Mining seafloor massive sulphides and biodiversity: what is at risk?

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Scientific exploration of the deep sea in the late 1970s led to the discovery of seafloor massive sulphides at hydrothermal vents. More recently, sulphide deposits containing high grades of ore have been discovered in the southwest Pacific. In addition to metal-rich ores, hydrothermal vents host ecosystems based on microbial chemoautotrophic primary production, with endemic invertebrate species adapted in special ways to the vent environment. Although there has been considerable effort to study the biology and ecology of vent systems in the decades since these systems were first discovered, there has been limited attention paid to conservation issues. Three priority recommendations for conservation science at hydrothermal vent settings are identified here: (i) determine the natural conservation units for key species with differing life histories; (ii) identify a set of first principles for the design of preservation reference areas and conservation areas; (iii) develop and test methods for effective mitigation and restoration to enhance the recovery of biodiversity in sulphide systems that may be subject to open-cut mining.

Keywords: conservation, deep sea, diversity, hydrothermal vent, mitigation.

Introduction

"In the depths of the ocean, there are mines of zinc, iron, silver and gold that would be quite easy to exploit", said Captain Nemo, hero of Jules Verne's Twenty Thousand Leagues Under the Sea (1870).

These words were science fiction until the 1979 discovery of metal-rich mineral deposits formed by hydrothermal vents in the deep sea (CYAMEX Scientific Team et al., 1979; Spiess et al., 1980). Geologists were quick to make the connection between deep-sea vent systems and ore-bearing ophiolite complexes on land (e.g. Oudin and Constantinou, 1984; Dilek and Newcomb, 2003). There was even an early proposal in the 1980s by the Minerals Management Service of the United States for mineral-lease offers in the newly proclaimed 200-mile US Exclusive Economic Zone on Gorda Ridge, off the coast of Oregon (Bailey, 1997), including a draft environmental impact statement (Zippin, 1983). Lack of enabling technology, low commodity prices, unexploited ore bodies on land, and prohibitive costs were undoubtedly the factors that precluded rapid development of an offshore mineral extraction industry (Petit, 1984). Perhaps an even more compelling reason for the mining industry to postpone plans to capitalize on mineral resources associated with hydrothermal vents was the growing appreciation that deep-sea hydrothermal vents sustain remarkable communities of animals and microorganisms exquisitely adapted to exploit sulphide-laden vent fluids that emanate from the seafloor (reviewed in Van Dover, 2000) and that the Gorda Ridge lease area included biological assemblages associated with hydrothermal vents (McMurray, 1990). The discovery of

ecosystems, microbe–invertebrate associations, and biochemical and physiological adaptations new to science fuelled the imagination and changed the way we view life in extreme environments (relative to the human condition) on our own planet and in the universe (Mix, 2006).

In the 1990s, there was a resurgent interest in extraction of copper, zinc, silver, and gold from seafloor massive sulphide deposits. This resurrection of mineral extraction was at least in part a consequence of the discovery of ore-quality seafloor massive sulphides in back-arc basins in the mid-1980s (Binns and Scott, 1993) and increasing accessibility of deep-sea environments through advanced technologies and assets. In 1997, Papua New Guinea issued exploration licences to Nautilus Minerals, Inc., a Canadian company, for a region of 5000 km^2 in Manus Basin, where seafloor massive sulphide deposits containing high grades copper, gold, zinc, and silver occur at depths >1000 m.

The general belief among deep-sea biologists through 2004 was that mining of deep-sea massive sulphides remained many decades into the future, despite the knowledge that the United Nations Convention on the Law of the Sea and the 1994 Agreement on the regime of seafloor mining established the International Seabed Authority (ISA) with jurisdiction over all seafloor resources in the area beyond national jurisdiction (also called the ABNJ or simply "the Area"). As part of its business, the ISA began to convene annual workshops on scientific and technical aspects of deep seafloor mining of minerals and the environmental impacts associated with mining.

The ISA workshop held in 2004 focused in part on seafloor massive sulphide deposits and on the definition of environmental

baselines for evaluating likely effects of exploration and exploitation (International Seabed Authority, 2007). Assuming a worst-case scenario, negative impacts of mining on active or inactive sulphide systems were reported to include the loss of sulphide habitat, degradation of sulphide 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, exposure of surrounding seafloor habitats (non-sulphide) to sedimentation and heavy metal deposition, cumulative impacts of multiple habitat loss events within a region, and a lost opportunity to gain knowledge about what is not currently known (Van Dover, 2007). This report also emphasized the need for reserves and sanctuaries, for which design principles were deemed likely to be regionally idiosyncratic (Van Dover, 2007).

Five mineralized areas at a single vent field known as Solwara 1 (~1600 m; Figure 1) in the territorial waters of Papua New Guinea are targets for the first open-cut mining effort using the cutter-suction technology, which is expected to take 2 years or more to complete (Gwyther, 2008). The severe economic downturn of 2008/2009 stalled progress towards commercial extraction of ores and unnatural loss of seafloor massive sulphide habitat. With growing interest in issues confronting the deep ocean (e.g. Koslow, 2007), it is timely to look again at the risk to biodiversity when mining of seafloor massive sulphides is permitted and to consider how conservation strategies might minimize or mitigate some of this risk.

Vent ecology basics

From a global perspective, polymetallic sulphide settings in the deep sea represent a complex mosaic of physical, chemical, and biological variables (Table 1) that are thought to be critical in determining the nature of the ecosystem and how the system will respond to habitat degradation (reviewed in Van Dover, 2000). These variables include active and inactive hydrothermal substrata, fluid-flow conditions, biogenic habitats, and successional stages, all within a globe-encircling archipelago-like spatial context under dynamic and ephemeral temporally varying conditions. Geological and geochemical contexts vary from one region to another—and even from one vent field to another—in ways that can have ecological and even evolutionary consequences (e.g. Le Bris et al., 2003; Govenar et al., 2005; Schmidt et al., 2008). Overlain onto these conditions is the imprint of a biogeographic syntax that maps distributions of vent-endemic taxa on a global scale. Very few, if any, vent-endemic species are globally cosmopolitan or even known from throughout a given ocean basin, and vent communities differ in their species lists from one region to another (Tunnicliffe and Fowler, 1996; Van Dover et al., 2002; Bachraty et al., 2009; Figure 2), as does the spacing between habitats (e.g. Baker and German, 2004) and the duration of venting (Hannington et al., 1995). This suggests that management and conservation strategies will not be the same from one place to another.

Our knowledge of species composition and biodiversity at even the most carefully studied active vent systems is incomplete. Repeated quantitative samples of invertebrates associated with mussel beds at hydrothermal vents around the world show similar patterns of species accumulation marked by failure to reach an asymptote—each new bulk sample at a given locale delivers one or more new species (e.g. Van Dover, 2002; Dreyer et al.,
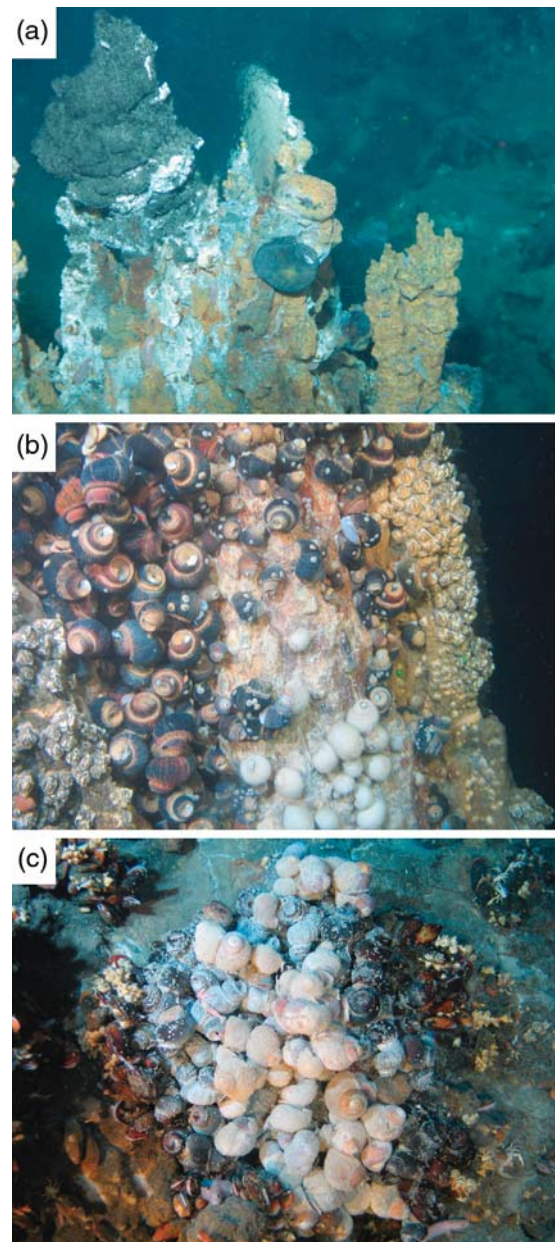

Figure 1. Active hydrothermal vents, Manus Basin. (a) Chimney with polynoid scale worms (*Branchinotogluma* sp.), alvinocarid shrimp (including *Chorocaris vandoverae*), and one large black snail (*Ifremeria nautilei*). (b) Chimney surface dominated by three species of snail (*Ifremeria nautilei*, *Alviniconcha* species 1 and 2) hosting chemosynthetic bacteria, barnacles (*Eochionelasmus* sp.), and limpets (*Olgasolaris* sp.). (c) Active sulphide community at a reserve site in Manus Basin that has a greater diversity of large animals than Solwara 1, including mussels (shown here peripheral to the central cluster of snails). Photos courtesy of Nautilus Minerals.

2005; Govenar et al., 2005). For invertebrates associated with mussel beds of the 9N vent field on the East Pacific Rise, 25% of the species in the species list derived from intensive bulk sampling efforts were singletons (i.e. a single individual of a given species was observed in the entire set of samples collected) and 50% of the species were represented by five or fewer individuals (Van Dover, 2003; Figure 3). There is therefore a very large

Table 1. Some key physical, chemical, and biological variables of deep-sea hydrothermal vent ecosystems.

Space	Distance between active sites
Time	Intervals between disturbance
	Duration of vent activity
Environment	Substratum
	Fluid chemistry
	Seasonality
	Geography
	Hydrography
	Topography
Biology	Species composition
	Time to sexual maturation
	Mode of fertilization
	Brood size
	Larval dispersal type
	Larval behaviour
	Duration of larval life
	Recruitment processes
	Predation and competition

proportion of rare, poorly known, and typically undescribed species, even at vents that have been studied for several decades. The role of these rare species in the ecosystem is uncertain, but it is expected that under conditions different from the prevailing ones, populations of some rare species may proliferate, while other abundant species may diminish. At the very least, rare species represent the evolutionary units of information and adaptive potential at risk of loss from the system.

Most species at active hydrothermal vents are typically considered to be endemic to the vent ecosystem: they are obligate vent inhabitants so might be particularly susceptible to extractive mining methods that quantitatively remove all individuals and colonized habitat. At least a few species once commonly thought to be restricted to vent ecosystems, however, can be found in other settings on the seafloor. Recent examples are certain limpet species in the genus *Lepetodrilus*, a widespread group of small limpets that are often numerical dominants among macrofaunal species at vents (e.g. Van Dover, 2003). *Lepetodrilus* species are now known to occur naturally at seeps, on sunken wood, and on whalebones, as well as at hydrothermal vents (Johnson *et al.*, 2008). In general, it is difficult if not impossible to prove conclusively that any species is restricted solely to vent habitats, although the species may so far only be known from vents. It can also be difficult and expensive to discover other habitats that can support a given species. Linkages between populations of species at vents and in other reducing environments are not yet well understood. Without additional population data and an understanding of source–sink dynamics, the role of each habitat type in the maintenance of a metapopulation is unknown.

Cryptic species—those that are genetically distinct but only subtly distinguishable morphologically—complicate our understanding of the diversity and distribution of vent species and thus the potential for local or global loss of species diversity through habitat loss or degradation. Recent studies reveal that vents host extraordinary and previously unappreciated cryptic species diversity. The best-studied example to date perhaps is again within the genus *Lepetodrilus*. Taxonomists have described 14 nominal species (Warén and Bouchet, 2001; Desbruyères *et al.*, 2006), but DNA barcoding of individuals within these species revealed at least half a dozen additional cryptic taxa with genetic divergences that match or exceed those of the nominal taxa (Johnson *et al.*, 2008; Matabos *et al.*, 2008).

Although microsatellite markers and other genetic fingerprinting methods are only beginning to be used to study the population genetics of marine invertebrates, these techniques can be powerful. For example, cohort analyses reveal instances of chaotic genetic patchiness in oysters (Hedgecock *et al.*, 2007), and assignment tests provide direct estimates of genetic connectivity in a Caribbean reef-building coral (Baums *et al.*, 2005); high-
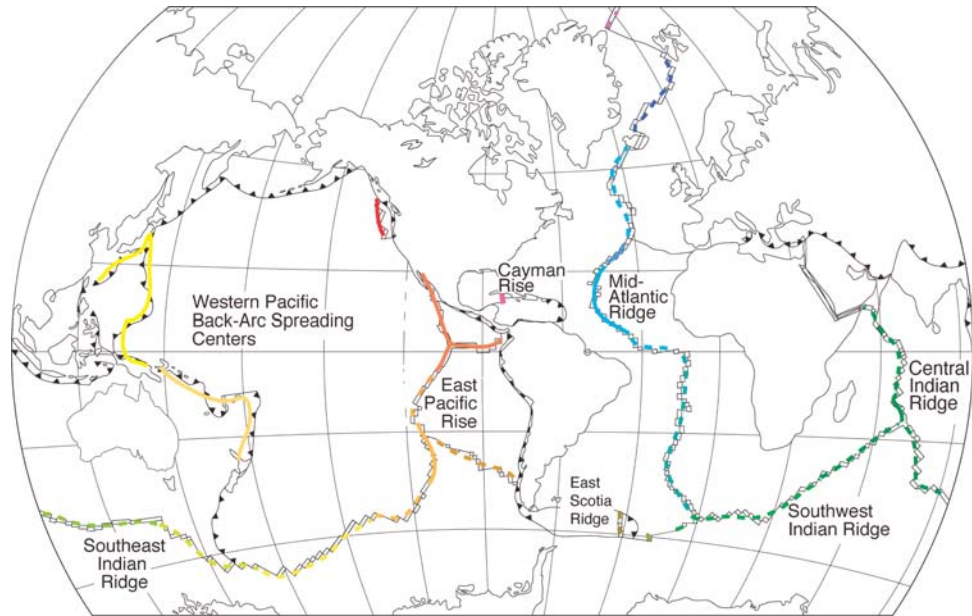
Figure 2. A model of the global biogeographic differentiation of invertebrate species associated with hydrothermal vents. Colours represent regions that share many of the same species; solid lines reflect areas where vent sites have been relatively well-described; dashed lines and colours interpolate biogeographic similarities between areas that have been explored.
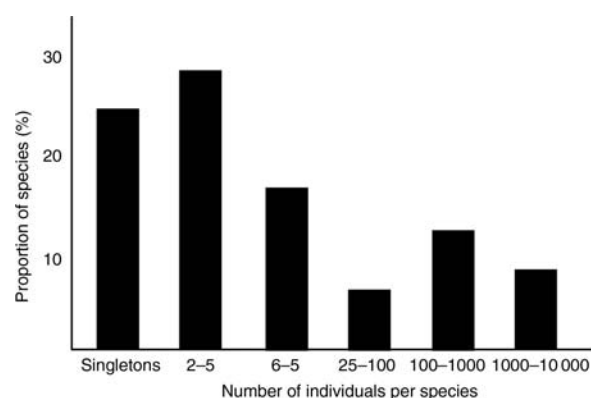
Figure 3. Species abundance (number of individuals) at hydrothermal vents on the northern East Pacific Rise. In all, 23 303 individuals were collected in 23 quantitative samples from mussel beds, representing 47 species. Singletons are species represented by one individual in the entire sampling effort. Data from Van Dover (2003).

resolution models of ocean circulation combined with genetic data assess the geographical scale of larval dispersal in mussels (Gilg and Hilbish, 2003), and there is a gathering appreciation of oceanographic distance in understanding genetic structure (White et al., 2010). Population structure has been reported even within populations of highly mobile species such as shallow-water squid (e.g. Shaw et al., 1999). The spatial scale of genetic subdivision within species has implications for the interpretation of dispersal and population dynamics, adaptation to human-driven landscape change, and consequent management of species that may be subjected to habitat loss by mining operations. Shallow-water species with lecithotrophic larvae or direct development may have a strong, fine-scale genetic structure (tens of centimetres; e.g. Calderon et al., 2007), and preliminary studies of population genetics in the giant tubeworm *Riftia pachyptila* (Shank and Halanych, 2007) hint at greater population structure than previously thought. The spatial scale of genetic subdivision within species can reveal important aspects of dispersal and population dynamics of species that may be subjected to habitat loss or degradation and is of value in defining best management practices.

Natural disturbance and response

Active hydrothermal-vent ecosystems are necessarily tied to volcanic and tectonic systems at mid-ocean ridge spreading centres, back-arc basin spreading centres, and seamount volcanoes; as such, they are subject to intermittent catastrophic destruction, including complete re-pavement by molten lava associated with volcanic eruptions (Delaney et al., 1998) that results in cessation of fluid flux and demise of populations dependent on microbial (chemoautotrophic) primary production. For most active hydrothermal-vent systems, the frequency and magnitude of natural catastrophic events are unknown. There are at least two well-documented instances of volcanic eruptions that took place at sites where prior work provided a baseline against which recovery of the vent community could be measured. Volcanic eruptions at the 9N vent field on the East Pacific Rise in 1991 (Haymon et al., 1993) and at Co-Axial Seamount on the Juan de Fuca Ridge in 1997 (Embley et al., 2000) reset the hydrothermal cycle. The visual impression of recovery of the native hydrothermal-vent

fauna was relatively rapid in both cases, i.e. with dominant biomass species returning to pre-eruption levels within 2–4 years post-eruption (Tunnicliffe et al., 1997; Shank et al., 1998). Recovery of diversity to pre-eruption levels is more difficult to assess, but may require more than 5 years for the number of species to match that of the pre-eruption regional species pool (Figure 4). In addition to catastrophic events, active hydrothermal systems may undergo natural cycles of frequent small-scale disturbances (flow decrease, flow increase, biological processes), with variable outcomes in terms of changes in species composition on very short and frequent time-scales (days to months; e.g. Sarrazin and Juniper, 1999; Govenar and Fisher, 2007). Still other hydrothermal-vent systems undergo little natural ecological change on a decadal time-scale (Copley et al., 2007), with catastrophic disturbance rare relative to the lifespan of species that make up the bulk of the biomass. Temporal dynamics of fluid flow, community structure, and succession therefore are also idiosyncratic among vent sites.

The occurrence of volcanism and other processes such as mineral deposition, blockage, and reorganization of subsurface conduits for vent fluids dramatically modify the ecosystem and suggest that organisms living at some active vents are adapted to withstand relatively frequent natural and severe loss or degradation of habitat (e.g. Tunnicliffe et al., 1997; Shank et al., 1998). Arguably, a mining-induced loss of critical habitat may

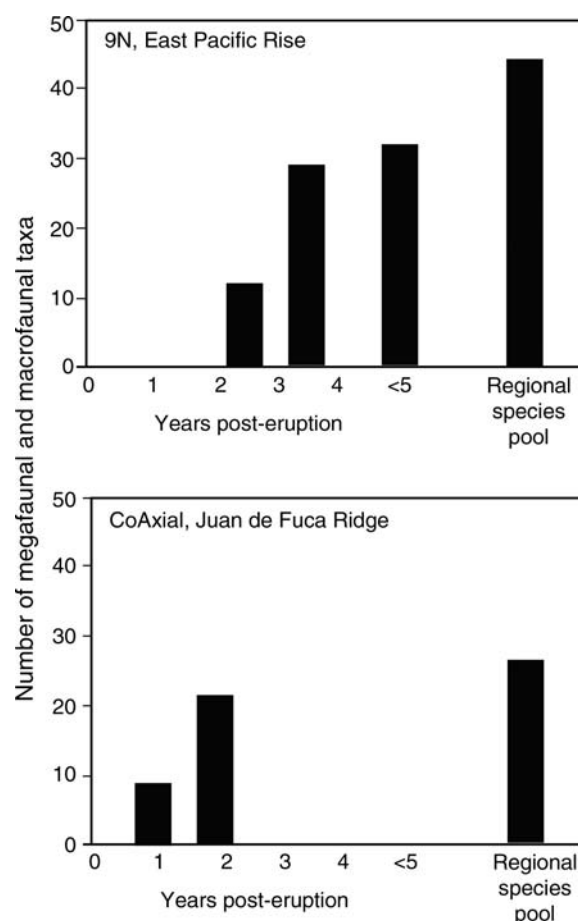**Figure 4.** Recovery of invertebrate diversity following volcanic eruptions. Data from Tunnicliffe et al. (1997) and Shank et al. (1998).

be no worse than what nature might deliver to these communities, were it to occur at the same rate and same spatial scale "in place" of a natural loss of or change in habitat quality. Natural loss of critical habitat, however, will not cease; mining-induced loss of habitat will be an additive factor of uncertain scale relative to natural events, with potential for cumulative impacts on the abundance and distribution of vent species.

Inactive seafloor massive sulphides

Defining best practices in mining relative to conservation of invertebrate diversity requires understanding of whether a seafloor massive sulphide deposit is active or inactive. Active sulphide deposits have detectable emissions and host specially adapted, endemic fauna that rely on chemoautotrophic primary production. Inactive deposits (also called relict or fossil deposits) have no detectable emissions and host suspension-feeding and grazing invertebrates that may also occur on rock outcrops not formed by hydrothermal mineralization (e.g. basalt). Inactive sulphide deposits have to date largely escaped study by deep-sea biologists, although investigation of the fauna of inactive sulphide deposits in Manus Basin indicates that in that location, inactive sulphides and other hard substrata are colonized by suspension-feeders (e.g. corals, barnacles, sponges; Figure 5) that depend on chemosynthetic production most likely advected from nearby active vent systems (Erickson *et al.*, 2009). Recent work on deep-sea corals indicates that they have slow growth rates (4–35 μm year^{-1}) and long lifespans relative to hydrothermal vent species—centuries rather than months or years (Roark *et al.*, 2005, 2009). Invertebrate taxa colonizing inactive sulphide mounds that might be targets of mining are much more poorly characterized than those colonizing active hydrothermal vents; we know virtually nothing about the rates of recruitment, succession, or population structure of organisms colonizing inactive sulphides in any ocean basin. We are not even sure if there might be a specialized fauna adapted to the particular geochemical and microbiological conditions of weathering sulphide mineral substrata.

Expected impact on benthic communities of single and cumulative mining events

Given the knowledge of vent communities that has accumulated over the past several decades, it is possible to make some educated guesses as to what the impact of a single mining event on the biodiversity of active vent systems (such as removal of a single vent field such as the Solwara 1 site in Manus Basin) might be. There are some explicit assumptions in this assessment: reserve sites will be identified and preserved from mining activity; these reserve sites will remain active and will serve as sources for recruits to mined areas; mining does not so alter fluid chemistry and substratum as to render the environment unacceptable to recruits or otherwise unable to support active vent communities.

Mining activities should not arrest the hydrothermal system, though it will probably alter the distribution of venting activity on a local scale (metres to hundreds of metres). The effect may be similar to that witnessed during disturbance and recovery associated with natural seafloor eruptions on the East Pacific Rise (Shank *et al.*, 1998). Mining will undoubtedly reshape the seafloor, removing vertical edifices and altering the texture of the substratum. Rapid regrowth of mineral chimneys is anticipated (e.g. Hannington *et al.*, 1995), but the assumption that the quality
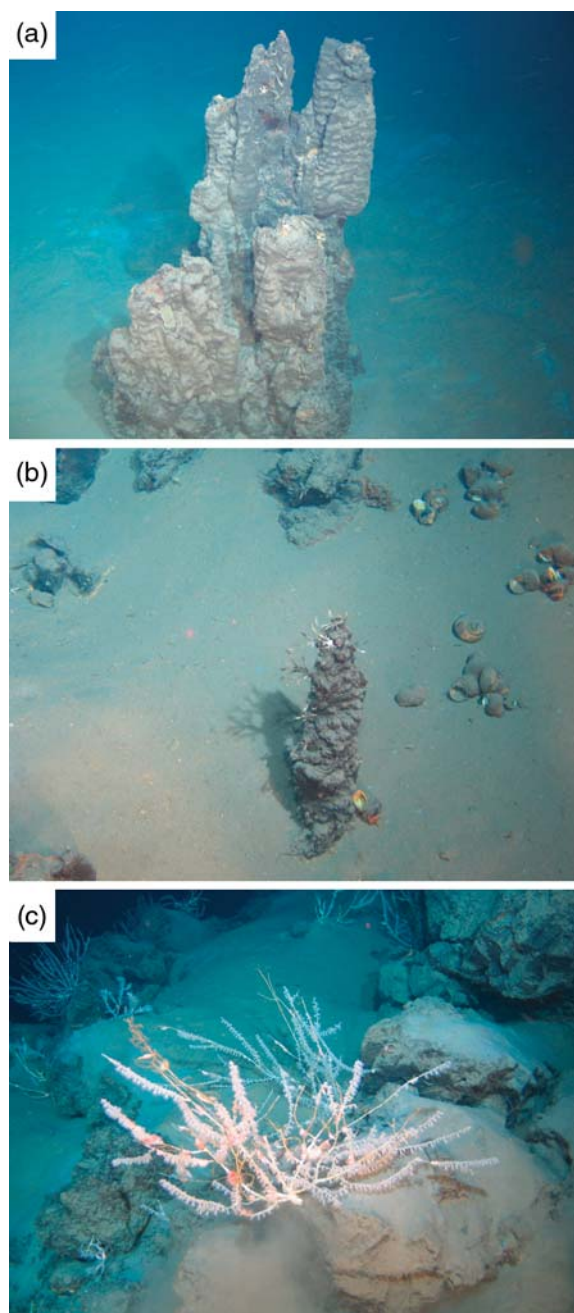

Figure 5. Fauna of inactive sulphide deposits, Manus Basin. (a) Relict chimney colonized by sessile, stalked barnacles (*Vulcanolepas* sp.) and mobile squat lobsters (*Munidopsis* sp.). (b) Chimney and chimney fragments colonized by stalked barnacles and squat lobsters, with shells of dead black snails (*Ifremeria nautilei*). (c) Bamboo corals (*Keratoisis* sp.) with anemones and barnacles on sulphide outcrops. Red laser dots (b and c) are separated by 10 cm. Photos courtesy of Nautilus Minerals.

of the habitat will quickly return to something approximating the pre-mining condition is challengeable.

For Solwara 1 in the Manus Basin, "visual" recovery of vent populations from mining activities is expected to be rapid: within 5 years, differences in biomass and even relative abundance of dominant taxa (snails, barnacles, limpets, shrimp, etc.) seem likely to be difficult to distinguish from pre-mining patterns.

Recovery of rare species may require decadal time-scales. Accumulation of other rare species also seems likely, with perhaps no net gain or loss of species diversity within a decade. The risk to genetic diversity will vary by species, depending on the extent to which species' populations are structured at fine scales (<10 km). For inactive sulphide mounds, "visual" recovery may be decadal in scale. Relatively low population densities and slow recruitment and growth rates will likely make it difficult to assess recovery, and apparent or real local loss of species for many years seems probable.

The impact on biodiversity of cumulative mining events in a given region is much more difficult to assess. To address this question, we must understand the number, size, and distribution of sources and sinks of larvae and dispersive juveniles and adults that are required to re-supply areas stripped of their biota. Habitat loss or degradation attributable to cumulative mining events seems likely to be associated with chronic reduction in population size and increased isolation (Stockwell *et al.*, 2003), which in turn can impede recovery.

Conservation strategies

Where mining of seafloor massive sulphides is permitted, conservation scientists must identify and help to implement strategies that will minimize the environmental impact of mining activities on biological systems. This will be an evolving process requiring adaptive management as monitoring and other studies allow impacts to be assessed and mitigation efforts to be applied and studied for their efficacy. Three priority recommendations are offered here.

First, a challenge before the scientific community is to recognize natural conservation units (genetic, species-specific, and biogeographic) in areas targeted for mining. Meeting this challenge requires better understanding of local habitat quality, habitat network geometry, and vectors at the landscape scale to inform best mining practices that minimize or eliminate significant environmental and evolutionary impacts and maintain the integrity of ecosystem services (including maintenance of populations and genetic diversity). These require a combination of approaches, including population genetics, ecology, physical oceanography, exploration, and mapping, that are part of the standard repertoire of deep-sea scientists and that can be applied individually or, ideally, in concert, to develop a better understanding of interactions among populations and requirements for sustainable development of mining interests.

Second, there is a need to develop first principles, a set of design recommendations, for preservation reference areas and conservation areas that can be applied to active or inactive sulphide deposits as they are being explored and developed for mining or other extractive purposes (e.g. bioprospecting, scientific research). Such guidelines have been proposed for the Clipperton–Clarion manganese nodule province to safeguard biodiversity and ecosystem function (C. R. Smith, pers. comm.), using the most current data and sound scientific principles within legal frameworks and environmental guidelines of the governing body (in this instance, the ISA) and incorporating the interests of mining and other stakeholders. Similar guidelines that take into account key features of sulphide-based systems and that address the interests of all stakeholders should be developed and adopted by the stakeholders.

Third, there is a need to develop and test methods for effective mitigation and restoration strategies to enhance recruitment and recovery of biodiversity in areas that may be subjected to open-cut mining. The deep sea is perhaps the last place where restoration scientists might have imagined a need today to find ways to prevent long-lasting impacts of human activities on the environment. Developing a network of permanent and temporary reserve areas is one step towards mitigation against loss of biodiversity and may be especially effective for active hydrothermal systems where population densities and reproductive capacity is high, but it may only be possible to determine the true efficacy of the design of these networks empirically; furthermore, the design seems likely to be idiosyncratic to locales and target taxa (what works for shrimp-dominated systems, for instance, may not be the appropriate design for tubeworm-dominated systems). Other steps towards habitat restoration may be important in facilitating recovery of inactive sulphide communities to pre-mining levels, but this requires a better understanding of recruitment and growth rates of corals, barnacles, sponges, etc., and habitat characteristics that are required for their successful colonization or transplantation (e.g. microtopographic relief).

Mining of seafloor massive sulphides, where permitted, will be a frontier use of the deep sea, with no precedent for how to monitor, regulate, and minimize habitat loss and degradation or to facilitate mitigation and restoration. Lessons learned and best management practices from activities that degrade or eliminate habitats on land, in coastal waters, and elsewhere in the deep sea (e.g. dredging, drilling, etc.) should be applied to seafloor massive sulphide systems, but new practices will undoubtedly need to be developed as well. Scientific research can help to clarify complex risks, identify gaps in knowledge, and provide an early warning of unexpected or unacceptable consequences. The mining industry has engaged in policy development with regard to environmental management through voluntary instruments such as the Draft Code of Environmental Management of Marine Mining (International Marine Minerals Society), which in turn draws on the Madang Guidelines of the South Pacific Applied Geoscience Commission (SOPAC). The ISA is also engaged in development of a comprehensive set of rules, regulations, and procedures related to mining activities (exploration and exploitation) in areas of the seafloor beyond national jurisdictions. Given that mining may take place in the deep sea, it is imperative that scientific research is undertaken in a proactive manner to allow us to propose strategies that minimize risks to biodiversity and ecosystem function in areas targeted for mining activities.

Acknowledgements

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