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

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ABSTRACT

A key question for the future management of the oceans is whether mineral deposits that exist on the seafloor of the deep ocean can be extracted without significant adverse effects to environmental sustainability and marine life. The potential impacts of mining are wide-ranging and will vary depending on the type of metal-rich mineral deposit being mined. There is, currently, a significant lack of information about deep-ocean ecosystems and about potential mining technologies: thus, there could be many unforeseen impacts. Here, we discuss the potential ecological impacts of deep-ocean mining and identify the key knowledge gaps to be addressed. Baseline studies must be undertaken, as well as regular monitoring of a mine area, before, during, and after mineral extraction.

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

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INTRODUCTION

Here, we consider the ecological risks associated with the extraction of seafloor massive sulfide deposits, ferromanganese (Fe–Mn) nodules and Fe–Mn crusts. Each deposit typically occurs in a different geological and oceanographic environment (Gollner et al. 2017) (FIG. 1). The deposits differ in mineralogy, metal composition, surface expression, morphology and spatial extent, resulting in different ecosystem structures and functions and different disturbance risks.

Individual seafloor massive sulfide deposits typically cover a relatively small area of the seabed (mounds may have diameters of ~100–200 m^2) compared with Fe–Mn nodules and crusts (extending over 10s–1000s km^2). In contrast to nodules that lie in or on the sediment of the lower energy abyssal plains, seafloor massive sulfide deposits may represent relatively dynamic environments (affected by active volcanism, plume fall out and slumping), and are three dimensionally extensive structures with rugged surface topography (as discussed by Petersen et al. 2018 this issue) (FIG. 2). Seafloor massive sulfide deposits can also represent environments that are stable over long timescales (e.g. Copley et al. 2007). Deposits at different water depths can be at varying stages of development: from very active, high temperature (typically 250–400 °C) vent sites, to lower temperature (20–50 °C) systems, characterized by 'shimmering' diffuse flow, to extinct seafloor massive sulfide deposits at ambient temperatures. Thus, there are a spectrum of environments, each with their own different temperature regimes, chemical fluxes and stability.

Seafloor massive sulfide deposits found in areas of hydrothermal venting support variable, but typically dense, faunal communities that have a much greater biomass and productivity than those found in other parts of the deep ocean (FIG. 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 Ocean, and crab dominance in the Southern Ocean (Van

Dover et al. 2018). Massive sulfide deposits at inactive vent sites appear to have lower density but higher diversity faunal communities than active vent sites (Levin et al. 2016). Inactive vent sites offer a long-lasting substratum in ambient conditions by which sponges, corals, and echinoderm assemblages can become established, each assemblage having different sensitivities to a given mining process (Levin et al. 2016). Given the species density, biodiversity, and biomass found at active and inactive vent sites, improved understanding of these ecosystems and the risks of anthropogenic disruption is urgently required, not least because mining of these deposits appears to be imminent, as described by Lusty and Murton (2018 this issue). Some of the mining impacts at a specific site will likely differ as a result of the variable ecology.

The deep-water abyssal plains contain abundant Fe–Mn nodules and cover a huge area. They are one of the world's most pristine environments (FIG. 3). These areas are not homogeneous but vary in topography, environmental conditions and biology. Apart from the nodules, the sediments are typically very fine, although bedrock is locally exposed. 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 the communities found on Fe–Mn crusts and hydrothermal vents.

The ferromanganese crusts that accumulate on seamounts and ridges represent hard, stable habitats over a range of water depths in the open ocean. Some seamounts are flat-topped, with extensive summit plateaus, but their topography can also be very rugged, including steep slopes and cliffs. Ocean currents can be highly variable, as described by Lusty et al. (2018 this issue). As a result, ferromanganese crusts tend to be exposed, thereby providing habitats for attached suspension feeders, such as cnidarians (e.g. corals) and sponges (FIG. 4). In some cases, individual corals and sponges can be very large and old. Dense forests of these fauna (FIG. 4) can support a wide variety of associated fauna, such as crustaceans, echinoderms and molluscs. The majority of communities inhabiting Fe–Mn-encrusted seamounts and ridges have not been well explored or characterized.

IMPACTS OF DEEP-OCEAN MINING

Mining Equipment and Techniques

The major metal-rich deep-ocean deposits each have distinct characteristics, but the mining approaches being envisioned will have some common key stages (FIG. 5). Some types of deep-ocean mining, such as the extraction of seafloor massive sulfide 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 to gather the mineral deposit from the seafloor. The minerals will then be transferred via a vertical transport system (a riser pipe) to a surface vessel, where they will be de-watered and transferred to transport barges. The processed 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. 2018).

Despite some general similarities, the seabed mining equipment that will be used to extract each of the three deposit types will be different. The equipment produced for the Solwara 1 seafloor massive sulfide project (off Papua New Guinea) (see Lusty et al. 2018 this issue), provides the best current indication of what seafloor production tools will be used and the way they will operate. In the Solwara 1 case, 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 will 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.

Ferromanganese crust extraction is likely to employ similar cutting and collection machines to those used for seafloor massive sulfide deposits. In contrast, mining Fe–Mn nodules will require seabed mining equipment most likely consisting 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). A mining operation may employ one or multiple collectors that are each likely to be over 10 metres wide. The collector would recover nodules in surface sediments (<50 cm deep) by mechanical means or by separating them 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 re-suspended by movement of the collector vehicle and hydraulic jets. Deeper sediment layers could be broken up into lumps that then might partly enter the collection system. Such residual sediment would be carried to the sea surface with the nodules and would likely be separated from the nodules and discharged back near the seabed.

General Environmental Impacts of Mining Operations

The mining of deep-ocean minerals, like any form of human industrial development, will impact the surrounding environment and biological communities, including community 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 seabed mining operation will spread in the water column and eventually settle on the seafloor, smothering any fauna in the directly disturbed area and the immediate surroundings. Sediment plumes may also arise from the surface de-watering operation. It is likely that surface discharge of particulates, although technically more straightforward, would be more harmful than discharges at depth, increasing the potential ecosystem effects by interacting with euphotic (photosynthesis possible) upper ocean systems, with organisms (e.g. plankton, marine mammals and turtles) and by enhancing the risks to humans by contaminating or otherwise impacting on 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 deep-water 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 Fe–Mn nodule mining, because the sediment grain size of the abyssal seafloor is so small. A sediment plume could cover at least twice the area of the operation, and likely more (Gjerde et al. 2016).

Mining Seafloor Massive Sulfide Deposits

The ‘footprint’ on the seafloor from extracting a single seafloor massive sulfide deposit will be smaller than for the other deposit types. However, seafloor massive sulfide mining will cause a range of impacts unique to these deposits, which will vary depending on the type of deposit being targeted (Van Dover 2014). The chemical composition of seafloor massive sulfides is distinct from Fe–Mn crusts and nodules: they potentially contain a wide range of trace metals (discussed by Peterson et al. 2018 this issue) that vary between deposit types. However, considerable efforts are being made to protect active vent sites from any mining activity because they harbour high-density, endemic faunal communities for an estimated deposit yield that is relatively small (Van Dover et al. 2018) (FIG. 2). Hydrothermally inactive vent sites are, therefore, more attractive for mining, though they should not be considered barren of life (Van Dover 2011). The impacts of mining seafloor massive sulfide deposits will be similar to those of extracting other deposit types: animals destroyed by the mining activity, removal of the primary substratum used by fauna, and the generation of sediment plumes. However, mining seafloor massive sulfide 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.

Mining Fe–Mn Nodules

Once considered to be a near-barren landscape, the Fe–Mn nodule field in the Clarion–Clipperton Zone is now known to host high biodiversity (Amon et al. 2016) (FIG. 3). As a result, Fe–Mn-nodule mining is expected to have a number of specific impacts on seafloor and water-column communities. Most obviously, the Fe–Mn 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). Ferromanganese nodules are not a renewable resource because they take millions of years to form. Removing the Fe–Mn nodules will, thus, have major impacts on the associated fauna, particularly as it has been suggested that half of megafaunal species in the Clarion–Clipperton Zone directly depend on the Fe–Mn nodules (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 Fe–Mn nodules and crusts.

Ferromanganese 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 impact the sediment geochemistry, which will likely kill the fauna living within the sediments and impair ecosystem recovery processes. In addition, the scale of Fe–Mn nodule mining will be 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 on this scale are rare in deep-ocean environments and may lead to effects that can be seen at regional scales, such as population reductions or even species extinctions.

Mining Fe–Mn Crusts

The mining of Fe–Mn 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 that include corals, sponges, echinoderms, and other invertebrates, sometimes in very dense populations. Many of these animals are not yet known to science, they may be long-lived (hundreds to thousands of years old for some corals and possibly sponges), be 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 that could be more prone to extinction from mining because they are well adapted to a specific habitat and set of environmental conditions. Ferromanganese crusts are also the most likely resource to be found in areas affected by other human activities, particularly deep-sea fishing, and that could result in cumulative negative impacts (Morato et al. 2010). The sediment plumes generated by mining operations may directly impact the fish and other pelagic organisms that tend to congregate on and above seamounts. Additionally, many commercially exploited fish species depend on the rich invertebrate assemblages that are 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-ocean 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 Fe–Mn crusts and nodules, the ecosystems found where mining is planned to take place tend to be slow-paced and are not usually subjected to the type of disturbances expected from mining. Even for seafloor massive sulfide 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 has been the disturbance and recolonization experiment (DISCOL) that was carried out in an area of Fe–Mn nodules off Peru at a water depth of 4,150 meters in 1989. This experiment disturbed the seafloor across several kilometers with nearly 80 plough tracks. The experimental site and other similar seafloor areas were re-investigated in 2015 through the European Union-based intergovernmental Joint Programming Initiative Healthy and Productive Seas and Oceans (JPI-Oceans) Programme. Even after 27 years, there was little change to the disturbed tracks: they looked much the same as 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. Even microbial communities struggled 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.

Deep-Sea Ecosystem Knowledge Gaps

A fundamental problem for predicting the impacts of deep-ocean mining is our limited knowledge about deep-sea ecosystems in general. The animals inhabiting Fe–Mn nodules, Fe–Mn crusts and seafloor massive sulfides are poorly known: many are 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, behaviours, 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 Fe–Mn 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 that have 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 seafloor massive sulfide deposit–hosting ecosystems. Identifying 'indicator' species in the deep-sea is, therefore, currently difficult, and this in turn prevents specific species-based conservation actions and inhibits our efforts to improve management actions.

ENVIRONMENTAL 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). First, 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 both the spatial and temporal patterns in physical and chemical conditions and of the faunal communities that inhabit the area. 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. A typical environmental impact assessment will assess the risks of the project in question and sensitivities of the environment. It should also identify alternative project plans that may reduce or mitigate the impacts of mining, helping to preserve unique and vulnerable communities (Durden et al. 2018). The negative impacts on an ecosystem are typically reduced by applying a four-stage mitigation hierarchy during mining operations. This hierarchy comprises four steps that are designed to be implemented sequentially: 1) avoid (e.g. move the project away from a vulnerable habitat); 2) minimize (e.g. by introduce new technology to model and reduce the sediment plume generated by a mining vehicle); 3) remediate (e.g. restore biodiversity to mined areas); and 4) offset (e.g. restore biodiversity in an equivalent area to that lost from mining). 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, be they 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 any 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 International Seabed Authority (based in Kingston, Jamaica), the role of which is reviewed by Lodge and Verlaan (2018 this issue). To date, the spatial allocation of exploration areas has been driven by contractor applications to the International Seabed Authority in areas of interest in the world's oceans. However, a regional management plan has been made for the Clarion–Clipperton Zone (Wedding et al. 2013), which currently includes nine areas known as the 'Areas of Particular Environmental Interest', where mining cannot currently occur. These Areas of Particular Environmental Interest are peripheral to the central section of the Clarion–Clipperton Zone, which holds the highest Fe–Mn nodule densities, and they each consist of a 200 × 200 km^2 protected zone, surrounded by a 100 kilometer buffer. The Areas of Particular Environmental Interest are designed to be geographically close enough to allow for biological connectivity with the proposed mining areas, so allowing re-colonization to occur after mining has ceased.

Further spatial management includes 'Preservation Reference Zones', which are areas established to monitor the effects of individual mining projects. Such zones are 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-ocean mining is made more complex by the high uncertainty associated with the impacts of mining, the environments and ecosystems affected, and how they will respond to disturbance. This uncertainty can be addressed in part by further research targeted at the areas and regions of exploitation interest. To better protect 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, at a minimum, decades 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.

Exploitation on such a large scale has never occurred before in the deep ocean; its environmental management is a nascent endeavour. 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, non-governmental organisations, and members of the public whose livelihoods depend on ocean resources. Most importantly, the International Seabed Authority 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, and the International Seabed Authority needs to stand by its commitment to ensure that the harmful effects from deep-ocean mining are minimized and that the deep-sea mining industry proceeds in an informed and careful manner in the future.

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FIGURES

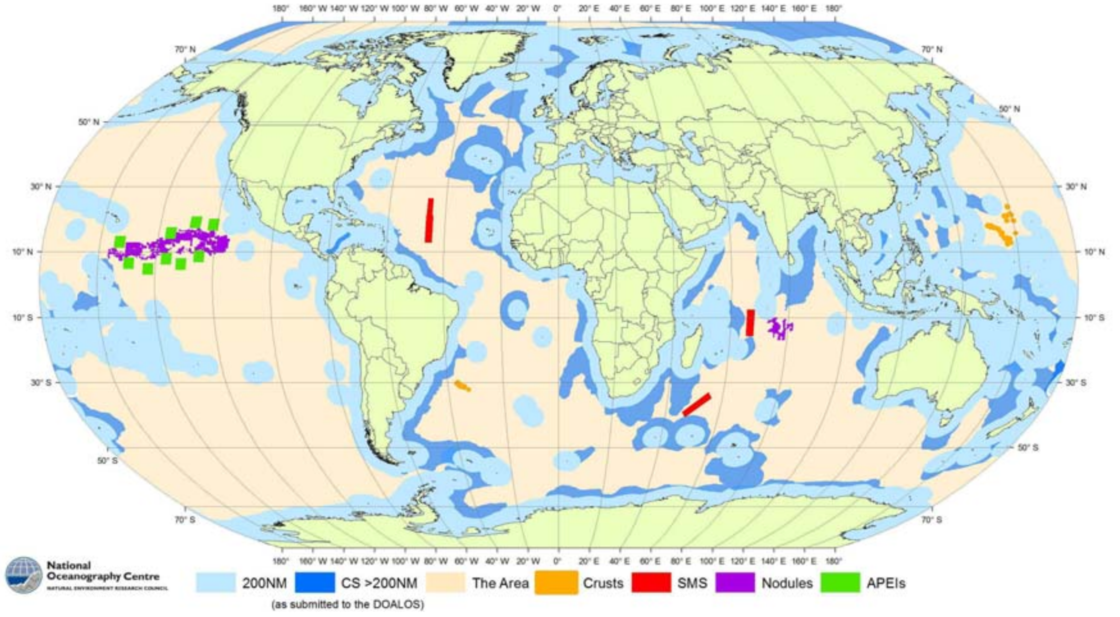

FIGURE 1 The locations of International Seabed Authority exploration contract areas for the three main metal-rich mineral resource types. Colour coding and abbreviations are as follows: light blue = seabed areas within 200 nautical miles (NM) of a coastal state; dark blue = continental shelf (CS) greater than 200 nautical miles (NM) of a coastal state; beige = the seabed region termed “the Area”, which is beyond national jurisdiction; orange = Fe–Mn crusts; red = seafloor massive sulfide (SMS) deposits; purple = Fe–Mn nodules; green squares = the Areas of Particular Environmental Interest (APEIs) in the Clarion–Clipperton Zone [shown in more detail on the map in Lodge and Verlaan (2018 this issue)]. Image: Alan Evans, National Oceanography Centre, Southampton (UK).

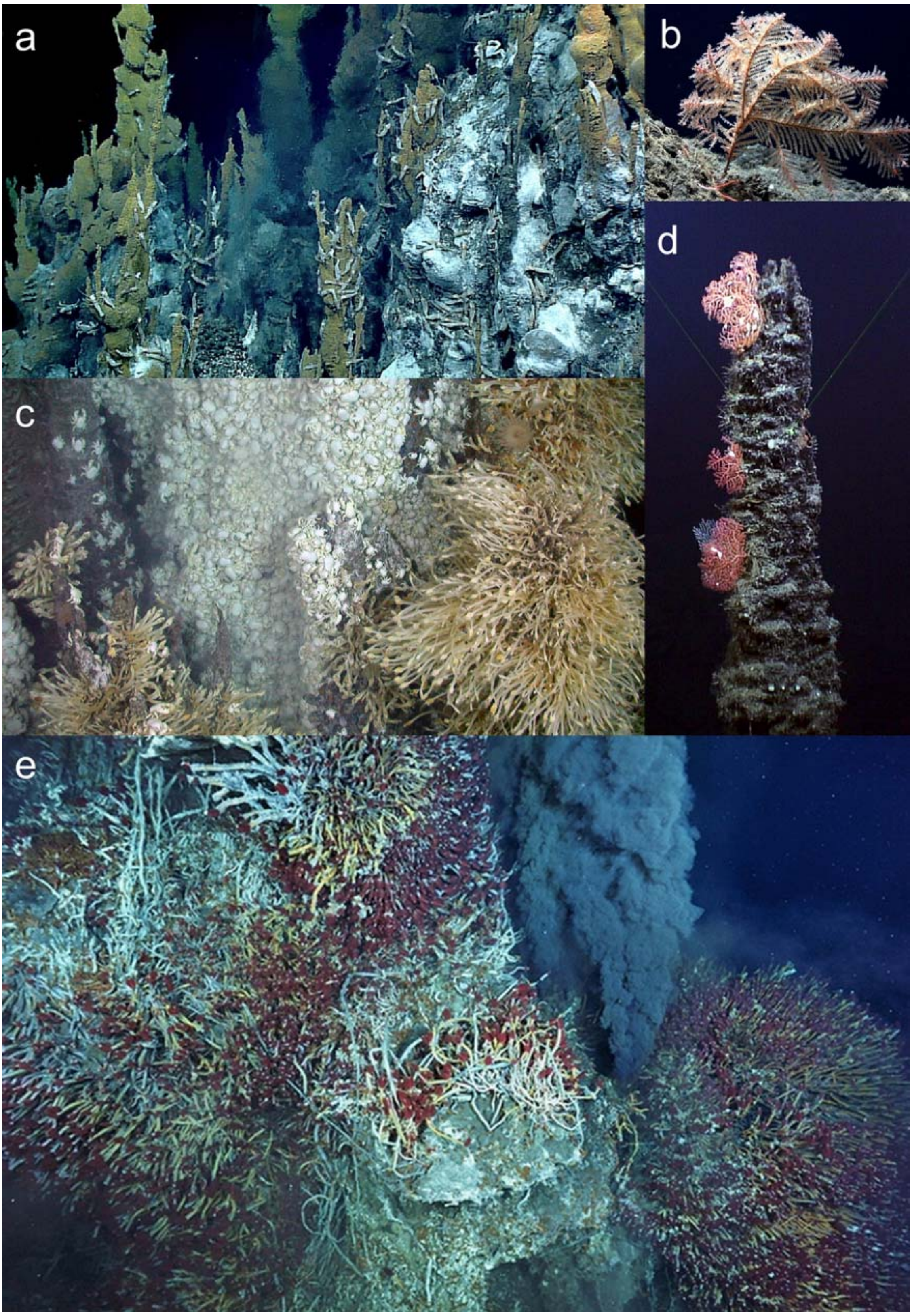
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FIGURE 2 Examples of hydrothermal vent communities. (**A**) Seafloor massive sulfides with associated communities of shrimps, crabs and snails discovered in 2016 at 3,863 m in the Mariana back-arc axis (west Pacific Ocean). IMAGE: NOAA'S OFFICE OF OCEAN EXPLORATION AND RESEARCH. (**B**) A black coral observed at 2,227 m in the Endeavour Rift Valley (northeast Pacific Ocean). IMAGE: 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 (Southern Ocean). IMAGE: NERC CHESSO CONSORTIUM. (**D**) Corals living on an extinct chimney at 2,203 m in the Mothra vent field (northeast Pacific Ocean). IMAGE: OCEAN NETWORKS CANADA. (**E**) *Ridgeia piscesae* tubeworm communities, likely hosting paralvinellid worms, scaleworms, limpets, and many other faunae in their bush-like structures. Near a black smoker at 2,133 m at the Endeavour segment of the Juan de Fuca Ridge (northeast Pacific Ocean). IMAGE: OCEAN NETWORKS CANADA.

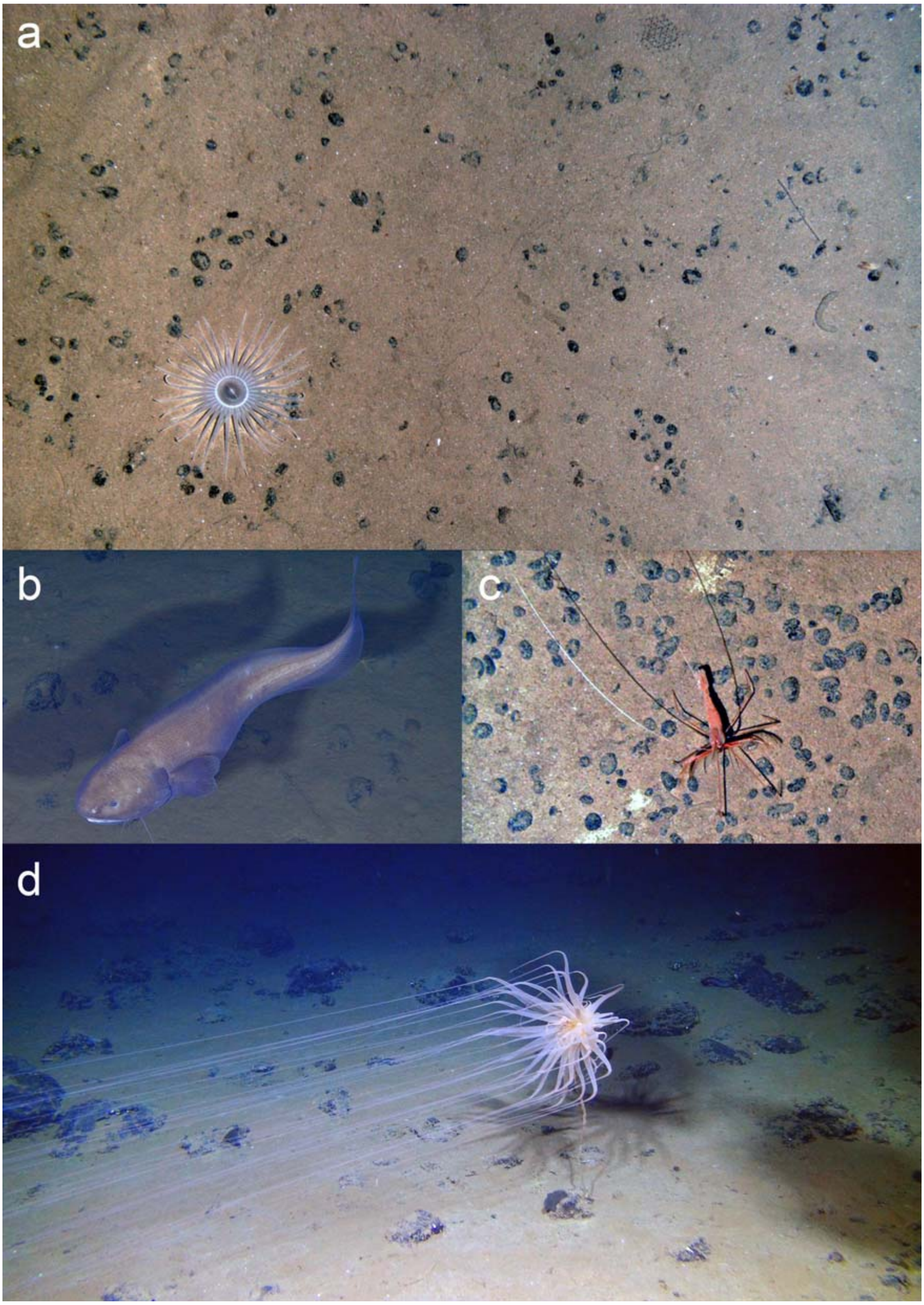
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FIGURE 3 Fauna from the Fe–Mn nodule fields in the Clarion–Clipperton Zone (Pacific Ocean). (**A**) An anemone (left) and small coral (right). IMAGE: NATIONAL ENVIRONMENT RESEARCH COUNCIL, RRS *JAMES COOK* CRUISE JC120. (**B**) Abyssal fish of *Bassozetus* species. IMAGE: DIVA AMON AND CRAIG SMITH (UNIVERSITY OF HAWAII AT MANOA, USA). (**C**) Decapod crustacean *Bathystylodactylus* species. IMAGE: NATIONAL ENVIRONMENT RESEARCH COUNCIL, RRS *JAMES COOK* CRUISE JC120. (**D**) Cnidarian *Relicanthus* species with very long tentacles streaming out into the seabed current. IMAGE: DIVA AMON AND CRAIG SMITH, (UNIVERSITY OF HAWAII AT MANOA, USA).

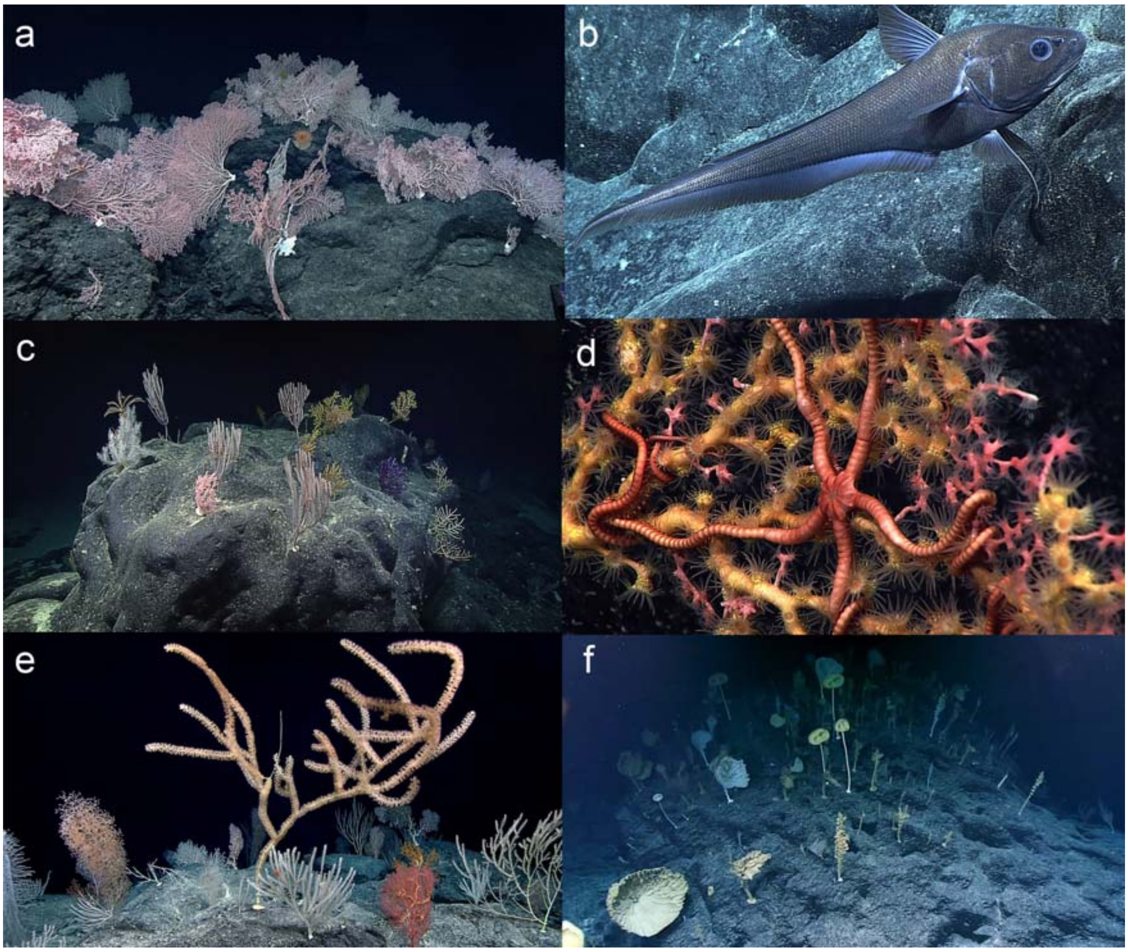
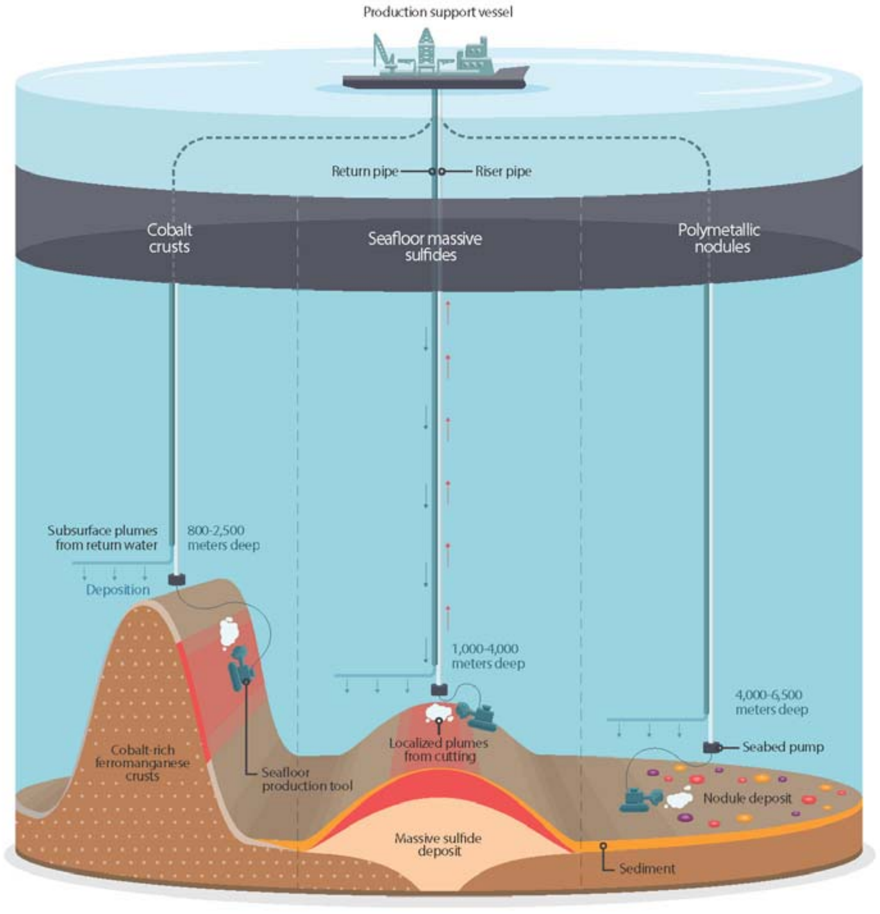


FIGURE 4 Faunal communities from Fe–Mn-encrusted seamounts in the Pacific Ocean. (**A**) An abundant community of large corals with anemones, crinoids and ophiuroids. (**B**) A rattail fish (*Coryphaenoides* species). (**C**) A diverse community of corals with associated crinoids and ophiuroids. (**D**) An ophiuroid living in a commensal relationship 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. ALL IMAGES: NOAA OFFICE OF OCEAN EXPLORATION AND RESEARCH.



Source: New Zealand Environment Guide

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FIGURE 5 Potential types of deep-sea mining operation. Image shows production support vessel on sea surface, with generalized subsurface mining equipment for the three main mining deposits shown below (left: Fe–Mn-encrusted seamounts; mid: seafloor massive sulfides; right; Fe-Mn nodules). IMAGE: THE PEW CHARITABLE TRUSTS.