sulphides, and this has slowed development. The crusts can be firmly attached to the underlying rock, and technological solutions are required to design a process to retrieve them while minimizing the collection of non-mineralized waste rock (ISA 2002).

The Chinese government has been active in exploration and development through the China Ocean Mineral Resources Association (COMRA). It submitted an application to the International Seabed Authority (ISA) to exploit cobalt-rich ferromanganese crust deposits in a 3 000 square kilometre area of the western Pacific (ISA 2012). COMRA, the largest producer of land-based rare-earth minerals, began surveying marine cobalt-rich crust resources in 1997. The Government of Japan, through the Japan Oil, Gas, and Metals National Corporation (JOGNEC), also submitted an application to the ISA to exploit cobalt-rich ferromanganese crust deposits in an equivalently sized area just north of the area of Chinese interest. These applications were considered and approved by the ISA at the 19th annual session in July 2013.

Ferromanganese crusts are most enriched with cobalt and other metals in shallow-water sites (800 to 2 500 metres water depth). In the Pacific, therefore, commercial prospects are likely to be concentrated within the sovereign waters of Pacific states. To support Pacific Islands in governing and developing these natural resources, SOPAC division of SPC is providing a range of information products, tech-

nical and policy support, and capacity-building activities through the Deep Sea Minerals in the Pacific Islands Region: a Legal and Fiscal Framework for Sustainable Resource Management project (Figure 1). This publication, created as part of that project, brings together expert knowledge about the geology and biology of cobalt-rich ferromanganese crusts and information about best practices related to the environmental management and technical aspects of mineral exploration and extraction.

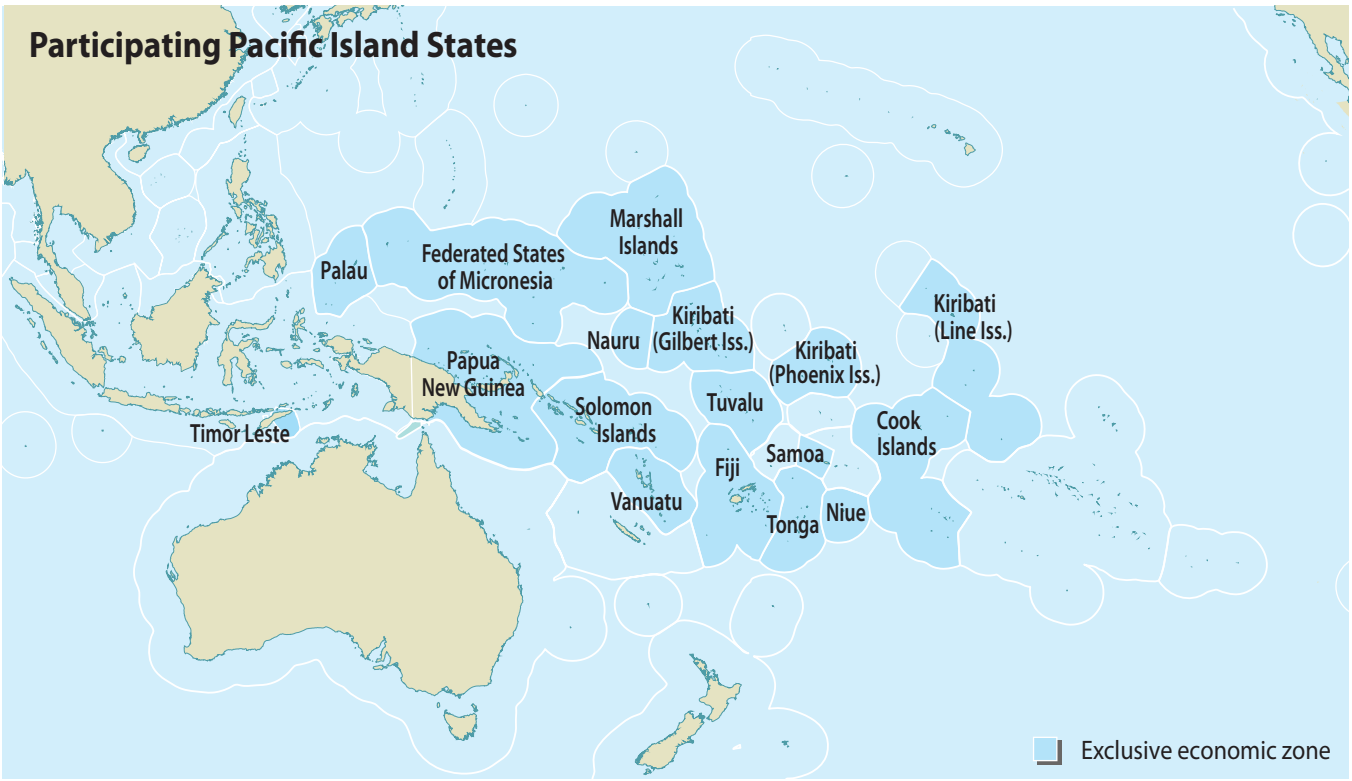

Figure 1. The Pacific ACP States (i.e., Africa-Caribbean-Pacific Group of States) participating in the European-Union-funded SPC Deep Sea Minerals Project.

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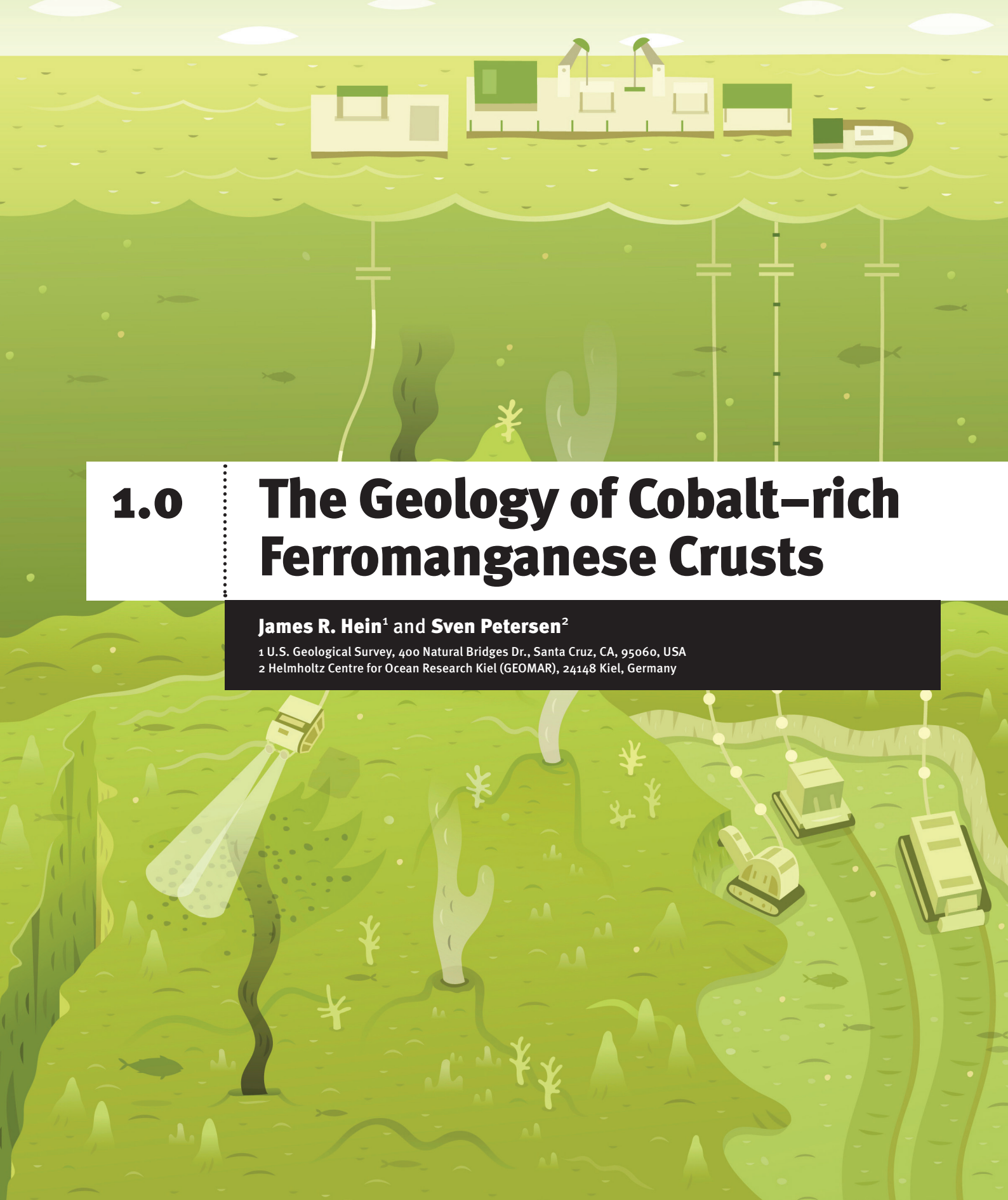


1.0 The Geology of Cobalt–rich Ferromanganese Crusts

James R. Hein[1] and **Sven Petersen**[2]

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 cobalt-rich ferromanganese crusts

Cobalt-rich ferromanganese crusts precipitate onto nearly all rock surfaces in the deep ocean. Their thickness varies from less than 1 millimetre to about 260 millimetres. They occur only where the rock surfaces are free of sediment. There, they form pavements of intergrown manganese and iron oxides. Ferromanganese crusts may also coat rock pebbles and cobbles. They form at water depths of 600 to 7 000 metres on the flanks of seamounts (undersea mountains with a height above 1 000 metres), knolls (heights of 200 to 1 000 metres), ridges, and plateaus. Crusts with sufficient mineral content to be of economic interest commonly occur at depths of about 800 to 2 500 metres (Hein *et al.* 2000, 2009). In the Pacific Ocean, there are more than 11 000 seamounts (57 per cent of the global total) and 41 000 knolls (Yesson *et al.* 2011, estimated from the latest global bathymetry), and many more might exist in uncharted waters (Wessel *et al.* 2010). Many seamounts are within the Exclusive Economic Zones (EEZs) of Pacific Island states (Figure 2). The Atlantic Ocean has fewer seamounts, and the cobalt-rich crusts that occur there are usually associated with hydrothermal activity at sea-floor-spreading centres, with the exceptions of the northeast and northwest continental margin areas.

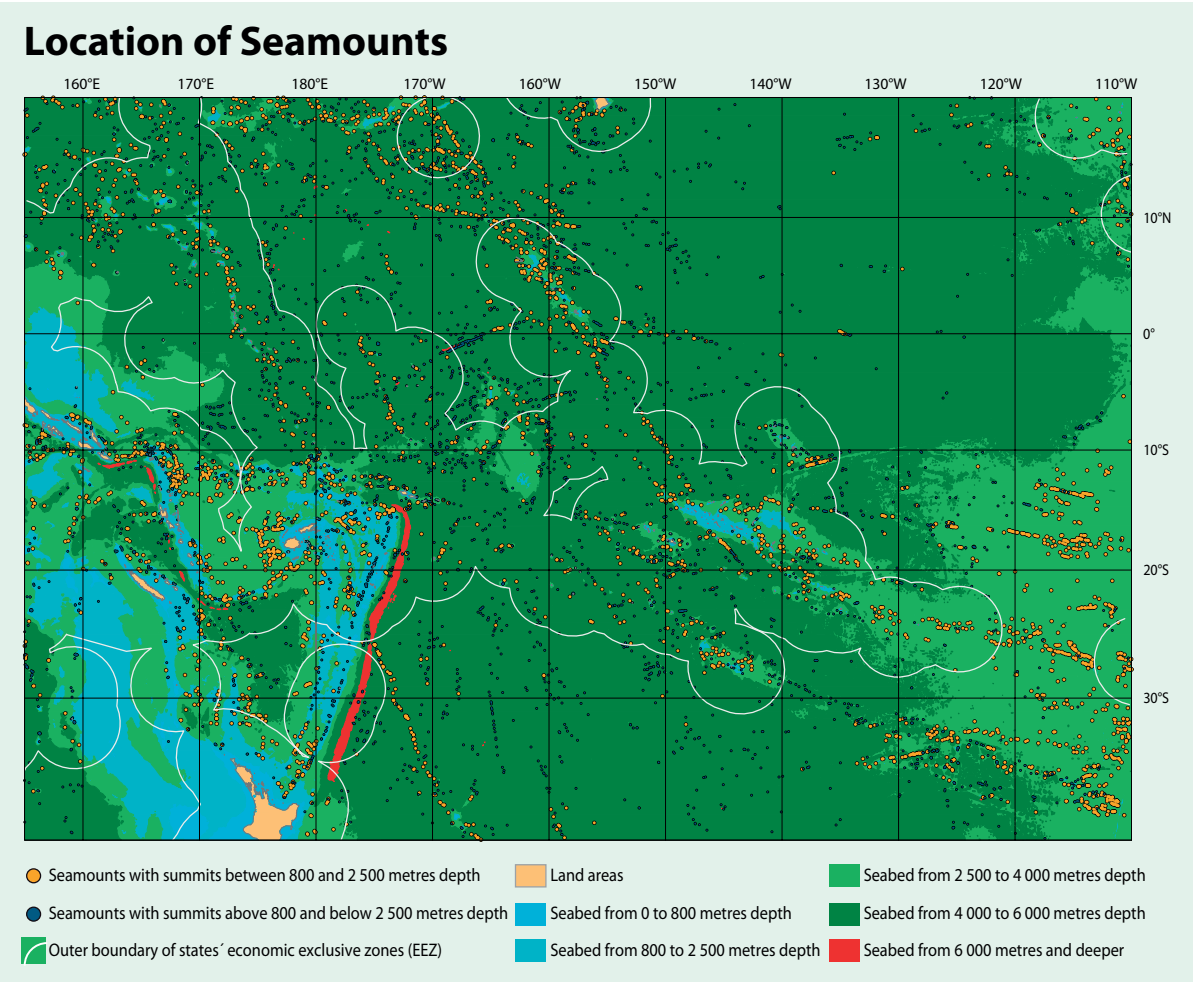


Figure 2. Bathymetric map of the Pacific showing the location of seamounts.

In the Pacific, the manganese and iron oxides precipitate out of cold ambient seawater (hydrogenetic) and are not associated with volcanic or hydrothermal activity (except at active volcanic arcs and hot-spot volcanoes). A wide array of metals and elements dissolved in ocean water are adsorbed (meaning to adhere to a surface) in large quantities onto the manganese and iron oxides (Figure 3). The main source of nearly all metals dissolved in seawater is erosion of the continents. The exception is manganese, which derives primarily from hydrothermal sources and mixes throughout the global ocean. The metals are adsorbed because of the crusts' very slow growth rates (1 to 5 millimetres per million years) and the enormous specific surface area (average 325 square metres per cubic centimetre of crust) (Hein *et al* 2000). The metals adsorbed include:

- trace metals, such as cobalt, nickel, and copper;
- rare metals, such as tellurium, platinum, zirconium, niobium, tungsten, and bismuth; and
- rare-earth elements, such as lanthanum, cerium, neodymium, europium, and terbium.

This makes ferromanganese crusts a potential resource for many of the metals used in emerging high-technology and green-technology applications.

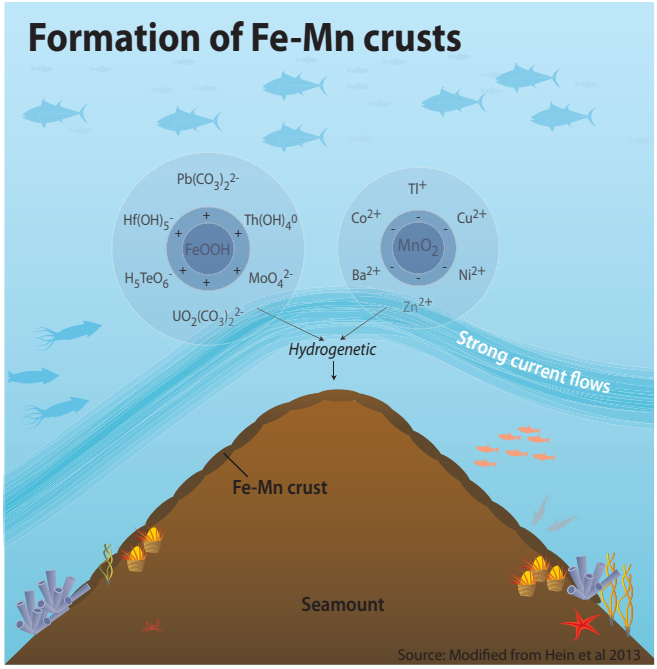
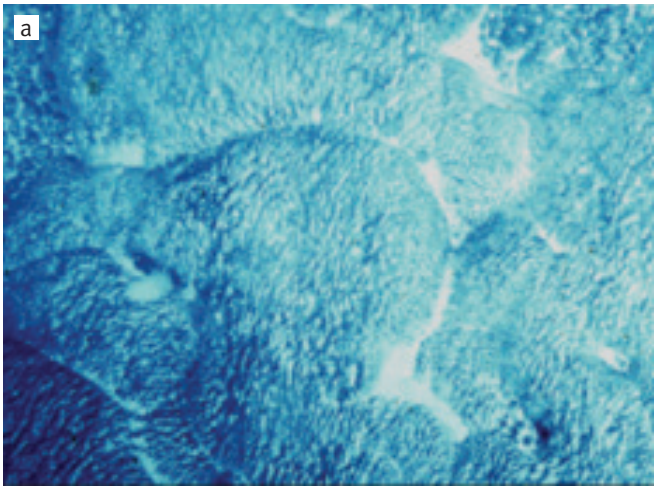
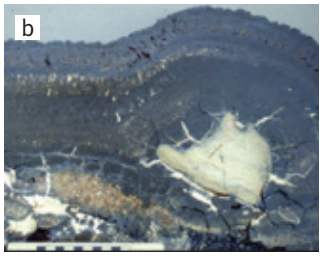


Figure 3. Formation of cobalt-rich ferromanganese crusts. *Adapted from Hein 2004.*





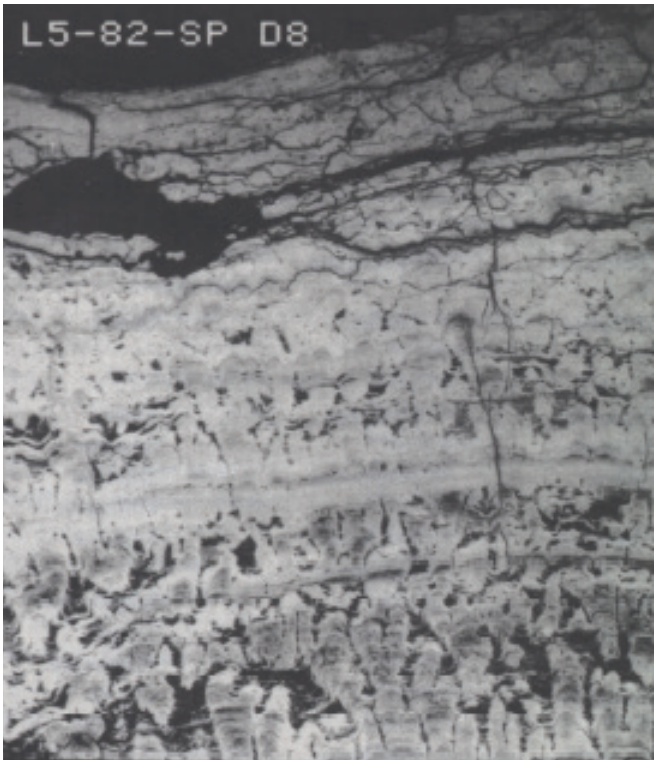
a: The seabed at 2 000 metres water depth showing ferromanganese crust pavement (~4 m by 3 m) on Horizon Guyot, Central Pacific. b: 18-cm-thick crust (D11-1) from 1 780 metres water depth within the Marshall Islands EEZ that started growing onto a substrate rock about 70 million years ago. c: A 12-cm-thick crust (CD29-2; cruise F7-86-HW) from the Johnston Island EEZ (USGS, Hein).

Hydrogenetic crusts, mixed hydrothermal-hydrogenetic crusts, and stratabound hydrothermal deposits

The crusts of economic interest are formed at the sea floor by precipitation from cold seawater (hydrogenetic), but iron and manganese oxides can also be created below the sea floor through hydrothermal processes. The hydrothermal deposits usually consist of stratabound layers of manganese, or iron, or manganese-cemented volcaniclastic and biogenic sediments. They are distinctly different in texture and composition from hydrogenetic ferromanganese crusts. The hydrogenetic crusts have similar amounts of iron and manganese, whereas the hydrothermal deposits are predominantly either iron or manganese (Hein *et al*. 2000). Hydrothermal activity dilutes the metals of economic interest, although small deposits can occasionally be enriched in lithium, molybdenum, chromium, zinc, nickel, or copper (Hein *et al*. 1997). At present, the economic potential of these hydrothermal deposits is uncertain, but might be reassessed with more investigation.

Farther away from the hydrothermal source, stratabound hydrothermal deposits grade into mixed hydrothermal-hydrogenetic crusts. These mixed-source crusts form at the seabed when the hydrothermal fluids exit the sea floor, mix with seawater, and precipitate onto hard rock surfaces. Those close to the hydrothermal source are very rich in iron and manganese but, like the stratabound deposits, have low concentrations of rare metals. As the distance from the source increases, the hydrothermal contribution wanes and the cold ambient seawater contribution dominates. Consequently, there is an increasing concentration of rare metals the farther away from the hydrothermal source the crusts are formed. The mixed hydrothermal-hydrogenetic crusts have no economic importance. Only the purely hydrogenetic (seawater source) crusts contain sufficient rare metals to be of current economic interest (Hein *et al*. 2000).

Ferromanganese crust on a boulder collected from the Ninety East Ridge, Indian Ocean. Photo courtesy of Evelyn Mervine.



Complex internal structure of ferromanganese crust. Photo courtesy of James R. Hein, USGS.

1.2 Metal concentrations and tonnage

Ferromanganese crusts have a simple mineralogy. They are composed predominantly of vernadite (manganese oxide, or MnO_2) and non-crystalline iron oxyhydroxide (FeOOH). This contrasts with manganese nodules, another type of deep sea mineral (see Volume 1B) containing similar metals, but having a more complex mineralogy – they are composed of two or three manganese minerals (vernadite, todorokite, and birnessite) in addition to non-crystalline FeOOH. Ferromanganese crusts also contain minor amounts of detrital minerals, such as quartz and feldspar. Most thick crusts (greater than about 60 millimetres) also contain a phosphate mineral called carbonate fluorapatite, which is a secondary mineral that forms long after the manganese and iron oxides have precipitated from seawater. Iron and manganese occur in approximately equal amounts in crusts (Figure 4). Cobalt, the trace metal of greatest economic interest, can be up to 2 per cent, but usually averages 0.5 to 0.8 per cent by weight (Figure 5). Ferromanganese crusts contain the highest concentrations of the rare metal tellurium, which is used in the solar cell industry to produce thin-film photovoltaics – the best material for converting sunlight into electricity.

The concentration of metals other than iron and manganese in ferromanganese crusts is affected by the concentration of metals in seawater (the source), the Fe/Mn ratio of colloids in seawater and in crusts, and the surface charge of the Fe-Mn colloids. Cobalt and many other rare metals are adsorbed onto vernadite, which is more abundant in crusts than nodules, and this explains their generally higher concentrations in crusts (Hein

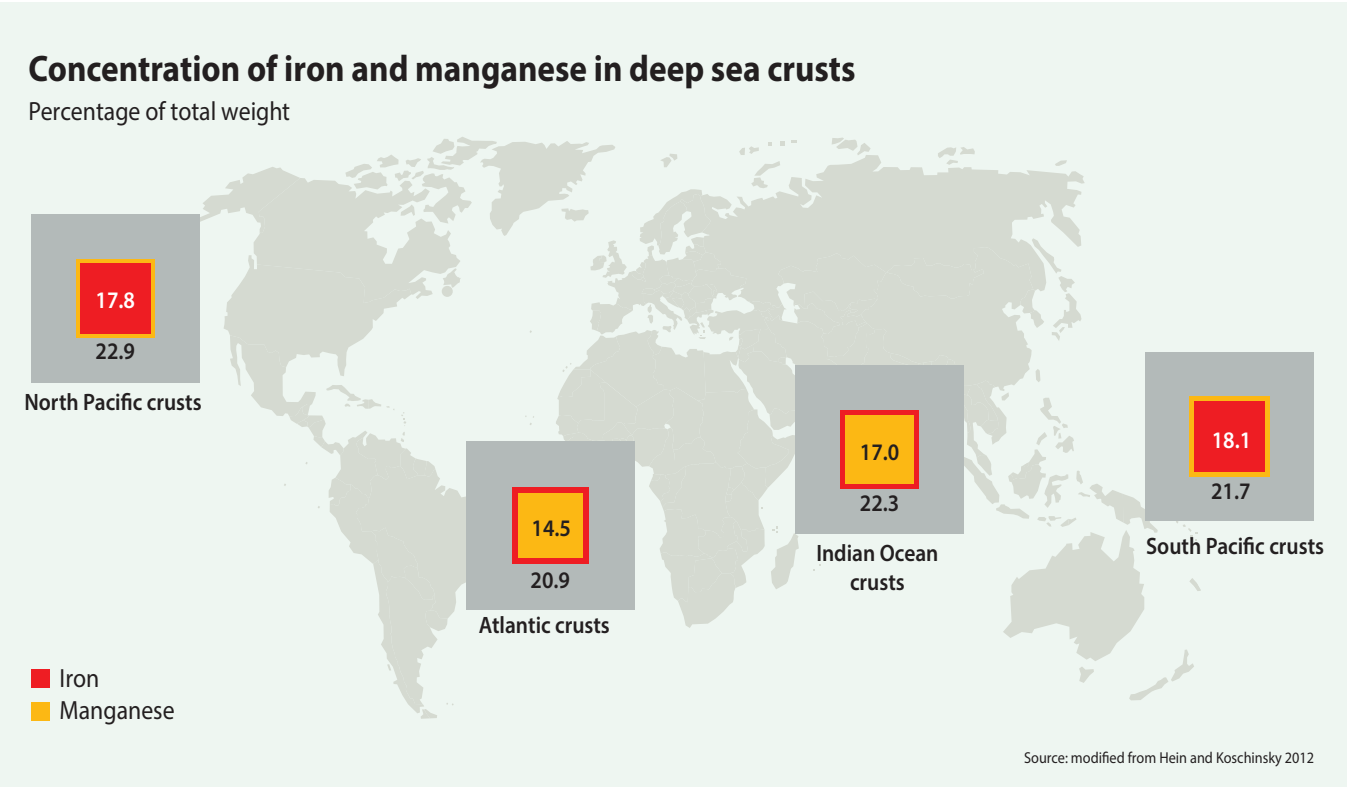


Figure 4. Concentration of iron and manganese in ferromanganese crusts.

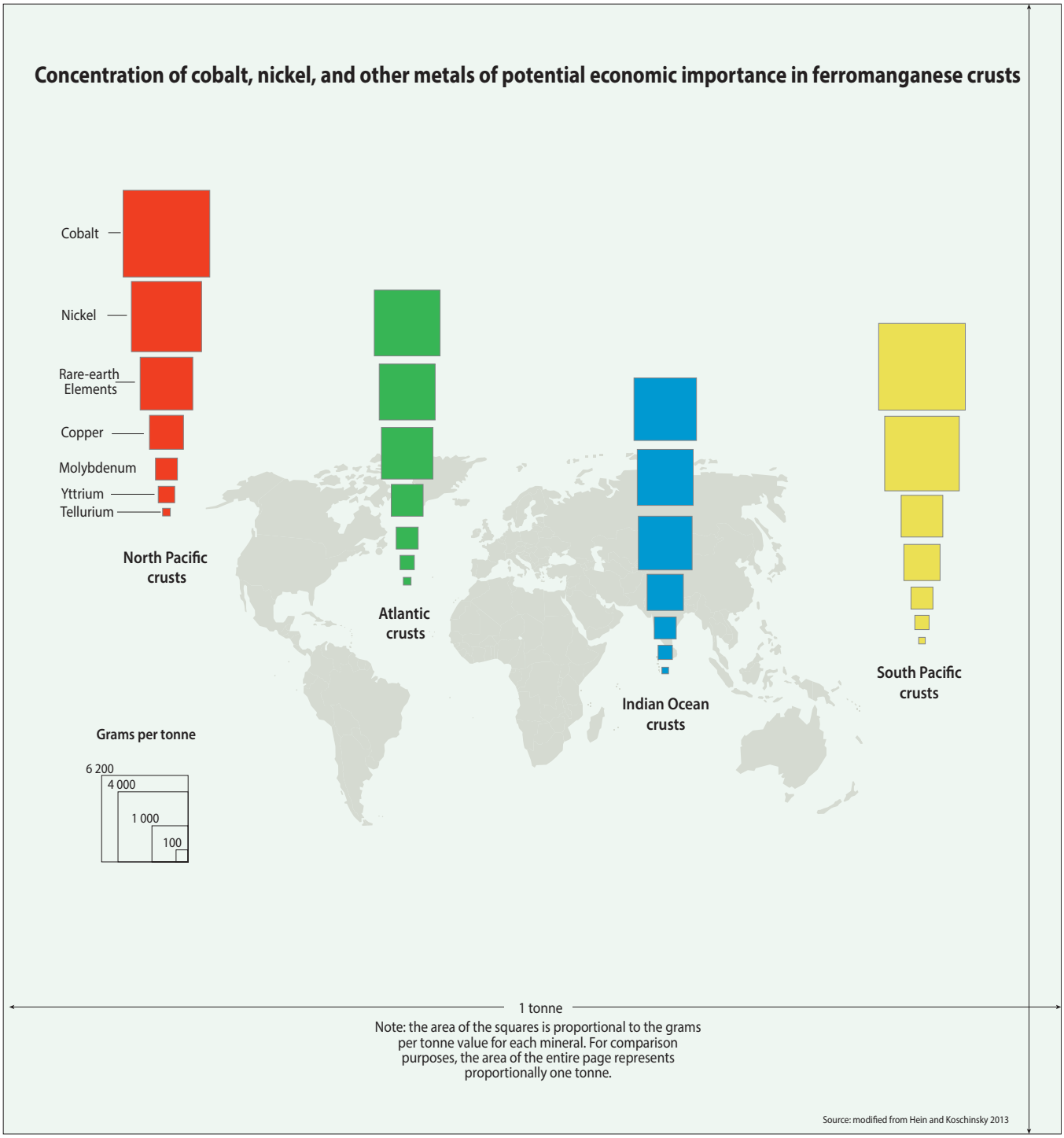


Figure 5. Concentration of metals of potential economic importance in ferromanganese crusts.

Ferromanganese crust on basalt substrate, collected during Monterey Bay Aquarium Research Institute (MBARI) cruise to the Taney Seamounts – a chain of four undersea volcanoes that lie about 300 kilometres due west of Monterey Bay, California – from August 5–13, 2010 (see http://www.mbari.org/expeditions/Taney10)

and Koschinsky 2013). The rare metals tellurium and platinum are also more highly concentrated in crusts than nodules because they are sorbed onto the iron oxyhydroxide phase, which is more abundant in crusts.

Little is known about the abundance of ferromanganese crusts in most areas of the global ocean. The thickest crusts with the highest concentrations of cobalt have been found on outer-rim terraces and on broad saddles on the summits of seamounts (Hein *et al* 2008). The central equatorial Pacific region – particularly the EEZs around Johnston Island and Hawaii (United States), the Marshall Islands, the northern part of the Federated States of Micronesia, and international waters of the mid-Pacific – is currently considered the most promising area for crust mining. A rough estimate of the quantity of crusts in the central Pacific region is about 7 533 million dry tonnes (Hein and Koschinsky 2013).

Ferromanganese crusts on seamounts in the central Pacific are estimated to contain about four times more cobalt, three and a half times more yttrium, and nine times more tellurium than the entire land-based reserve base of these metals. These crusts also contain the equivalent of half of the bismuth and a third of the manganese that makes up the entire known land reserve base (Hein and Koschinsky 2013).

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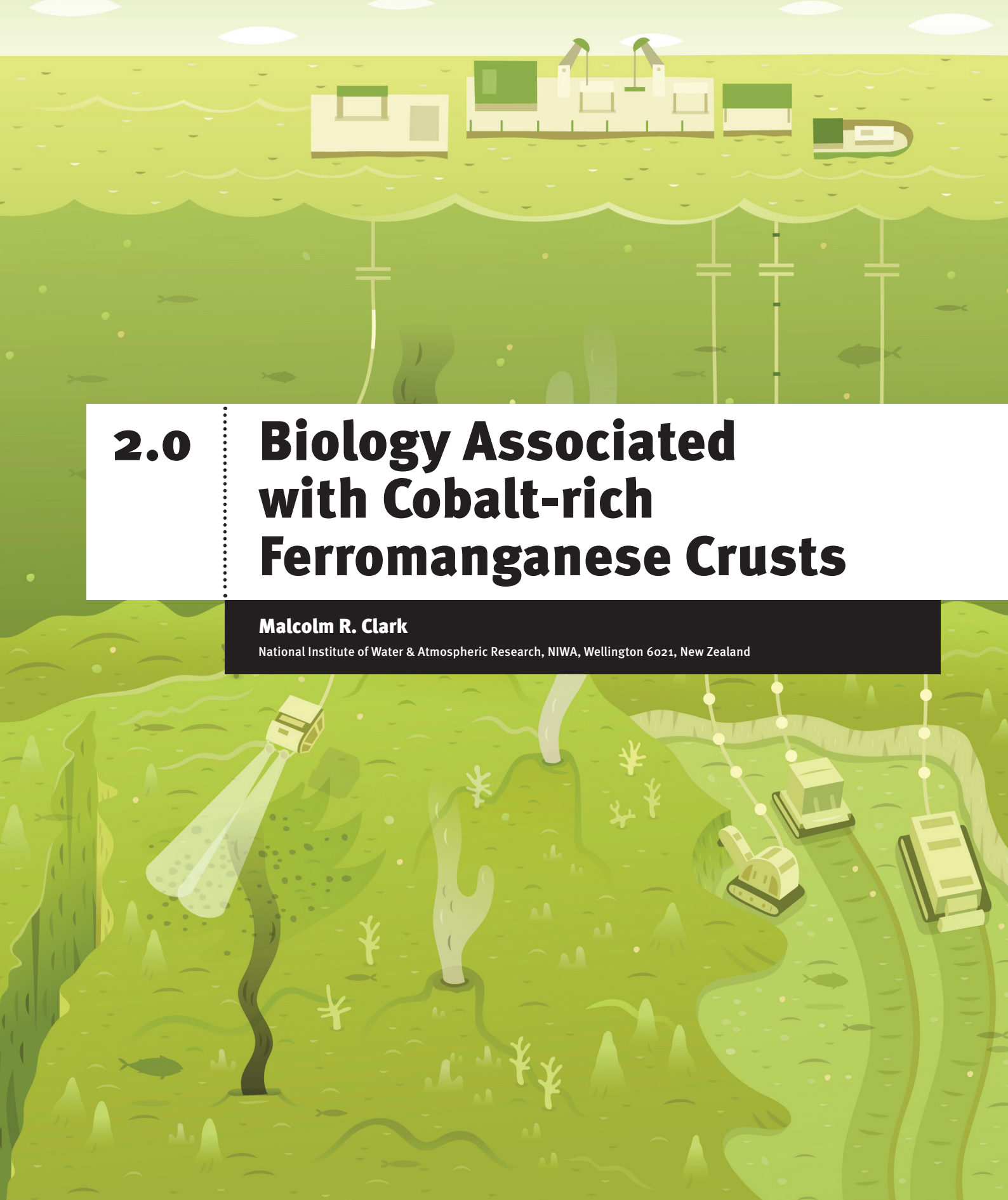


2.0 Biology Associated with Cobalt-rich Ferromanganese Crusts

Malcolm R. Clark

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

2.1 Habitats and biodiversity associated with cobalt-rich ferromanganese crusts

Cobalt-rich ferromanganese crusts (Fe-Mn crusts) are found throughout the global oceans on the summits and flanks of seamounts, ridges, and plateaux. They form only on bare rock surfaces and are therefore distributed where oceanic currents keep the seamounts free of sediment. The process is very slow, taking millions of years for development of thick crusts.

3.1.1 Geographic context

In the southwest Pacific region, crusts form on the summits and flanks of seamounts, especially large flat-topped guyot features (isolated volcanic mountains), at depths of about 400 metres down to 4 000 metres. There are several thousand seamounts

Biogeography: mapping the distribution of species

Much of the open ocean has never been sampled, especially the deep sea. Even in the case of seamounts, which have been the focus of international efforts, only a few hundred have been studied, out of hundreds of thousands worldwide. However, we know that the distribution of animals varies considerably between areas.

Biogeography examines the geographic distribution of fauna and flora, generally at the larger scale of similar faunal communities.

A biogeographic classification puts together information on biological composition, species distributions, and physical

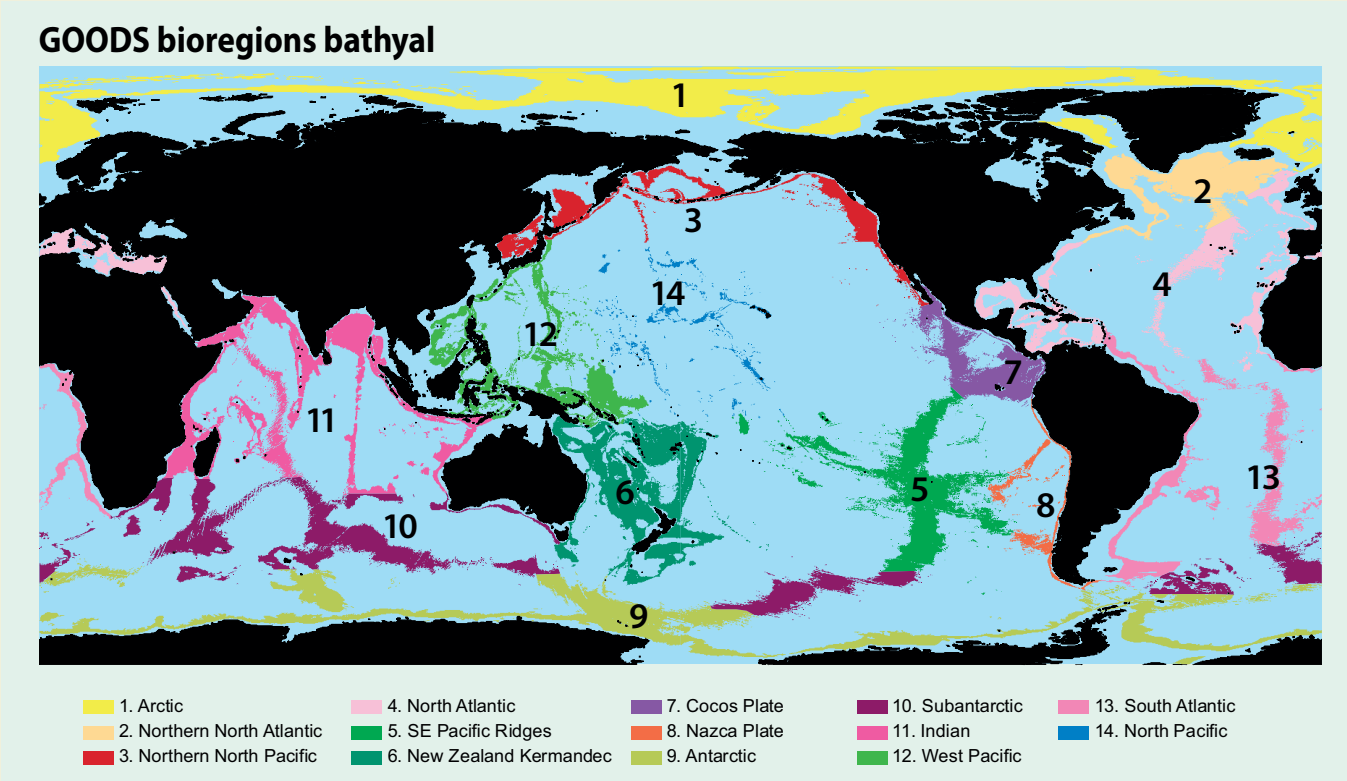


Figure 6. Lower bathyal provinces. *Depth range 800 to 3000 metres (UNESCO, 2009).*

at suitable depths within the region, although the thickest and most enriched crusts occur between 800 metres and 2 500 metres (see section 2.1).

The physical characteristics of seamounts vary throughout the region, and, consequently, the distribution of ferromanganese crust differs among Pacific Island states. The differing physical conditions affect the distribution of biological communities, particularly benthic (sea-floor) invertebrate species that are strongly driven by depth, substrate type, and current flow (Clark *et al*. 2010). Research carried out by Japan in association with SOPAC in the 1990s showed varying sediment conditions in cobalt-rich regions. Off Kiribati and Tuvalu, high proportions of the sea floor were covered by clay or foraminiferal ooze, while there was much greater coverage by hard crust in areas off Western Samoa, the Marshall Islands, and Federated States of Micronesia (Fukushima 2007). General benthic communities in the region are thought to be broadly similar: a biogeographic classification for bathyal zones (depths of 800 to 3 500 metres) grouped the entire southwest Pacific into four large biogeographic provinces (UNESCO 2009). This implies that the pool of species available throughout the region is similar over large areas. However, an environmental classification done specifically for seamounts showed that considerable variation might be expected within the larger provinces, based on depth, organic carbon flux to the sea floor, oxygen level, and proximity to neighbouring seamounts (Clark *et al*. 2011a).

and environmental conditions to derive geographical groupings with similar attributes. Within these regions, the biodiversity is believed to be generally similar. This can help managers and policy makers plan for use and conservation of the marine environment.

In 2007, a multidisciplinary scientific expert group developed a new biogeographic classification of the open-ocean and deep sea areas of the world. This has become known as the GOODS report (UNESCO 2009). It classifies specific ocean regions on the basis of a range of oceanographic factors (such as tempera-

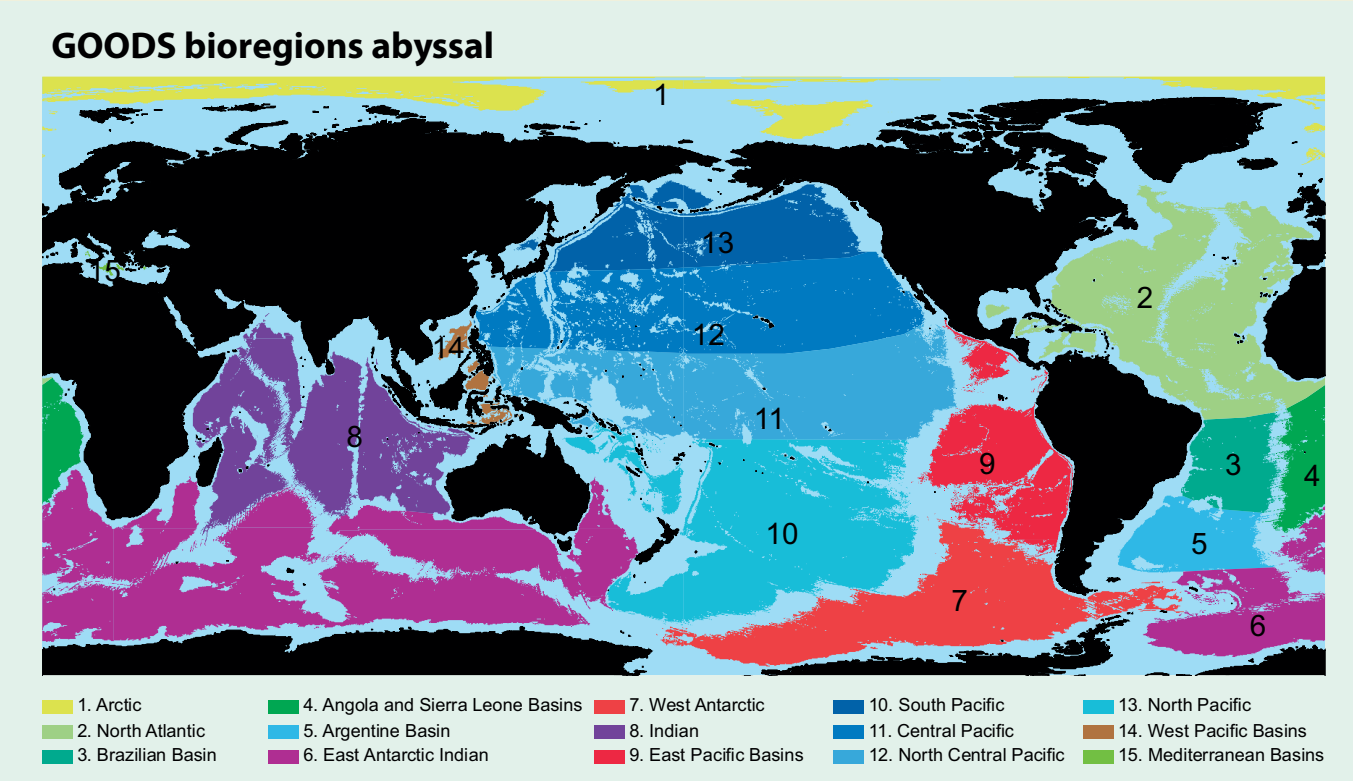


Figure 7. Abyssal provinces. *Depth range 3500 to 6500 metres (UNESCO, 2009).*

ture, salinity, oxygen, and particulate organic carbon flux) and topographical features (such as bathymetry, plate boundaries, sea-floor sediment, seamounts, and hydrothermal vents). These characteristics were used to select relatively homogeneous regions in terms of habitat and associated biological communities. The process was dominated by physical factors, but these were modified through knowledge of patterns of community composition and processes of dispersal, isolation, and evolution. The classification is considered a living document, and boundaries are subject to further refinement.

Pelagic waters were divided into 30 global provinces. Benthic areas were subdivided into 14 bathyal (800 to 3 500 metres depth; Figure 6), 14 abyssal (3 500 to 6 500 metres depth; Figure 7), and 10 hadal (more than 6 500 metres depth) provinces. In the general Pacific Islands region, there are 8 lower bathyal provinces, and 4 abyssal provinces. Within such a broad regional classification, more detailed schemes can be developed, such as seascape definition (Harris and Whiteway 2009), which is based on topography, or for a specific feature like seamounts (Clark *et al*. 2011).

2.2 Composition of communities

The physical environmental conditions described above mean that ferromanganese crust habitat is characterized by rocky substrate, reasonably swift current flows, and a wide depth range (Figure 8). The rocky substrate makes the habitat suitable for sessile animals, such as corals and sponges, that require hard surfaces on which to attach, but generally unsuitable for burrowing animals, which require soft muddy sediments (although soft sediment will occur in small patches). Swift currents that occur around seamounts or steeply sloping topography can limit the type or shape of animal that can live in such a dynamic environment and not be swept away. However, filter feeders that require good current flow to bring food particles to them without excessive sediment can find such conditions advantageous. The flanks of seamounts span a wide depth and temperature range, meaning that a large variety of animals can find suitable conditions to live.

There has been considerable biological research undertaken on seamount communities in various parts of the Pacific Ocean, but most studies investigating fauna on ferromanganese crusts have been done in the central Pacific Ocean and around Hawaii (Grigg *et al*. 1987, Mullineaux 1987, Clark *et al*. 2011b). There has been extensive research on seamounts off New Zealand, Australia, and New Caledonia, but this has not been focused on ferromanganese crust habitat. However, the Japan-SOPAC surveys carried out between 1985 and 2005 included biological investigations of megabenthic fauna (large invertebrate animals, greater than 1–2 centimetres) in areas of manganese nodules, sea-floor massive sulphides, and ferromanganese crusts (for example, Fukushima 2007). The sampling stations included a number of seamounts and locations that were classified as ferromanganese crust. These sites were located within the EEZs of Kiribati, Tuvalu, Samoa, the Marshall Islands, and Federated States of Micronesia. The number of sea-floor photographs taken ranged from 590 (covering 0.35 hectare) in Samoa to more than 3 400 off the Marshall Islands (covering 2 hectares).

These surveys recorded a variety of high taxonomic groups, including foraminiferans, sponges, corals, squids, echinoderms (sea stars, sea cucumbers, feather stars), crabs, and sea squirts. These cover the range of invertebrate megafaunal groups (at least to Class level) normally found in deep sea environments. Large foraminiferans (single-celled animals that form large mats) are conspicuous and diverse on crust areas (Mullineaux 1987), especially the large xenophyophores (Fukushima 2007). Faunal abundance was markedly higher in ferromanganese crust areas than on manganese nodules, but less than at vent sites for polymetallic sulphides, although variance of mean estimates is very high (Figure 9). Fukushima (2007) also noted that high densities of suspension feeders, especially feather stars and sea pens, were distributed along the edges of crusts. This is consistent with relatively strong current flows providing such feeders with a good supply of particulate material, although sea pens are normally found on soft sediment rather than rocky substrates.

Seamounts can have highly variable substrate composition (Wright 2001) and accordingly host a wide variety of fauna (Clark *et al*. 2010). Typically, however, the large biogenic-forming corals and sponges dominate the megafauna (Rowden *et al*. 2010). An initial comparison of seamounts off Hawaii revealed no significant difference between the faunal composition of ferromanganese-crust and non-ferromanganese-crust features, with similar numbers and composition of the main groups – sponges, corals, anemones, crabs, sea stars, sea urchins, brittle stars, sea cucumbers, feather stars (Clark *et al*. 2011b). Depth was the main driver of faunal composition. There were, however, differences

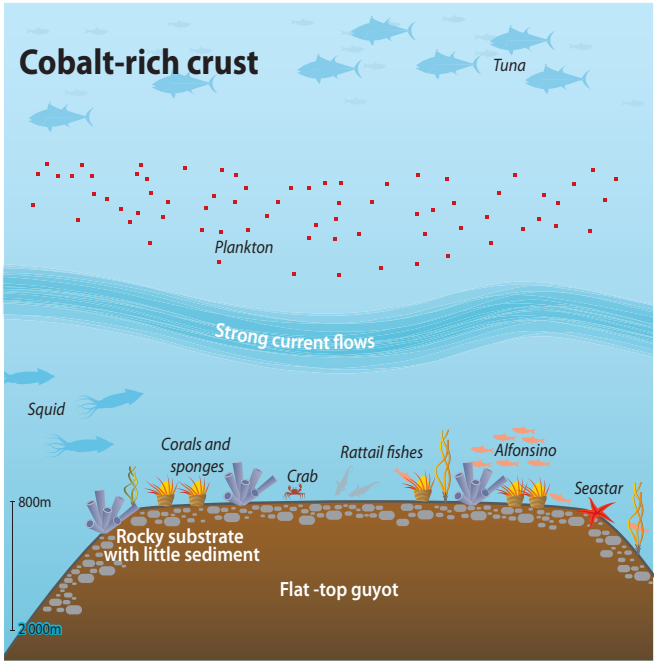


Figure 8. A generalized schematic of biological characteristics associated with ferromanganese crust on a seamount in the Pacific (with reference to Fukushima 2007 and Clark et al. 2011b).

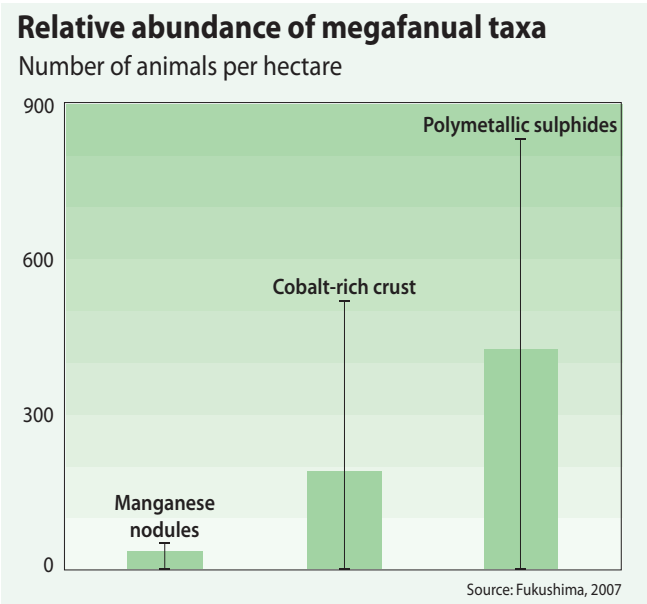
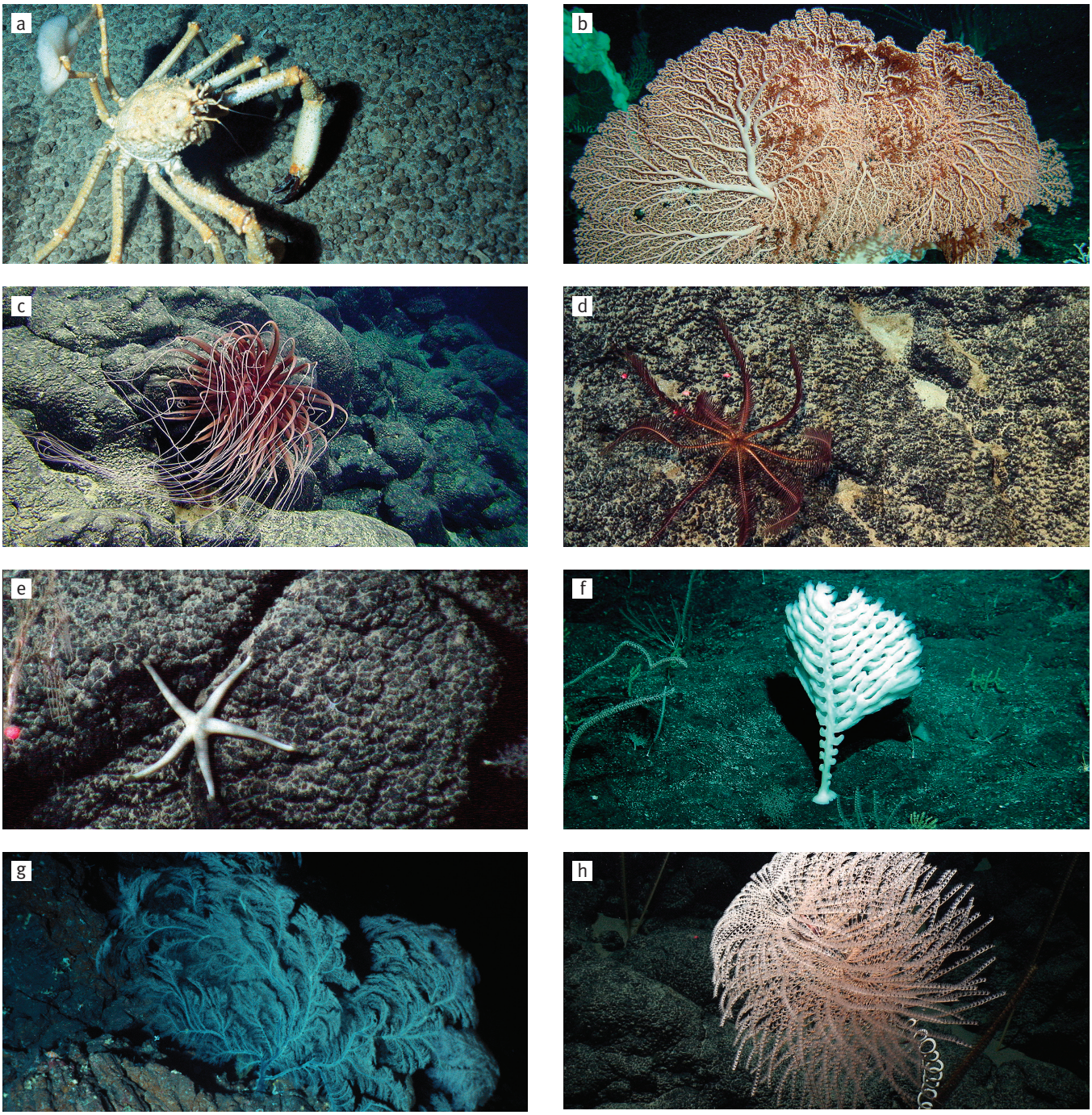


Figure 9. Relative abundance of megafaunal taxa (number of animals per hectare) from the different substrate types sampled during Japan-SOPAC surveys. *Adapted from Fukushima 2007.*

in distribution (and likely abundance) between seamounts, with a number of species being recorded much more frequently on ferromanganese crust. Whether crustal composition has a major effect on the biological communities is unresolved, as seamount comparisons have often been confounded by differences in depth, and substrate type is often not considered. A follow-up study to Clark *et al.* (2011b) included substrate type in the analysis and found indications that the level of sea-floor coverage by ferromanganese crust may, in fact, influence community composition (author's unpublished data). Cross Seamount, south of Hawaii, has relatively thick crust on its flanks, which have been described as "sparse and barren" (Grigg *et al.* 1987). However, isolation from other seamounts or shallow waters can restrict successful recruitment, so the scarcity of biota might not be related to the chemical composition of the crust. Foraminifera have been shown to settle at higher densities on crust than on basalt substrate (Verlaan 1992). More research is required to improve our understanding of the relationship between faunal community structure and crust composition.

A number of abundant taxa found on deep sea seamounts are slow-growing and long-lived. Cold-water corals, in particular, live for hundreds to thousands of years (Roarck *et al.* 2006; Rogers *et al.* 2007). These slow growth rates, together with variable recruitment due to intermittent dispersal between seamount populations (Shank 2010), mean that recovery of vulnerable species (and the assemblages they form) from human impacts, such as fishing or mining, is predicted to be very slow (Probert *et al.* 2007). Studies on seamounts off New Zealand and Australia have shown few signs of recolonization or recovery after 10 years of closure to bottom-trawling operations (Williams *et al.* 2010), and signs of dredging on the Corner Rise seamounts were still clearly visible after a period of up to 30 years (Waller *et al.* 2007).

The pelagic environment associated with seamounts is well known for hosting large aggregations of surface fish, sharks, seabirds, and marine mammals (see chapters in Pitcher *et al.* 2007). Seamounts have been identified as hotspots for large pelagic fish biodiversity (Morato *et al.* 2010a). In the western South Pacific, they are important sites of commercial longline fisheries for skipjack (*Katsuwonis pelamis*), bigeye (*Thunnus obesus*), yellowfin (*Thunnus albacares*), and albacore (*Thunnus alalunga*) tuna (Morato *et al.* 2010b). Alfonsino (*Beryx splendens*), pink maomao (*Caprodon longimanus*), and several species of deepwater snapper (*Etalis spp., Pristipomoides spp.*) are also abundant bentho-pelagic species in areas of the southwestern Pacific and can form dense aggregations over the summits of seamounts (Lehodey *et al.* 1994; Sasaki 1986; Clark *et al.* 2007; McCoy 2010). The biomass of these higher predators appears to be supported by a combination of factors, including localized oceanographic currents that can cause upwelling, eddies, and even closed-circulation cells around seamounts, a continuous flow of plankton to the seamount from a wider oceanic area, and diurnal trapping of zooplankton by the physical barrier of the seamount summit (Clark *et al.* 2010). Many seamounts in the PIC region extend to within 800 to 1 000 metres of the surface, which is within the depth range of the deep scattering layer (DSL). This is a mix of zooplankton (such as shrimps, euphausiids, and copepods) and mesopelagic fish (such as lantern fish and small squid) that migrate vertically upwards at night and down during the day. Where the DSL makes contact with the seamount summit and upper flanks, there is a zone of interaction between pelagic and benthic ecosystems. Much of the animal production driven by phytoplankton in the near-surface waters sinks over time in the form of dead animals and detritus (the flux of particulate organic carbon, or POC). POC raining onto the sea floor plays an important role in supporting biodiversity. Even at abyssal depths, a strong correlation has been observed between levels of surface production and densities of small infaunal worms (Mincks & Smith 2006).



A selection of fauna photographed on cobalt-rich crust sea floor on seamounts off Hawaii. All photos courtesy of Chris Kelley, HURL.(a) an homolid crab, Paramola japonica*, at a depth of 400 m; (b) the precious coral* Corallium laaunse*, recorded at East Laysan Seamount, 1 600 m; (c) a giant sea anemone,* Boloceroides daphneae*; (d) a comatulid feather star, or crinoid; (e) a seastar of the genus* Henricia*, which is common on seamounts over 1 000 m; (f) a Farreid sponge,* Farrea occa*, photographed from the Pisces V submersible on Pioneer Bank at a depth of 1 700 m; (g) the black coral* Myriopathes ulex*; (h) a spectacular Chrysogorgid coral* Iridogorgia bella.

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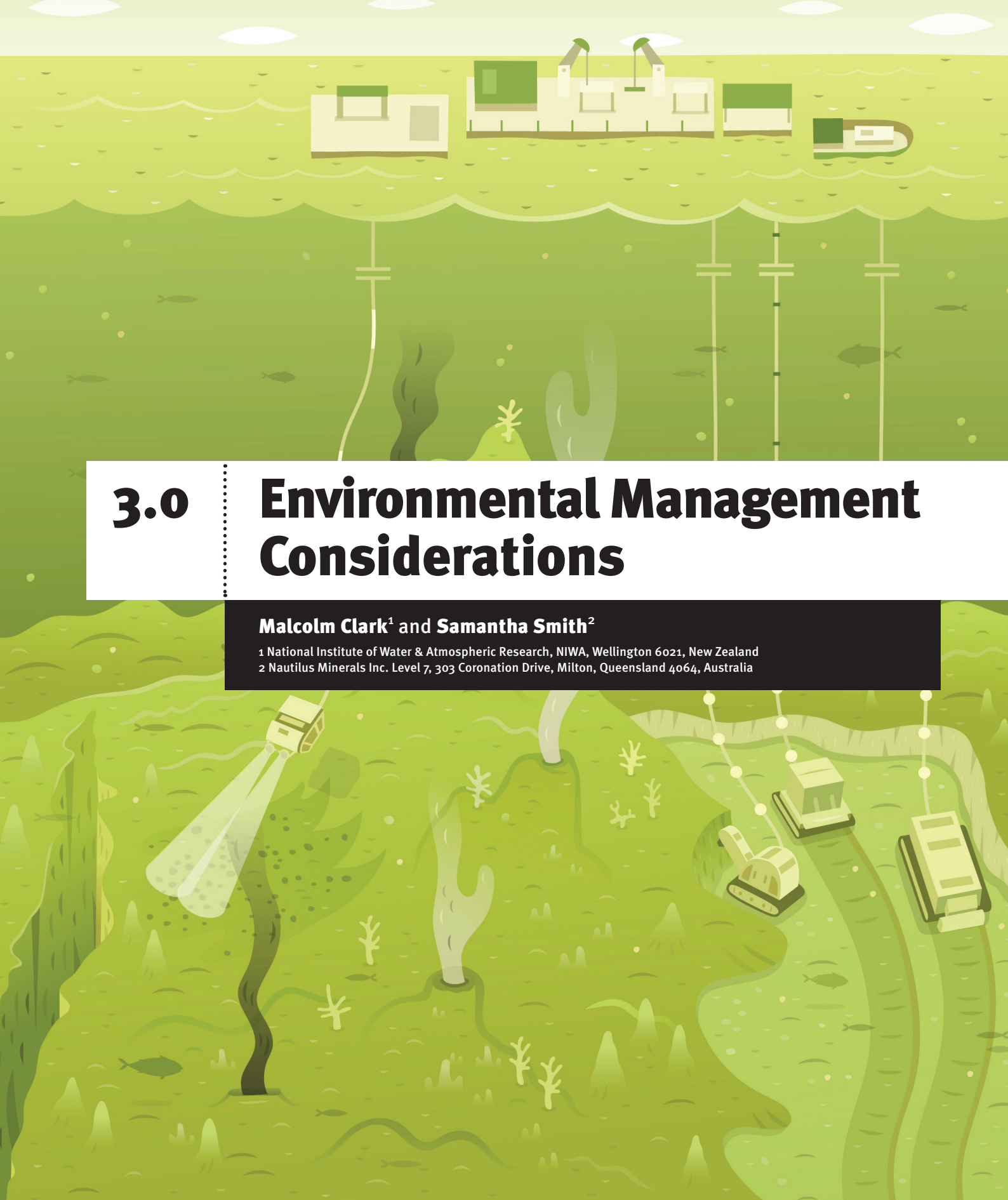

3.0 Environmental Management Considerations

Malcolm Clark[1] and **Samantha Smith**[2]

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.

Cobalt-rich ferromanganese crusts are of potential interest for deep sea mineral extraction. As described earlier in this volume, the crusts typically occur on large seamounts, particularly in guyot (flat-topped) features where summits vary from depths of 800 metres to 2 500 metres. In this section, we describe the likely environmental effects of deep sea ferromanganese-crust extraction activity, with a particular emphasis on the specific characteristics of biological communities associated with seamounts and ferromanganese crusts. 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 clearly defining the environmental objectives that will guide the management of any mining operation. These will vary regionally and nationally, but they are typically directed at two broad goals:

- to maintain overall biodiversity and ecosystem health and function (as mandated by international law); and
- to reduce, mitigate, and, where possible, prevent the impacts of mining and pollution that can affect wider habitats and ecosystems.

A further consideration is the integration of environmental management strategies with other efforts and agreements related to the conservation and sustainable use of the marine environment. This includes national and regional initiatives, as well as global frameworks, such 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.

3.2 General environmental management approaches and principles

Responsible environmental management objectives involve balancing resource use with maintaining deep-ocean ecosystem biodiversity. Management should therefore include consideration of any functional linkages of the ecosystem with the subsurface biosphere, the water column, the atmosphere, and the coasts, as well as the full range of goods and services that the ecosystem provides (Armstrong *et al*. 2010).

Management approaches can focus on a single sector (such as one area or one human activity) or a single species. However, there is increasing recognition of the importance of an ecosystem approach to management (EAM). 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

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. (Figure 10)

Level 1 includes activities, such as exploration or scientific research, that involve drilling to a cumulative depth of up to 2 500 metres. Level 2 includes such activities as drilling to a cumulative depth of more than 2 500 metres. 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 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 responsibilities are separate, falling to the Mineral Resources Authority (MRA).

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.

Key elements involved in obtaining an environment permit in PNG are potentially 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 the 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.

maintaining the biological richness and ecological processes necessary to sustain the composition, structure and function of the habitats or ecosystems concerned." 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 and guiding principle in the exploitation of any resource – and the deep sea is no exception – is the precautionary approach. One of the primary foundations of the precautionary approach, and globally accepted defi-

The 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 in 2011 developed a 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 and approval of an environment permit application, an environment permit is awarded if successful. A common condition of the permit is for an environmental management plan (including monitoring plans) to be approved prior to the commencement of operations.

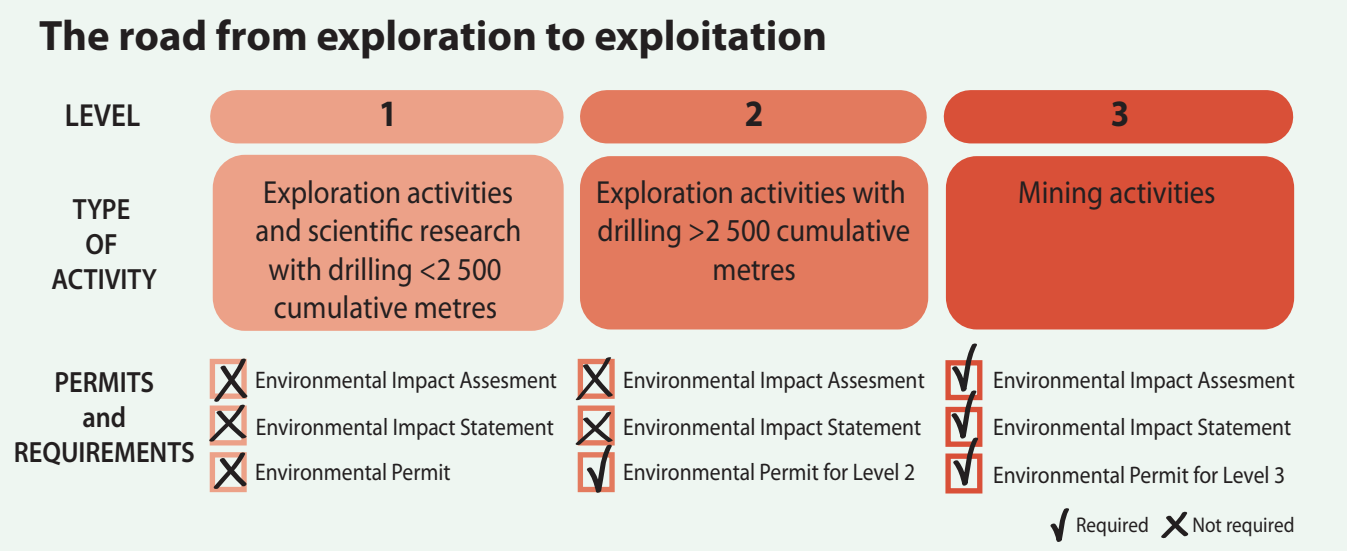

Figure 10. Environmental impact assessment and environmental permitting process considerations – an example from Papua New Guinea.

nitions, 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/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 that of adaptive management, which attempts to reduce uncertainties over time in a structured process of "learning by doing" (Walters and 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 managers having the flexibility to make rapid management decisions to ensure that conservation objectives are being met.

Marine spatial planning (MSP) is a management tool used increasingly by countries to manage multiple uses of their territorial seas. MSP maps what activities can be undertaken where, manages conflicts among competing marine activities, and reduces environmental impact by analysing 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 minerals exploitation in the deep sea, including:

- International Seabed Authority: Polymetallic sulphides and cobalt-rich ferromanganese crusts deposits: establishment of environmental baselines and an associated monitoring programme during exploration (ISA 2007).
- Pacific ACP States Regional Legislative and Regulatory Framework for Deep Sea Minerals Exploration and Exploitation (SPC 2012).
- Madang Guidelines of the South Pacific Applied Geoscience Commission (SOPAC 1999).
- International Marine Minerals Society: 2011 Code for environmental management of marine mining (http://www.immsoc.org/IMMS_downloads/2011_SEPT_16_IMMS_Code.pdf).

3.3 Environmental studies

Part of the EIA process involves carrying out environmental studies to define the existing environment or baseline conditions 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 11.

If the proposed project is close to shore, other considerations may include nearshore studies, such as coral reef studies, etc. 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 seabed mineral activities. Ideally, they will include an evaluation of natural variability in the structure and function of communities to ensure that changes caused by mining can be separated from natural fluctuations in species distribution and densities. 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 press).

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' partnership 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 11. List of potential 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 biodiversity of cobalt-rich ferromanganese crusts

The faunal communities associated with ferromanganese crusts have been described in detail in the preceding section on habitats and ecosystems. There are some key characteristics that need to be considered specifically for this environment when assessing potential impacts:

- The dominant benthic fauna on seamounts are often sessile corals and sponges. These may include species with a wide distribution as well as those that are endemic or only occur in a small region. Their slow growth rates and high longevity make recovery from disturbance either unlikely or very long-term.
- It is uncertain whether seamounts with ferromanganese crusts have different fauna from non-ferromanganese-crust features. This uncertainty needs to be addressed. If there is no difference, then mining sites and protected sites should be relatively easy to select. If there are distinct communities specific to seamounts with ferromanganese crusts, then conservation strategies will need more detailed evaluation.
- Faunal composition changes with water depth, and seamounts have a large depth range. As the species composition and abundance change, so too do the vulnerability/resilience of benthic communities. Therefore, the depth of an extractive activity must be considered when developing management plans or designing for conservation.
- Knowledge of the biodiversity associated with ferromanganese crusts is poor, and considerable basic data need to be collected during the exploration phase of any mineral development.

3.5 Environmental impacts

Like 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, 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 covered 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 section 5 on mining ferromanganese crusts, there are four key components to deep sea-floor 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.

While mineral processing (concentrating) is part of the minerals life cycle, it is not specific to deep sea minerals. Here we focus only on issues related to deep sea mineral-extraction processes. 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, 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 (Figure 12).

Sea floor

Like any mining project (and many development projects), disaggregating the minerals on the sea floor will result in the physical removal of habitat and animals. Mobile swimming animals might be able to move aside, as could some crawling invertebrates (such as crabs, seastars, or sea cucumbers), but most sessile benthic fauna in the path of the mining operation will be affected, although impacts will differ from site to site. The types of vehicles and systems described in Chapter 5 will all involve digging or scraping the top section of the sea-floor substrate and will inevitably affect surface and near-surface animals.

In general, seamount environments with ferromanganese crust can host a high proportion of emergent sessile upright epifauna that extend above the sea floor. This group includes such animals as corals, sponges, anemones, and crinoids (Fukushima 2007; Clark *et al*. 2010, 2011). These long-lived epifaunal animals perform a structural role within benthic communities, providing a microhabitat for other species (Nalesso *et al*. 1995). In the southwest Pacific, colonies of cold-water coral species such as *Solenosmilia variabilis* and *Goniocorella dumosa* provide niches for many other animals, including fishes, other scleractinians, stylasterids, bryozoans, stoloniferans, sponges, polychaetes, ophiuroids, asteroids, bivalves, gastropods, crabs, and anemones (Freiwald *et al*. 2004). Rogers (1999) recorded over 850 species found in association with beds of the northern hemisphere equivalent, *Lophelia pertusa*. Removal of such benthic animals from areas where they form the dominant communities will potentially cause a reduction in habitat complexity and associated benthic invertebrate biodiversity. Physical disturbance of these communities can cause a shift in dominant species from large sessile types to small, fast-growing, opportunistic, colonizing species, scavengers, and juveniles (Clark and Rowden 2009; Althaus *et al*. 2009).

Recovery of disturbed habitat and benthic communities could take a long time. Sessile invertebrates removed during experiments to mimic nodule mining at abyssal depths – although deeper than where crust mining might occur – showed no recovery after seven years (Kaneko *et al*. 1997; Bluhm 2001). Williams *et al*. (2010) analysed the effects of bottom-trawl fishing on seamounts at depths of 700 to 1 200 metres off New Zealand and Australia and found little sign of recovery of seamount benthos ten years after the cessation of fishing.

Disturbance of the sea floor will increase the mixing of sediments and overlying water. There could be changes in the chemical makeup of the seawater adjacent to the sea floor (Rumohr 1998), and chemical release from the sediment can be enhanced by disturbance (ICES 1992). There have been few stud-

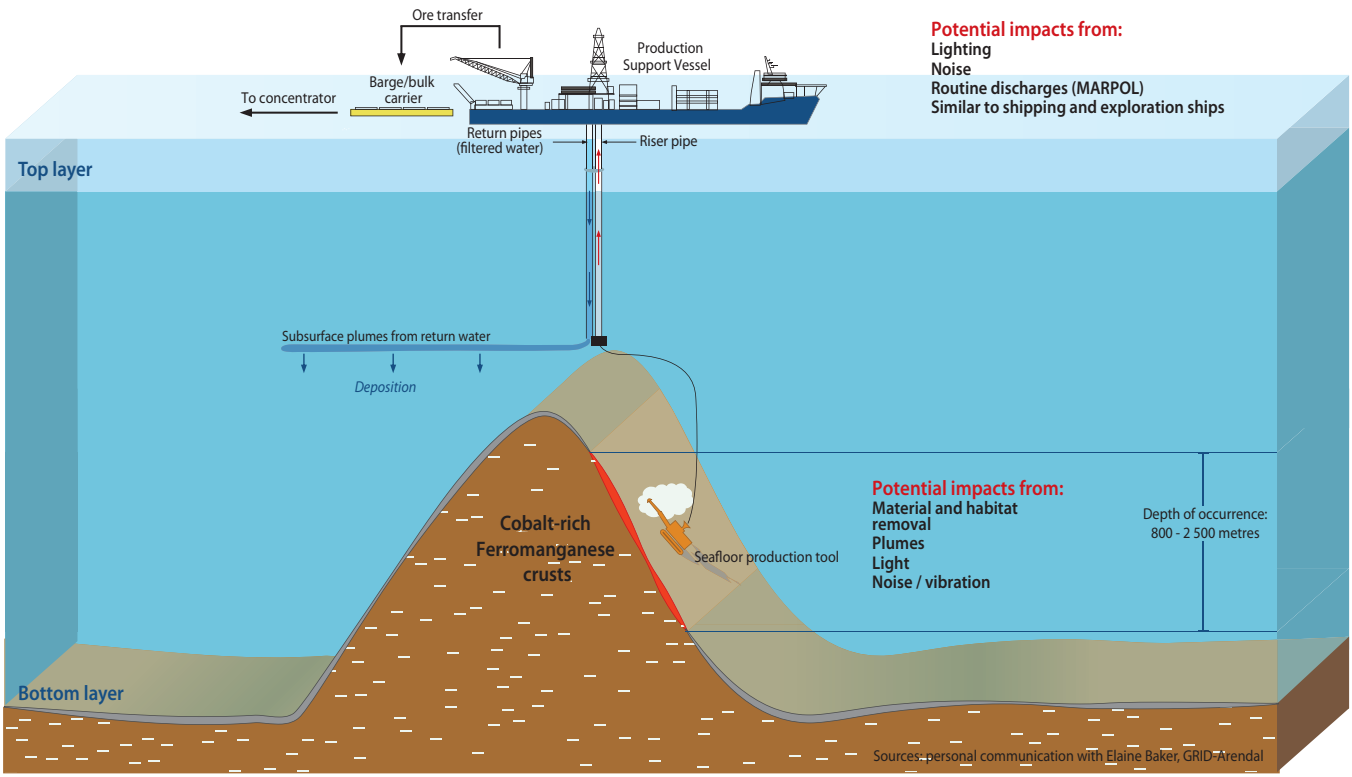

Figure 12. Sea-floor ferromanganese crust mining system and related sources of potential environmental impact.

ies on eco-toxicity related to deep sea mining activity. Potential chemical changes are difficult to predict and may act in different ways (Zhou 2007).

Gear that digs into the sediment can have an impact through direct crushing of buried infauna, compacting the substrate through increased weight of machinery or equipment, or, conversely, by stirring up the sediment, dislodging animals, and later leaving a suspended sediment cloud that slowly settles. Ferromanganese crust forms on surfaces that are largely free of sediment (Hein 2002), but most seamount substrate is heterogeneous, with a patchy distribution of soft and hard substrate (Wright 2001). Yamazaki *et al.* (1993, 1996) found that crusts can frequently be buried under centimetres of calcareous sediment that would be removed during mining. With a large-scale mining operation, sediment is likely to be disturbed. In addition, down-slope flows of sediment-laden water may occur (Beckmann 2007). Even if there is little soft substrate, the physical scooping or grinding action of mining vehicles will likely cause some re-suspension of sediments. The effects are likely to be site-specific and will depend on the type of technology used. They will also depend strongly on the nature of the fauna, the sea-floor material, and oceanographic conditions in the area. However, filter-feeding animals, such as corals, sponges, and mussels, depend upon clean current flow containing the small animals and particles that are their food. The feeding efficiency of such filter feeders could also be affected through clogging of the small pores. The settlement success of some corals appears sensitive to small amounts of sediment, which can smother the juveniles (Rogers 1999).

The operation of sea-floor production tools will increase levels of introduced noise, vibration, and light. Noise and vibration together can affect the auditory senses and systems of some animals. There can be direct damage to other animals, discomfort that might cause avoidance reactions, or an increase in background noise that can interfere with communication between animals or limit their ability to detect prey (Popper *et al.* 2003). Light can repel or attract some animals. For example, many fish display attraction or avoidance responses to light, varying by species. Bright lights can blind some species, and this has been a concern with research operations around hydrothermal vents (InterRidge 2006). These types of indirect effects are not well understood and will need monitoring from the outset. Animals that can be affected include benthic invertebrates, fishes, and deep-diving marine mammals.

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 and 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 may need to be considered if the ore delivery system is not fully enclosed.

The presence of the lifting system and transitting equipment could cause physical damage to individual fish and free-swimming invertebrates from accidental direct contact. However, given the wide geographical distribution of most mesopelagic animals, any localized mortality is likely to have only a very minor impact on populations or stocks. Additional consideration of this issue may be warranted if the proposed development site is within an area of animal aggregation for spawning or feeding, or is a nursery ground for juvenile life history stages. This could be particularly important in the southwest Pacific, where tuna fish stocks, especially skipjack, appear to have a more localized distribution than other species. Little is known about the distribution of juvenile tuna.

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 associated barges/platforms. 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 of the sea, somewhere within the water column, or back near the sea floor. The feasibility of various alternatives, especially return to near the bottom, may depend on the total depth of water that is being operated in, among other factors. Discharge water will probably contain some fine material. This discharge water will likely have elevated metal concentrations compared to ambient seawater, given that it has spent time in contact with the metal-rich ore. It may also have different physical properties (e.g., temperature, salinity) from the body of water to which it is returned. Hydrodynamic modelling will be required to estimate the fate and appropriate depth of the discharge and to inform discharge equipment design. The extent of impact will be an important consideration, since plumes can reach 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, but will need to be considered. 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. A specific issue to evaluate in the western Pacific is whether tunas are attracted to moored vessels or platforms. Bigeye tuna have increased densities associated with fish-aggregation devices (surface or subsurface structures), and commercial fisheries occur in these areas. Air pollution and routine discharge are also associated with these vessels.

If the dewatering-plant discharge water is released within the upper 200 metres 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 may 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 discharge makes it important to monitor surface changes. It will be up to individual jurisdictions to determine whether or not 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 and operation. Direct physical impacts are potentially extensive. Estimates of the size of a commercial mining operation vary between several hundred and several thousand square kilometres, depending on the region and assumptions made about crust thickness and extent (Zhou 2007; Sharma 2007; Hein *et al*. 2009; He *et al*. 2011). The proportion of area affected will differ between conical seamounts (where it will be high, even though the surface area of mining may be small) and guyot-ridge features (where a much larger area can be mined, but the overall proportion of the feature may be smaller). Whether or not a site is mined will depend on several factors, including crust ore grade, crust thickness and continuity, topography/bathymetry, and environmental conditions. Not all ferromanganese crust resources will be commercially viable, and currently there is no feasible technology for extracting crusts from the sides of seamounts.

If a sediment plume is created through dispersal by currents, it could have a larger footprint than the physical mining area. There is also the possibility of plumes extending upwards into the water column, although it should be noted that engineering design minimizes plumes. Similarly, the area affected by discharge of the wastewater and fine materials could be more extensive than the mined area. There have been few direct measurements of actual plume generation, but Yamazaki *et al*. (2001) documented the distribution of resedimentation, which extended at least several hundred metres from the centre of a scraping operation on a seamount. Sediment and water column plumes will disperse with distance, and this dilution will mean there is a gradient of impact, with effects lessening with distance from the mining site.

The likelihood that, even on a cobalt-rich-crust seamount, resedimentation might extend over a considerable area adjacent to the physical operation means care is needed when defining conservation sites. Such areas will need to be far enough away from mining sites to avoid any potential "downstream" effect.

Accidental events and natural hazards

In addition to what is covered above, it is important to consider accidents and natural hazards. These include such events as a ship breaking up and sinking in bad weather, a collision between vessels, spills and oil leaks from the vessel/platform entering the sea, and leaks from the riser pipe, sea floor to vessel lifting system or sea-floor equipment (e.g., hydraulic oil leaks). Commercial operators and national management agencies must minimize the risk of such events. At the same time, they must be prepared to respond if such events do happen. These precautions are generally covered under national or international regulations and are not detailed here.

3.7 Mitigation and management measures

Mitigation and management measures will have to be developed in consultation with a broad range of stakeholders, including persons who consider 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 might be classed as negligible, low, moderate, or high. Once these have been defined, they can inform a cost-benefit analysis to predict mining feasibility. There are a number of ways to prevent, mitigate, and minimize impacts, and several can be considered in the context of ferromanganese crust 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 (within reasonable financial constraints). This may include such aspects as 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 reduce impacts on water quality. The plans should address, among other things, deck drainage, non-dewatering process water, wastewater discharges, waste management, and ballast water. A working example of a management plan is that recently developed by the International Seabed Authority (ISA 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;
- an approved sewage treatment plant certified to meet relevant international standards and/or other relevant regulations to handle normal ship discharges, such as treated 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 the mine site/mine lease areas. If there are no suitable control site areas within the immediate area, then consider if there is a similar site nearby. 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). Bearing in mind that a proponent has only mining rights within the area for which the licence was granted, it might be up to the relevant governing authority to decide whether or not to set aside an area outside the mining lease. 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 partially be mined, or areas set aside for conservation.
- evaluating other generic measures, if feasible, including installation of artificial substrates to encourage more rapid colonization by fauna impacted by mining, and animal relocation if there are populations of rare, endemic, or highly endangered species.
- 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 the benthic fauna if discharges spread over a wider area than the mining sediment plume. In very deep water, discharging near the seafloor 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.
- employing reserve networks, such as marine protected areas (MPAs). 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 national level and sometimes at a much larger spatial scale than a single mining operation. Inter-gov-

ernmental 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 13).

Note the likelihood that, even on a cobalt-rich ferromanganese -crust seamount, resedimentation may extend over an appreciable area adjacent to the physical operation. This means that care is required when defining conservation sites. They will need to be far enough away to avoid any potential "downstream" effect.

Temporal: The time scales of ferromanganese crust growth and faunal recovery in the abyssal deep sea almost certainly make consideration of temporal 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 13. Key element of marine reserve design (ISA 2008).

Key messages for environmental management

Scientific knowledge is limited in deep sea ferromanganese crust environments in the western Pacific, but sufficient information exists from global seamount research – especially in the Pacific around New Zealand, Australia, and Hawaii – to guide initial environmental management decisions.

Seamount ecosystems are highly variable, but they can be hotspots of biodiversity and localized species abundance. Ferromanganese crust habitats can host high densities of sessile biogenic fauna that are vulnerable to physical disturbance. Some species may have a wide geographical and depth distribution, but this needs to be balanced against biological characteristics (such as physical structure, slow growth, specific colonization factors) that can make such communities highly sensitive to impacts and slow to recover.

Successful management of deep sea mining is reliant on a cooperative and integrated approach among all stakeholders. The southwest Pacific has a well-developed fisheries management regime in place for tuna fisheries. Hence, it is important to ensure that environmental management options for mining are compatible and consistent with those for fisheries.

Baseline studies of animal composition, distribution, and abundance are necessary before exploitation begins, and they must be followed by a regular monitoring program.

Multidisciplinary science will be required, involving collaboration among industry, academia, relevant communities or interest groups, and government agencies.

Ferromanganese-crust mining on deep seamounts will have impacts on both species and habitats. Impacts should be mitigated by effective management strategies that reflect the ecosystem approach and the precautionary principle.

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.

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

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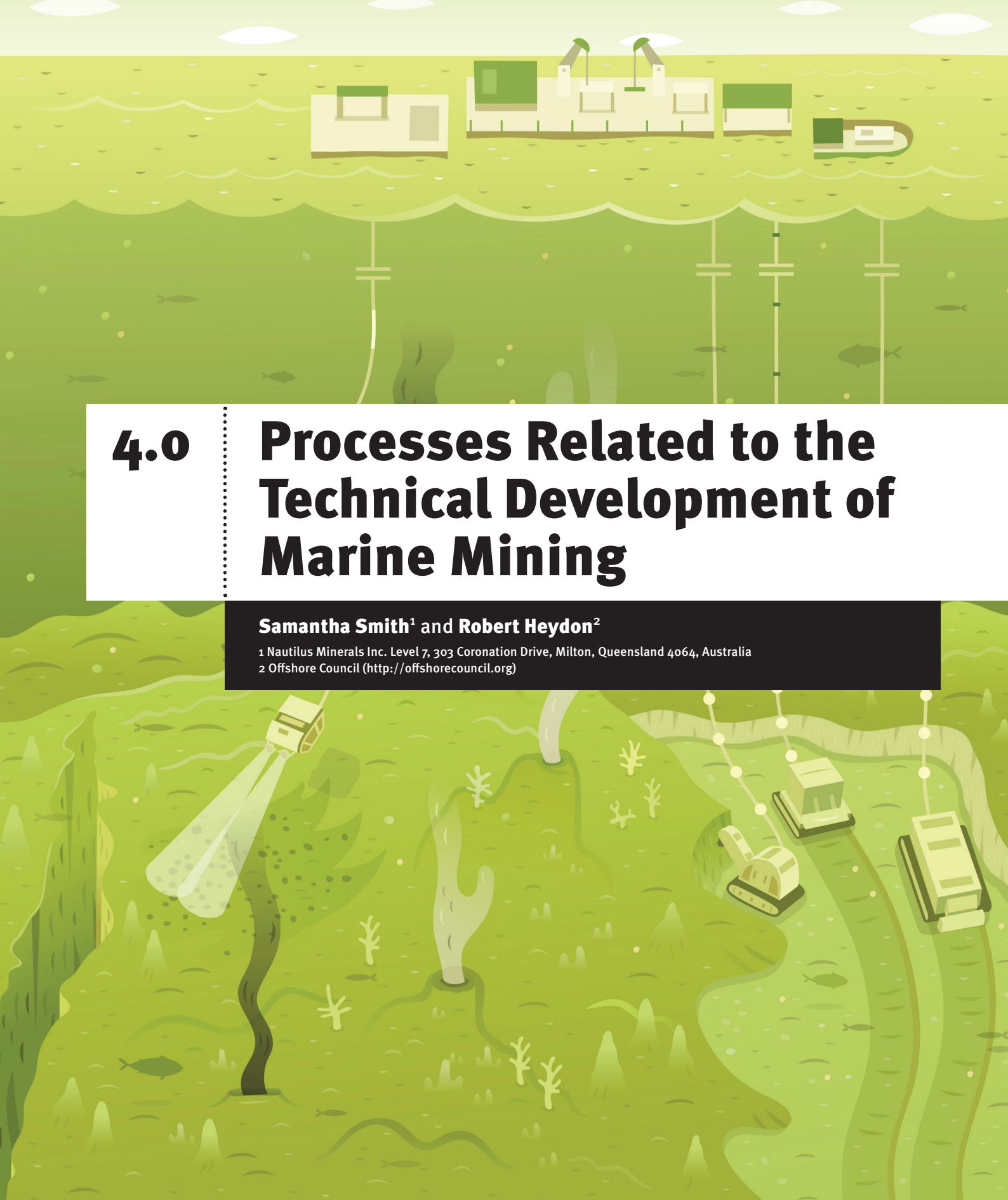

4.0 Processes Related to the Technical Development of Marine Mining

Samantha Smith[1] and **Robert Heydon**[2]

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. 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. However, the extraction of ferromanganese crusts may be more difficult than the sea-floor massive sulphides or manganese nodules discussed in Volumes 1A and 1B of this series. Crusts are formed on the steep sides of seamounts, making the terrain potentially difficult for remotely operated vehicles. In addition, separating the thin mineralized deposit from the underlying rock without producing large amount of waste rock may be a challenge.

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 and drilling devices (Figure 14).

Exploration for ferromanganese crusts typically involves the following steps:

- bathymetric mapping of seamounts using acoustic surveying (for example, wide-swath multibeam echo sounder systems) and analysis of bathymetric data (Figure 15);
- determining distribution of hard-rock outcrops and sediment-covered areas of seamounts using back-scatter images from side-scan sonar systems. These images can be ground-truthed using camera/video tows. Small-scale features can be imaged using an autonomous underwater vehicle (AUV) equipped with bathymetry, side-scan, and photo/video capabilities;
- ferromanganese crust sampling to determine metal grade and crust thickness. Once sampling sites are identified, dredge hauls, TV grab samplers, and core samplers can obtain samples using winches on the ship. More detailed and precise sampling can be carried out using a remotely operated vehicle (ROV);

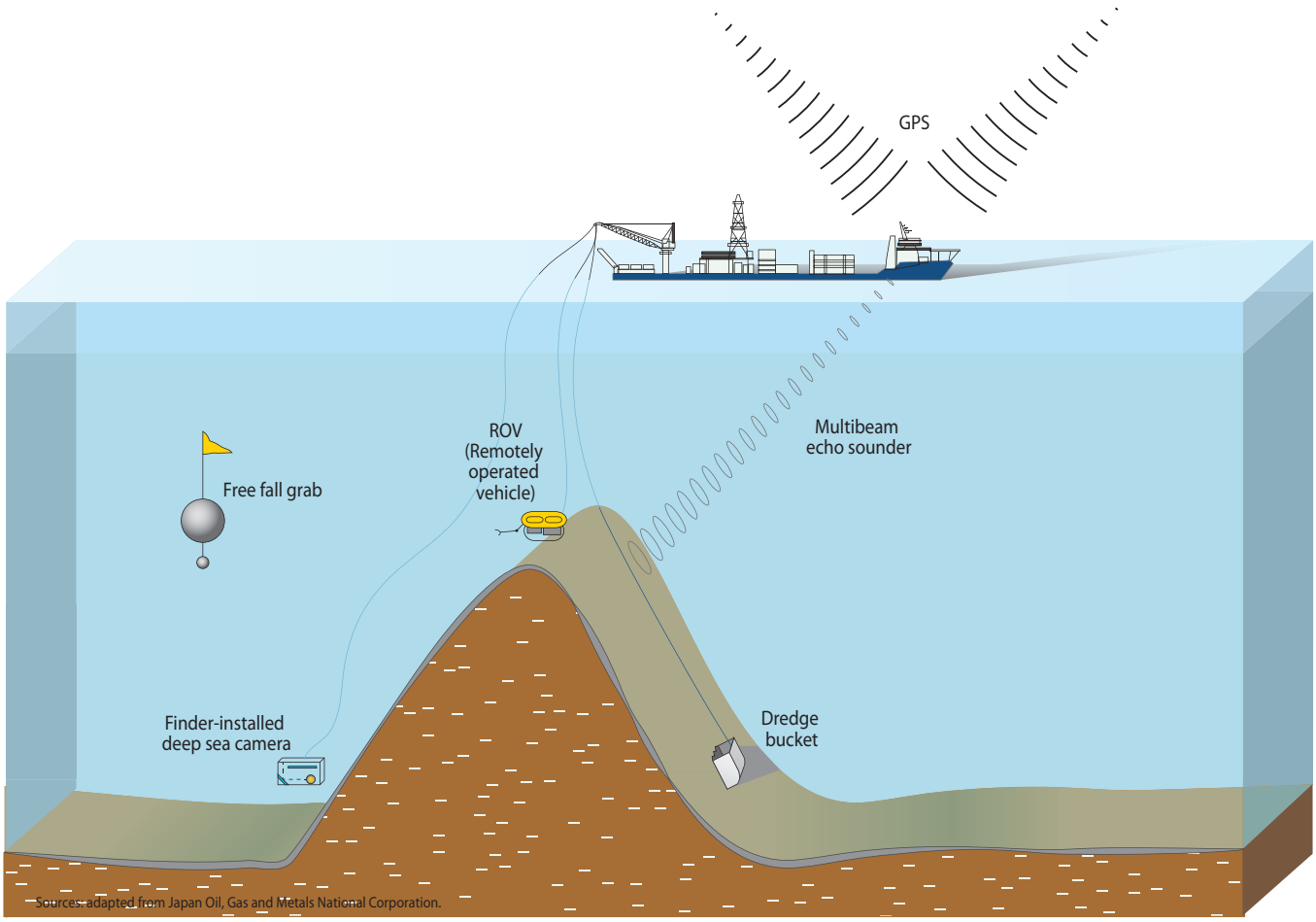

Figure 14. Examples of exploration tools.

- metal grade analysis can be estimated on board the exploration vessel and later verified at land-based laboratories;
- carrying out geotechnical studies to assess the physical, chemical, and mechanical properties of the crusts and their environment will feed into both the environmental baseline studies as well as the engineering design studies for mining technology development, in particular the design of a cutter head capable of recovering the crust without acquiring any of the substrate rock;
- calculating the size and grade of the resource;
- carrying out environmental baseline studies; and
- measuring in situ the detailed distribution of crust thicknesses. While this technology is not yet developed, it may involve either a multi-spectral seismic instrument or a gamma-radiation detector.

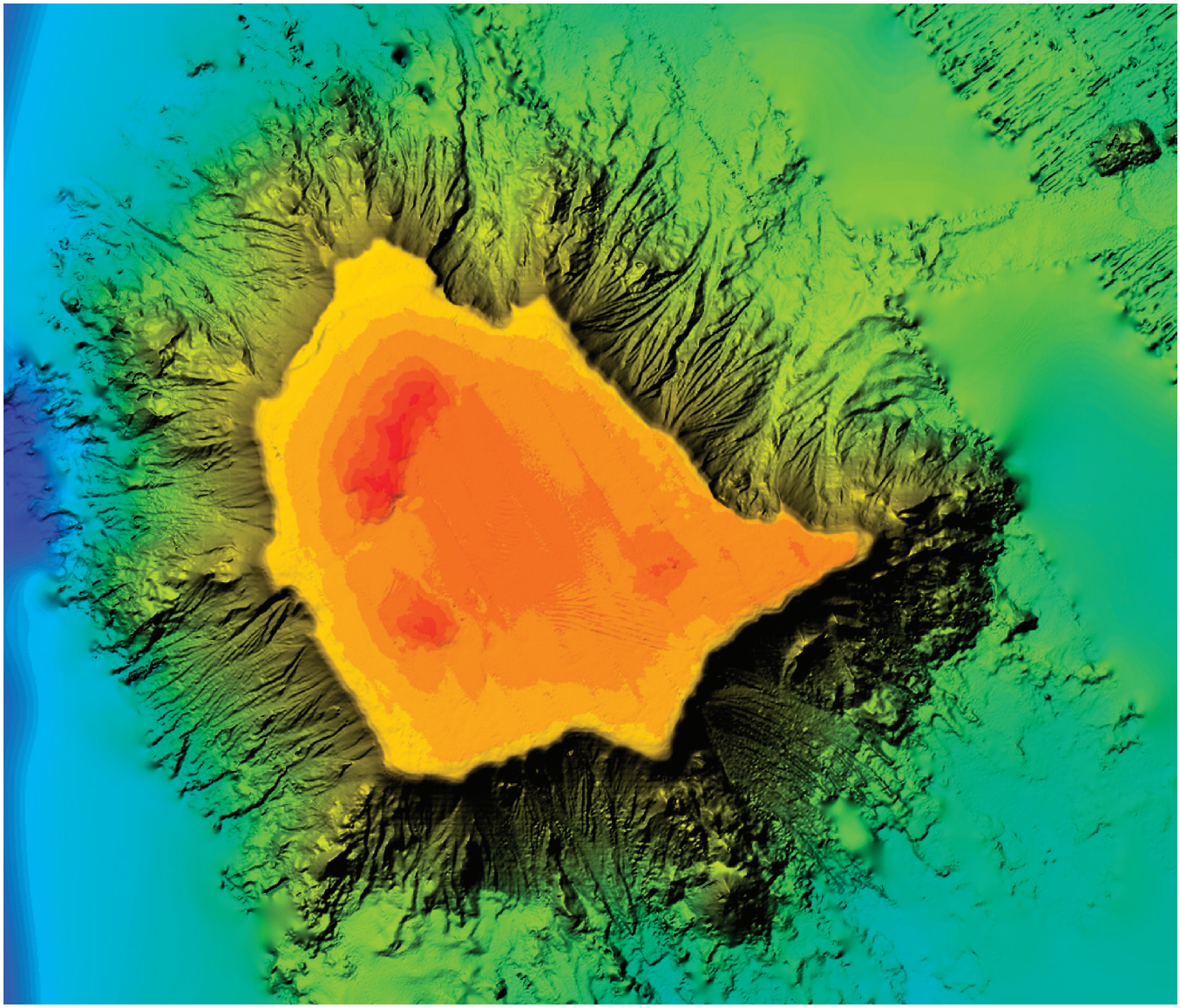

Figure 15. Gifford Guyot, Tasman Sea, southwest Pacific Ocean. *This multibeam sonar image was collected in 2007 aboard the RV Tangaroa during a Geoscience Australia marine survey. The flat top of the guyot is about 250 m deep.*

4.2 Mining

It is envisaged that deep sea mineral extraction will involve the following basic processes:

- extraction of minerals from the sea floor using remotely operated sea-floor production equipment;
- transport of a slurry of ore and seawater vertically from the sea floor to a vessel or platform on the sea surface;
- if substrate rock is collected, separation of ore and gangue using froth flotation onboard ship;
- 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 (either land-based or an offshore silo vessel) and disposal of the separated waste rock and seawater; and
- transport of the ore to land for treatment and/or processing.

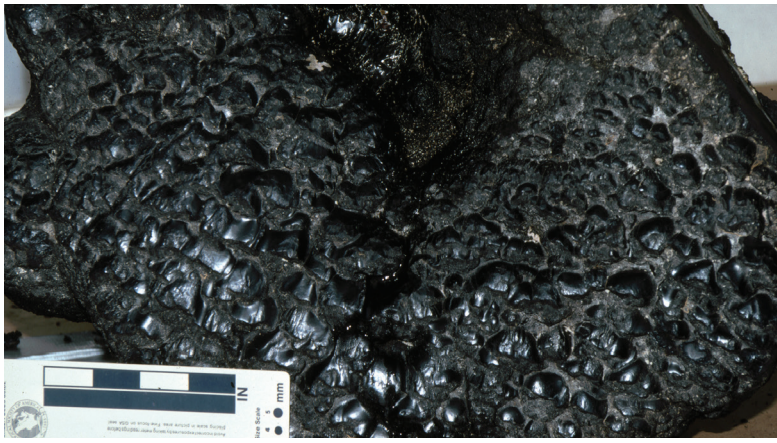

Photo courtesy James R. Hein, USGS

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, where its purpose is to supply a large deck space and a stable platform from which the mining operations are controlled and undertaken. The PSV and its supporting vessels support all mining, recovery, dewatering, and offshore loading activities.

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 using 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. In calm seas, being on board a vessel equipped with dynamic positioning feels very much like being on land; it is very stable.

The vessel will also need to reposition the various sea-floor mining machines and to optimise the motions of barges and/or bulk carriers moored alongside. 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 Sea-floor production tools/collectors

Technologically, the mining of ferromanganese crusts is much more complex than the mining of manganese nodules and sea-floor massive sulphides (see volumes 1A and 1B in this series). The variable thickness of the crusts and the steep, rugged environment pose significant challenges to the design and operation of remotely operated collection tools. Most of the engineering data related to crust mining in China, Russia, and Japan are proprietary and, therefore, the extent to which the relevant technology currently exists is not publically known.

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 centred around 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 seafloor 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.

Much of the RALS and its components will be taken directly from the offshore oil and gas industry where these items are field-proven in similar applications.

Photo courtesy James R. Hein, USGS

4.2.4 Dewatering plant

The dewatering plant, situated on the PSV, will dewater the mine slurry to below the transportable moisture limit for the ore, while minimizing material losses. Excess seawater, once separated from the ore, will likely be discharged back to sea. The location of the discharge (i.e., near the sea floor or within the midwater column) will likely depend on the total depth of water being operated in, among other (including environmental) factors.

4.2.5 Onshore logistics / ore handling

Ore may either be transported directly from the PSV to market or, alternatively, taken to a port close 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. Current indications appear to be that the ports of small Pacific Island states are unlikely to be used for this purpose. Ore transportation, handling, offloading, and stockpiling are well-established and well-understood operations. If ore handling is undertaken at port, the onshore storage and load-out facilities at the port will receive ore from the offshore site via transportation barges and stockpile for subsequent load-out onto bulk carriers for transportation to a concentrator site or direct delivery to smelters.

Glossary

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

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

Abyssal zone – the deep sea (2 000 metres or more) where there is no light. It is the single largest environment on Earth, and it covers over 85 per cent of all ocean basins.

Algae – the simplest plants; may be single-cell (such as diatoms) or quite large (such as seaweeds). The vast majority of these plants rely on photosynthesis for food and are, therefore, restricted to the upper parts of the water column where there is sunlight.

Absorbed – the filling of pores in a solid.

Adsorbed – the binding of molecules or particles to a surface.

Ambient – describes the surrounding environment.

Assemblage – a neutral substitute for "community" but implying no necessary interrelationships among species; also called species assemblage. Refers to all the various species that exist in a particular habitat.

Bathymetry – the study of the variations in water depth: e.g., sea-floor elevations; the topography of the sea floor.

Benthic zone – refers to the ecological region that is associated with the sea floor. Organisms living in this zone are called benthos.

Benthos – the collection of organisms of or pertaining to the immediate vicinity of the sea floor.

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.

Bioregionalization – a process to classify marine areas from a range of data on environmental attributes. The process results in a set of bioregions, each reflecting a unifying set of major environmental influences that shape the occurrence of biota and their interaction with the physical environment.

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

Community – an assemblage of populations of different species, interacting with one another and sharing an environment.

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

Detrital – loose fragments or grains that have been worn away from rock.

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 – a place-based management approach in which the associated human population and economic/social systems are seen as integral parts of the ecosystem. Most importantly, ecosystem-based management is concerned with the processes of change within living systems and sustaining the services that healthy ecosystems produce. Ecosystem-based management is therefore designed and executed as an adaptive, learning-based process that applies the principles of the scientific method to the processes of management.

Endemic species – those species that are found exclusively in a particular area and/or environment type. As such they are of conservation concern because they are not widespread and may be confined to only one or two protected areas.

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

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

Gangue – non-economic minerals that are mixed with the wanted minerals in an ore deposit. Separating the minerals from the gangue is known as mineral processing.

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 to describe or represent in some way the motion of a fluid, especially water and/or water containing particulate matter.

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

Infauna – animals that live within sediments of the ocean floor.

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

Island arc – a chain of volcanoes forming an arc-shape, parallel to the boundary of two converging tectonic plates. Magma produced at depth below the overriding plate rises to the surface to form volcanic islands.

Macrofauna – organisms retained on a 0.3 mm to 0.5 mm 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). It allows planners to consider the cumulative effect of maritime activities and to minimize conflict between multiple uses of the same area. Marine protected areas and fisheries reserves are examples of marine spatial planning components.

Meiofauna – animals passing through a 0.3 mm sieve and retained on 0.032 to 0.063 mm sieves (depending on the taxon studied).

Megabenthic community – a community comprising megafauna, which are large (+45 kg) benthic organisms.

Megafauna – animals larger than 45 kg in weight.

Microalgae – phytoplankton; small plants visible under a microscope, such as diatoms.

Microfauna – small, microscopic animals (less 0.063 mm), such as protozoa, nematodes, small arthropods, etc. Microfauna exist in every habitat on Earth.

Mineral reserves – part of the mineral resource that is valuable and which is technically, economically, and legally feasible to extract.

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

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).

Precautionary principle – a globally accepted definition resulting from the work of the Rio Conference, or "Earth Summit" in 1992. Principle #15 of the Rio Declaration notes: "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."

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.

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

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

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.

Taxonomic group – animal or plant group having shared characteristics. Each group is given a rank, and groups of a given rank can be aggregated to form a super group of higher rank and thus create a hierarchical classification. The groups created through this process are referred to as taxa (singular: taxon).

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. There are two major types of zooplankton: those that spend their entire lives as part of the plankton (called Holoplankton) and those that only spend a larval or reproductive stage as part of the plankton (called Meroplankton).