Mining Deep-Ocean Mineral Deposits: What are the Ecological Risks?

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ABSTRACT

A key question when managing deep-ocean resources is whether seafloor mineral deposits can be extracted without adversely affecting environmental sustainability and marine life. The potential impacts of mining are wide-ranging and will differ among the three principal types of metal-rich mineral deposit. A significant lack of information about deep-sea ecosystems and the mining technologies that will be used means there could be many unforeseen impacts. Here, we discuss the potential ecological impacts of deep-sea mining and identify the key knowledge gaps to be addressed to underpin the regulation of the sector. We also highlight the need to undertake baseline studies as well as regular monitoring programs before, during, and after the mineral extraction processes.

KEYWORDS: Deep-sea mining, environmental impact, sustainability, ecology

INTRODUCTION

Here, we consider the ecological risks associated with the extraction of seafloor massive sulfides (SMS), ferromanganese (FeMn) nodules and FeMn crusts. Each deposit typically occurs in a different geological and oceanographic environment

(Gollner et al. 2017) (Figure 1). The deposits differ in mineralogy, metal composition, surface expression, morphology and spatial extent, resulting in different ecosystem structures and functions and risks of disturbance.

Individual SMS deposits typically cover a relatively small area of the seabed (mounds may have diameters of ~100–200 square meters) compared with FeMn nodules and crusts (extending over 10s–1000s square kilometers). In contrast to nodules that lie in or on the sediment of lower energy abyssal plains, SMS deposits can form in relatively dynamic geological environments (affected by active volcanism, plume fall out and slumping), and are three dimensionally extensive structures (as discussed by Petersen et al. 2018 – this issue) with rugged surface topography (Figure 2). SMS deposits can also occur in systems that are stable over long timescales (e.g., Copley et al. 2007). Deposits in different stages of development, ranging from very active, high temperature (typically 250–400°C) vent sites to lower temperature (20–50°C) systems, characterized by 'shimmering' diffuse flow, and extinct deposits (eSMS) at ambient temperatures, provide a spectrum of environments, with different temperature regimes, chemical fluxes and stability.

SMS deposits found in areas of hydrothermal venting support variable, but typically dense faunal communities with much greater biomass and productivity than those found in other parts of the deep ocean (Zierenberg et al. 2000) (Figure 2). Despite the high local abundances of fauna, the species present are often rare, with limited distributions. Active vent communities vary dramatically within regions and across the globe; generally, these have tubeworm-dominated assemblages in the East Pacific, snail and barnacle dominance in the West Pacific and Indian Oceans, shrimp dominance in the Atlantic, and crab dominance in the Southern Ocean (Van Dover et al. 2018). eSMS appear to have lower density but higher diversity faunal communities than active vent sites (Levin et al. 2016). Offering a new long-lasting substratum in ambient conditions, inactive vent sites enable sponges, corals, and echinoderm assemblages to establish, with different sensitivities to mining processes (Levin et al. 2016). Given the species densities, biodiversities, and biomasses found at active and inactive vent sites, improved understanding of these ecosystems and the risks of anthropogenic disruption is urgently required, as mining of these deposits appears to be imminent, as discussed by Lusty and Murton (2018 – this issue), and some of the impacts will likely differ as does the ecology of these deposit types.

The abyssal plains with abundant FeMn nodules, generally between 4000 to 6000 m depth, cover a large area and are one of the world's most pristine environments (Figure 3). These areas are not homogeneous and vary in topography, environmental conditions and biology. Apart from the nodules, the sediments are typically very fine, although exposed bedrock outcrops in places. Samples of the fauna of this area show extremely high biodiversity for many groups, but regional diversity is poorly characterized and the connectivity between areas is unknown for most species. The visible fauna are primarily xenophyophores (giant single-celled organisms), cnidarians (e.g. corals and anemones) and sponges, but include large crustaceans, echinoderms (e.g. sea cucumbers) and fishes (Amon et al. 2016). Many organisms, large and small, live on the nodules themselves. Sediment-dwelling fauna are primarily nematodes, foraminiferans, polychaete worms and crustaceans. The density of fauna is generally low relative to FeMn-crust communities and hydrothermal vents.

FeMn crusts mostly occur on seamounts and ridges between 800 and 2500 meters. Some seamounts are flat-topped (guyots) but most of the topography tends to be steep. Currents can be highly variable. As a result, the crusts tend to be exposed and so provide habitat for attached suspension feeders, such as cnidarians (e.g. corals) and sponges (Figure 4). In some cases, individuals can be very large and old. Dense forests of these fauna can occur (Figure 4) that support a wide variety of associated fauna, such as crustaceans, echinoderms and molluscs. The majority of communities inhabiting FeMn-encrusted seamounts and ridges have not been well explored or characterized.

IMPACTS OF DEEP-OCEAN MINING

Deep-Ocean Mining Equipment and Techniques

The major metal-rich deep-sea deposits each have distinct characteristics but the mining approach envisaged will have some common key stages (Figure 5). Some types of deep-ocean mining, for example the extraction of SMS deposits, may be comparable to that currently conducted on land and use similar equipment. In the early stages of development of the industry, it is likely that equipment design will be an extension of existing land-based mining techniques and subsea trenching and dredging equipment, integrated with remote system technology. All deposits types will require a seafloor collector device, which gathers the mineral deposit from the seafloor. The minerals will then be transferred via a vertical transport system (termed a riser pipe) to a surface vessel, where they will be de-watered and transferred to transport barges. Processing water, containing suspended sediment and mineral particulates, will either be discharged from the vessel at the sea surface or carried via another vertical transport system to be discharged at depth (Weaver et al. 2017).

Despite some general similarities, the seabed mining equipment that will be used to extract each of the deposit types will be different. The equipment produced for the Solwara 1 SMS project, discussed by Lusty et al. (2018 – this issue), provides the best current indication of the nature of the seafloor production tools and the way they will operate. Three track-mounted robotic tools will be used to extract the deposits. One cutting machine will prepare the ground for subsequent mining, by flattening rough topography and creating benches for the other machines to operate on. A second cutter will mine along the benches. Both cutters excavate rock by a continuous cutting process, comparable to the continuous mining machines used on land. A collecting machine will then suck the disaggregated rock, generated by the cutters, off the seafloor as a slurry and pump it into the riser system. FeMn crust-extraction is likely to employ similar cutting and collection machines to those used for SMS deposits. In contrast, for mining FeMn nodules, seabed mining equipment will most likely consist of a vehicle carrying a collector possibly on sled runners, which may be self-propelled at a speed of about 0.5 meters per second, using tank-like tracks or with Archimedes screws (Oebius et al. 2001; Jones et al. 2017). There may be one or more collectors, likely over 10 meters wide, which would collect nodules in surface sediments (<50 centimeters deep) by mechanical means or separated from the sediment using water jets. The seabed collecting devices will be connected with systems that pump the nodules from the seabed to the surface through a riser.

During mining operations, some of the flocculent surficial sediment would be resuspended by hydraulic jets and movements of the mining collector. Deeper sediment layers may be broken up into lumps that could partly enter the collection system. The residual sediment carried to the sea surface with the nodules would likely be separated from the nodules and discharged near the seabed.

General Impacts of Mining Operations

The mining of deep-sea minerals, like any form of human development, will impact the surrounding environment and biological communities, including their structure and functioning. The mining vehicle is likely to disturb the sediment in wide tracks, compacting the sediment in its path and moving sediment to the edge of the track areas. The organisms near the mining operation that cannot escape will be crushed and probably killed by the machines. Noise and light pollution from the mining machinery and support vessels will impact biological communities from the sea surface to the deep-ocean floor. Sediment plumes created by the mining operation will spread in the water column and eventually settle on the seafloor, smothering the sediment and its fauna both over in the directly disturbed area and surroundings.

Sediment plumes will be created at the seabed by operations and from the dewatering outflow pipe after processing either at the seabed or in the water column. It is likely that surface discharges of particulates, although technically more straightforward, would be more harmful than discharges at depth, increasing the potential ecosystem effects by interacting with euphotic upper ocean systems, organisms (e.g. plankton, marine mammals and turtles) and enhancing the risks of impacts to humans by contaminating or otherwise impacting commercial fishing stocks. Releasing sediment-laden water at depth could also have far-reaching impacts; for example, seabed communities may be smothered, nutrients could be introduced to otherwise nutrient-poor systems, toxic metals could be mobilized, and deepwater fisheries may be contaminated in a similar way to those at shallower depths. Models suggest that large sediment plumes will be created that spread over extensive areas, particularly in the case of FeMn-nodule mining, as the sediment grain size of the abyssal seafloor is small. It is estimated that the sediment plume will cover at least twice the area of the operation and likely more (Gjerde et al. 2016).

SMS

The seafloor mining footprint from extracting a single SMS deposit will be smaller than for the other deposit types. However, SMS mining will cause a range of impacts unique to these deposits, which will vary depending on the type of SMS deposit being targeted (Van Dover 2014). The chemical composition of SMS is distinctive from FeMn crusts and nodules and they potentially contain a wide range of trace metals (discussed by Peterson et al. 2018 – this issue) that vary between SMS deposit types. However, considerable efforts are being made to protect active vent sites from any mining activity as they harbor high-density, endemic communities and the estimated deposit yields are relatively small (Van Dover et al. 2018) (Figure 2). Hydrothermally inactive vent sites are, therefore, more attractive for mining but should not be considered barren of life (Van Dover 2011). The impacts of mining SMS deposits will be similar to those of extraction of the other deposit types (e.g., animals destroyed by the mining activity, removal of the primary substratum used by fauna, and the generation of sediment plumes). However, mining SMS deposits will likely result in greater levels of chemical pollution than for the other deposit types, primarily resulting from the oxidation of newly exposed sulfides and the subsequent release of heavy metals into the water column. These metals are toxic and will likely have a negative impact on the species inhabiting the area surrounding the mine site – either directly, or via secondary effects, such as reducing levels of available oxygen in the water. Non-vent organisms may also use vent sites for aspects of their lives, for example, some skates incubate their egg cases at active hydrothermal vent sites. The effects of mining on these organisms will be difficult to quantify and monitor.

FeMn Nodules

Once considered to be a near-barren landscape, the FeMn-nodule field in the CCZ is now known to host high biodiversity (Amon et al. 2016) (Figure 3). As a result, FeMn-nodule mining is expected to have a number of specific impacts on seafloor and water-column communities. Most obviously, the FeMn nodules themselves provide a hard surface that is home to a wide variety of life, including sponges, corals, anemones, worms, foraminifera, nematodes and microbes. In turn, many of these larger organisms provide a substratum, or foundation, for other animals to inhabit (e.g., sea stars and small crustacea on corals) (Mullineaux 1987; Gooday et al. 2015; Amon et al. 2016). Removing the FeMn nodules, which will take millions of years to grow, assuming they reform in the same locations, will thus have major impacts on the associated fauna, particularly as it has been suggested that half of megafaunal species in the CCZ depend on the FeMn nodules directly (Amon et al. 2016; Vanreusel et al. 2016). A recently discovered example of this is the white "Casper" octopus that lays its eggs on sponge stalks growing on FeMn nodules and crusts (Purser et al. 2016). FeMn nodules are found in very stable environments on soft sediments with strong vertical stratification and low concentrations of organic matter (Mewes et al. 2014). Disturbance of sedimentary environments like these will lead to the disruption of the surface sediment (5−20 cm deep) and cause exposure of deeper sediment layers and compaction. These changes will have impacts on the sediment geochemistry, which will likely kill the fauna living within the sediments and impair recovery processes. In addition, the scale of FeMn nodule mining is particularly large, with the potential for areas of several hundred square kilometers to be disturbed each year by a single operation (Smith et al. 2008). Impacts of this scale are rare in deep-sea environments and may lead to effects that can be seen at regional scales, such as population reductions or even species extinctions.

FeMn Crusts

The mining of FeMn crusts will also have a variety of environmental impacts (Schlacher et al. 2014). The extraction process will entirely remove the mineral-rich surfaces of the seamounts, which are inhabited by benthic fauna, including corals, sponges, echinoderms, and other invertebrates, with some present in very dense populations. Many of these animals are not yet known to science, long-lived (hundreds to thousands of years old for some corals and possibly sponges), fragile, and larger individuals may be responsible for much of the reproductive output, which is needed to safeguard future populations. Isolated seamounts may host endemic species, which are more prone to extinction from mining as they are well adapted to a specific habitat and set of environmental conditions. FeMn crusts are also the most likely resource to be found in areas affected by other human activities, particularly deep-sea fishing resulting in cumulative impacts (Morato et al. 2010). The sediment plumes generated by mining operations may directly impact fish and other pelagic organisms, which tend to congregate on and above seamounts. Additionally, many commercially exploited fish species depend on rich invertebrate assemblages found on seamounts as nursery grounds and as hiding places to avoid predators. Thus, mining may also have secondary impacts on fish communities and the ecosystem services they provide.

Ecosystem Degradation and Recovery

All deep-sea mining operations will result in the degradation and loss of habitats, potentially resulting in extinctions of endemic and/or rare taxa and decreased species diversity of all size classes. Other deep-sea-mining impacts include modified trophic interactions, a risk of transplanting organisms from one mining site to another and lost opportunities to gain knowledge about what is currently unknown (Boschen et al. 2013). For both FeMn crusts and nodules, the ecosystems found where mining is planned to take place tend to be slow-paced and not subjected to regular disturbances like those expected from mining. Even for SMS deposits at hydrothermal vents, which are often considered a relatively dynamic habitat, remarkable decadal stability has been observed (Copley et al. 2007; Du Preez and Fisher 2018). As a result, it is expected that recovery from any mining disturbances will be extremely slow, particularly when important structuring habitats (e.g., nodules, vent chimneys and corals) are removed by the mining activities. In summary, there is great uncertainty surrounding the natural environment in and around the deep-ocean mineral deposits currently being considered for extraction, as well as about the full impact of mining and the resilience of associated ecosystems and their potential for recovery.

Existing information on the ecological effects of mining and potential recovery times is limited, despite deep-ocean mining-related research having been conducted since the 1970s (Jones et al. 2017). The most intensive assessment, the disturbance and recolonization experiment (DISCOL) carried out in an area of FeMn nodules off Peru at a water depth of 4150 meters in 1989, disturbed the seafloor across several kilometers, with nearly 80 plough tracks. This experimental site and other similar seafloor areas were re-investigated in 2015 through the JPI-Oceans Programme. Even after 27 years, there was little change to the disturbed tracks, with a high resemblance to when they were first made. Detailed biological studies showed that while some mobile species moved back into the tracks, there was very little recolonization of disturbed areas, with even microbial communities struggling to recover (Gjerde et al. 2016). Recovery from commercial-scale mining is likely to be even slower, as both the temporal and spatial scales of disturbance will be much larger than those of the experiments. These regional-scale impacts could result in local extinctions and population declines, reducing biological connectivity and reproductive success, as larval supply decreases with distance from unaffected populations.

Knowledge Gaps

A fundamental problem for predicting the impacts of deep-sea mining is our limited knowledge about deep-sea ecosystems in general. The animals inhabiting FeMn nodules, crusts and SMS are poorly known, with many expected to be new to science. There is also a lack of basic ecological information, for example, on the species present and their population sizes, behaviors, distributions, life histories, growth rates, reproductive patterns and dispersal potential. We don't know, for the vast majority of organisms, how and if populations are connected, and what is needed for the maintenance of viable communities. Some species that have been evaluated show wide distributions and connectivity between populations on scales of hundreds of kilometers, but assessments of FeMn-nodule systems show that there are also a large number of rare species, which tend to occupy a smaller geographic range (Glover et al. 2002). These patterns may be an artefact of limited sampling, but many species are known from only a few individuals with poorly understood ecological roles, particularly for the smaller animals. Typical conservation measures on land tend to focus on rare species for inherent value, or the ecosystem functions they support. The presence of rare species may also be used as an indicator of ecosystem health and high biodiversity although common species also play key roles in SMS deposit-hosting ecosystems. Identifying 'indicator' species in the deep sea is therefore currently difficult, preventing specific species-based conservation actions and inhibiting efforts to improve management actions.

ENVIRONMENT MANAGEMENT: REDUCING THE IMPACT OF DEEP-OCEAN MINING

Whilst deep-sea mining is destructive and generally regarded as inherently unsustainable, there are many opportunities to reduce the impacts through good management practices (Durden et al. 2017). Firstly, extensive fundamental research needs to be done in each area planned for mining to ascertain baseline conditions. This research should incorporate high-resolution mapping, and assessments of the spatial and temporal patterns in physical and chemical conditions and the faunal communities inhabiting the areas. Ecosystem functioning (the combination of biological and physical interactions) should also be studied, to prevent mining-related ecosystem collapse and to ensure that the ecosystem services that we rely on will be provided during and after mining. Overall, this information will result in a better understanding of the communities that are at risk and can be incorporated into environmental management plans.

The next stage is to evaluate the potential impacts of the mining operation by undertaking Environmental Impact Assessments (EIAs). A typical EIA assesses the risks of the project and sensitivities of the environment. It also identifies alternative project plans that may reduce or mitigate the impacts of mining, helping to preserve unique and vulnerable communities (Durden et al. 2018). The risks are typically reduced by applying a 4-stage mitigation hierarchy, whereby, in order of preference, risks are: 1) avoided (e.g., by moving the project away from a vulnerable habitat); 2) minimized (e.g., by introducing new technology to model and reduce the sediment plume generated by a mining vehicle); 3) restored; or 4) offset. The last two options, restoration and offsetting, are considered impractical for deep-sea mining at present as a result of a range of biological, technical, financial and legal issues (Van Dover et al. 2017). Once a project's risks have been reduced as much as is practical, a decision can be made as to whether the economic, social, and political benefits of the project outweigh the costs, environmental or otherwise. If the project is approved, then plans can be made for ongoing environmental monitoring to identify and measure the impacts of the project. If these negative effects become too severe, the project can be curtailed. These management strategies should be continued throughout the life of the project and after it has been decommissioned.

The mining company primarily carries out the environmental management of individual mining projects. However, additional regional management is necessary for sustainable mining on broader scales to achieve wider conservation objectives. Decisions about mine site placement, the number of active mines, and the designation of marine protected areas, are best made by the agency responsible for the regulation of mining within a region. In the case of deep-sea mining, this is principally the ISA. To date, the spatial allocation of exploration areas has been driven by contractor applications to the ISA in areas of interest in the world's oceans. However, a regional management plan has been made for the CCZ (Wedding et al. 2013), which currently includes nine areas, known as Areas of Particular Environmental Interest (APEIs), where mining cannot currently occur. These APEIs are peripheral to the central CCZ, which has the highest FeMn nodule densities, and they each consist of a 200 x 200 square kilometer protected zone, surrounded by a 100-kilometer buffer. The APEIs are designed to be geographically close enough to allow for biological connectivity with the proposed mining areas so re-colonization can occur after mining has ceased. Further spatial management includes Preservation Reference Zones (PRZs), which are areas put in place to monitor the effects of individual mining projects, and, by being representative areas where mining cannot occur, may also act as protected areas. Many areas of mining interest do not have a regional environmental management plan. These plans need to be developed prior to mining and should take into account a range of factors including the mining type, potential impacts, specific ecosystems, connectivity, vulnerability and the optimal approaches for management.

Management of deep-sea mining is made more complex by high uncertainty on the mining impacts, the environments and ecosystems affected, and how they will respond to disturbance. This uncertainty can be addressed in part by further research targeting the areas and regions of exploitation interest. In addition, protecting large and/or connected areas, precaution and the ability to adapt management approaches as more information becomes available will also be important.

CONCLUSIONS

Current interest in deep-sea mining is focused on three habitats for which we are lacking fundamental baseline knowledge about species composition, ecology, and natural environmental conditions. It is, however, without doubt that deep-sea mining has the potential to have far-reaching impacts on our oceans, both shallow and deep. While some impacts will be resource-specific, mineral deposit extraction will broadly affect local and regional marine communities by removing suitable habitats, creating far-reaching sediment plumes and reducing population sizes (or, in the case of rare or specialist species, causing extinctions). Deep-sea mining will impact habitats, which will take decades, at least, to recover. The need for baseline information about reproduction, growth, population sizes, diversity, distributions and more is essential for successful environmental impact assessments and sustainable management of these habitats during mineral extraction. As exploitation on such a large scale has never occurred before in the deep sea, its environmental management is a nascent endeavor. For the impacts of deep-sea mining to be minimized, there is a requirement for cooperation between all stakeholders on a national and international level: industry, policymakers, scientists, NGOs, and members of the public whose livelihoods depend on ocean resources. Most importantly, the ISA will need to continue to enforce coherent strategic planning and management. This needs to take place on both local and regional scales for all areas in which there is interest in mining, if the ISA is to stand by its commitment to ensure the harmful effects from deep-sea mining are minimized and that deep-sea mining proceeds in an informed and careful manner in the future.

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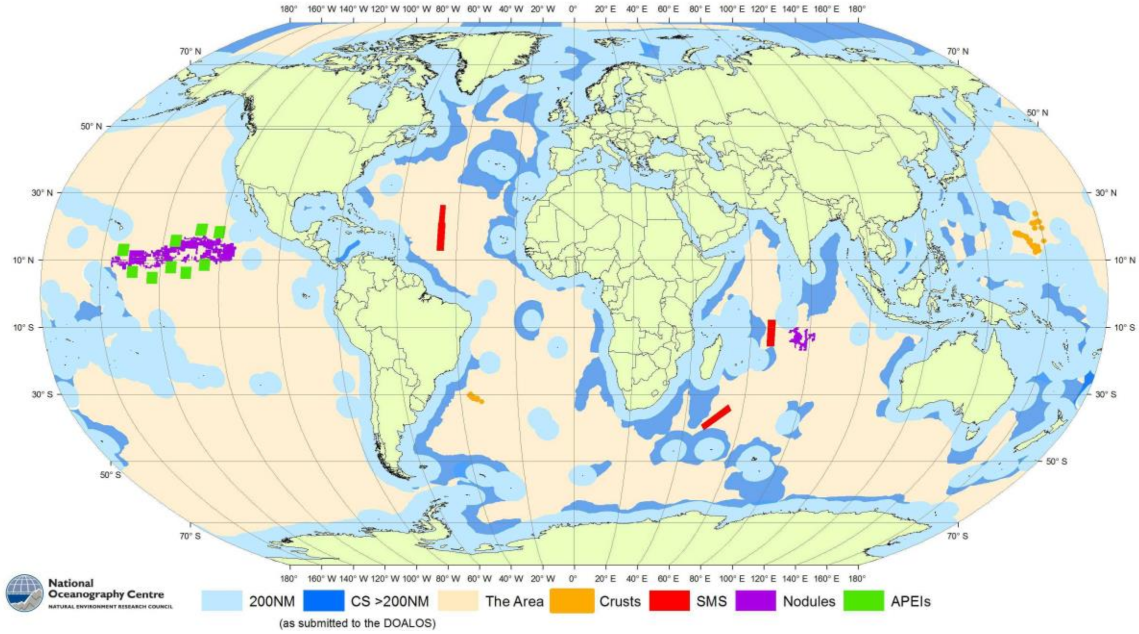

Figure 1. The locations of ISA exploration contract areas for the three main metal-rich mineral resource types in the “the Area” beyond national jurisdiction for seafloor massive sulfides (SMS), FeMn nodules and crusts. The Areas of Particular Environmental Interest (APEIs) in the Clarion Clipperton zone are indicated and shown in more detail on the map in Lodge and Verlaan (2018 – this issue). Also shown are seabed areas within national jurisdiction (extending to 200 nautical miles and to the continental shelf beyond 200 nautical miles) and the Area. Image credit: Alan Evans, National Oceanography Centre, Southampton.

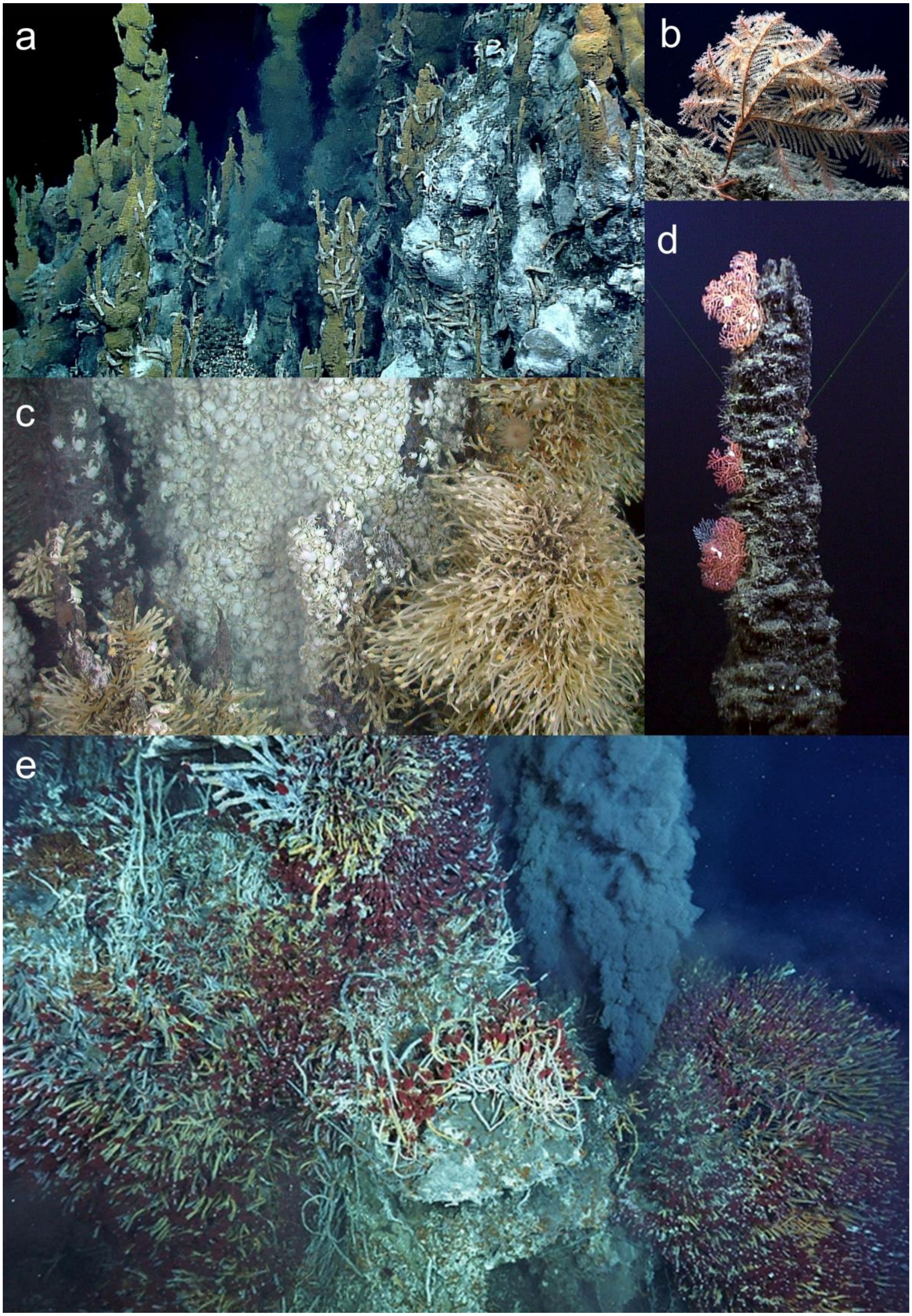
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Figure 2. Some example images from hydrothermal vents. (a) Seafloor massive sulfides with associated communities of shrimp, crabs and snails discovered in 2016 at 3,863 m in the Mariana back-arc axis, West Pacific Ocean. Image credit: NOAA's Office of Ocean Exploration and Research. (b) A black coral observed at 2,227 m in the Endeavour rift valley, Northeast Pacific Ocean. Image credit: Ocean Networks Canada. (c) Squat lobsters and stalked barnacles dominate this chimney, attaining high biomass, in the E9 vent field of the East Scotia Ridge. Image credit: NERC ChEsSo Consortium. (d) Corals living on an extinguished chimney at 2,203 m in Mothra vent field, Northeast Pacific Ocean. Image credit: Ocean Networks Canada. (e) *Ridgeia piscesae* tubeworm communities, likely hosting paralvinellid worms, scaleworms, limpets, and many other fauna in their bush-like structures found near a black smoker at 2,133 m at the Endeavour segment of the Juan de Fuca Ridge, Northeast Pacific Ocean. Image credit: Ocean Networks Canada.

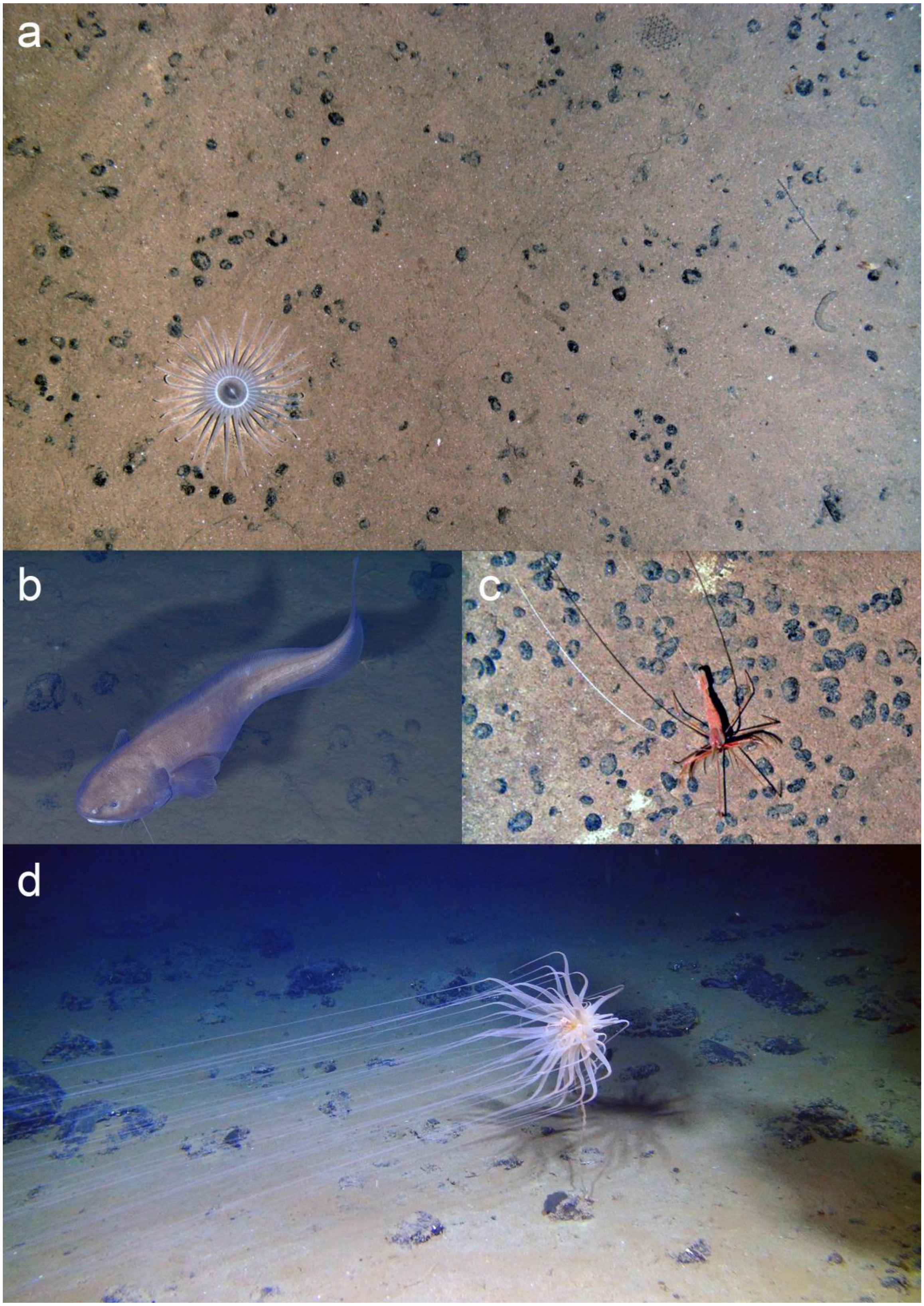
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Figure 3. Some example images from FeMn-nodule fields in the Clarion-Clipperton Zone, Pacific Ocean. (a) an anemone (left) and small coral (right); (b) abyssal fish *Bassozetus* sp.; (c) decapod crustacean *Bathystylodactylus* sp.; (d) cnidarian *Relicanthus* sp. with very long tentacles streaming out into the seabed current. Image credits: (a and c) National Environment Research Council, RRS *James Cook* Cruise JC120; (b and d) Diva Amon and Craig Smith, University of Hawaii at Manoa.

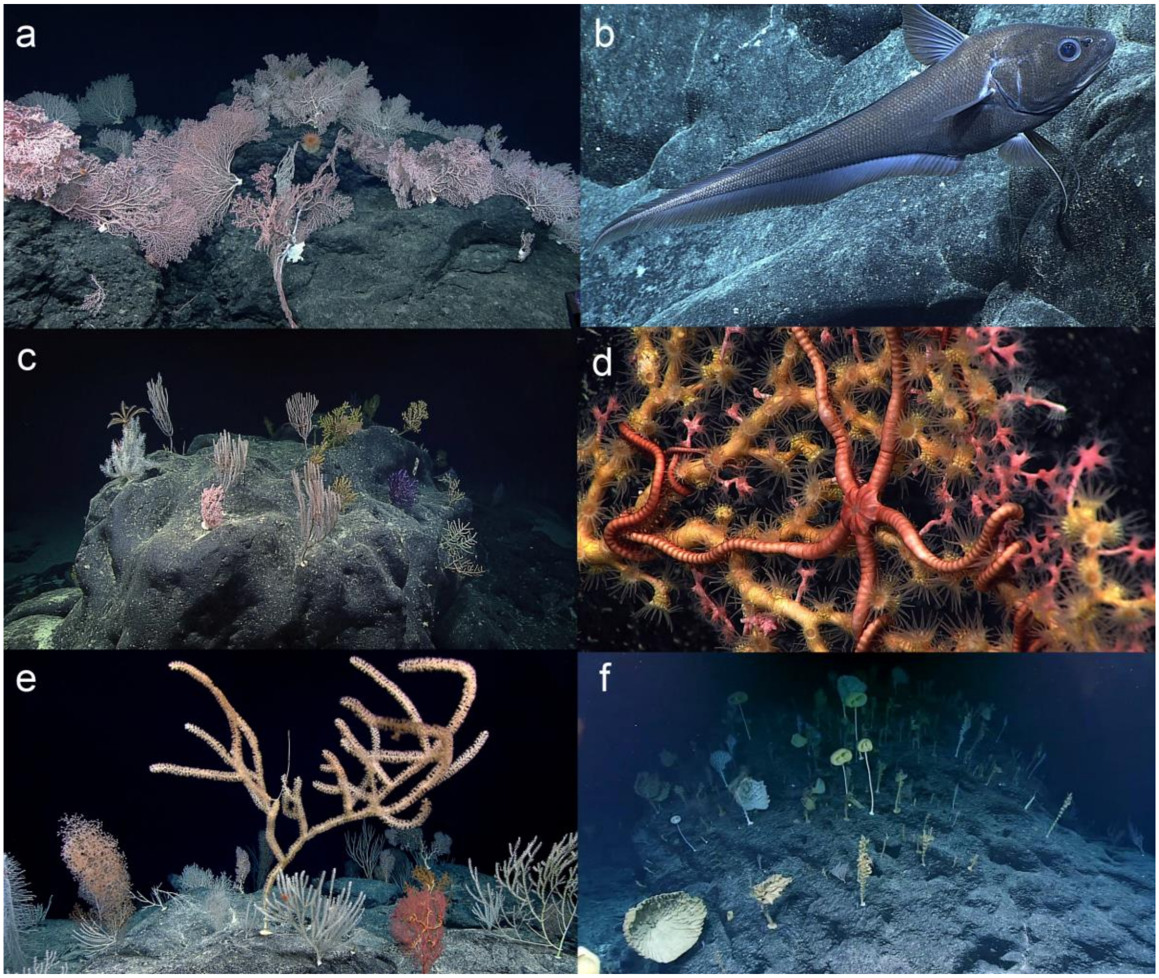
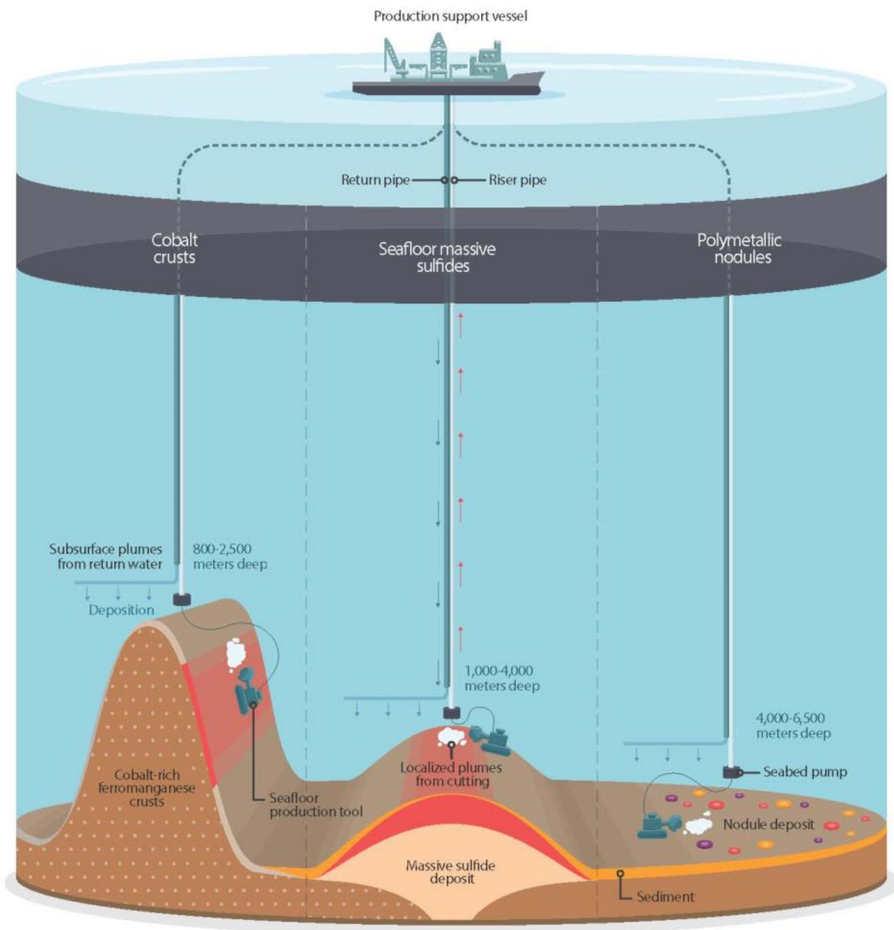


Figure 4. Some example images from FeMn-encrusted seamounts in the Pacific Ocean. (a) An abundant community of large corals with anemones, crinoids and ophiuroids; (b) A rattail fish (*Coryphaenoides* sp.); (c) A diverse community of corals with associated crinoids and ophiuroids; (d) An ophiuroid living commensally on a coral that is overgrown in some places by zoanthids; (e) A diverse and abundant coral and sponge community; (f) A community dominated by sponges. Image credits: NOAA Office of Ocean Exploration and Research.



Source: New Zealand Environment Guide

Figure 5. Potential types of deep-sea mining operation. Image credit: 2017 The Pew Charitable Trusts.