Ocean & Coastal Management 84 (2013) 54–67

Contents lists available at ScienceDirect

Ocean & Coastal Management

journal homepage: www.elsevier.com/locate/ocecoaman

Review

Mining of deep-sea seafloor massive sulfides: A review of the deposits, their benthic communities, impacts from mining, regulatory frameworks and management strategies

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ARTICLE INFO

Article history:
Available online 6 August 2013

ABSTRACT

Seafloor massive sulfide (SMS) deposits form in a suite of hydrothermal settings across a range of depths. Many deposits are of a tonnage and mineral grade comparable to land deposits and are attractive to mining companies. Economically viable deposits can be either active or inactive, with different biological communities present at each. These benthic communities may include specially adapted and endemic fauna that could be severely impacted by mining activity. Although there is currently no active SMS mining, recent research from Industry and scientific investigations is able to inform decisions on the management of SMS deposits, including appropriate mitigation strategies to minimise the impact of mining activities. Mitigation strategies will likely focus on facilitating recolonisation of areas impacted by mining, spatial management with open and closed areas and reducing the effects of sediment plumes from mining activity. Regulation of mining activity at SMS deposits can be complex, falling under national and international legislation alongside codes of practice issued by industry and other stakeholders. Despite decades of research effort, there are still many unknowns about the ecology of SMS deposits, in particular for inactive SMS sites and the genetic and demographic connectivity of populations among deposits. With considerable industry interest in the exploitation of SMS deposits in the Western South Pacific Ocean, there is an urgent need to assess the potential impact of SMS mining, particularly on the benthic fauna, so that appropriate management strategies can be designed and implemented.

1. Introduction

Seafloor Massive Sulfide (SMS) deposits are areas of hard substratum with high base metal and sulfide content that form through hydrothermal circulation and are commonly found at hydrothermal vent sites. The high base metal content, along with commercially exploitable concentrations of gold and silver, have interested mining companies for decades with some of the first exploration and feasibility studies in the marine environment occurring in the 1980s at 21°N on the East Pacific Rise (Crawford et al., 1984) and in the Red Sea (Amann, 1985). Initial assessments of global marine mineral resources included SMS deposits (Emery and Skinner, 1977) even before the hydrothermal vents that formed them were discovered in 1977 (Corliss et al., 1979). However, the cost of extraction, falling mineral prices and technological barriers appeared to halt potential SMS mining in the deep sea before it became a commercial reality (Van Dover, 2011). Recent increases in mineral prices and mineral demand through the industrialisation of countries such as China and India, alongside technological advances have led to SMS mining becoming economically viable, with particular interest in SMS deposits in the Exclusive Economic Zones (EEZ) of Papua New Guinea (PNG) and New Zealand (NZ). In PNG, exploration licenses and mining leases were granted by the government in 1997 and 2011 respectively (http://www.nautilusminerals.com/). In NZ, the potential for deep-sea hydrothermal deposits was first assessed more than 20 years ago (Glasby and Wright, 1990) with large areas of seabed along the Kermadec and Colville Ridges being licensed for prospecting in 2002 (http://www.nzpam.govt.nz/cms/online-services/current-permits/).

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http://dx.doi.org/10.1016/j.ocecoaman.2013.07.005

Hydrothermally active sites are known to host unique communities of organisms dependent on the metal- and sulfide-rich vent fluids that support the chemosynthetic bacteria at the base of the food web (reviewed in Van Dover (2000)). Such communities are of considerable interest to science, in particular for biogeographic studies (e.g. Moalic et al., 2012) and understanding the origin of life on Earth (e.g. Corliss et al., 1981). These benthic communities are vulnerable to disturbance and localised loss; mining SMS deposits will remove all benthic organisms inhabiting the substratum, with any high-turbidity, and potentially toxic sediment plumes resulting from mining activities likely to impact upon benthic communities downstream (Gwyther, 2008b). Recovery of communities at SMS deposits disturbed by mining activities will rely on recolonisation from neighbouring populations, however, other than detailed studies at sites in PNG (Collins et al., 2012; Thaler et al., 2011), very little is known about the connectivity (genetic or demographic) of populations or the spatial distribution of benthic fauna at SMS deposits.

Management strategies are required that can conserve the special biological communities and ecology of SMS deposits whilst enabling economically viable extraction of their valuable mineral resources (International Seabed Authority, 2011b; Van Dover, 2011). Such resource management requires a robust legislative framework, clear management objectives, and comprehensive information on the SMS deposits themselves, their wider environment and the biological communities they support. Unfortunately, there are considerable gaps in our understanding of the ecology of SMS deposits that prevent the refining of existing legislation to better manage activities at SMS deposits (International Seabed Authority, 2011b). This review aims to summarise the current knowledge on SMS deposits, their benthic biological communities, the probable impacts of mining, existing legislative frameworks and management strategies to regulate mining, with particular reference to the proposed mining of the Manus Basin in the PNG EEZ, and the Kermadec volcanic arc system in the NZ EEZ. In particular, this review is designed to provide the necessary background information for those involved in managing SMS resources.

2. The geology of seafloor massive sulfides

2.1. Formation and location of SMS deposits

SMS deposits form through hydrothermal activity; cold seawater percolates down through the seafloor, is heated through geothermal energy, becomes buoyant and rises, dissolving metals and sulfides from the surrounding rocks. These hydrothermal systems can be low intensity (typically <200 °C), which are generally thought unimportant in the formation of SMS deposits, or high-intensity (typically 200–400 °C), which although located at fewer more discreet sites, tend to concentrate mineral deposits (Rona, 1985). The location of SMS deposit formation depends on circulation. In 'leaky' systems, mixing of primary hydrothermal fluids and seawater occurs beneath the seafloor so that SMS deposits occur within the oceanic crust, whereas in 'tight' systems hydrothermal fluids are expelled through vents where they mix with seawater to precipitate SMS deposits on the seafloor (Rona, 1985). Rapid precipitation of metal sulfides from their host hydrothermal fluid in tight systems leads to chimney formation, with chimney collapse and coalescence forming sulfide mounds (Humphris et al., 1995).

SMS deposits can also form where hypersaline seawater in the subsurface hydrothermal convection system enhances the emission of metal-rich vent fluid. This fluid then becomes trapped by the density-stratified brines and precipitates out onto the basin floor, such as in the Red Sea (Alt et al., 1987; Amann, 1985; Bäcker and Schoell, 1972; Rona, 1985). As well as SMS (also known as polymetallic sulfide deposits (PMS), henceforth referred to as SMS) typically associated with high-temperature vents, there are various other deposits associated with hydrothermal activity. These include low-temperature hydrothermal vents and associated mineral deposits (LTH), near-field metalliferous sediments (NFS), distal metalliferous sediments (DIS) and vein and breccia deposits (VSD). LTH are typically found at the margins of high-temperature vent fields and have low sulfide mineral accumulations; NFS consist of metal-rich particulates from high-temperature vent plume fallout; DIS are also formed from plume fallout but at greater distance from the plume source, and VSD occur where faulting and uplift exposes the mineralised stockwork of a hydrothermal vent system (Hannington et al., 2002). Of these mineral deposits, SMS are the only deposits currently being investigated for commercial exploitation. SMS deposits can be either inactive or active, with continued hydrothermal activity required to build on existing deposits. However, the distinction between active and inactive deposits is not always clear, with rapid switching in activity of deposits complicating the definition of active and inactive areas (Gwyther, 2008b).

According to the InterRidge vent database, there are approximately 600 hydrothermal vents known globally from plume signals or direct observations (Beaulieu, 2010), with many more vents expected to be discovered from unchartered waters (Baker and German, 2004). Recent estimates suggest that at mid-ocean ridges alone, there are approximately 700 vent sites to discover (Baker and German, 2004). Plume signal detection has been used to identify the location of many hydrothermal vent sites and their associated SMS deposits but this technique will underestimate SMS deposit distribution because inactive portions of the mid-ocean ridge system may host inactive deposits thousands of years old (Hannington et al., 2011). Recent estimates of global SMS deposits suggest deposits occur on average every 100 km along the oceanic plate boundaries with approximately 900 modern deposits globally (Hannington et al., 2011). From the approximately 600 hydrothermal vents discovered, there are only 95 confirmed SMS deposits on the publically available InterRidge Database (Beaulieu, 2010), although since the database was last updated, more deposits have been identified, increasing the current total to 165 (Hannington et al., 2011). These deposits have a broad spatial distribution (Fig. 1) and have been found across a range of depths (Table 1), with the shallower, more easily accessible (and so more economically viable) deposits likely to be mined first (Rona, 2003).

SMS deposits have been found in many hydrothermal vent localities and in a variety of hydrothermal settings. These include along fast-spreading ridges, such as the East Pacific Rise (Francheteau et al., 1979; Spiess et al., 1980), slow-spreading ridges, such as the Mid-Atlantic Ridge (Fouquet et al., 1994; Kong et al., 1985; Krasnov et al., 1995; Murton et al., 1995; Rona et al., 1986) and the Central Indian Ridge (Halbach et al., 1998; Herzig and Plüger, 1988; Plüger et al., 1990) and ultraslow ridges, such as the Mid-Cayman Spreading Centre (Connelly et al., 2012).

Large SMS deposits associated with metal-enriched sediments have been found in the Red Sea (Alt et al., 1987; Amann, 1985; Bäcker and Schoell, 1972; Rona, 1985). SMS deposits have also been found in sediment-filled basins in the Gulf of California (Lonsdale et al., 1980), on sedimented ridges along the Juan de Fuca Ridge (Mottl et al., 1994; Zierenberg et al., 1996) and in association with felsic volcanism in the Eastern Manus Basin (Binns and Scott, 1993). Known deposits are also located in back-arc spreading centres, such as the Central Manus Basin (Both et al., 1986), Mariana Trough (Craig et al., 1986; Kastner et al., 1986), Lau Basin (Fouquet et al., 1991), Okinawa Trough (Halbach et al., 1989), East Scotia Ridge (Rogers et al., 2012) and along arc systems, such as the Kermadec Arc (de Ronde et al., 2001; Stoffers et al., 1999; Wright et al., 1998).

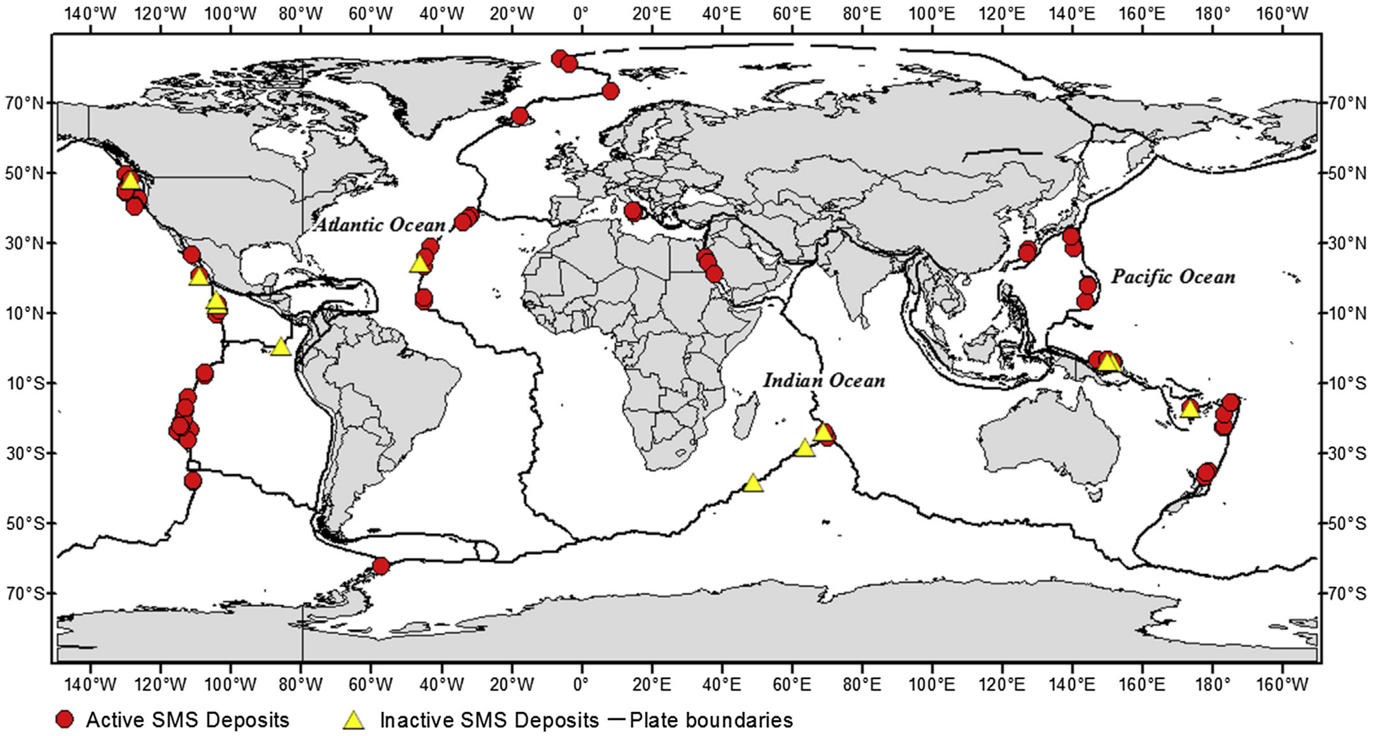

Fig. 1. Global distribution of SMS deposits. Red circles: active deposits; yellow triangles: inactive deposits. Using data from the InterRidge Database (Beaulieu, 2010). Note that more deposits are known (see Hannington et al., 2011) but their positions are not available to complete this figure. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Whether a deposit is from a fast-spreading or slow-spreading centre will influence the distribution and frequency of occurrence of SMS deposits (Rona, 1985), affecting the mineral grade and economic viability of mining a deposit. The hydrothermal setting of deposits also affects their density, with active deposits at slow- and fast-spreading ridges occurring on average every 174 km and 54 km respectively (Hannington et al., 2011), whilst back-arc spreading centres host deposits at similar densities to slow-spreading ridges (Hannington et al., 2011). There is also the potential for a large number of inactive unknown sites, so the spacing of inactive deposits is uncertain.

2.2. *Mineral composition and size of deposits*

Deposits are typically enriched with base metals (iron, zinc, copper and lead), sulfides and numerous other elements, including calcium, lead, gold, silver, arsenic, cobalt, molybdenum and platinum (Krasnov et al., 1995). The exact mineral composition of deposits varies according to hydrothermal activity, tectonic setting and the section of the deposit sampled. For example, although active deposits from the Mid-Atlantic Ridge (MAR), East Pacific Rise (EPR), Central Indian Ridge (CIR), Lau Basin and Okinawa Trough are broadly comparable in iron, zinc and copper concentrations (Fouquet et al., 1991; Halbach et al., 1989; Krasnov et al., 1995), deposits from back-arc basins tend to have lower iron and higher gold content than from Mid-Ocean Ridge (MOR) systems (Von Damm, 1990). There are subtle differences between active and inactive deposits, with active deposits at MOR systems having a higher calcium content and inactive deposits being enriched with silver and gold (Krasnov et al., 1995). The temperature of venting will influence mineral composition with high (>300 °C) and low (<300 °C) temperature venting associated with copper and zinc enrichment respectively (Hannington and Scott, 1988), such as in deposits from the CIR (Halbach et al., 1998). The percentage metal composition may also vary within deposits, with concentrations of iron, copper and zinc all increasing with increasing penetration of deposits in the Okinawa Trough (Halbach et al., 1989). Precious metals also occur in high concentrations in SMS deposits, with the most gold-rich deposits also containing the highest silver, arsenic and lead concentrations, typically in low-temperature Zn-rich deposits (Hannington et al., 1986). The gold and silver composition of SMS deposits depends on numerous site-dependent factors, including temperature, pH, total reduced sulfur concentrations, salinity and the oxidation state of the hydrothermal fluid (Hannington and Scott, 1988).

Recent estimates suggest that global massive sulfide deposits in the modern volcanic zones of the global ocean amount to 6×10^8 tonnes, with an estimated copper and zinc mass of 3×10^7 tonnes, comparable to the discovered metal in modern massive sulfide deposits on land (Hannington et al., 2011). As well as having ore grades comparable to land deposits (Hannington et al., 2011), SMS deposits in the sea can occur on a scale comparable to them, although many land deposits are an order of magnitude greater in size (Hoagland et al., 2010). The size of SMS deposits can vary widely, such as at the TAG and Broken Spur sites along the MAR. The TAG site includes an SMS mound 250 m diameter and 50 m high, topped with hydrothermal vent chimneys (Rona et al., 1986), whilst the Broken Spur site hosts at least five sulfide mounds ranging in size from 5 m high and 3 m diameter to 40 m high with a 20 m base (Murton et al., 1995). Deposits at MAR are comparable in size to those at the Southern Explorer Ridge where ten of the largest sulfide mounds had a diameter of 150 m and depth of 5 m, amounting to a total of 2.7–4.5 million tonnes of SMS deposit (Hannington and Scott, 1988). Estimates of gold and silver deposits at Southern Explorer Ridge alone amount to 2.0–3.4 tonnes of gold and 255–396 tonnes of silver (Hannington and Scott, 1988).

The SMS deposits that will likely be amongst the first to be mined occur in the Manus Basin, north of PNG. Investigations have

Table 1
Summary of SMS deposit locations and depths using the InterRidge Database (Beaulieu, 2010). Note that more deposits are known (see Hannington et al., 2011) but their positions and physical characteristics (active/inactive, depth) are not available to complete this table.

Ocean	Region	Activity	Maximum or single reported depth (m) of individual deposits
Indian	Red Sea	Active	1540–2200
	Central Indian Ridge	Active	2460–3320
		Inactive	2850
	Southwest Indian Ridge	Inactive	1500–2940
Mediterranean	Aeolian Arc, Tyrrhenian Sea	Active	200–1000
Southern Ocean	Bransfield Strait	Active	1080
North Pacific	Explorer Ridge	Active	1850
	Gorda Ridge	Active	2800–3300
	Gulf of California	Active	2000
	Izu-Bonin Arc	Active	1110–1360
	Juan de Fuca Ridge	Active	1540–2450
		Inactive	2400
	Galapagos Rift	Inactive	2600
	Mariana Arc	Active	1470
	Mariana Trough	Active	3640–3676
	Northern East Pacific Rise	Active	2520–2650
		Inactive	2000–2600
	Okinawa Trough	Active	740–1450
South Pacific	Kermadec Arc	Active	930–1800
	Lau Basin	Active	1764–2500
	Manus Basin	Active	1500–2500
		Inactive	1920–2500
	North Fiji Basin	Active	1980–2000
		Inactive	2000
	Pacific-Antarctic Ridge	Active	2200–2240
	Southern East Pacific Rise	Active	2270–3000
Arctic	Kolbeinsey Ridge	Active	400
	Lena Trough	Active	4000
	Mohns Ridge	Active	2400
	Gakkel Ridge	Active	4100
North Atlantic	Northern Mid-Atlantic Ridge	Active	865–3670
		Inactive	3900

identified a mineralised ore body at a site called “Solwara 1” consisting of a mound 2 km in diameter rising 200 m above the seafloor. The ore consists of 870 000–1 300 000 tonnes, containing 6.8–7.5% weight copper and 4.8–7.2 g t^{-1} of gold (Gwyther, 2008b). Other deposits currently being explored for mining potential include those in the NZ EEZ along the Kermadec arc–back-arc system (de Ronde et al., 2001; Stoffers et al., 1999; Wright et al., 1998), where deposits exist at exploitable depths of 150–200 m in the Bay of Plenty (Stoffers et al., 1999), 870–930 m at Clark Seamount (Malahoff, 2008) and as deep as 1150–1800 m at Brothers Seamount (Wright et al., 1998). Deposits at Brothers Seamount are also rich in base (Wright et al., 1998) and precious (de Ronde et al., 2011) metals with high concentrations of copper, zinc, iron and gold (up to 15.3% weight, 18.8% weight, 19.1% weight and 91 g t^{-1} respectively).

3. The benthic communities of seafloor massive sulfide deposits

3.1. Communities at SMS deposits

Two main types of benthic communities are found at SMS deposits, a chemosynthetic community of hydrothermal vent specialists inhabiting active deposits; and a community of background fauna colonising inactive deposits (also known as periphery and halo fauna). A third community is also hypothesised to exist, comprising specialised fauna adapted to the unique chemical environment of weathering inactive deposits (Van Dover, 2007, 2011).

The community of hydrothermal vent specialists has been studied in great detail at numerous locations – see reviews by Lutz and Kennish (1993) and Van Dover (2000). This community is supported by chemosynthetic bacteria reliant on the methane or sulfide-rich vent fluids for primary production (Karl et al., 1980). Many vent specialists are in symbiosis with these chemosynthetic bacteria and can only survive in close proximity to vent fluid emissions. For example, the tubeworm *Riftia pachyptila* has no mouth or gut and obtains its energy from the endosymbiotic bacteria housed within a specialised sack-like organ, the trophosome (Cavanaugh et al., 1981; Felbeck, 1981; Jones, 1981). Hydrothermal vent fauna typically have high biomass and low diversity (Grassle, 1985) compared to the background fauna, with certain species, such as *R. pachyptila*, having rapid growth rates enabling colonisation of new vent habitat (Lutz et al., 1994). Despite relatively low diversity, there have been more than 500 new species described from hydrothermal vents, with more expected to be described as more vent fields are discovered (Desbruyéres et al., 2006). The degree of activity, whether venting is high or low temperature, will also influence the communities present, with different species associated with high- and low-temperature venting.

The community of background fauna colonising inactive deposits has not been as well studied with the majority of research effort being directed at vent communities. The background fauna resembles fauna of seamount communities with organisms typically being sessile, filter-feeding, long-lived and slow-growing, including taxa such as sponges, hydroids, corals, anemones, squat lobsters, ophiuroids and holothurians (Collins et al., 2012; Galkin, 1997; Van Dover and Hessler, 1990). These taxa take advantage of the hard substrata provided by inactive SMS deposits.

There have not been any studies to date confirming or refuting the existence of the third community, the hypothesised specialised fauna hosted by weathering inactive deposits. Van Dover (2007) has noted that there are species that have been described from inactive sulfide deposits, including the polynoid polychaete, *Eunoe alvinella*, and the archaeogastropod limpets *Neolepetopsis verruca* and *Neoleptopsis densata*, although whether these species are restricted to particular inactive deposits remains to be seen.

3.2. Faunal distribution at SMS deposits

At the deposit scale, biological communities show distinct zonation in relation to distance from hydrothermal vent emissions. There is a central vent zone dominated by vent fauna, a distal vent zone with maximum densities of non-vent fauna and a non-vent impact zone with higher densities of non-vent fauna relative to regional values (Arquit, 1990). The distance at which these zones occur in relation to active hydrothermal venting will differ between SMS deposit sites. For example, at Snake Pit, MAR, the central vent zone occurred within 10–80 m of active black smoker chimneys and the distal vent zone occurred 120–180 m from active chimneys (Sudarikov and Galkin, 1995). At Ashes vent field, JdFR, the central vent zone extended for 100 m from the vents, the distal vent zone occurred at 100–725 m and the non-vent impact zone extended from 725–1300 m (Arquit, 1990). The high density of fauna around vent sites relative to background levels, known as the ‘halo’ effect, also occurs in the Manus Basin, PNG. Inactive SMS deposits in the vent periphery were found to host a range of invertebrates with greater densities (Galkin, 1997), including sponges, hydroids, corals, anemones, squat lobsters, ophiuroids and holothurians. High densities of background fauna in proximity to vents are thought to occur through enhanced food supply, with tissue stable isotope values indicating the contribution of a chemosynthetic food source to halo fauna diet (Erickson et al., 2009).

The geochemical environment also varies within single active deposits, with a complicated micro-distribution of habitat patchiness supporting complex distributions. For example, at hydrothermal vents on the East Scotia Ridge the faunal assemblage consisting of *Kiwa* sp., gastropods, barnacles and anemones displayed zonation at both within-chimney and between-chimney scales (Marsh et al., 2012).

3.3. Global biogeography of SMS communities

SMS communities often exist in relative isolation with distances of anything between 100s and 1 000s of km between vent fields, potentially restricting genetic mixing between sites through limited larval dispersal. On a global scale, tectonic processes can isolate hydrothermal vent fields over millions of years, leading to speciation and the formation of unique biological communities that can be broadly separated into biogeographic provinces (e.g. Van Dover et al., 2002).

The patchy nature of sampling within hydrothermal settings has led to an evolving appreciation of hydrothermal vent biogeography with province boundaries re-defined as sampling effort has increased and new hydrothermal vent fields have been discovered. The first biogeographic province model had seven provinces (Tunnicliffe, 1997), whilst subsequent models identified four (Mironov et al., 1998), five (Moalic et al., 2012), six (Bachraty et al., 2009; Van Dover et al., 2002), and eight provinces (Tunnicliffe et al., 1998; Tyler and Young, 2003). A recent review by Rogers et al. (2012) proposes a total of 11 biogeographic provinces (Fig. 2) comprising the Mid-Atlantic Ridge (MAR), East Scotia Ridge (ESR), Northeast Pacific (NEP), North East Pacific Rise (NEPR), South East Pacific Rise (SEPR), South of the Easter Microplate (SEM), Indian Ocean (IO), Northwest Pacific (NWP), West Pacific (WP), Central/Southwest Pacific (CSWP) and the Kermadec Arc (KA). These provinces are distinguished by faunal composition and structure of the vent communities, and particularly by their most abundant species.

As more vent fields are discovered, more biogeographic provinces may be identified or increased sampling could better define gradients and lead to fewer separate provinces. It is also possible that some locations will be identified to be of particular importance as sources or stepping stones for the dispersal of fauna among the distinct provinces (Moalic et al., 2012).

3.4. Connectivity of SMS deposit populations

Population connectivity (defined here in terms of genetic connectivity as opposed to demographic connectivity) is controlled by a suite of factors, including the local hydrographic regime, the distance between sites, small spatial-scale habitat suitability, the evolutionary history of the population in question, and life history characteristics (Gardner et al., 2010; Reisser et al., 2011; Wei et al., 2013). The connectivity and dispersal of 14 vent endemic species was reviewed by Vrijenhoek (1997), who suggested that vent species fall under four models of connectivity and dispersal; 1) the island model, where gene flow occurs without geographical bias; 2) the isolation by distance or stepping-stone model, where genetic differentiation increases with geographical distance; 3) segment-scale divergence, where genetic differentiation is associated with offsets between ridge segments; and 4) ridge-scale isolation, where isolation by distance occurs along a ridge axis. The island model includes species such as *Bathymodiolus thermophilus* and *Calyptogena magnifica*; the stepping-stone model includes *R. pachyptila*; segment-scale divergence includes Alvinellid worms and ridge-scale isolation includes the brooding amphipod *Ventiella sulfuris.*

If populations within a region demonstrate high genetic connectivity then there is mixing between the populations, implying areas disturbed by mining could be recolonised by other populations in the region without significant loss of genetic diversity.

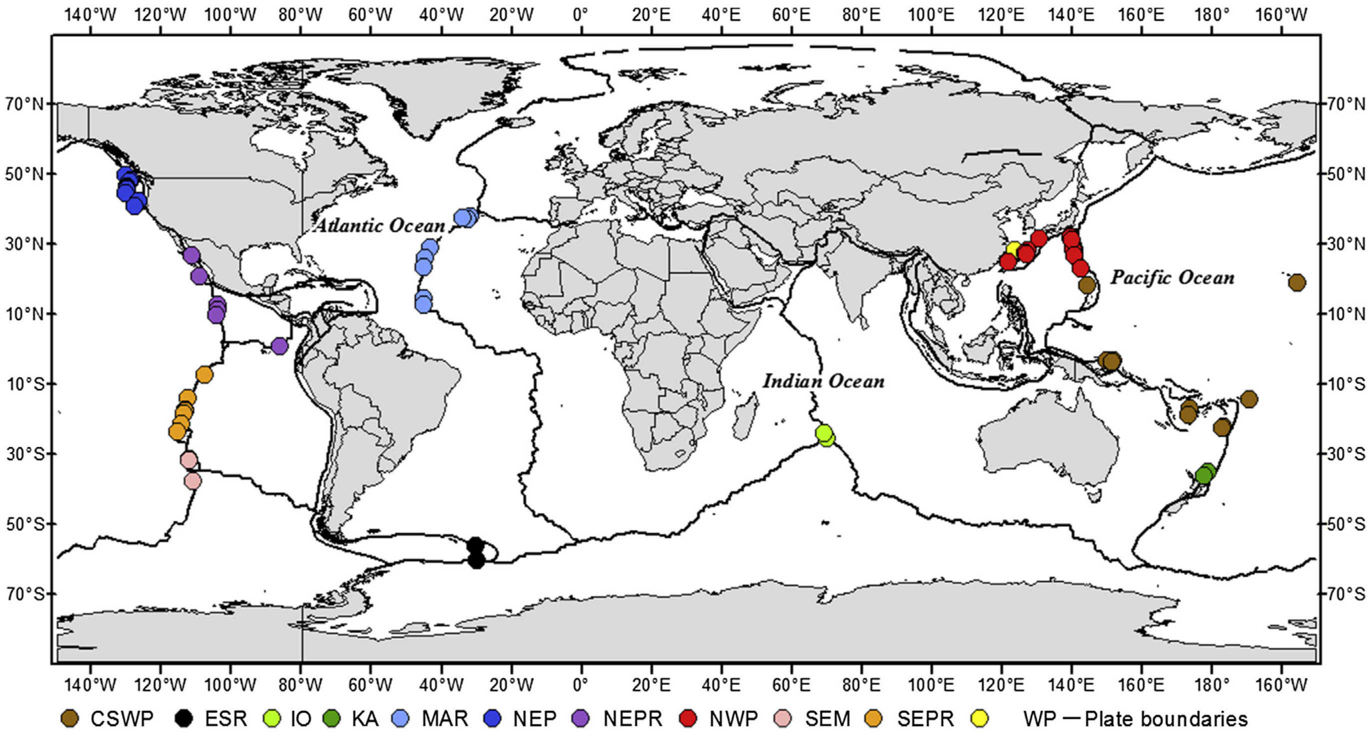

Fig. 2. Map of the global biogeography of hydrothermal vents communities, after Rogers et al. (2012). Abbreviations are CSWP: Central South West Pacific, ESR: East Scotia Ridge, IO: Indian Ocean, KA: Kermadec Arc, MAR: Mid-Atlantic Ridge, NEP: Northeast Pacific, NEPR: North East Pacific Rise, NWP: North West Pacific, SEM: South of the Easter Microplate, SEPR: South East Pacific Rise, WP: Western Pacific.

Hydrothermal vent fauna populations can demonstrate high levels of genetic connectivity, such as *Ifremeria nautilei* populations from Manus Basin, where connectivity was assessed using mitochondrial DNA COI sequence variation and nine nuclear microsatellite markers (Thaler et al., 2011). There was no population structure at patch (within a structure, such as a chimney), mound (between chimneys at a deposit) or site (between deposits) scale (Thaler et al., 2011). This suggests that local populations are highly connected by gene flow. Patterns of apparent genetic connectivity can also depend on the markers used. For example, high connectivity among *R. pachyptila* populations along a 4 000 km stretch of the northern EPR and Galapagos Rift was inferred from comparing ten enzyme encoding loci (Black et al., 1994). However, a study using amplified fragment length polymorphisms as a genomic DNA fingerprinting technique found differentiation among *R. pachyptila* populations from all regions and within each region, suggesting a more patchy population structure with some individuals separated by just 400 m being genetically distinguishable (Shank and Halanych, 2007). The most recent investigation using one mitochondrial and three nuclear gene loci suggests the connectivity of *R. pachyptila* populations decreases with geographic distance supporting a linear stepping-stone model of dispersal (Coykendall et al., 2011).

The pelagic larval development (PLD) of a species has major implications for population connectivity, with a longer PLD likely to lead to greater population connectivity. As such, the life history characteristics of vent fauna can help explain observed patterns in genetic connectivity between populations. For example, the free-swimming, lecithotrophic Waréns larva of *I. nautilei*, and the subsequent planktotrophic larval stage are thought to provide high dispersal capability (Reynolds et al., 2010) and contribute to the lack of population structure (high levels of gene flow) within the Manus Basin (Thaler et al., 2011). When life history characteristics are combined with information on the local hydrographic regime, models can be produced predicting the connectivity of populations. In the case of *R. pachyptila*, its wide dispersal ability results from a long larval life span (average 38 days, Marsh et al. (2001)). However, the hydrodynamics can affect dispersal distance. Current reversals at 9°N along the EPR restrict dispersal distances to <100 km and along axis flow at 13°N enables dispersal distances of up to 245 km (Marsh et al., 2001). The physical structure of an environment will influence the hydrodynamics and hence larval dispersion and population connectivity. For example, there is larval retention within axial valleys at sites along JdFR and Explorer Ridge, where larvae are retained within vent fields or even sections of a ridge (Metaxas, 2004). Populations at hydrothermal vents on seamounts also demonstrate high larval retention (Metaxas, 2011). For example, along the Mariana and Kermadec Arcs, populations are patchily distributed and spatially constrained (Metaxas, 2011).

Populations of vent fauna may be connected with populations from other chemosynthetic environments. Although the majority of vent species have only been found at vent sites, approximately 5% of vent species have been found at other chemosynthetic environments, including whale falls and seeps, and a further 9% are found at other non-vent habitats (Wolff, 2005). These environments have been controversially proposed as potential ‘stepping-stones’ for vent fauna, aiding colonisation of chemosynthetic habitat over longer distances (Smith, 1989), although this could only be possible for the few species shared between vents and other chemosynthetic environments. Within the New Zealand region, at least one solemyid clam, *Acharax clarificata* and one sponge, *Pseudosuberites* sp., have been found at both seeps and active vent sites, with certain genera also shared between seep and active vent sites in the region (Baco et al., 2010). At vent sites on the MAR, the ophiuroid *Ophioctenella acies* was found only at active vents (Stöhr and Segonzac, 2005; Tyler et al., 1995), whilst the other four ophiuroids at active vent sites, *Ophiactis tyleri*, *Ophiocten centobi*, *Ophiomitra spinea* and *Ophiotreta valenciennesi rufescens*, were also found in neighbouring non-vent habitats (Stöhr and Segonzac, 2005). In addition, *O. acies* is known to inhabit methane seeps in the northwest Atlantic (Van Dover et al., 2003).

3.5. Recolonisation of SMS deposits

Hydrothermal vent species are vulnerable to habitat loss through mining activities but if vents remain active following disturbance, deposits could rebuild. Rapid re-growth of chimneys was observed during exploration of proposed mining sites at Solwara 1 in PNG, where 58 cm of new chimney lattice formed within 12 months and in one case, 60 cm formed within 2 days of disturbance (Gwyther, 2008a). In time, these new deposits could be colonised by fauna from nearby vent communities.

Recolonisation of SMS deposits will most commonly occur via transport of larvae as the distances between vent sites are generally too great for colonisation by motile adults. Experiments to investigate recolonisation commonly involve the provision of artificial substrata, which are recovered after a certain time and assessed for recruitment. These experiments can be used to deduce temporal and spatial patterns in recruitment and colonisation that can form the basis of predictions about recolonisation following mining disturbance. At 9°50′N on the EPR, basalt blocks were deployed to assess the influence of neighbouring *R. pachyptila*, *Tevnia jerichonana* and *B. thermophilus* colonies on settlement of tubeworms, (Hunt et al., 2004). In addition, basalt blocks deployed at the JdFR were used to assess the spatial variation of colonisation and influence of vent fluid properties and biological interactions on the colonisation process (Kelly and Metaxas, 2008; Kelly et al., 2007). Colonisation experiments at diffuse vents at Axial Volcano, JdFR, revealed more diverse and rich faunal assemblages colonising complex habitats, such as a sponge-like matrix, than the basalt-like substrate most similar to the seafloor (Kelly and Metaxas, 2008).

Natural recolonisation events have occurred at a much larger scale than experimental observations, following eruptions along the JdFR (Lutz et al., 1994) and EPR at 9°N (Tunnicliffe et al., 1997), which killed the established vent communities. These large scale natural events point to a rapid recolonisation by vent fauna, with JdFR vents recolonised by the dominant taxon *Ridgeia piscesae* within 7 months, and a return of one-third of the regional vent species pool within 2 years (Tunnicliffe et al., 1997). At 9°N, EPR, 30 cm long *T. jerichonana* and 1.5 m long *R. pachyptila* were established within 1 yr and 2 yr respectively (Lutz et al., 1994) demonstrating rapid growth rates. Such rapid re-colonisation can only occur where re-colonising organisms are able to disperse across the distance between vent communities or where a section of the community is retained to seed new populations (Tunnicliffe et al., 1997), as in the case of 9°N where re-colonisation was thought to occur from surviving adults (Haymon et al., 1993), revealing the importance of self-recruitment to the settlement and recolonisation process. Recolonisation may occur more slowly at sites where populations are patchily distributed and spatially constrained with high larval retention, such as at hydrothermal vents on seamounts along the Mariana and Kermadec Arcs (Metaxas, 2011). Such populations have high local recruitment but low potential for colonisation of new locations (Metaxas, 2011) suggesting a limited ability to recolonise areas disturbed by mining activity.

Recolonisation may not always be by the same species that comprised the original vent community. Following an eruption at EPR 9°56′N in 2006 (Tolstoy et al., 2006), there was significant change in the species composition of larval supply and colonists compared with the larval supply and colonists prior to the eruption.

As all biological communities at active SMS deposits were removed between 9°47′N and 10°08′N, colonising larvae must have been supplied from more distant vent communities, resulting in a shift in community composition (Mullineaux et al., 2010).

3.6. Recovery potential

Information on the connectivity of populations and the recolonisation ability of species can inform assessment on the recovery potential for populations disturbed by mining activity. Unfortunately there are few species from SMS deposits where both the population connectivity and recolonisation potential have been assessed. Certain species appear to have a high recovery potential, such as *I. nautilei* within the Manus Basin, where high levels of population connectivity (Thaler et al., 2011) suggest individual populations have a relatively high recovery potential with mining activity likely to have a minimal impact on genetic diversity within the region. Other species, with different life history characteristics and dispersal mechanisms, could be more vulnerable to disturbance. *R. pachyptila* population connectivity decreases with geographic distance, supporting a suspected ‘stepping-stone’ method of dispersal (Coykendall et al., 2011), meaning that recolonisation could be prevented if one of the ‘stepping-stones’ is removed by mining activity. Hence, despite the rapid growth rate of *R. pachyptila*, its ability to rapidly recolonise areas subjected to natural disturbance (Lutz et al., 1994) and its long larval life span (Marsh et al., 2001), it may have a lower recovery potential than *I. nautilei.*

The rates of recovery of benthic communities are likely to vary between fast- and slow-spreading sites, with fast-spreading sites likely to rebuild deposits through hydrothermal activity quicker leading to suitable habitat for recolonisation becoming more rapidly available. Arc systems, such the Mariana and Kermadec Arcs, are thought to have a lower recovery potential than mid-ocean spreading centres as a result of the patchily distributed and spatially constrained populations (Metaxas, 2011). While recolonisation following mining-induced disturbance may be relatively quick at some locations, natural disturbances will continue alongside those attributable to mining (Van Dover, 2011), with the compound effect of anthropogenic and natural disturbances likely to increase the recovery time for active deposit communities.

The possibility of ‘stepping-stone’ refuges for vent species in the form of other chemosynthetic habitats could increase the recovery potential for species found in multiple chemosynthetic environments. These refuges would only be available to the few species found in multiple habitats, with the rest of the SMS community potentially having a lower recovery potential. An example is the ophiuroid fauna at vent sites along the MAR (Stöhr and Segonzac, 2005; Tyler et al., 1995; Van Dover et al., 2003), where similar species within the same community may have different recovery potential from disturbance, in part due to the possible role of refuge sites. The existence of ranges in recovery potential within the same community makes it difficult to generalise the recovery potential of vent communities as a whole.

Although widespread background fauna are not endemic to inactive SMS deposits, and their populations are potentially not as vulnerable to habitat loss as vent specialists, background fauna tend to have slower growth rates than vent specialists and as a consequence the recovery times from disturbance are expected to be longer (Van Dover, 2011). The recovery time for background fauna is likely to be on the timescale of years or even decades, with similar megafaunal assemblages at seamounts that have been subjected to trawling showing no signs of recovery over a 5- to 10-yr period following the cessation of disturbance (Williams et al., 2010).

If the hypothesised community containing specialist fauna at inactive deposits is found to exist, then this community would be the group most vulnerable to disturbance from mining activity. These fauna are likely to be restricted to specific deposits and will suffer habitat loss without the prospect of inactive deposits being replaced through hydrothermal activity. Until the existence of this community is confirmed, its potential for recovery is impossible to predict.

4. Impacts of SMS mining on the benthic community

Mining of SMS deposits consists of three stages, prospecting, exploration and exploitation, all of which have associated impacts. Prospecting is the search for SMS deposits, including an estimation of deposit size, distribution, composition and economic value. Exploration follows prospecting and involves the analysis of defined deposits, the use and testing of mining equipment and facilities and undertaking environmental, technical, economic and commercial studies. The final exploitation phase involves the recovery for commercial purposes of SMS and the extraction of the minerals contained, including the construction and operation of mining, processing and transportation systems (International Seabed Authority, 2010).

To date, no commercial SMS mining activity has occurred anywhere in the world. The lack of a precedent makes it difficult to predict the potential impacts (Gwyther, 2008b). According to the International Seabed Authority (2011b), impacts will also be different at the various mining stages, with exploitation likely to have a high-intensity of direct impact, a local scale of spatial activity (<1 000 m) and an activity duration of years. The probability of an accidental event causing environmental damage is small, although the persistence of impact following mining activity could continue for decades in the absence of effective mitigation or restoration activities (International Seabed Authority, 2011b).

Impacts of SMS mining are predicted to occur across all marine environments (benthic, bathypelagic, mesopelagic and epipelagic) ranging from site to regional scale over both short and prolonged durations (summarised in Table 2) (Gwyther, 2008b). Within the benthic environment alone, there is a range of habitats including both hard and soft substrata with different communities residing on or in each. The benthic organisms also span a range of sizes, including the microfauna (<63 μm), meiofauna, (63–500 μm), macrofauna (500 μm–5 cm) and megafauna (>5 cm), with different ecological characteristics, including the nature and extent of dispersal, mobility, feeding strategies and trophic interactions. Such a suite of habitats, faunal assemblages and ecologies means that the response of benthic organisms to SMS mining will vary widely, complicating any attempt to generalise the identification and mitigation of impacts. The nature and the scale of those impacts (both spatial and temporal) are also likely to be different at different deposits. Table 2 summarises the only site-specific impact assessment currently available (see Gwyther (2008b) for full assessment), but different sites may have additional impacts to consider. The impacts from SMS mining will also vary with the methods and equipment used. For example, the predicted impacts from the proposed SMS mining methods of the Japan Deep Sea Technology Association (DESTA) are more varied with a greater risk of smothering (Fukushima and Okamatsu, 2010) than those for Solwara 1 outlined in Table 2.

Modelling studies of the dispersal of unconsolidated sediment discharge at Solwara 1 indicated that increased sedimentation thicknesses of up to 500 mm may occur within 1 km of the discharge site (Gwyther, 2008b). Some particulate material may extend up to 10 km from the site, but settle at lower than natural rates. Existing sediment thicknesses at and around Solwara 1 are 6 m deep in places (Gwyther, 2008b). Return water plumes may

Table 2
Summary of the potential impacts on the biological environment from SMS mining at Solwara 1, PNG, summarised from Gwyther (2008b). Environment classifications: benthic (seafloor); bathypelagic (water column >1 000 m); mesopelagic (water column 200–1000 m); epipelagic (water column <200 m). Spatial scales: site (<1 km from project location); local (1–10 km); regional (>10 km). Temporal scale: short duration (<1 yr, generally for duration of project); prolonged (>1 yr after completion of project).

Environment	Impact	Scale
Benthic	Change in seafloor surface structure from habitat removal	Site, short duration – prolonged
	Smothering of organisms by sediment plume generation from seafloor mining tool activity	Site, short duration
	Change in species diversity from organism loss	Site, short duration – prolonged
	Smothering of organisms from loss of material from riser transfer pipe	Site, short duration
	Loss of adjacent communities by changed hydrothermal activity	Site, short duration – prolonged
	Smothering effects of plumes discharged at depth from dewatering	Local, short duration
	Reduced water quality from hydraulic leak	Site, short duration
	Toxic effects on benthic organisms from loss of material from riser transfer pipe	Site, short duration
Bathypelagic	Toxic effects of plumes discharged at depth from dewatering	Local, short duration – prolonged
	Loss of organisms attracted to suction area by SMT lights	Site, short duration
	Reduction of bioluminescence by plume generation	Local, short duration
Bathypelagic, mesopelagic, epipelagic	Toxic effects on pelagic biota, including bioaccumulation from release of metals into water column	Local – regional, short duration
	Disturbance of cetaceans by noise from mining and vessel equipment	Local – regional, short duration
Epipelagic	Nutrient increase and increased productivity from discharge of macerated waste and treated sewage	Site, short duration
	Toxic effects from spillage of ore or hazardous material from the mining surface vessel	Site, short duration
	Death of indigenous fauna resulting from exotic species introduction via ballast water and hulls	Regional, prolonged

extend 5–10 km from the mining site, with maximum deposit thickness of 0.1 mm and rates of settling less than existing deep-sea sedimentation rates (Gwyther, 2008b). Sediment and water column plumes will disperse with distance, and hence "downstream" effects will be less than at the site where they are formed. This dilution will mean there is a gradient of impact, with effects lessening with distance away from the mining site. The potential distance and depth of sedimentation effects will vary among sites, and will need to be assessed in any prospective mining area. With regards to the toxicity of these plumes, it is thought that high concentrations of heavy metals will pose minimal risk to the fauna adapted to active SMS deposits (Gwyther, 2008b). However, this material may prove toxic to fauna adapted to inactive deposits or the general background fauna.

Impacts specific to benthic communities at SMS deposits were reviewed by Van Dover (2007, 2011), and are summarized in Table 3. Alongside the obviously negative impacts of mining, such as the loss of sulphide habitat and biodiversity, the search for commercially viable deposits and the environmental surveys carried out by or for mining companies, will have benefits for science (reviewed by Van Dover (2007, 2011)). The discovery of new SMS sites will occur at a faster pace, and there will be an improved understanding of SMS deposit ecology through the involvement of scientists in impact assessment studies and long-term monitoring programs. Through industry-led scientific programs, new species could be discovered and the knowledge of life in extreme environments will expand.

Table 3
Potential impacts on the benthic community from mining activities, combined from Van Dover (2007, 2011).

Potential impacts on the benthic community from mining activities
Loss of sulfide habitat
Degradation of sulfide habitat quality
Modification of fluid flux regimes
Local, regional, or global extinction of endemic or rare taxa
Decreased diversity (at all levels: genetic, species, phylogenetic, habitat, etc.)
Decreased seafloor primary production
Modification of trophic interactions
Risk of transplanting organisms from one mining site to another
Exposure of surrounding seafloor habitats (non-sulfide) to sediment and heavy metal deposition
Cumulative impacts of multiple habitat loss events within a region
Lost opportunity to gain knowledge about what is currently not known

5. International and national regulation of SMS mining

The management of SMS mining is controlled by different legislation according to the jurisdiction under which the proposed mining project falls. Within the EEZ or legal continental shelf of a country, all mining regulation and management falls under national jurisdiction. All seabed that does not fall within the EEZ or legal continental shelf of a country is termed 'the Area' and is managed by the International Seabed Authority (ISA) as determined by the 1982 United Nations Convention on the Law of the Sea. All States party to the Convention must apply to the ISA for licences to prospect, explore and exploit mineral resources in the Area. The ISA has issued regulations governing prospecting and exploration for SMS deposits, which were adopted in May 2010 (International Seabed Authority, 2010). Contractors must establish environmental baselines against which impacts from mining activities can be assessed, carry out environmental monitoring programmes, and take measures to prevent, reduce, and control pollution and other hazards to the marine environment (see Sections 6 and 7). Contractors must assess if serious harmful effects to vulnerable marine ecosystems, such as those associated with hydrothermal vents, will occur as a results of mining activity, and applications for mining can be rejected where substantial evidence indicates the risk of serious harm to the marine environment.

Other international conventions, such as the Stockholm Declaration (1972) (http://www.unep.org/Documents), the Rio Declaration (1992) (http://www.unep.org/Documents), the Convention on Biodiversity (1993) (http://www.cbd.int/convention/text/) and the World Summit on Sustainable Development (2002) (http://www.un.org/jsummit/html/documents/summit_docs.html), influence the drafting of marine mining legislation by signatory countries. The Stockholm and Rio Declarations emphasise the need for environmental protection and environmental impact assessment in sustainable development, alongside the need to share scientific knowledge and adopt the 'precautionary principle'. The Convention on Biodiversity also supports the precautionary principle alongside endorsing an ecosystem approach to management and area-based management tools. The World Summit on Sustainable Development calls for representative networks of marine protected areas to promote conservation and management of the oceans.

As well as legislation, there are two main codes of conduct issued by stakeholder groups that are concerned with activities at SMS deposits; the InterRidge Statement of Commitment to

Responsible Research Practices (Devey et al. (2007), http://www.interridge.org/IRStatement) and the International Marine Minerals Society (IMMS) Code for Environmental Management of Marine Mining (International Marine Minerals Society, 2011). The InterRidge Statement acknowledges that scientific research can affect communities at hydrothermal vents and signatories agree to avoid activities that can impact the sustainability of vent communities or lead to long-term degradation of vent sites, including avoiding non-essential collections and transplanting material between sites. The IMMS Code consists of a statement of environmental principles for marine mining and operating guidelines for application by industry, regulatory agencies, scientists and other interested parties. It is a voluntary code that aims to encourage environmental best practice and transparency in commercial operations. The Code also emphasises the precautionary approach, the involvement of local and scientific communities and responsible and sustainable development. The Code emphasises a need to “consider *biological* resource potential and value of living organisms at potential marine mining sites as well as the *mineral* resource potential and value”. The IMMS Code also highlights the need for procedures that aid in the recruitment, re-establishment and migration of biota following mining activities and supports the study of undisturbed, comparable habitats that are close to the mining site before, during and after mining activities.

The only SMS mining project to date that has been granted a mining lease is within the territorial waters of PNG and is principally governed by two items of national legislation, the Mining Act (1992) and the Environment Act (2000). The Mining Act declares all minerals to be owned by the national government and controls all exploration, processing and transport of minerals. The Environment Act is administered by the Department of Environment and Conservation (http://www.dec.gov.pg/legislation.html) and requires an Environmental Impact Statement (see Section 6) prior to permits for mining being granted, with further conditions including installation of monitoring equipment, undertaking an environmental management program, baseline studies and a rehabilitation program. An area where mining is still at the exploratory stage is within the NZ EEZ, which falls under two pieces of national legislation. The Crown Minerals Act 1991 legislates for minerals within the 12 nautical mile limit, but the potential sites for SMS mining exists beyond this, yet still within the EEZ. The Exclusive Economic Zone and Continental Shelf (Environmental Effects) Act (2012) manages the environmental effects of numerous activities, including SMS mining, beyond the 12 nautical mile limit. The Act has only recently been enacted, and regulations governing activities are still being developed (as of June 2013).

6. Management of SMS mining

6.1. Management objectives

Management of mining at SMS deposits will depend on the development of objectives that that are specific to a country or to a particular situation. However, most management objectives will aim to balance the exploitation of resources and conservation of SMS ecosystems. These objectives will drive the subsequent science and management measures necessary to avoid, mitigate and remedy impacts. Management objectives should include conservation goals for ecosystems associated with SMS deposits, such as “to protect the natural diversity, ecosystem structure, function and resilience of… vent communities” (International Seabed Authority, 2011b; Van Dover et al., 2012) whilst enabling responsible utilisation of mineral resources.

6.2. Environmental impact assessment

Assessing and predicting the potential impacts of SMS mining on the marine environment is a requirement of the ISA regulations (International Seabed Authority, 2010) and the Stockholm and Rio Conventions. An environmental impact assessment (EIA) usually includes an initial ‘desk-top’ scoping study, and field-based environmental or baseline surveys and an ecological risk assessment (ERA) (Collins et al., 2013a). EIA involves evaluating the probable environmental impacts of a proposed project or development, taking into consideration beneficial and adverse socio-economic, cultural and human-health impacts. Following identification of potential impacts, the likelihood of events occurring and the potential severity of those impacts are used to estimate risk. Based on this assessment of risk, mitigation strategies can be proposed that either reduce the likelihood of events occurring or reduce their potential severity, and hence the overall risk associated with the activity. As such, the potential impacts associated with SMS mining will vary according to the proposed mining methods. The results of the EIA (including the effects of proposed activities and any mitigation strategies) are summarised in an Environmental Impact Statement (EIS). The EIS is a document that incorporates an overall assessment of the mining project, providing managers with proposed measures to minimise environmental impact and maximise legislative compliance (Collins et al., 2013a). General recommendations (a “template”) for EIS were developed at a specific ISA workshop (International Seabed Authority, 2011a) and it is expected that any EIS submitted to the ISA will “substantially comply” with these recommendations (International Seabed Authority, 2011a). The general template includes a need for description of the offshore environment, including the biological environment. There should be a description of the effects on individuals, communities, populations and metapopulations, within the pelagic, mid-water and benthic environments. Developers must also submit an Environmental Management Plan, including sections on mitigation and management, monitoring, and reporting.

6.3. Mitigation strategies

Mitigation strategies vary according to what part of the environment they are trying to protect and the nature and extent of impacts of the mining. In the case of benthic communities, there are two main potential impacts from SMS mining, although there are also many others (see Section 4). The first is the loss of all organisms in the immediate area of mining operations and the second is the smothering of organisms in the general vicinity by potentially toxic sediment plumes. For the first, proposed mitigation strategies should aim at maximising the potential for recolonisation of areas impacted by mining from surrounding populations and the preservation of undisturbed communities similar to the impacted community. For the second, mitigation strategies should aim at reducing the concentration, size and toxicity of particles in sediment plumes associated with various mining activities.

Enhancing the recruitment and re-establishment of biota following mining is one of the recommendations of the IMMS Code (International Marine Minerals Society, 2011). This can be achieved through ‘set aside’ areas, used exclusively as “impact reference zones” and “preservation references zones” as stipulated by the ISA (International Seabed Authority, 2010). Impact reference zones are used to assess the effects of activities on the marine environment whilst preservation reference zones are areas where there is no mining to ensure representation of an unimpacted seabed biota. These sites should be upstream, support a similar biological community and be far enough away not to be impacted by mining, yet close enough to supply colonising larvae to the impacted site (Van

Dover, 2007). For example, off PNG the South Su reference site is located 2 km upstream of the Solwara 1 mining site and has a similar biological community to the mining site, suggesting it could act as a suitable set aside site and an effective supply of larvae for recolonisation of Solwara 1 (Collins et al., 2012). Nautilus Minerals Inc., the company licenced to mine off PNG, also proposes to enhance recolonisation through quasi-permanent refuge areas, where the temperature is too great for the seafloor mining tool to operate (>35 °C), and temporary refuges. Temporary refuge sites will not be mined until there are signs of recovery from mining activity at other sites, enabling local retention of organisms that could supply recently mined zones in Solwara 1 with colonising larvae. Nautilus also propose to re-locate fauna from mined sites to temporary refuges or even outside of the mining area to help retain an adult spawning population that would aid recolonisation. In addition, Nautilus proposes to deploy artificial hard substrata for recolonisation by slow-growing sessile taxa such as corals in regions where inactive SMS deposits have been mined (Gwyther, 2008b). However, the colonising communities will probably differ according to the substrate provided (Kelly and Metaxas, 2008), which should be taken into consideration. There is also a range in life history characteristics and so recolonisation potential of species at SMS deposits, which must be considered when formulating management or mitigation strategies.

Reducing the concentration, size and toxicity of particles in sediment plumes can be achieved through modifications to mining equipment or procedures. In the case of Nautilus (Gwyther, 2008b), the suction mouth of the seafloor mining tool is designed for minimal escape of suspended material during cutting. The material returned to the bathypelagic environment following dewatering at the surface is planned to contain material <8 μm in diameter, reducing both the grain size and quantity of sediment able to contribute to smothering effects. Assessment of natural suspended sediment concentrations within the area to be mined suggests that the benthic community may have adapted to a relatively high suspended sediment environment, with the additional sediment load from mining activity potentially having little effect (Gwyther, 2008b). By reducing the escape of suspended material through suction mouth design, minimising the time that waste from dewatering spends at the surface undergoing geochemical change and releasing this waste 25–50 m above the seabed, the risk of exposure to toxic plumes is limited (Gwyther, 2008b).

As well as site or deposit scale mitigation measures, such as set aside areas and modifications to mining equipment, there is also a need for larger scale mitigation measures as part of spatial management. It is important to identify spatial management goals for SMS communities at various levels, including site, deposit, region and even biogeographic province level. Spatial management of SMS sites through a series of open and set aside sites (i.e. closed areas) would ensure the retention of undisturbed examples of the SMS communities targeted by SMS mining. Set aside areas should ideally be present as part of a larger network of protected areas to enable ecosystem level conservation. Networks of chemosynthetic ecosystem reserves (CERs) have been proposed as a way to protect the diversity, structure, function and resilience of these ecosystems alongside managing the use of the ecosystem's mineral resources (International Seabed Authority, 2011b). Any network of protected areas should also be distributed among biogeographic provinces in order to ensure adequate representation of the different faunas (International Seabed Authority, 2011b). For example, tubeworm and clam dominated communities of the South East Pacific Rise Province (Corliss et al., 1979; Spiess et al., 1980) may respond differently to disturbance compared to shrimp and mussel dominated communities of the Mid-Atlantic Ridge Province (Murton et al., 1995) or the Kiwa crab and stalked barnacle communities of the East Scotia Ridge Province (Rogers et al., 2012). The relative sizes of these provinces may also contribute to their vulnerability to disturbance. Smaller biogeographic provinces, such as the Kermadec Arc province, NZ, may be more vulnerable to localised and total extinctions, although as more vent fields are discovered the relative sizes of provinces may change. The spatial design of CERs at hydrothermal vents hosting SMS deposits should follow the Dinard Guidelines, as outlined by the International Seabed Authority (2011b). The first marine protected area designated for its hydrothermal vent fields, the "Endeavour Hydrothermal Vents Marine Protected Area," is also the world's first CER, containing five vent fields split between four management areas catering for observational research, education and outreach and more intrusive research (http://www.pac.dfo-mpo.gc.ca/oceans/protection/mpa-zpm/endeavour/docs/EHV-CHE-mgmtplan-gestion-eng.pdf).

7. Methods to investigate and manage impacts from SMS mining

7.1. Baseline studies

There needs to be a comprehensive baseline study carried out before any mining operation begins, in order to measure the subsequent impacts of mining at a site (International Seabed Authority, 2010; International Marine Minerals Society, 2011). The study should assess the marine environment at and in the vicinity of the proposed site, and should take into consideration seasonal and inter-annual variation in environmental parameters. As well as data on the geophysical, geochemical, geological and oceanographic environment, this baseline study needs to comprehensively describe the biological communities. In the case of the benthic fauna, this should include faunal distribution patterns, population connectivity and ecological characteristics relevant to vulnerability and recovery potential. Detailed recommendations for the baseline part of the environmental study were developed by a specific ISA workshop (International Seabed Authority, 2004) and were recently reviewed at an international workshop, VentBase 2012 (Collins et al. (2013b), http://www.ventbase.org/)

Faunal distribution patterns at SMS deposits are closely linked to the geochemical environment, with different communities existing at active and inactive deposits. A single mining site is likely to contain numerous active and inactive deposits, leading to complicated within-site faunal distribution patterns. To investigate both within-site and within-deposit faunal distribution patterns, biological communities should ideally be observed *in situ* using video or still image transects collected by manned/unmanned submersibles or towed camera equipment (Collins et al., 2013a). The subsequent distribution maps can be used to infer potential connectivity between populations, inform targeted biological sampling and link the distribution of fauna with hydrothermal emissions and/or particular substrates. Knowledge of such associations twinned with distribution maps of active and inactive SMS deposits along imaged transects can then be used to predict the distribution of faunal communities in un-surveyed areas across the mining site and its vicinity. These maps can help plan the distribution of mining and set aside areas, minimising disturbance to important habitat and communities.

Ecotoxicologal investigations should form an important part of the baseline study, in particular in establishing acceptable concentrations of heavy metals from discharge of mining waste. For example, the high natural background levels of heavy metals at Solwara 1 led to the conclusion that the proposed concentrations of mining waste discharge would not have any measurable effects on the highly-adapted, specialised hydrothermal vent fauna (Gwyther, 2008b). However, the background fauna and fauna at inactive SMS deposits are not adapted to a high heavy metal environment and could be vulnerable to mining waste discharge. One of the issues with standard ecotoxicology studies and bioassays is that the test organisms are generally from shallow water environments, so the effect of physiological adaptations to the deep-sea environment (pressure, darkness, cold) is not considered. For example, the test organisms used by Nautilus for ecotoxicology tests were the alga *Nitzshia closterium*, the marine copepod *Acartia sinjiensis*, and the amphipod *Mekita plumulosa*, none of which occur at Solwara 1 (Gwyther, 2008b). The alternative would be to use deep-sea organisms, preferably those found at inactive SMS deposits or as background fauna, but maintaining these organisms at appropriate environmental conditions throughout a bioassay would be challenging and the cost potentially prohibitive. Acute bioassays could be completed *in situ* using an ROV but these assays need to be repeated over time to be informative about the chronic and accumulative effects of mining waste discharge.

7.2. Long-term monitoring

The effects of SMS mining need to be continually assessed as part of a long-term monitoring programme (International Seabed Authority, 2010). Co-operation with the ISA in the monitoring of environmental impacts is explicit in the applications for both prospecting and exploration by contractors in the Area. Annual reports detailing the implementation and results of the monitoring programme are mandatory, ensuring impacts from mining are constantly reviewed and assessed (International Seabed Authority, 2010). The proposed mining at Solwara 1 in PNG is also subject to national requirements for monitoring programmes under the Environmental Act 2000, with Nautilus having developed a detailed plan both for baseline studies and subsequent monitoring (Gwyther, 2008b).

Monitoring programs will utilise baseline data to measure any changes in the environment as a result of mining activity. For example, faunal distribution surveys can be repeated and the maps generated compared with baseline survey data to quantify changes in the spatial extent of key species over time in response to SMS mining. Settlement plates can be deployed to assess whether the colonising community has the same species composition as the previous community and/or set aside area. Genetic analysis comparing the fauna colonising artificial or newly-generated natural substrate to the original populations could enable the source of colonisers to be identified and the suitability of set aside areas to be assessed. The monitoring program needs to be implemented at suitable spatial and temporal scales (IMMS, 2011), although the appropriate length of long-term study required is at present unclear. Levels of natural variation need to be evaluated before any appreciable operations begin, in order to establish fluctuations that could, for example, be seasonal or related to changing chemical conditions. Also, following disturbance, succession of species composition and abundance is to be expected, and so any monitoring must span sufficient time. Recovery from natural disturbance at sites along the EPR (Lutz et al., 1994; Mullineaux et al., 2010) and Juan de Fuca Ridge (Tunnicliffe et al., 1997) and the rapid re-growth of deposits at Solwara 1 (Gwyther, 2008a) indicate that monitoring for a few years following the cessation of mining activities may be sufficient. However, experimental polymetallic nodule mining resulted in disturbance to the benthic community assemblage for at least 26 years following mining activity (Miljutin et al., 2011), suggesting that in keeping with the precautionary principle, suitable long-term monitoring could be on the scale of decades rather than years.

Monitoring programmes by themselves are all very well, but they need to be evaluated against pre-determined decision rules. The latter will be derived from management objectives, and involve a management response when a monitored parameter value exceeds a certain level. For example, mining may have to stop in an area if sediment plume deposition thicknesses exceed a certain depth.

7.3. The need for replication

The design of baseline, impact and long-term monitoring studies also needs to consider the importance of replication to address the natural environmental variability at SMS sites at both temporal and spatial scales. Ideally, this should utilise a design similar to BACI (before-after-control-impact, Green (1979)) or Beyond BACI (Underwood, 1991, 1992), with multiple unimpacted (control or set aside) and impacted (mined) sites (Collins et al., 2013a). However, BACI design at SMS sites will probably be asymmetrical with the potential for multiple unimpacted sites but only one impacted site (Underwood, 1991, 1992), as mining is likely to be concentrated at one site. There is also the question of cost. Coastal or shallow water impact studies may be able to investigate multiple sites but the logistics (time and cost) of investigating multiple sites in deep-sea SMS mining impact studies may be prohibitive. Although costly, replication is as important in forming robust scientific conclusions within the deep sea as it is within the coastal zone and only through using methodologies as rigorous as those in the coastal zone can SMS ecosystems be effectively managed under the precautionary principle (Collins et al., 2013b).

8. Conclusions

Although SMS mining is still at the prospecting and exploratory phase, exploitation of SMS deposits will probably occur in the next few years in the Western Pacific. Globally, numerous deposits have been identified from a suite of hydrothermal environments and depths, with a range in deposit size and mineral content. SMS deposits can either be hydrothermally active or inactive, although the distinction between these is not always clear. As well as commercially viable ore, deposits are also host to complex biological communities. These include a chemosynthetic community of hydrothermal vent specialists adapted to active deposits and a community of background fauna inhabiting inactive deposits. There is also the potential for another community to exist at inactive deposits adapted to the weathered sulfide habitat. Benthic communities demonstrate complex distributions at deposits, with the vent communities also exhibiting particularly constrained biogeographic patterns. The connectivity, recolonisation and potential recovery of populations at SMS deposits have not been studied in detail; vent populations have been investigated at various locations but the ecology of populations at inactive deposits is largely unknown. As there is no precedent for SMS mining, predicting the impacts is challenging. However, impacts are predicted to occur across all marine environments ranging from site to regional scale over short and prolonged durations. The nature of these impacts will vary between deposit locations and with the equipment and methods used. Regulation of SMS mining falls under different legislation according to the jurisdiction under which the proposed project falls. Within the EEZ or legal continental shelf of a country, SMS mining is regulated by national legislation; outside of this, projects are regulated by international legislation implemented by the International Seabed Authority. There are also various codes issued by stakeholders to encourage best practice in activities at SMS deposits. Current regulations generally demonstrate commitment to the protection of the marine environment but without considerably more information on SMS deposit ecology it will be a challenge to make decisions on suitable management and mitigation strategies. Management of SMS mining should include the development of clear management objectives, a comprehensive environmental impact assessment, implementation of suitable mitigation strategies, establishment of a long-term monitoring program, and clear decision rules associated with changes. It should be acknowledged that alongside the negative impacts of SMS mining on the communities at deposits, there is also an opportunity for improved understanding of deposit ecology through involvement with industry surveys and assessments and that there is a global need for the minerals found in SMS deposits.

Acknowledgments

REB and AAR acknowledge the fruitful discussions with VentBase 2012 workshop participants which helped inform this article. REB is supported by PhD scholarship funding from National Institute of Water and Atmospheric Research and Victoria University of Wellington.

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