DEEP SEA MINERALS

1A | Sea-Floor Massive Sulphides
A physical, biological, environmental, and technical review

Edited by Elaine Baker and Yannick Beaudoin

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CONTENTS

Introduction

Hydrothermal vents were first discovered at the Galapagos Rift in 1977 (Corliss *et al* 1979). Observations made in 1979 from the manned submersible Alvin on the East Pacific Rise revealed vents where superheated water was emerging from the sea floor at temperatures exceeding 350ºC. These vents were actively forming massive sulphide deposits rich in metals. The resultant, chimney-shaped black smokers – so called because they emit smoke-like plumes of dark particles – hosted a vent-adapted biological ecosystem made up of a complex community of large clams, tubeworms, and other previously undiscovered creatures that rely on chemosynthetic bacteria for their survival. The history of early sea-floor hydrothermal-system research can be found in Lowell *et al* (1995).

On land, massive sulphide deposits created through volcanic action are major sources of copper, lead, and zinc. Many of the known deposits also contain significant amounts of gold and silver. The recognition that these deposits originally formed in the ocean helped promote exploration to discover marine sea-floor massive sulphide (SMS) deposits.

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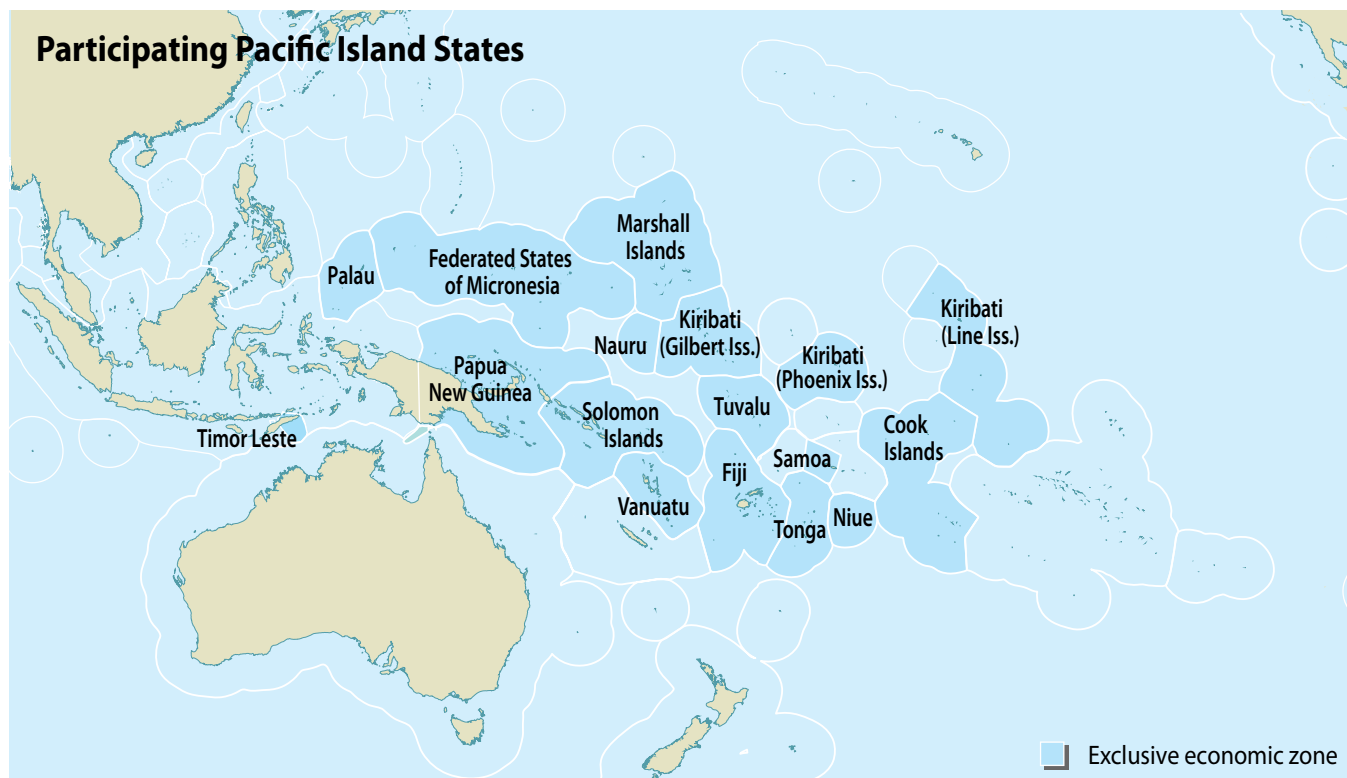
Figure 1. The Pacific ACP States (i.e., Africa-Caribbean-Pacific Group of States) participating in the European-Union-funded SPC Deep Sea Minerals Project.

The existence of known high-grade SMS deposits in the Pacific, and the progress towards extraction of metals from a Manus Basin site (Papua New Guinea), have increased interest around the region in the commercial development of SMS. To support Pacific Islands in governing and developing these natural resources, 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 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 on the geology and biology of SMS deposits and information about best practices related to environmental management and technical aspects of mineral exploration and extraction.

1.0 The Geology of Sea-Floor Massive Sulphides

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1.1 The formation and occurrence of sea-floor massive sulphides

Sea-floor massive sulphides (SMS) are deposits of metal-bearing minerals that form on and below the seabed as a consequence of the interaction of seawater with a heat source (magma) in the sub-sea-floor region (Hannington *et al* 2005). During this process, cold seawater penetrates through cracks in the sea floor, reaching depths of several kilometres below the sea-floor surface, and is heated to temperatures above 400°C. The heated seawater leaches out metals from the surrounding rock. The chemical reactions that take place in this process result in a fluid that is hot, slightly acidic, reduced, and enriched in dissolved metals and sulphur.

Due to the lower density of this evolved seawater, it rises rapidly to the sea floor, where most of it is expelled into the overlying water column as focused flow at chimney vent sites. The dissolved metals precipitate when the fluid mixes with cold seawater. Much of the metal is transported in the hydrothermal plume and is deposited as fallout of particulate debris. The remainder of the metal precipitates as metal sulphides and sulphates, producing black and white smoker chimneys (see box) and mounds (Figure 2).

The minerals forming the chimneys and sulphide mounds include iron sulphides, such as pyrite (often called fool's gold), as well as the main minerals of economic interest. These include chalcopyrite (copper sulphide) and sphalerite (zinc sulphide). The precious metals gold and silver also occur, together with non-sulphide (gangue) minerals, which are predominantly sulphates and silicates. The metals originate from immiscible sulphides, ferromagnesian silicates, and feldspars that make up the volcanic rocks beneath the sea floor (Hannington *et al* 2005). It has been suggested that rising magmatic fluids may also be a source of ore metals, particularly at sites where hydrothermal systems are producing SMS deposits in close association with subduction zones and island arcs. The enriched magmatic fluid would then mix with the circulating seawater (Yang and Scott 1996; 2006).

Since black smokers were first discovered, more than 280 sulphide occurrences have been identified in all oceans (Hannington *et al* 2011), indicating that hydrothermal convection is widespread (Figure 3).

Most sulphide occurrences – 65 per cent – have been found along mid-ocean ridges (Hannington *et al* 2011), with another 22 per cent occurring in back-arc basins and 12 per cent along submarine volcanic arcs. Very few sites – only 1 per cent – have been observed at intraplate volcanoes (Figure 4). Spreading centres (mid-ocean ridges and back-arc basins) have a combined length of 67 000 kilometres (Bird 2003), whereas submarine volcanic arcs have a total length of 22 000 kilometres, 93 per cent of which occurs in the Pacific (de Ronde *et al* 2003).

At mid-ocean ridges, high-temperature venting occurs mainly in the axial zones of the spreading centres and is associated with basaltic volcanism. At slow-spreading ridges, however, long-lived detachment faults may divert fluid flow away from the ridge axis. The associated sulphide deposits can, therefore, be found several kilometres away from the ridge axis. Volcanic arcs and back-arc basins develop as a result of subduction of oceanic crust at a convergent plate boundary. Hydrothermal systems in these environments are broadly similar to those at mid-ocean ridges. However, the geology and tectonic setting

The colours of smoke

Hydrothermal chimneys discharge various colours of smoke, including black, grey, white, and yellow. The smoke is actually dense clouds of fine particles of sulphide, sulphate, oxide minerals, and/or sulphur, all suspended in seawater. Black smokers have the highest fluid temperatures (greater than 330°C), and the particulates are predominantly sulphide minerals. Particulates associated with white smokers are dominated by sulphate minerals that form at lower temperatures (300-150°C). Grey smokers expel both sulphide and sulphate minerals and form at intermediate temperatures. Yellow smokers occur at several sites that are related to subduction zone processes (volcanic arcs and back arcs). They form at the lowest temperatures and their particulates are mainly sulphur. This colour series also reflects the oxygen content of the fluid, with the amount of oxygen increasing as the mineral form moves from sulphide to sulphur to sulphate.

Basics of a hydrothermal vent - a Black Smoker
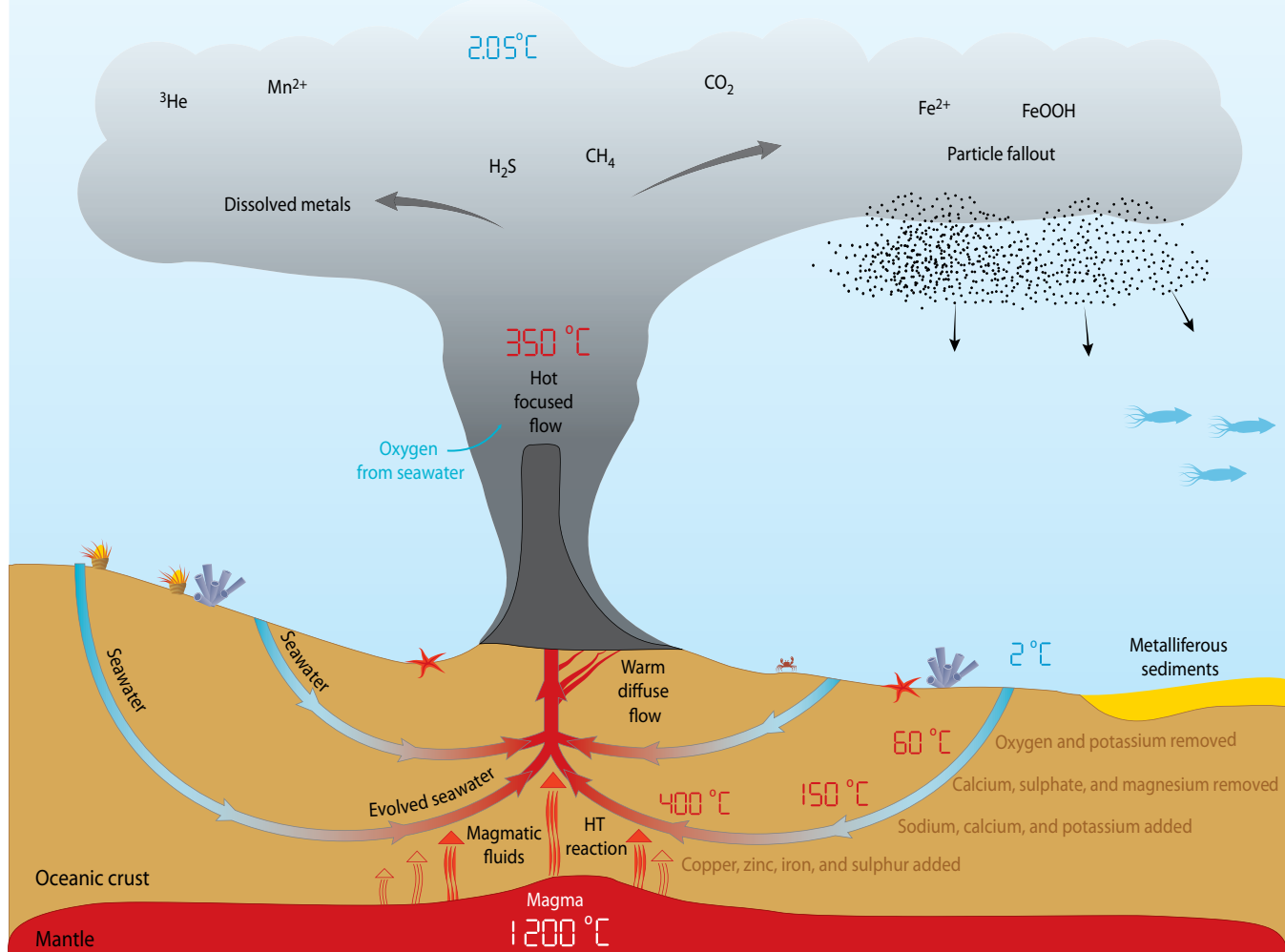
Figure 2. Basics of a hydrothermal vent. *Seawater percolates through the sea floor and is modified by chemical exchange with the surrounding rocks and rising magmatic fluid. The altered seawater is released back into the ocean at the vent site and forms a hydrothermal plume. The rising plume mixes rapidly with ambient seawater, lowering the temperature and diluting the particle concentration. The plume will continue to rise through seawater as long as it is less dense than the surrounding seawater. Once the density of the hydrothermal plume matches the density of the seawater, it stops rising and begins to disperse laterally. In a scenario like this, 90 per cent of the metals are lost to the plume and do not take part in the metal deposit formation process.*

Global distribution of hydrothermal vent fields

Confirmed vent fields

Gakkel Ridge
Hellenic Arc
Aeolian Arc
Red Sea
Okinawa Trough
Kuril Arc
Aleutian Arc
Juan de Fuca Ridge
Izu-Bonin Arc
Mariana Arc and Back-Arc
Manus Basin
N. Fiji Basin
Woodlark Basin
New Hebrides Arc
Tonga Arc and Lau Back-Arc
Kermadec Arc
Central Indian Ridge
East Pacific Rise
Galápagos Rift
Lesser Antilles Arc
Mid-Atlantic Ridge
S.W. Indian Ridge
S.E. Indian Ridge
Chile Rise
Pacific-Antarctic Ridge
E. Scotia Ridge
Bransfield Strait

Unconfirmed vent fields

Gakkel Ridge
Hellenic Arc
Aeolian Arc
Red Sea
Okinawa Trough
Kuril Arc
Aleutian Arc
Juan de Fuca Ridge
Izu-Bonin Arc
Mariana Arc and Back-Arc
Manus Basin
N. Fiji Basin
Woodlark Basin
New Hebrides Arc
Tonga Arc and Lau Back-Arc
Kermadec Arc
Central Indian Ridge
East Pacific Rise
Galápagos Rift
Lesser Antilles Arc
Mid-Atlantic Ridge
S.W. Indian Ridge
S.E. Indian Ridge
Chile Rise
Pacific-Antarctic Ridge
E. Scotia Ridge
Bransfield Strait

Mid-ocean ridge
● Confirmed
● Unconfirmed

Arc volcano
▲ Confirmed
▲ Unconfirmed

Back-arc spreading center
■ Confirmed
■ Unconfirmed

Intra-plate volcano & Other
◆ Confirmed

— Ridge & Transform
--- Trench
Exclusive Economic Zones

Source: S. Beaulieu, K. Joyce, and S.A. Soule, 2010, Interridge and Woodshole
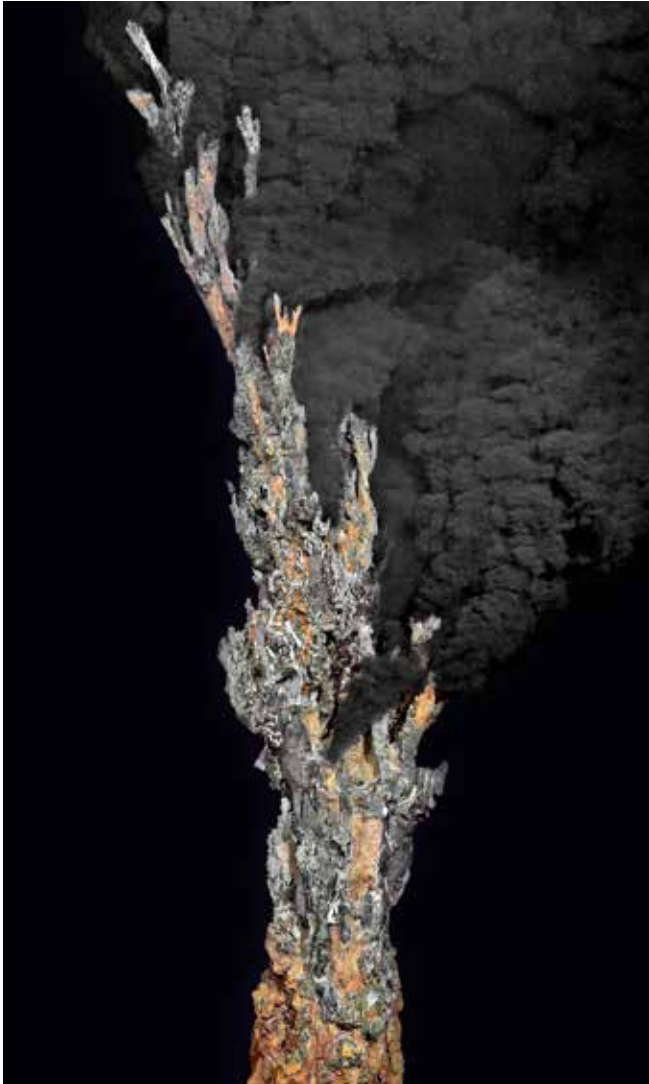
The largest black smoker discovered to date (since collapsed) measured almost 45 metres high and occurred on the Juan de Fuca Ridge. Following destruction, chimneys have been measured to grow as fast as 30 centimetres per day. The biggest chimneys are generally found on slow spreading ridges (like the Mid-Atlantic Ridge). On fast spreading ridges like the East Pacific Rise, chimneys are rarely more than 15 metres high. Photomosaic of a 5 metre high chimney in the central Atlantic. Image courtesy of GEOMAR.

Figure 3. Global distribution of sea-floor hydrothermal systems and related mineral deposits. *Confirmed vents are those where hydrothermal activity has been observed at the sea floor. The unconfirmed sites are inferred to be active based on plume surveys. From version 2.0 of the InterRidge Global Database (Beaulieu et al 2010).*

Distribution of known SMS occurrences
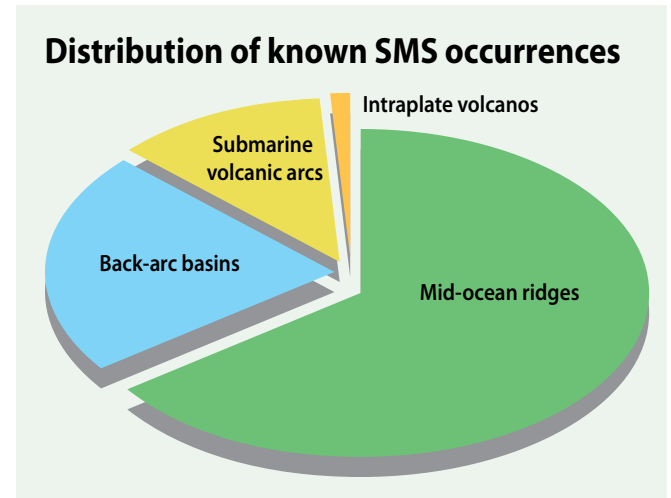
Figure 4. Distribution of known sea-floor massive sulphide occurrences in different environments.

influence the composition of the hydrothermal fluids and also, ultimately, the mineralogy and chemical composition of the associated sulphide deposits. The apparent differences are related to variations in host-rock composition, as well as to direct input of magmatic volatiles and metals into the hydrothermal circulation cell (Yang and Scott 1996; de Ronde *et al* 2011). The occurrence and distribution of sulphide deposits seems to be related to overall magmatic activity along plate boundaries.

The total number of vent sites that exist on the modern sea floor is not known, although several hypotheses have been used to infer their abundance. Estimates based on Earth's heat flow indicate that approximately one black smoker per kilometre of ridge axis is necessary to explain the heat flux through the oceanic crust (Mottl 2003). The distribution of hydrothermal plumes along the spreading axis and over volcanic arcs has also been used to infer similar values (Baker and German 2004; Baker 2007). It should be noted, however, that the latter approach only considers active hydrothermal fields. Evidence suggests that there are many more inactive sites than active sites (Hannington *et al* 2011).

1.2 | Metal concentrations and tonnages

While the number of discoveries of SMS occurrences is steadily rising, most deposits are small in size and tonnage of contained sulphide. Hydrothermal vent systems do not generally incorporate metals into sulphide deposits efficiently. Much of the metal is lost to the hydrothermal plume and dispersed away from the vent sites. Large deposits form only where sediments allow for efficient trapping of the metals due to metal-precipitation below the sea floor (as in Middle Valley and Okinawa Trough; Zierenberg *et al* 1998; Takai *et al* 2012) or where hydrothermal activity occurs for long periods of time, as with sulphide mineralization related to large detachment faults. Based on information about the age of the sulphides and the underlying volcanic crust, it appears that tens of thousands of years are needed to form the largest known deposits, such as the Semyenov and Krasnov deposits of the Mid-Atlantic Ridge (Cherkashov *et al* 2010). These deposits can be up to several hundreds of metres in diameter and are estimated to have total masses on the order of 5 to 17 million tonnes of contained sulphides.

Geochemistry of massive sulphides in various tectonic settings

Figure 5. Concentrations of copper, zinc, and lead in sea-floor massive sulphides formed in different geological settings (Source: GEOMAR)

The composition of SMS deposits is highly variable, and not all elements contained in the sulphides are of commercial interest. For example, SMS deposits along the East Pacific Rise and, to some extent, those along the Mid-Atlantic Ridge are primarily composed of iron sulphides that currently have no economic value. In contrast, sulphide occurrences in the southwest Pacific contain concentrations of copper and zinc, which make them more economically attractive (Figure 5). Valuable metals such as gold and silver are trace components of the sulphides but can be highly en-

riched in some deposits, reaching concentrations of several tens of grammes/tonne for gold and several hundreds of grammes/tonne for silver (Figure 6). Other trace elements – bismuth, cadmium, gallium, germanium, antimony, tellurium, thallium, and indium – are normally contained in SMS in low quantities (at levels measured in grammes/tonne), but can be significantly enriched in some deposits, especially those that form at volcanic arcs. Weathering of old SMS on the seabed can upgrade the metal contents in the deposit due to the formation of secondary copper-rich sulphides.

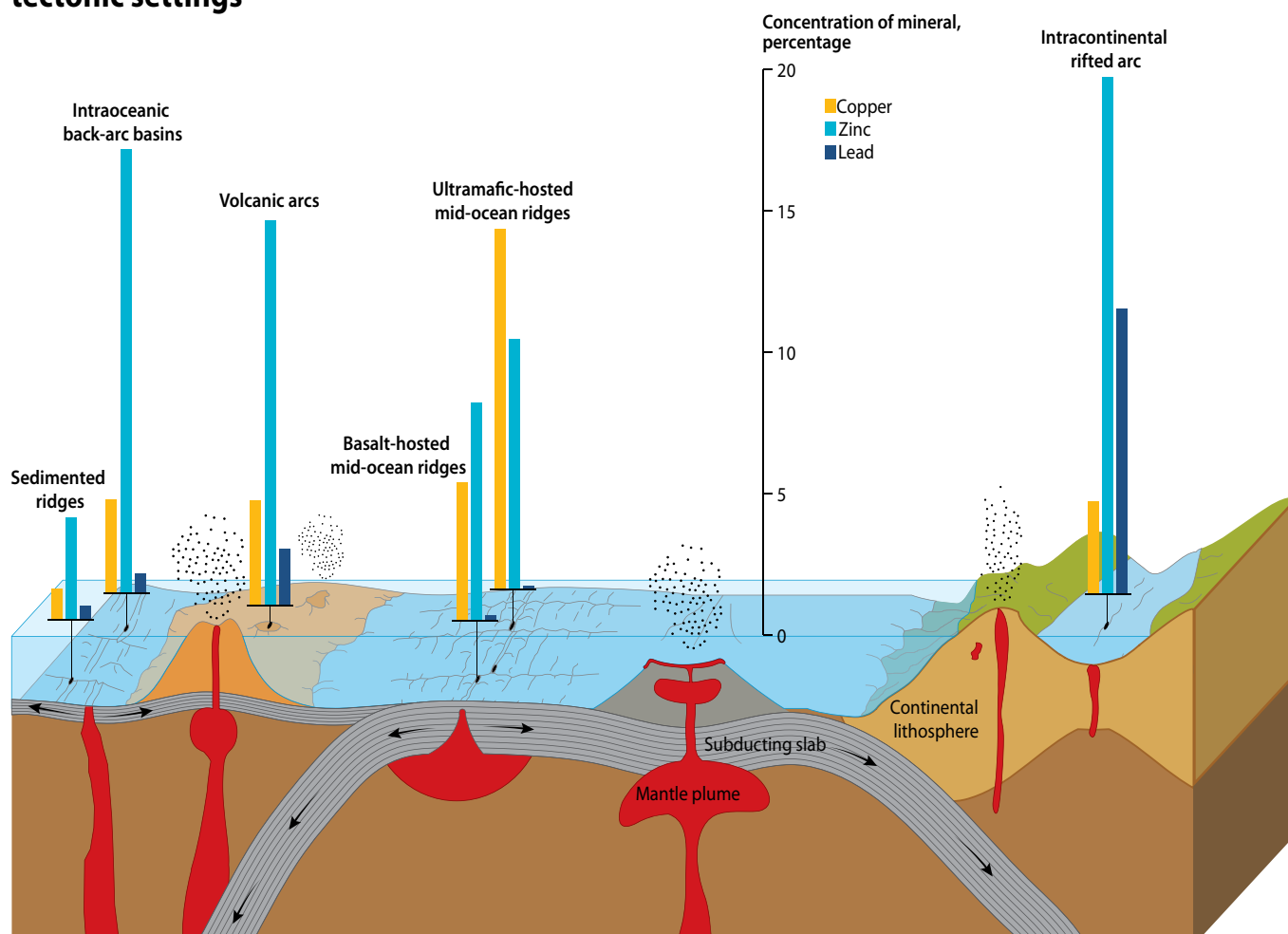## Geochemistry of massive sulphides in various tectonic settings
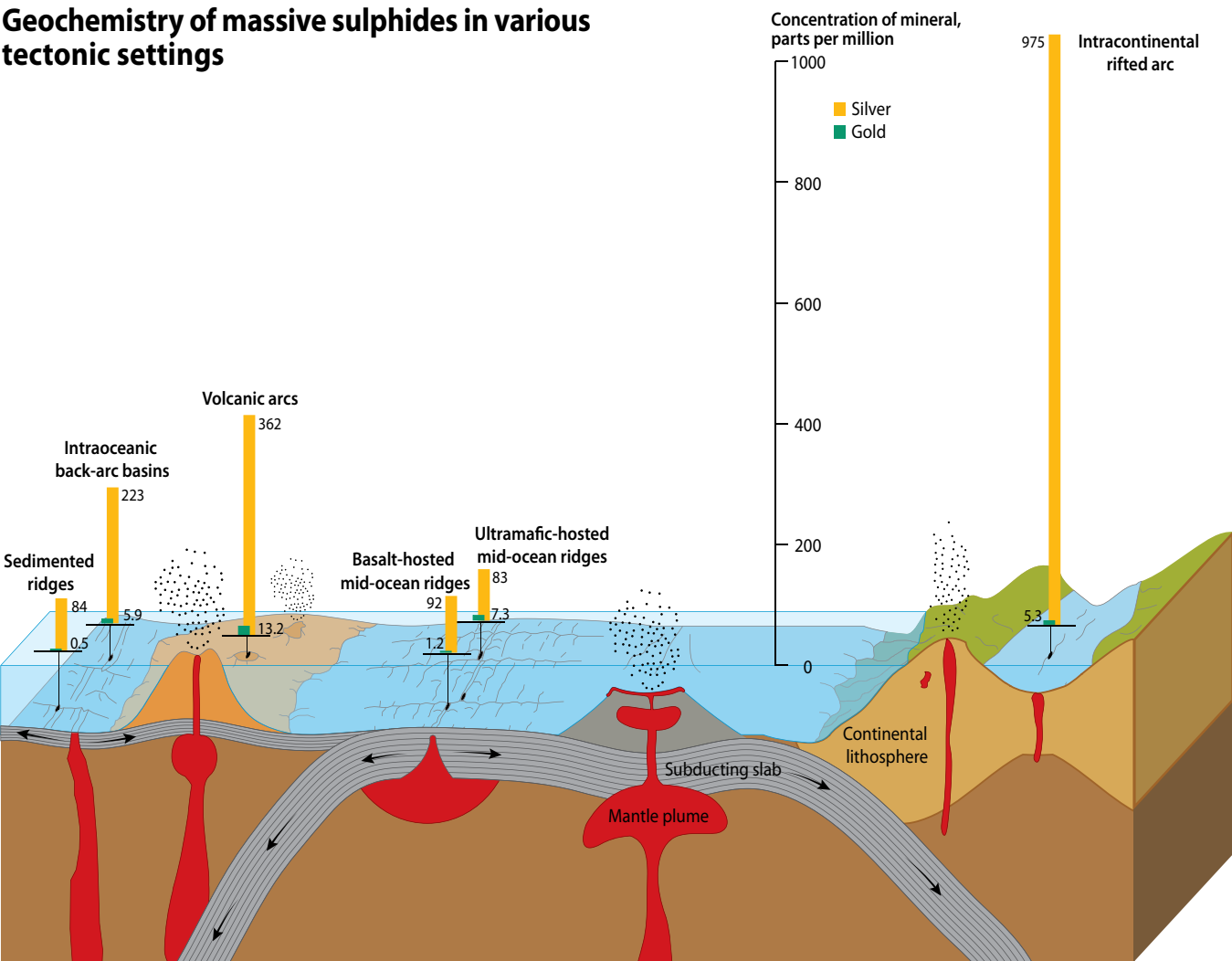
Figure 6. Concentrations of gold and silver in sea-floor massive sulphides formed in different geological settings *(Source: GEOMAR)*

The geochemical composition of SMS is not only variable on a regional scale, but also varies at the deposit or even hand-specimen scale, reflecting strong gradients in fluid temperatures (Figure 7). Copper-rich minerals typically line the high-temperature upflow zones and fluid conduits. The outer parts of the deposits consist of minerals that are rich in iron and zinc, such as pyrite, marcasite, and sphalerite. These are usually deposited at lower temperatures as the hydrothermal fluid mixes with seawater. As a result of this heterogeneity, the sampling of black smoker chimneys, which commonly show high concentrations of copper, might not be representative of the bulk composition of the deposits. Many published grades of sea-floor sulphide deposits are strongly biased due to sampling of high-temperature chimneys, which are easier to recover than sub-sea-floor mineralization. Unfortunately, with the exception of a few deposits that have been drilled through the Ocean Drilling Program or by commercial or scientific projects, little is known about the interiors of most SMS deposits.

Due to lack of information about the important subsurface component of deposits, it is difficult to estimate the resource potential of most SMS. Initial estimates of the abundance and distribution of sulphide deposits in well-studied areas indicate that approximately 1 000 large sulphide deposits may exist on the modern sea floor (Hannington *et al* 2011). However, some of the largest deposits, such as those along the central Mid-Atlantic Ridge, are dominated by iron sulphides of no commercial interest. Other factors that affect current commercial viability are water depth, distance to land, and sovereign jurisdiction. An analysis of known deposits indicates that only about ten individual deposits may have sufficient size and grade to be considered for future mining (Hannington *et al* 2011). However, many smaller, metal-rich deposits could be incorporated into a single mining operation, making mining of these smaller SMS deposits viable.

Figure 7. Examples of sea-floor massive sulphides from various tectonic settings. *Pyrite-rich chimney from the basalt-hosted Turtle Pits hydrothermal field, 5°S on the Mid-Atlantic Ridge (upper left). A massive chalcopyrite chimney from the ultramafic-hosted Logatchev hydrothermal field (lower left) and a gold-rich copper-zinc massive sulphide from the PACMANUS field, Papua New Guinea. Note the copper-rich core and the brownish zinc-rich exterior of the sample, exemplifying a typical temperature zonation in SMS. Barite constitutes a major part of this sample (right, scale on sample is 5 cm). Photo courtesy of GEOMAR.*

Bismarck Sea sea-floor massive sulphide

The western Pacific is characterized by SMS systems related mainly to westward-dipping subduction zones, which produce hydrothermal activity along back-arc basins and island arcs (Martinez and Taylor 1996).

The Bismarck Sea is a back-arc basin formed in the last three million years by the southward slab rollback of the Solomon Sea Plate under New Britain. Extensive exploration in the Bismarck Sea over the last few years has led to the discovery of numerous active and inactive hydrothermal systems within the national jurisdiction of PNG (Both *et al* 1986; Tufar 1990; Binns and Scott 1993; Auzende *et al*. 2000; Binns *et al* 2002; Tivey *et al* 2006; Jankowski 2010; Reeves *et al* 2011). Currently, two SMS systems and two sulphate systems have been documented in the western part of the Bismarck Sea. The active Central Manus spreading centre

hosts six SMS systems, while nine SMS systems have so far been located in the eastern Manus Basin, mainly associated with the young volcanic edifices at Pual Ridge and SuSu Knolls (Figure 8). At several other hydrothermally active sites in the Bismarck Sea, no sulphide deposits have been discovered.

The complexity of the tectonic setting within the Bismarck Sea is reflected in the wide range of compositions of volcanic rocks. Overall, the composition of magmas along the Manus Basin changes in a west-to-east direction, from mid-ocean-ridge basalt to more arc-like compositions closer to the New Britain Arc (Sinton *et al* 2003). Chemical changes also occur in the SMS systems themselves, linked to changes in the composition of substrate rocks, water depth, and contribution of magmatic volatiles to the hydrothermal system. Most systems at the Willaumez and Central Manus spread-
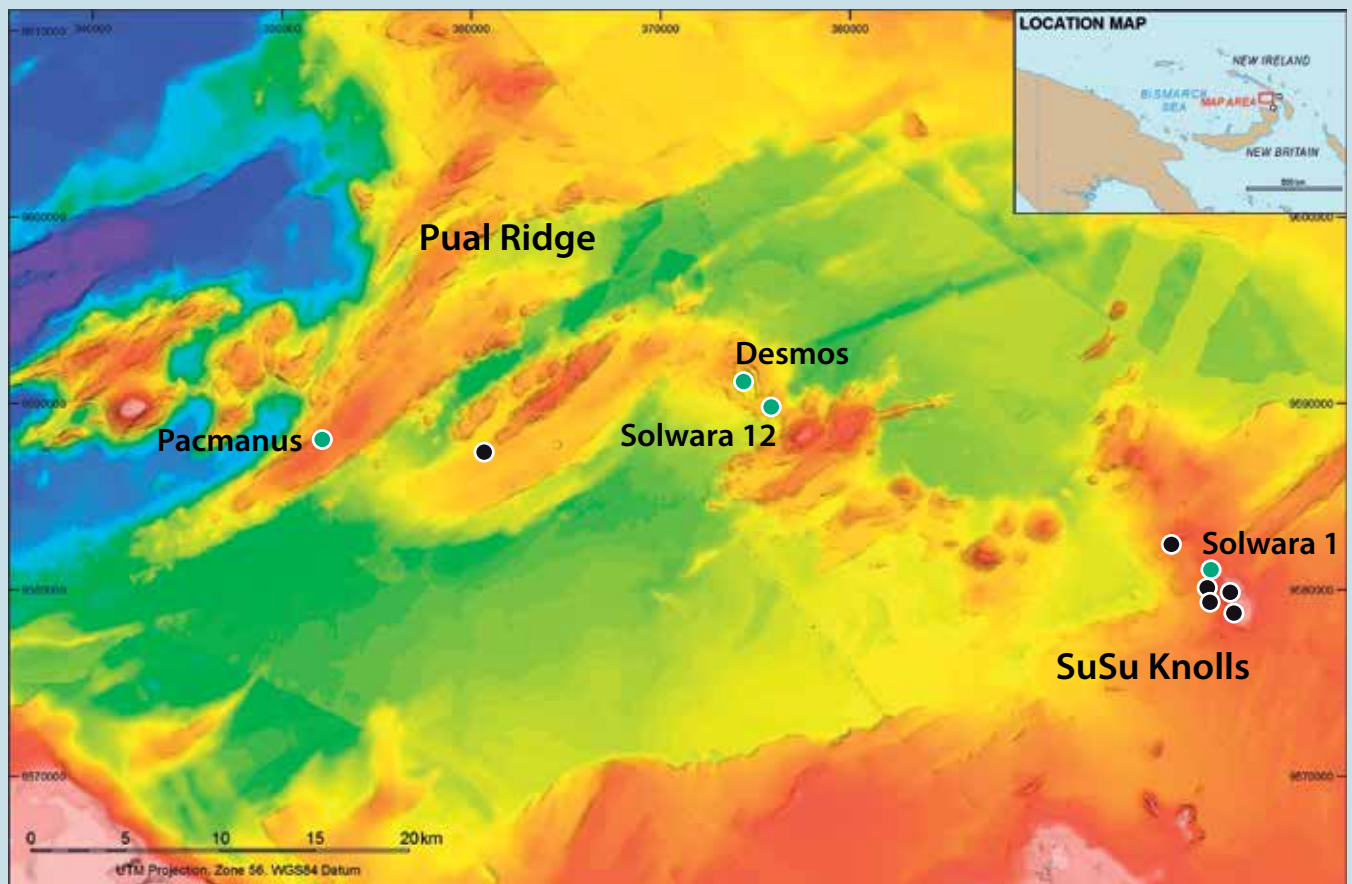

Figure 8. Location of Pual Ridge and SuSu Knolls, as well as SMS deposits in the eastern Manus Basin. *Inset shows location of the eastern Manus Basin in relation to major plate tectonic structures.*

ing centres are small and consist mainly of scattered zinc-rich chimneys with exit temperatures reaching 302°C (Gamo *et al* 1996). Systems from the Pual Ridge and SuSu Knolls are distinguished by higher copper, gold, and silver contents (Table 1), making them especially interesting from an economic point of view. At the PAC-MANUS site near the crest of Pual Ridge, discontinuous vent fields occur over a strike length of two kilometres and show exit-fluid temperatures up to 358°C (Reeves *et al* 2011). While some small mounds are present, scattered chimneys protruding from felsic volcanic rocks characterize most sites. High-temperature venting, up to 332°C (Bach *et al* 2012), and SMS systems have also been observed at the North Su and South Su sites. There, crosscutting volcanic ridges indicate structural control on melt ascent and fluid migration, a setting common for many ancient land-based sulphide systems. This area also hosts the roughly 2.5-million-tonne Solwara 1 deposit (estimated at 2.6 per cent copper equivalent, or CuEq), over which the southwest Pacific's first mining lease for SMS

mineral extraction has been granted. Additionally, several smaller active and inactive systems have been documented in the vicinity. Solwara 12, another site of commercial interest, is associated with a caldera located between Pual Ridge and SuSu Knolls.

A characteristic feature of many SMS systems in the eastern Manus Basin is the contribution of magmatic volatiles and metals. This is evidenced by the intense alteration of the host lavas, low-pH fluids, occurrence of abundant elemental sulphur at several sites (such as North Su and South Su), and the presence of metal-rich inclusions in host rocks (Yang and Scott 1996). The chemical data from Solwara 1 and Solwara 12 clearly show the difference in resource evaluation between surface sampling and drilling. The sub-seafloor deposits have lower values of both base and precious metals. Present-day exploration techniques mainly search for water column anomalies produced by active vent systems, leaving considerable potential for the discovery of inactive systems in the area.

Location	size/tonnage	N	Cu	Zn	Au	Ag	depth (m)
			wt.%		ppm		
Western Manus Basin							
Solwara 11	-	26	1.6	16.9	1.2	180	1390 - 1450
Solwara 18	-	2	0.3	19.6	0.2	110	1310
Central Manus Basin							
Vienna Woods, Solwara 2	-	215	1.2	21.0	10.0	355	2470 - 2500
Solwara 03	-	31	1.1	21.3	15.2	642	2560 - 2590
Solwara 10	-	12	7.7	15.2	2.5	165	2240
Solwara 14	-	14	1.4	19.2	3.3	97	2240
Solwara 16	-	6	2.1	18.6	2.8	105	2160
Eastern Manus Basin							
Suzette (Solwara 01)	90 000 m²	250	9.7	5.4	15.0	174	1460
Suzette (Solwara 01)*	1 030 000 t	indicated	7.2	0.4	5.0	23	1460
Suzette (Solwara 01)*	1 540 000 t	inferred	8.1	0.9	6.4	34	1460
North Su	-	4	7.1	1.6	4.8	39	1183
South Su	-	4	7.4	9.2	6.8	191	1309
Solwara 05 (N of North Su)	30 000 m²	12	6.0	8.3	14.6	282	1635 - 1680
Solwara 09 (west of North Su)	15 000 m²	17	6.3	10.6	19.9	296	1680
PACMANUS	45 000 m²	336	7.4	22.5	13.7	267	1650 - 1815
Solwara 12 (near Desmos)	-	10	7.0	22.6	13.7	425	1870
Solwara 12 (near Desmos)*	230 000 t	inferred	7.3	3.6	3.6	56	1870
Solwara 13 (Yuam Ridge)	30 000 m²	7	9.1	30.7	4.7	546	2000

*Table 1: Chemical composition of SMS from the Bismark Sea. For most sites, the average composition of surface samples is given, which might not be representative of the entire deposit. For Solwara 1 and 12, where a resource estimate has been published, the data on surface samples is also provided. (N= number of samples analysed; * = resource estimate based on drilling information; results for PACMANUS include data from Solwara 4, 6, 7, and 8, which are considered here to be part of the same hydrothermal system. Sources: Hannington et al, 2010, 2011; Lipton 2012)*
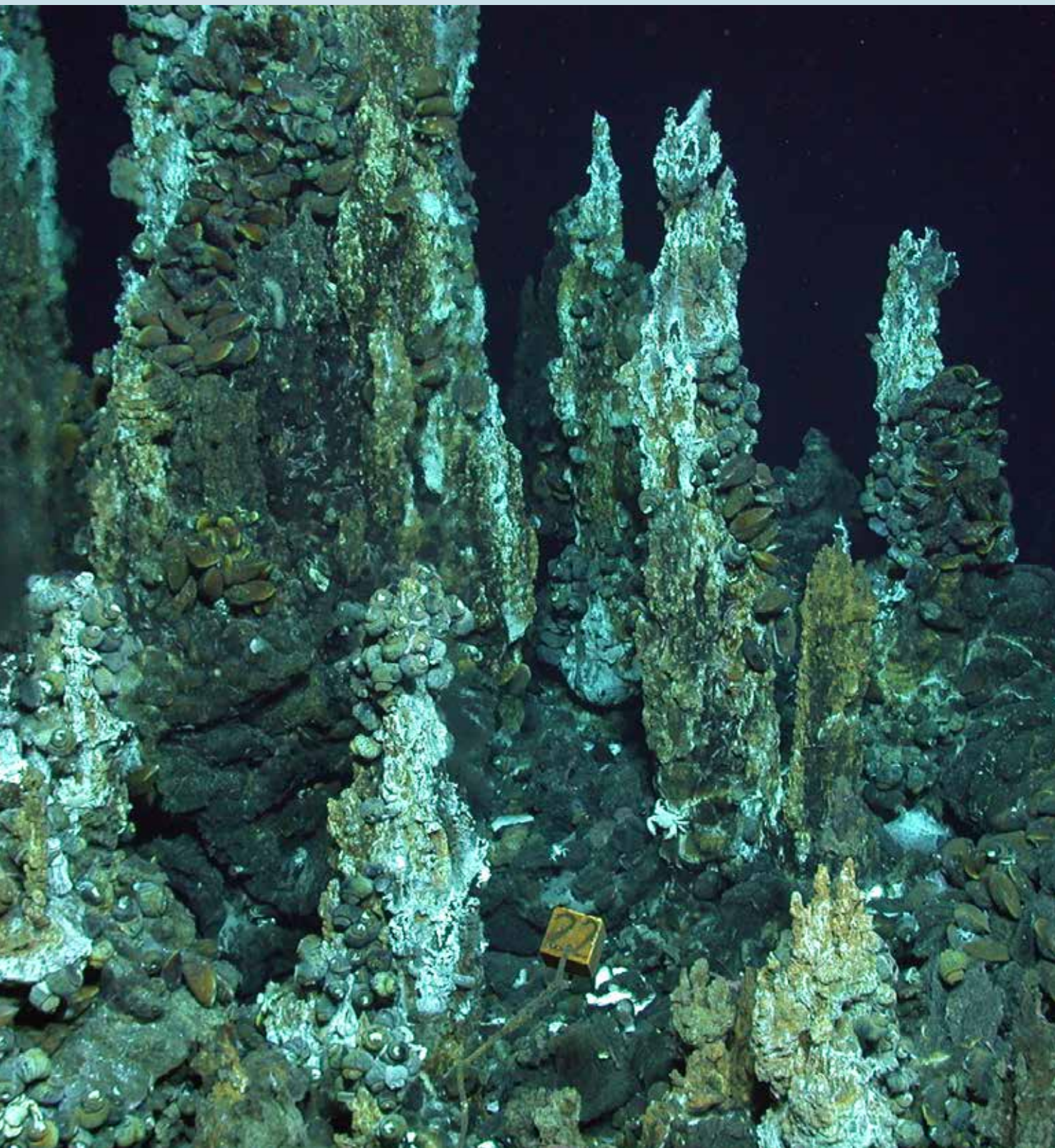
Photo courtesy of Chuck Fisher.

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2.0 Biology Associated with Sea-Floor Massive Sulphide Deposits

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Habitats and biodiversity associated with sea-floor massive sulphide deposits

Hydrothermal vents occur in areas of undersea volcanic activity, most commonly associated with plate boundaries. The same geochemical processes that contribute to the formation of SMS deposits also bring hot fluid, rich in reduced chemicals, to the sea floor. These chemicals are toxic to most animals, but they can be used as an energy source for growth by chemoautotrophic bacteria, organisms that get energy through a chemical process rather than by photosynthesis. As a result, hydrothermal vents provide an abundant source of bacteria-based food in a chemical and thermal habitat that most animals cannot tolerate (Figure 9).

However, a diverse array of animals has evolved the adaptations necessary to tolerate this extreme habitat and thrive. The list includes at least 600 species, called vent-endemic species, that are only known to exist at hydrothermal vents (Desbruyères *et al.* 2006a). Many vent-endemic species have evolved a sym-

biotic, or mutually beneficial, relationship with chemoautotrophic bacteria, which allows them to benefit directly from the energy in hydrothermal vent fluids and reach densities of hundreds to thousands of individuals per square metre. Vent-endemic species, along with a limited number of other species that can tolerate and indirectly benefit from the extreme environment, form distinct vent communities.

In addition to the physiological challenges associated with exposure to extreme chemistry and widely varying temperatures, the vent-endemic species must also evolve adaptations to allow them to exploit a habitat that is very patchy and ephemeral, likely to disappear suddenly. Hydrothermal venting is not continuous along the plate margins. For example, vent site spacing along a spreading centre can range from a few kilometres to hundreds of kilometres. Within a site, sources of venting fluid
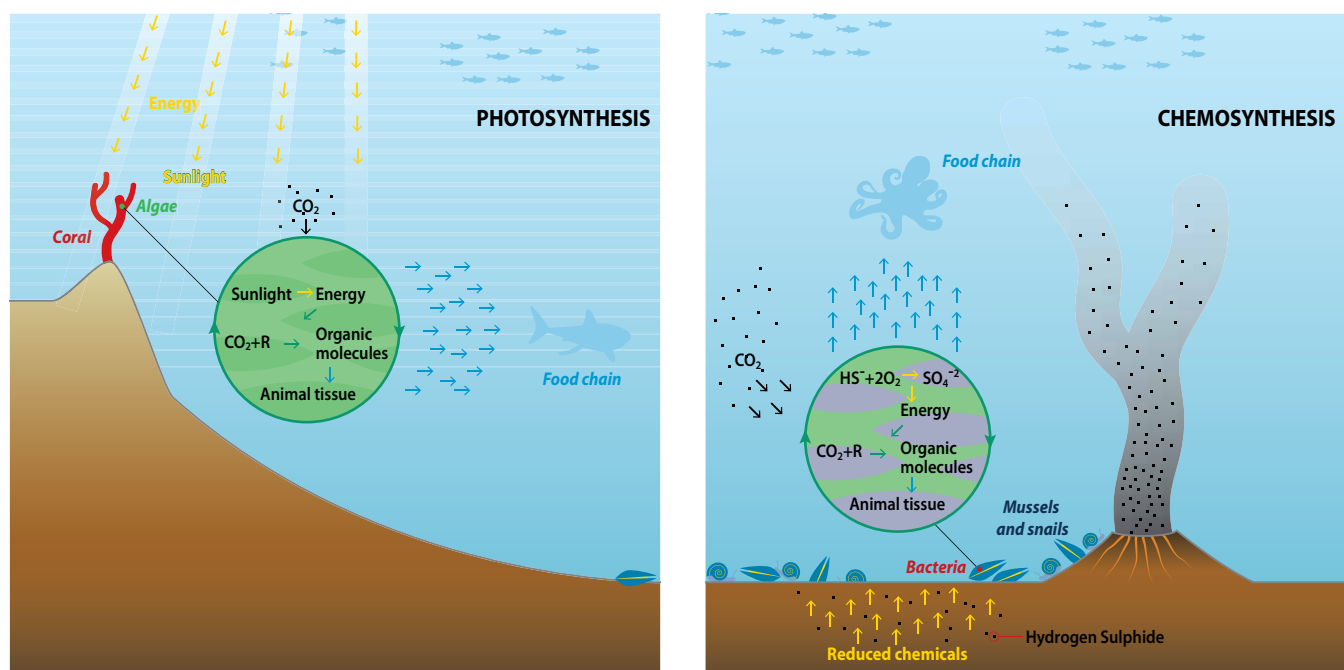

Figure 9. Chemoautotrophic symbiotic relationships. These relationships are similar to the symbiosis between shallow-water reef corals and their photosynthesizing algae. Like some species of corals, which must be exposed to sunlight to reap the benefits of their algal partners, vent animals must live exposed to hydrothermal vent fluids in order to benefit from their bacterial symbionts.

*Ancient lineages of stalked barnacles (*Vulcanolepus sp*) from the Lau Basin and Kermadec Volcanic Arc (left, photo courtesy of the NSF Ridge 2000 program) and Yeti crabs from Antarctic vents (right, photo courtesy of T. Shank) host symbiotic bacteria on their appendages. The bacteria are thought to provide food for the hosts.*

might be anywhere from a metre to hundreds of metres apart (Ferrini *et al* 2008; Baker 2009). Volcanic and tectonic activity are both common on active spreading centres, and both affect the point sources of hydrothermal fluid emission and the longevity of individual sites. Tectonic activity can alter the hydrothermal plumbing at a site, blocking or redirecting hydrothermal venting. Volcanic activity can result in sites being partly or completely repaved with hot lava. Either type of activity can partially or completely wipe out the site's endemic communities.

Over about 25 years of intensive study of vent sites in the 9-10° latitude N area of the East Pacific Rise, scientists have observed two cycles of local extermination and recolonization of vent communities as a result of volcanic activity (Haymon *et al* 1993; Tolstoy *et al* 2006). The East Pacific Rise, however, is a fast-spreading centre, where the plates move apart at a rate of more than 10 centimetres a year and large volumes of magma erupt, so these events may be more common here than at other vent sites. On the Mid-Atlantic Ridge, which is a slow-spreading centre where plates separate at approximately 2.5 centimetres a year, this kind of activity is much less frequent. One well-studied site on this ridge, the TAG site (Rona 1973) is thought to have been active for tens of thousands of years, although individual chimneys and sources of diffuse flow within the TAG mound are active for much shorter periods (White *et al* 1998). Because of the patchy and ephemeral

nature of hydrothermal venting, endemic faunal populations must have dispersal and recruitment capabilities that allow them to recolonize new sites regularly. However, the dispersal capabilities and resultant genetic connectivity among sites in an area varies by species and region (Vrijenhoek 2010). Vent community structure will reflect adaptations to the natural frequency and intensity of disturbance (Miller *et al* 2011).

At hydrothermal vents, both lava flows and sea-floor mineral deposition result in creation of hard substrate that rises above the surrounding sea floor. These structures can provide habitat for other groups of animals that are not directly tied to active hydrothermal flow and, in fact, are unlikely to tolerate exposure to hydrothermal fluid. Inactive (old) hydrothermal vent sites and inactive hydrothermal chimneys at active sites can both provide prime substrate for rich suspension-feeding assemblages dominated by corals and echinoids not normally found on the deep sea floor. These animals are often slow-growing and long-lived (Probert *et al* 1977). In addition to exposure to food broadly found in the benthic water, these communities may also benefit from primary production at nearby active vents (Erickson *et al* 2009). The animals living on inactive-vent sulphide structures and the infauna of inactive sediments in the vicinity of venting are not well studied, although the indications are that these communities may also depend to some extent on production from vents (Levin *et al* 2009).
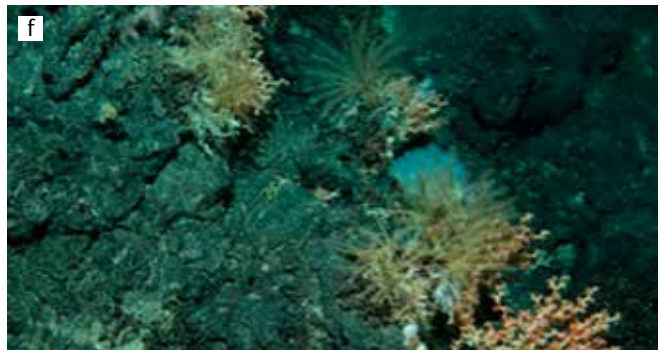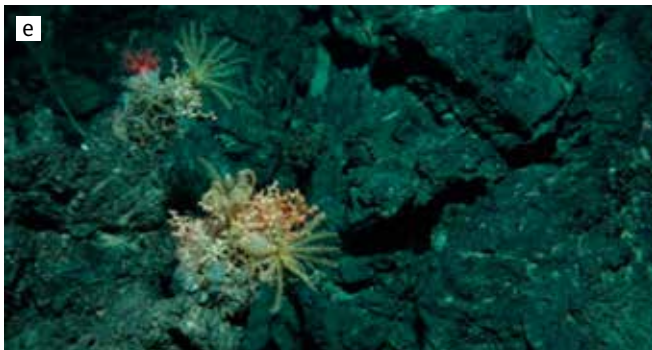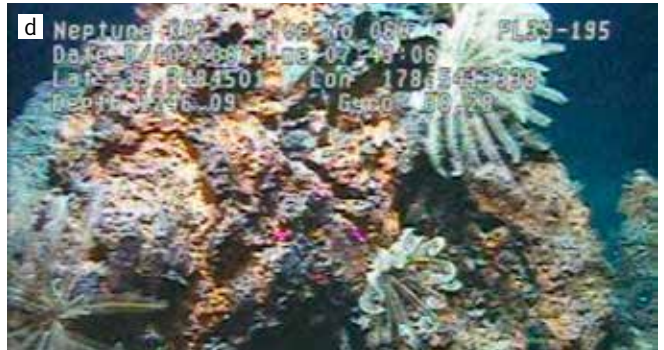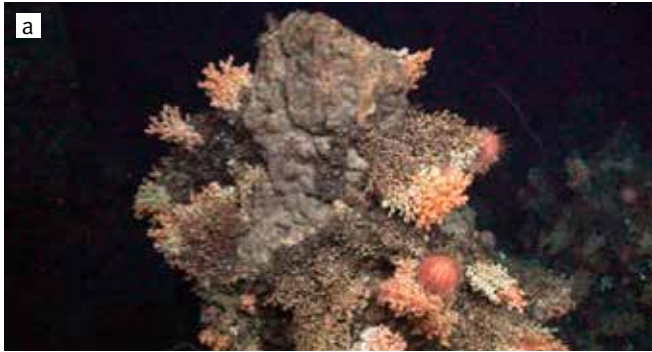
Sea-floor images (a-d) showing inactive sulphide chimneys with rich assemblages of epifauna, including scleractinians (stony corals), echinoids (sea urchins), brisingids (sea stars) and crinoids (sea lilies); and (e-h) less dense assemblages of the same type of organisms on volcanic lavas away from SMS deposits. Rumble II West volcano, Kermadec Volcanic Arc. Photos courtesy of Neptune Resources (Kermadec) Ltd (a-d) and NIWA (e-h).

2.2 | Global distribution of vent organisms

Hydrothermal vents with generally similar chemical/thermal habitats exist in all of the world's oceans. However, there are significant differences among vent communities in different regions of the world. For example, the giant tubeworms that dominate many vent habitats in the eastern Pacific have never been seen at Atlantic, Indian Ocean, or southwest Pacific vent sites. On the Mid-Atlantic Ridge, swarms of endemic vent shrimp with chemoautotrophic symbionts cover many hydro-thermal chimneys. In the Indian Ocean, shrimp, anemones, and big, symbiont-containing snails constitute the largest portion of the biomass. Analysis of the composition of vent communities suggests at least five biogeographic provinces for vent fauna, although the number and boundaries of these provinces have yet to be resolved with any certainty (Van Dover *et al* 2002; Bachraty *et al* 2009; Moalic *et al* 2011; Rogers *et al* 2012).

The scaly foot snails found at vents on the Central Indian Ridge in the Indian Ocean have scales composed of iron sulphides and are the only animals known to produce metal armour. Photo courtesy of CL Van Dover.
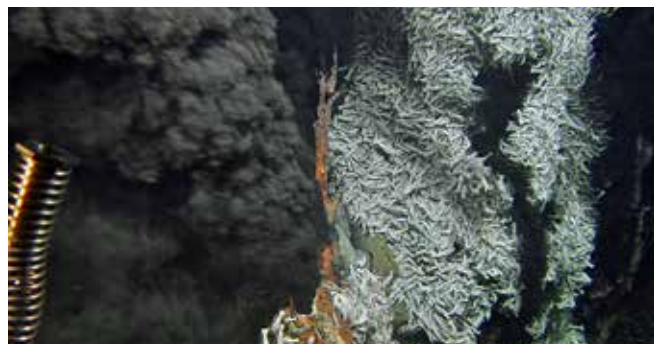
*Shrimp on the Mid-Atlantic Ridge and on Indian Ocean vents (*Rimi-caris sp*) have lost their eyes but have evolved large light-sensing patches on their backs to "see" the chimneys they call home. They are not found in the southwest Pacific. Photo courtesy of IFREMER.*

*Because of the myriad of adaptations necessary to live at hydrothermal vents, most animals cannot survive there. However, the endemic vent fauna represent a source of evolutionary innovation not found elsewhere on Earth. They often occur in extremely high densities at hydrothermal vents. Giant tubeworms (*Riftia pachyptila*) from the East Pacific Rise are among the fastest-growing animals on Earth. They have no mouth, gut, or anus and live their entire adult lives with one end of their bodies immersed in a hot tub and the other in ice-cold water. They are not found in the southwest Pacific. Photo courtesy of IFREMER.*

2.3 | Composition of vent communities in the western Pacific

In the western Pacific, hydrothermal venting is widespread, not only along back-arc spreading centres, but also on undersea volcanoes at a wide range of depths. Settings and styles of hydrothermal venting are diverse in the western Pacific, and the chemistry of hydrothermal fluid is also quite variable due to differences in geology and water-rock interactions at different depths. Furthermore, there are numerous and complex potential geographic and oceanographic barriers to dispersal between hydrothermal sites in the western Pacific, leading to isolation of populations and resultant speciation over evolutionary time (Desbruyères *et al* 2006b). The cumulative result of all of these factors is the likely presence of multiple biogeographic provinces, associated with hydrothermal venting, between New Zealand and Japan. A recent analysis suggests there may be at least four biogeographic provinces within the western Pacific alone (Rogers *et al* 2012).

Within most vent sites, one can further divide the animals and communities according to macrohabitat and microhabitat. The hottest habitat occupied by animals at vents is normally found near the top of active and growing chimneys and hydrothermal flanges. The latter are outgrowths from the main body of the sulphide structure and are associated with pooling of high-temperature fluid beneath the flange. Only a few specialized animals can tolerate this habitat, where body temperatures may approach 60°C (Cary *et al* 1998; Girguis and Lee 2006). Other distinct habitats, with particular thermal and chemical characteristics, are inhabited by their own endemic vent animals (Henry *et al* 2008; Podowski *et al* 2009, 2010). In the western Pacific, snails in the genus *Alviniconcha* normally occupy the warmest habitats and can tolerate temperatures up to about 45°C. Although sometimes found mixed in with *Alviniconcha spp.* snails, the snail *Ifremeria nautilai* is more often found in vent-fluid habitats with temperatures that range from a few degrees above ambient to about 20°C. The mussel *Bathymodiolus brevior* is often found in aggregations mixed with *Ifremeria nautilai*, but also seems to thrive when exposed to very dilute hydrothermal fluid at near-ambient temperatures. Each of these species of symbiont-containing fauna is associated with a number of other species of vent animals that normally occur in the same habitats (Podowski *et al* 2009, 2010). Current research suggests that the fauna associated with inactive hydrothermal structures or sediments are not endemic to vents, but are a subset of the filter-feeding communities found on other areas of hard substrate at similar depths in the region (Limen *et al* 2006; Levin *et al* 2009; Van Dover 2011).

A rather low-biomass animal community of shrimp, crabs, and specialized polychaete worms commonly covers the relatively new, often hot and bright-white surfaces near the tops of chimneys and on hydrothermal flanges. Austinogreid crabs, shrimp, and the scale worm Branchinotogluma segonzaci *on a flange in the Tu'I Malila vent field on the Eastern Lau spreading centre. Photo courtesy of Chuck Fisher.*

In slightly cooler areas, both on chimneys and lavas, one can find high-biomass communities dominated by two genera of golf-ball-sized snails and/or specialized mussels. They live with a variety of endemic shrimp, worms, and crabs that tolerate constant exposure to warm, chemically rich, and normally toxic vent fluid.

A species of Alvinoconcha snail and the austinogreid crabs nestled in shimmering waters on the Eastern Lau spreading centre. Photo courtesy of NSF Ridge 2000 program.

Aggregations of the snail Ifremeria nautilai on active hydrothermal chimneys on the Eastern Lau spreading centre. Photo courtesy of NSF Ridge 2000 program.

Dense bed of the undescribed mussel Bathymodiolus sp. on Monowai volcano, Kermadec volcanic arc. Photo courtesy of NOAA/NIWA/GNS.

Even in peripheral areas with minimal exposure to very dilute vent fluid, one finds luxuriant communities of vent-endemic animals, including several species of anemones and barnacles.
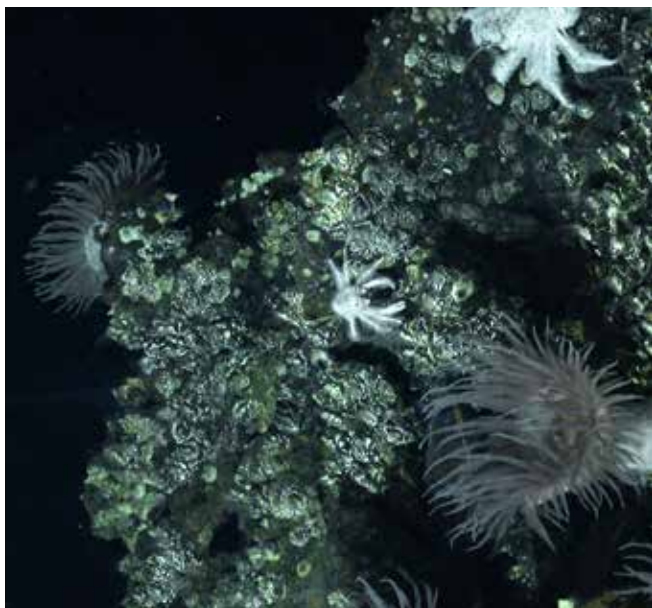
Anemones and barnacles in the Kilo Moana vent field on the ELSC. Photo courtesy NSF Ridge 2000 program.

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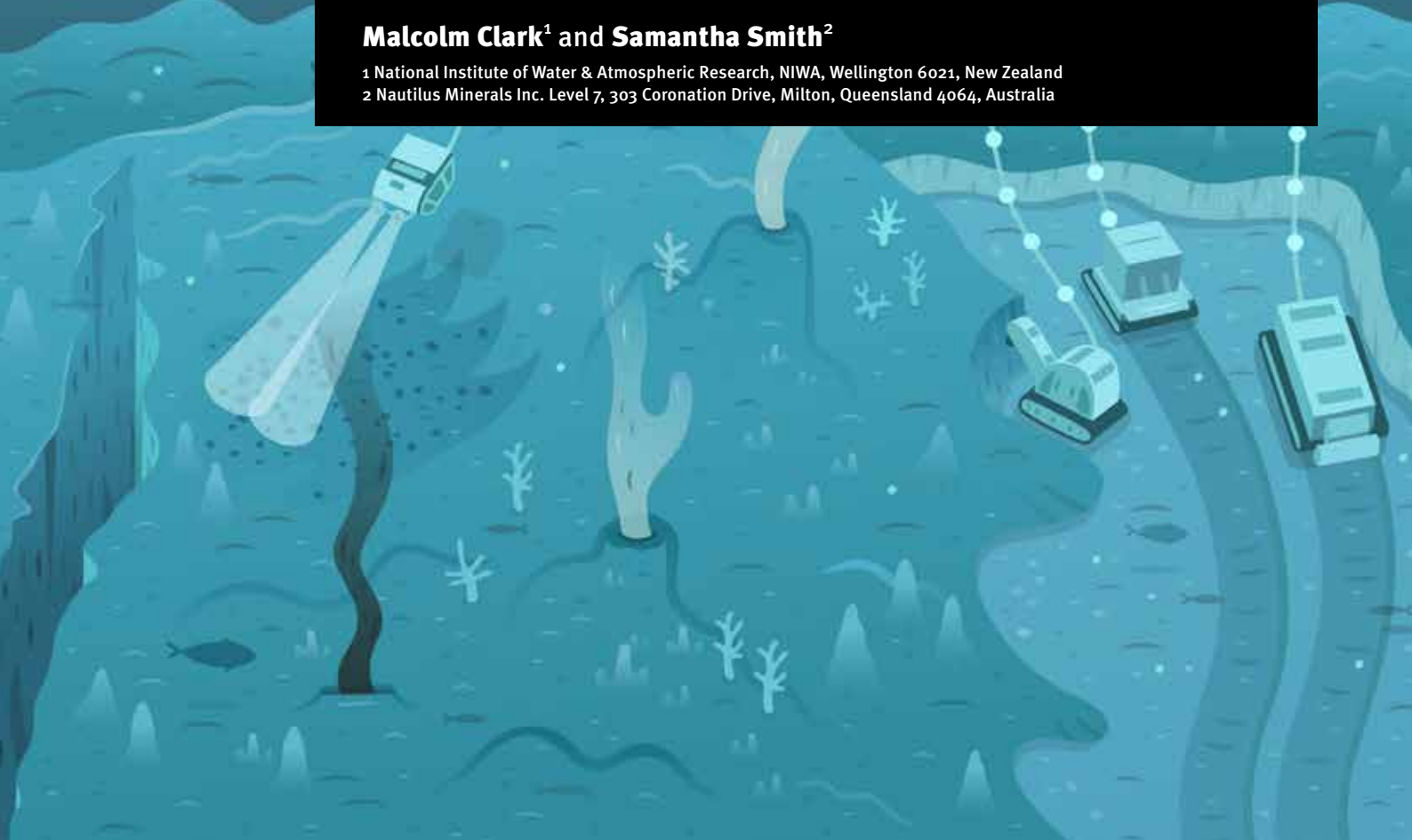
3.0 Environmental Management Considerations

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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 such human activities 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 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 SMS extraction, with a particular emphasis on the specific characteristics of biological communities associated with sea-floor massive sulphide habitats. Management options are discussed, and options are recommended to 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 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 (such as national marine park declarations and, in the case of the Pacific, the Noumea Convention for the protection of the natural resources and environment of the South Pacific) 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.

Photo courtesy of MARUM, University of Bremens.

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 between the ecosystem and 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

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 (Figure 10). 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 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. 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

resources, whilst 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 in the exploitation of any resource is the precautionary approach. One of the primary foundations of the precautionary approach, and globally accepted defi-

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 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. 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.

The road from exploitation to exploitation

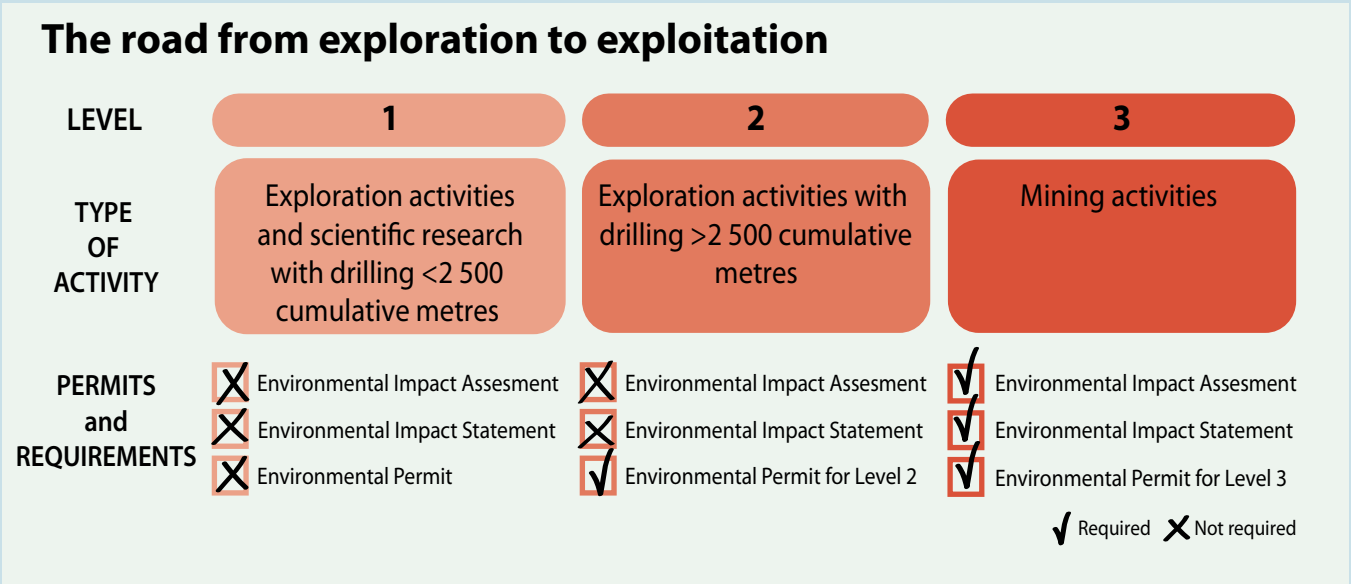| LEVEL	1	2	3
TYPE OF ACTIVITY	Exploration activities and scientific research with drilling <2 500 cumulative metres	Exploration activities with drilling >2 500 cumulative metres	Mining activities
PERMITS and REQUIREMENTS	☒ Environmental Impact Assesment ☒ Environmental Impact Statement ☒ Environmental Permit	☒ Environmental Impact Assesment ☒ Environmental Impact Statement ✓ Environmental Permit for Level 2	✓ Environmental Impact Assesment ✓ Environmental Impact Statement ✓ Environmental Permit for Level 3

✓ Required ✗ Not required

Figure 10. Environmental impact assessment and environmental permitting process considerations – an example of a permitting process for a proposed SMS project.

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.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 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 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 SMS mining in the deep sea, including:
- International Seabed Authority: Polymetallic sulphides and cobalt-rich ferromanganese crusts deposits: establishment of environmental baselines and an associated monitoring program during exploration (ISA 2007).
- 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).
- Environmental management of deep sea chemosynthetic ecosystems: justification of and considerations for a spatially-based approach (Van Dover *et al* 2011, SPC 2012).

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 could include nearshore studies such as coral reef studies. 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 prep).

Collaborative research

There are at least two examples in the Pacific of highly effective collaborative research that has achieved both commercial and scientific goals: Nautilus Minerals with a consortium of international experts, including deep sea scientists, and Neptune Minerals with the National Institute of Water and Atmospheric Research.

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.

Photo courtesy of MARUM, University of Bremen.

3.4 Defining characteristics of SMS systems

The description in Chapter 2 of faunal communities associated with SMS highlights several key characteristics to be considered specifically for this environment when assessing potential impacts. These considerations, and others, are summarized here. Knowledge of species composition and biodiversity at hydrothermal vent sites is incomplete. Many species are poorly understood, and likely many are still undiscovered (German *et al* 2011). Observations to date indicate that the dominant species and faunal communities vary through the western Pacific.

Sometimes, parts of an SMS deposit are still actively venting, while other parts are dormant. At locations in the Pacific Island region where active venting occurs, typical biomass-dominant sessile animals include gastropods (snails), barnacles, and bathymodiolid mussels. More mobile animals include shrimp, crabs, and eel-pout fish. Many species from hydrothermal vent sites are considered endemic to the vent environment and reliant on venting activity and its particular environmental characteristics (such as depth, temperature, and chemical composition). These endemic species are localized, so their populations could be severely affected by relatively small-scale mining activities.

There is much to learn about the dispersal and colonization potential of vent species. It has been suggested that the dominant megafauna can colonize new vent sites relatively quickly following such disturbances as volcanic eruptions. Evidence for this has been observed at the East Pacific Rise and Juan de Fuca Ridge hydrothermal vent systems (Tunnicliffe *et al* 1997; Shank *et al* 1998). Because venting activity is ephemeral and often variable at a local scale, the animal populations associated with vents must be adapted to, or at least tolerant of, this natural variability. For example, because hydrothermal vent activity is transient at various time scales, animals have to be adapted to move (or disperse their eggs and larvae) between sites if venting stops.

Animals associated with dormant SMS sites are non-chemosynthetic fauna, dominated by standard sea-floor/hard-substrate taxa, such as attached barnacles, stony corals, octocorals, sponges, and slow-moving feather stars and brittle stars. Many of these fauna are slow-growing and long-lived. These animals are part of a wider regional pool of species, typical of deep sea animals found elsewhere, including on basalt (and other) outcrops. Recovery of these fauna from disruptive human activities may take decades to centuries because of their slow growth, and this factor needs to be balanced against the likelihood that mining activity will have less impact on the wider species pool.

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, therefore, the practical management objective will not be to preserve all habitat and local animal communities, but to balance the impacts of exploitation with conservation objectives. Impacts on the social and economic status of human populations will also need to be considered and are 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 will be dealt with separately below.

Impacts associated with normal operations

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.

Processing the ore (concentrating) to remove target metals is a key component of the mining operation, although it is not specific to deep sea minerals and is likely to occur after the extracted material has been transported to shore (currently offshore vessel-based mineral-processing is not considered viable). So while there may be impacts associated with processing, here we focus on extraction processes occurring at the mine site.

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 mid-water column, and the surface of the sea (Figure 12).

It is important to keep in mind that whether a site is mined will depend on several factors, including metal content, grade, size of deposit, topography/bathymetry, venting activity level, environmental conditions, etc. Not all SMS deposits will be commercially viable, and some will be too hot and/or too steep to develop. Estimates suggest 75 to 90 per cent of SMS deposits will remain untouched (Hannington *et al* 2011).

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), but sessile benthic fauna in the path of the mining operation will be affected, although impacts will vary from site to site.

Physical removal of large areas of a particular habitat type is likely to cause loss of habitat for some faunal groups. SMS mining will reshape the sea floor, removing vertical edifices and altering the texture of the substratum. However, it is anticipated that the vertical edifices (chimneys) will re-form at actively venting areas. While mining activities should not stop the hydrothermal system, they could alter the distribution of venting activity on a scale of metres to hundreds of metres (Van Dover 2011). The effect could be similar to disturbance and recovery associated with natural sea-floor eruptions on the East Pacific Rise (Shank *et al* 1998). There, after five years, it is believed a reasonably stable community resembling the pre-eruption faunal assemblage has re-established. A similar sequence was observed at the Juan de Fuca Ridge (Tunnicliffe *et al* 1997).

Recovery from deep sea mineral extraction operations will depend upon the species mix and will vary between sites. Van Dover (2011) notes that, for hydrothermal vent fauna, recolonization by the biomass-dominant species after a major disturbance could happen in just a few years at actively venting sites. However, for dormant sulphide mounds, visual recovery could take a decade or more. Williams *et al* (2010) found little sign of any recovery of hard-substrate benthos on seamounts off New Zealand, ten years after the cessation of fishing.

As previously mentioned, mining is not expected to stop hydrothermal activity/venting. Indeed, it is expected that chimneys at actively venting sites will re-form, providing new hard substrate. However, inactive sites – that is, dormant chimney structures – will not grow back, and any impact to the hard substrate habitat will be long-term.

In areas of sea floor with soft sediment, most of the infauna is found in the top 5 to 8 centimetres (Giere 1993). Gear that digs into the sediment can have an impact through direct crushing, compacting the substrate through increased weight of ma-
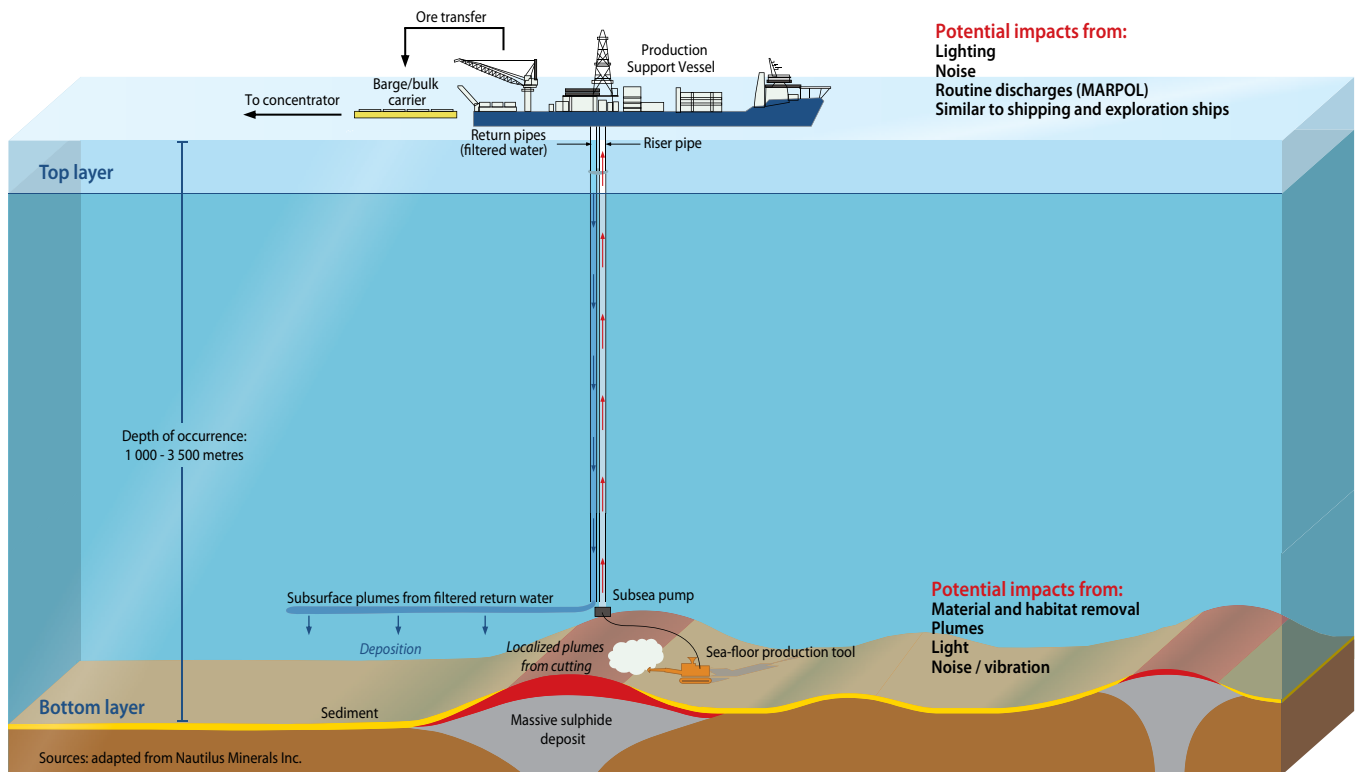
Figure 12. Example of a sea-floor massive sulphide mining system and related sources of potential environmental impact.

chinery or equipment, or, conversely, by dislodging animals and stirring up the sediment, which then re-settles. Disturbance of the sea floor will increase the mixing of sediments and seawater adjacent to the sea floor, although this may not be a major issue for SMS, since the target areas will be mostly comprised of hard substrate. Chemical release from the sediment might be enhanced (ICES 1992). This potential impact, along with all others, will need to be considered in the context of the environmental conditions that occur naturally. For example, at actively venting sites, metal release from the sea floor is an existing aspect of the natural environment.

SMS operations will probably target areas of hard substrate, such as chimney fields or SMS mounds. At some sites, overlying sediment will need to be removed to access sub-sea-floor SMS deposits. Even if there is little soft substrate, the physical scooping or grinding action of mining vehicles can cause some re-suspension of sediments. Naturally occurring particulate plumes are an important characteristic of actively venting hydrothermal vent fields. However, we do not know if this

feature has induced in vent communities a level of tolerance for the sediment plumes that might be caused by human-associated disturbance.

Settling of fine sediment from the dewatering plant discharge could affect sea-floor organisms, especially if the discharge occurs near the sea floor. Filter-feeding animals, such as corals, sponges, and mussels, rely on a food supply delivered by a clean current flow. If a plume of suspended sediment is present, the feeding efficiency of nearby downstream filter feeders could 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). Impacts from suspended sediment are likely to be site-specific and dependent on the type of technology used, the nature of the fauna, the sea-floor material, and oceanographic conditions in the area.

Other impacts to consider include noise, vibration, and light, all of which can either attract or repel fauna.

Midwater column

Potential impacts to the water column also need to be considered. Water-column activities could 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.

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 mineralized material and the water column may need to be considered more carefully if the ore delivery system is not fully enclosed. For an enclosed system, it is currently envisaged that material travelling up the lifting system will resemble a slurry, with about 10 to 20 per cent solids (mineralized material) and 80 to 90 per cent seawater (Coffey 2008).

The presence of the lifting system and transiting equipment could cause physical damage to individual fish and free-swimming invertebrates from accidental direct contact. 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 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.

Dewatering involves the separation of the seawater from the 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 or processing mineral facility, the seawater that has been separated from the ore will likely be discharged back into the sea. This discharge could occur at the sea surface, somewhere within the water column, or near the sea floor. The feasibility of various alternatives, especially the option of returning the discharge to near-bottom, may depend on the water depth of the site and other factors such as current flow and water-column stratification. Given the high grades thought to be associated with SMS deposits, it is likely that the developer would aim to retain all material possible, including fine particles. However, this might not be technically feasible, and the discharge water could still contain some fine material. Current technology suggests this material will have a size fraction up to around 8 microns (Coffey 2008). The discharge water will probably have elevated metal concentrations compared to ambient seawater, since it will have spent time in contact with the metal-rich ore. Its physical properties, such as temperature and salinity, might also be different from those of the body of water to which it is returned. Hydrodynamic modelling will be needed to estimate the fate of the discharge and to guide design of discharge equipment, such as diffusers, and standards, such as the appropriate depth and direction of discharge. 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. These are not exclusive to mining, but they will need to be considered. Among the impacts are noise and lights from the main vessel operation and from support vessels and bulk carriers moving in and out of the area. Air pollution and routine discharge are also associated with these vessels.

If the dewatering plant's discharge water is released within the upper 200 metres of the water column, the depth to which light generally penetrates in the open ocean, reduction in light penetration could affect primary productivity on a local scale. Reduced phytoplanktonic production due to a significant plume near the surface could also lead to localized oxygen depletion.

Individual jurisdictions will determine whether surface discharge of dewatering process water should be permitted. Decision making may involve such considerations as international law and standards, distance from shore or reefs, productivity and biodiversity of the surface waters, and other uses of the surface waters, such as fisheries (especially tuna fisheries around most of the Pacific islands).

3.6 ⋮ The potential extent of impacts

If a sediment plume is created through dispersal by currents, it will have a larger footprint than the physical mining area. There is also the possibility of plumes extending upwards into the water column, although engineering design should minimize such movement. Similarly, the area affected by discharge of the waste water and fine materials could be more extensive than the mined area. 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.

Accidental events and natural hazards

In addition to potential impacts from normal operation, it is important to consider accidental events and natural hazards. These include such possible problems as spills and oil leaks from the vessel/platform, which enter the sea, and leaks from the riser pipe or from sea-floor equipment (e.g., hydraulic oil leaks). Although unlikely, such extreme events 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 these sorts of events and must be prepared to respond in the event they do happen. Such precautions are generally covered under national and/or international regulations and are not detailed here. Natural hazards, such as extreme weather events, volcanic activity, etc., will also need to be considered in the management plans.

The Integrated Ocean Drilling Programme has conducted numerous scientific investigations of hydrothermal sites around the world. Pictured here is the Deep Sea Drilling Vessel JOIDES Resolution. Photo courtesy of Elaine Baker.

3.7 Mitigation and management measures

A key issue at the outset, before any exploration or exploitation, is the clear definition of environmental objectives that will guide management. These will vary regionally and nationally, but are typically directed at maintaining overall biodiversity and ecosystem health and function (see Volume 2 of this series). It is important to bear in mind that these objectives must be balanced against what is technically and economically feasible. A broad range of stakeholders, including persons who consider they are likely to be affected by the activities, scientists, and engineers, will need to be consulted during the formulation of mitigation and management measures.

Once these measures are developed, a review of the potential impacts will be necessary to determine the residual impacts of the development. Criteria for assessing residual impacts in the marine environment are based, wherever practicable, on probable extent, duration, and severity. Extent refers to whether the impact will be site-specific, local, or regional. Duration might be either prolonged or short. Severity could be classed as negligible, low, moderate, or high. Once these criteria have been defined, a cost-benefit analysis should be undertaken.

Where deep sea mineral extraction does occur, there are a number of ways to prevent, mitigate, and minimize impacts, and several have been considered within the context of SMS mineral extraction. Some of these are listed below.

Sea floor
The main impacts on the sea floor are expected to be material, habitat, and fauna removal, re-suspension of sediments, noise, vibration, and light. To limit the impacts, possible mitigation and management strategies include:
- setting part of the habitat, with representative animals, aside to serve as a reference area and a source of animals to assist recolonization of the impacted site;
- relocating some representative animals;
- installing artificial substrates to help recolonization by animals;
- order of extraction – where possible enhance progressive rehabilitation;
- considering location, positioning, and method of any sub-sea discharge to limit its impacts;
- employing technologies/methodologies, where possible, so that sediment re-suspension is minimized during cutting; and
- limiting the number and/or size of mine sites.

Midwater column
The main impacts in the midwater column are expected to be the presence of the ore transfer system, the transit of equipment between the sea surface and the sea floor, and discharge of seawater and sediment from the dewatering plant. To limit impacts to the midwater column, possible mitigation and management strategies include:
- considering filtration to as small a size as practicable where any sub-surface discharge occurs;
- developing and implementing emergency response procedures in the event of accidents leading to spills that might affect water quality; and
- using fully enclosed ore delivery systems.

Surface
The main impacts at the surface are expected to be the presence of the production support vessel or platform, barges, noise, light, and the potential discharge of seawater and sediment from the dewatering plant. To limit the impacts at the surface, possible mitigation and management strategies include:
- releasing discharge and water from the dewatering plant, where possible, at least below the top 200 metres of the water column (that is, below the light zone);
- developing and implementing environmental management plans that specifically cover waste minimization and loss prevention, in order to reduce impacts on water quality. The plans should address, among other things, deck drainage, wastewater discharges, waste management, and ballast water;
- developing and implementing emergency response procedures in the event of accidents leading to spills that could affect water quality;
- adopting effective mitigation measures to minimize the risk of injury to marine animals from ship strike or collision;
- installing an approved sewage treatment plant, certified through relevant international standards, to handle such normal ship discharges as treated sewage;
- maintaining deck lights on surface levels at the lowest levels needed to ensure safe working conditions; and
- developing safety, health, and environmental policies and plans for all offshore operations.

Key messages for environmental management

Scientific knowledge is limited in deep sea SMS environments, but sufficient knowledge exists to guide initial environmental management decisions.

The faunal communities of hydrothermal vent systems are highly adapted to the specific environmental conditions of vent sites (depth, temperature, and water chemistry), and sites often have many vent-endemic species. These localized communities may be highly vulnerable to disturbance from mining operations that could affect entire vent fields. The degree of connectivity between localized communities is unknown for most species. However, because such communities form around naturally ephemeral venting, they may be able to disperse and recolonize relatively quickly.

In contrast to the vent communities, the fauna of the surrounding non-hydrothermal area are often part of a wider regional species pool, and their distributions are not as localized. However, these species can be long-lived and slow-growing. As a consequence, their overall populations may be less vulnerable to disturbance than vent communities, but very slow to recover. Due to their wide distribution, disturbance from mining activity is unlikely to affect the regional species pool. Management of any mining operation needs to consider the range of faunal communities in the general area of mining.

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

Multidisciplinary science is required, involving collaboration among industry, academia/research organizations, relevant communities or interest groups, and government agencies.

Environmental management plans will be situation-specific, but they are likely to combine best-practice mining operation to reduce environmental impacts, spatial management that protects similar areas and communities from impact, and temporal actions that improve the chances of recolonization of fauna in mined areas.

Continuation of the wide-ranging involvement from mining companies, policy makers, lawyers, managers, economists, scientists, conservation agencies, NGOs, and societal representatives will be an important element in 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

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Deep sea mineral exploration and mining technology is aimed at the efficient identification and economic extraction of sea-floor mineral resources. Recently, there have been significant advances in offshore technology, engineering, and equipment, predominantly fuelled by the offshore oil and gas, dredging, and telecommunications industries. Much of this technology, especially trenching technology for laying pipelines, can be applied to deep sea mineral extraction, bringing the deep sea mining industry closer to commercialization.

Steps involved in the exploration and extraction of SMS deposits include:
- identifying potential targets;
- testing potential targets and prospect delineation;
- evaluating the resource;
- extracting minerals from the sea floor using remotely operated mining equipment;
- transporting the ore, via a lifting system, from the sea floor to a production support vessel on the sea surface;
- dewatering of the ore on board a production support vessel or platform;
- transferring the ore from the production support vessel to a transport barge or bulk carrier;
- transporting the ore to land for treatment and/or processing; and
- transporting concentrate and saleable products to market.
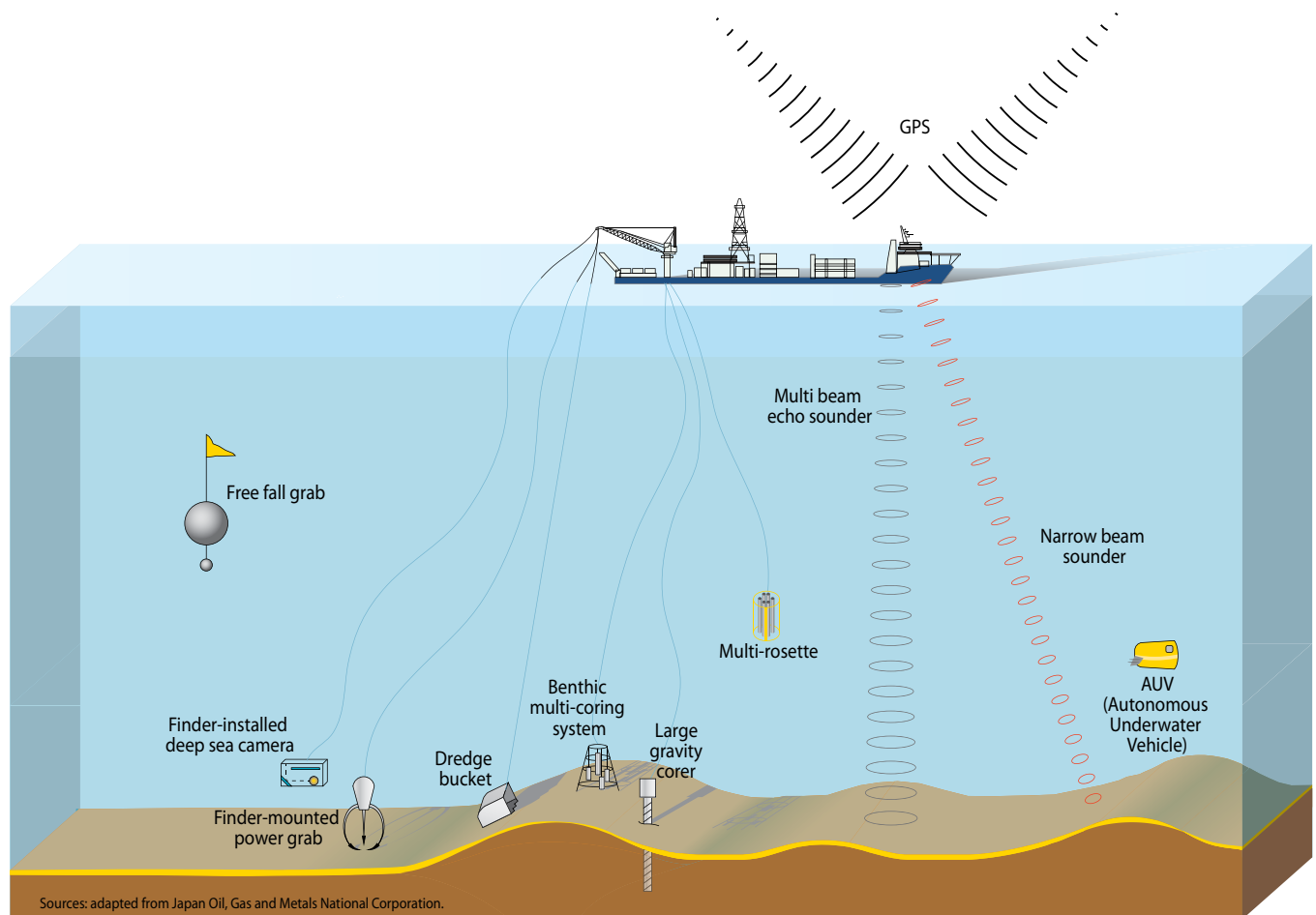
4.1 | Exploration

Exploration involves the identification, delineation, and evaluation of deep sea mineral resources and generally requires sophisticated, multi-purpose research vessels using advanced technologies, such as deep sea mapping equipment, autonomous underwater vehicles (AUVs), remotely operated vehicles (ROVs), water sampling equipment, photographic and video systems, and seabed sampling and drilling devices (Figure 13).

4.1.1 Target identification

SMS deposits are commonly raised sulphide mounds on the sea floor, with either fossil or active black smoker chimneys. Targets

Photo courtesy of GEOMAR.

GPS

Multi beam
echo sounder

Narrow beam
sounder

Free fall grab

Multi-rosette

AUV
(Autonomous
Underwater
Vehicle)

Finder-installed
deep sea camera

Benthic
multi-coring
system

Large
gravity
corer

Dredge
bucket

Finder-mounted
power grab

Sources: adapted from Japan Oil, Gas and Metals National Corporation.

Figure 13. Examples of exploration tools.

typically can be identified by sea-floor topography, water-column temperature anomalies, or anomalous redox potential, using regional geophysical and geochemical methods. The methods are low impact and the same as or similar to those used in conducting marine scientific research, such as:

- sidescan sonar;
- multibeam bathymetry;
- electromagnetics;
- three-dimensional plume mapping; and/or
- water-chemistry testing.

Data are collected from ship-mounted sensors and deep-towed systems, which "fly" close to the sea-floor. From these data, maps are created at a resolution high enough to select possible SMS sites. The resolution is rarely good enough to identify the sulphide structures directly, so a target testing phase is necessary.

4.1.2 Target testing and prospect delineation

Following target identification, possible SMS deposits are confirmed by direct inspection using underwater vehicles (AUVs
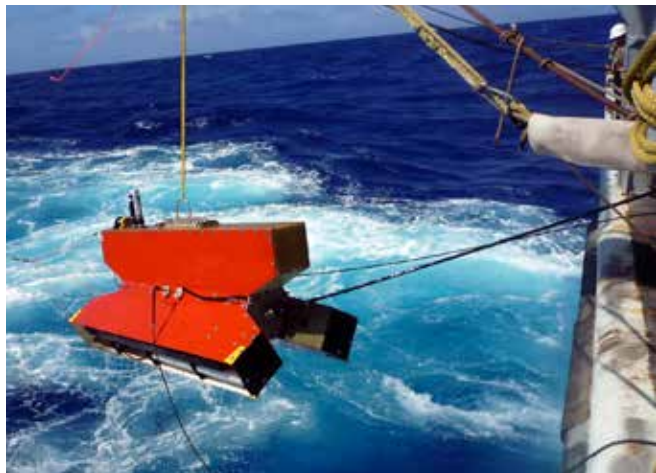

Photo of the IMI-30 deep-towed sidescan sonar. The IMI-30 is a 30 kHz sonar built and operated by the Hawaii Mapping Research Group at the University of Hawaii. It is designed to be towed from 100 to 500 m above the sea floor and obtain high resolution sonar images. It can reach depths up to 6 000 m. It is shown being deployed from the R/V Thomas G Thompson *in the southern Mariana back-arc basin area in 2012. Photo courtesy of Hawaii Mapping Research Group at the University of Hawaii.*

Operation of the British Geological Survey seabed drill from the R/V Sonne. *Photo courtesy of S. Petersen, GEOMAR.*

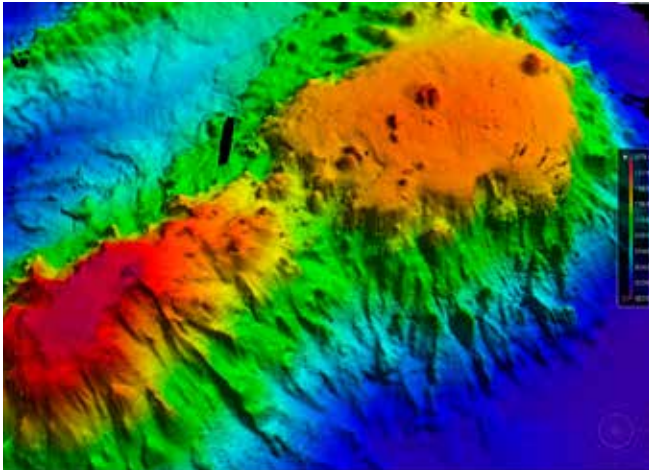*The Autonomous Benthic Explorer (ABE) is a robotic underwater vehicle used for exploring the ocean to depths of 4 500 metres). Photo courtesy of WHOI.*

Operation of the British Geological Survey seabed drill from the R/V Sonne. *Photo courtesy of S. Petersen, GEOMAR.*

and ROVs) and physical sampling of sea-floor rocks. This stage may involve:

- AUV and ROV mapping using video cameras on a systematic grid or traverse through the target area;
- grab sampling from the ROV to collect samples from the target area;
- AUV-based geophysical surveys to define the approximate resource boundaries on the sea floor; and
- high-resolution bathymetry surveys.

Prospect delineation provides a two-dimensional picture of the deposit, which allows an estimation to be made regarding the deposit's surface area.

4.1.3 Resource evaluation

Following prospect delineation, the best SMS prospects are advanced to resource status by systematic resource drilling and sampling. This allows a three-dimensional estimate to be made of the deposit's size.

High-resolution multi-beam bathymetric image acquired during one of the EMEPC campaigns. Photo courtesy of EMEPC.

Sample collected by the ROV LUSO near S. Miguel Island (Azores). Photo courtesy of EMEPC.

ROV maintenance. Photo courtesy of EMEPC.

ROV dives near the Azores Islands. Photo courtesy of EMEPC.

4.2 Mining

Mining is expected to 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;
- dewatering of the ore on board a vessel or platform;
- transfer of the ore from the vessel to a transport barge or bulk carrier/storage facility (silo vessel offshore or land-based) 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, where 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 thruster propellers 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 the 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 Sea-floor production tools/collectors

While there are numerous methods and technologies that might be employed to cut and gather the SMS ore, the current state of the art is multiple sea-floor production tools (SPTs) used to excavate the material from the sea floor in benches.

This excavation system is based on existing cutting technology. Each of the machines is configured differently and performs an individual task, such as levelling the ground or cutting up the bulk of the material. The current approach for the sea-floor production system is analogous to many surface mining systems, where it is common for a more flexible and mobile machine to

prepare the site, usually followed by a separate, dedicated, high-production system.

4.2.3 Lifting system

A number of methods have been investigated to transport 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 ore particles excavated from sea-floor deposits (mined slurry) 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.

Much of the design for 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.

4.2.4 Dewatering plant

The dewatering plant, situated on the PSV, will dewater the slurry to below the transportable moisture limit for the ore, while minimizing any material losses. The seawater that has been separated from the ore will likely be discharged back to the sea. The location of the discharge (near the sea floor or within the midwater column) will likely depend on the total depth of water, among other factors.

4.2.5 Onshore logistics / ore handling

Ore may 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. Ore transportation, handling, offloading, and stockpiling are well-established and well-understood operations. Should these operations be undertaken at port, the onshore storage and load-out facilities will receive ore from the offshore site via transportation barges. The ore will be stockpiled for subsequent loading onto bulk carriers that will transport it to a concentrator site or directly to a smelter.

Glossary

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

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.

Back-arc basin – basin developed between an island arc and the continental mainland formed as a result of oceanic plate subduction. Back-arc basins are typically found along the western margin of the Pacific Ocean.

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

Benthic zone – refers to the ecological region that is associated with the seafloor. 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 which shape the occurrence of biota and their interaction with the physical environment.

Black smoker – hydrothermal vent on the sea floor where soot like material is ejected from chimneys. The material is actually super-heated water containing large concentrations of dissolved minerals. As the super-heated water meets the very cold ocean-bottom water, the dissolved minerals precipitate out and settle onto the surrounding rock. This causes the chimneys to grow in height over time.

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

Chemosynthesis – the formation of organic material by certain bacteria using energy derived from simple chemical reactions. Chemosynthetic bacteria provide the foundation for the biological colonization of vents

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.

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.

Evolved seawater – seawater that circulates through the earth's crust at vent sites is heated up and reacts with the surrounding rock to produce the mineral-rich vent fluids.

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).

Flange – in relationship to hydrothermal deposits, flanges are outgrowths from the main body of a sulphide structure and are associated with pooling of high-temperature vent fluids beneath the flange. The trapped fluid overflows around the edge of the flange and percolates up through the flange.

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 a fluid, in particular, 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.

Hydrothermal – forming from hot fluids; in this context, it refers to metals that come from the leaching of rocks by hot fluids along spreading ridges. Seawater is heated up as it approaches magma at the spreading ridges and then it returns to the sea floor, where it is expelled into the ocean carrying relatively high concentrations of leached metals.

Hydrothermal plume – an emission of relatively warm, metal-rich water (hydrothermal fluid) from the seafloor.

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 the volcanic islands.

Macrofauna – organisms retained on a 0.3 mm to 0.5 mm sieve.

Magma – molten or semi-molten material within the earth's crust from which igneous rock is formed by cooling.

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.

MARPOL – international convention for the prevention of pollution from ships. "MARPOL" is short for marine pollution. The country where a ship is registered (flag state) is responsible for certifying the ship's compliance with MARPOL's pollution prevention standards.

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

Megafauna – animals larger than 45 kg in weight.

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

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.

Mid-ocean Ridge – a mountainous area where the Earth's tectonic plates are gradually moving apart. Upwelling magma rises up to fill the gap and form new sea floor. The magma creates a heat source, producing hydrothermal vents along the ridge.

ODP – Ocean Drilling Program, an international consortium that studied the history and composition of Earth's ocean basins.

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).

Polychaete worms – heat-tolerant worms (often called tube worms) found at hydrothermal vents. The worms survive with the assistance of symbiotic bacteria.

Protozoans – a diverse group of generally motile single celled 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 organisms – organisms that are attached to a substrate such as the rocky sea floor and are not able to move around.

Subduction zone – region where two tectonic plates colide. The plate with the lowest density will ride over the edge of the other plate. This heavier plate is said to be "subducted" as it is forced to bend and plunge under the lighter plate.

Substrate – the surface a plant or animal lives upon. The substrate can include biotic or abiotic materials.

Sulphide mound – a hydrothermal mound formed by successive black smoker chimneys. The mound can be up to several tens of metres thick and several hundred metres in diameter.

Xenophyophores – single-cell protozoans, abundant on the abyssal plains. They can grow to a surprising large size (up to 20 cm) and have a diverse range of appearance. They are deposit 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. 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).