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An Overview of Seabed Mining Including the Current State of Development, Environmental Impacts, and Knowledge Gaps

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Rising demand for minerals and metals, including for use in the technology sector, has led to a resurgence of interest in exploration of mineral resources located on the seabed. Such resources, whether seafloor massive (polymetallic) sulfides around hydrothermal vents, cobalt-rich crusts (CRCs) on the flanks of seamounts or fields of manganese (polymetallic) nodules on the abyssal plains, cannot be considered in isolation of the distinctive, in some cases unique, assemblages of marine species associated with the same habitats and structures. In addition to mineral deposits, there is interest in extracting methane from gas hydrates on continental slopes and rises. Many of the regions identified for future seabed mining are already recognized as vulnerable marine ecosystems (VMEs). Since its inception in 1982, the International Seabed Authority (ISA), charged with regulating human activities on the deep-sea floor beyond the continental shelf, has issued 27 contracts for mineral exploration, encompassing a combined area of more than 1.4 million km^2, and continues to develop rules for commercial mining. At the same time, some seabed mining operations are already taking place within continental shelf areas of nation states, generally at relatively shallow depths, and with others at advanced stages of planning. The first commercial enterprise, expected to target mineral-rich sulfides in deeper waters, at depths between 1,500 and 2,000 m on the continental shelf of Papua New Guinea, is scheduled to begin early in 2019. In this review, we explore three broad aspects relating to the exploration and exploitation of seabed mineral resources: (1) the current state of development of such activities in areas both within and beyond national jurisdictions, (2) possible environmental impacts both close to and more distant from mining activities and (3) the uncertainties and gaps in scientific knowledge and understanding which render baseline and impact assessments particularly difficult for the deep sea. We also consider whether there are alternative approaches to the management of existing mineral reserves and resources, which may reduce incentives for seabed mining.

Keywords: deep sea mining, biodiversity loss, seabed disturbance, regulations, manganese nodule, seamount, hydrothermal vent, International Seabed Authority

INTRODUCTION

Rising demand for minerals and metals, in tandem with the depletion of land-based resources, has led to a surge of interest in marine mineral resources. Although no commercial scale deep-sea mining has taken place, a range of mining operations are active in the shallow seabed. However, exploration contracts for deep-sea resources have been awarded to companies from countries including China, the United Kingdom, Belgium, Germany, France and Japan for three different mineral resources: seafloor massive sulfides (SMS), ferromanganese crusts and polymetallic nodules. Mining the seabed carries significant environmental concerns, some of which have been highlighted over the past 5 years in relation to applications for mining in continental shelf regions (for example, ironsands and phosphorite mining in New Zealand waters; New Zealand Environmental Protection Authority, 2016). Given the nature, scale and location of proposed seabed mining activities, serious and widespread negative impacts on biodiversity are inevitable and likely to be irreversible (Van Dover et al., 2017). Other impacts include conflict with other users of the sea, such as the fishing industry and pharmaceutical firms looking to exploit marine genetic resources (Armstrong et al., 2012).

The deep sea (areas covered with >200 m depth of seawater) covers around 360 million km^2 of the Earth's surface (∼50%) and represents 95% of the global biosphere in terms of inhabitable volume (Thistle, 2003; Smith et al., 2009; Danovaro et al., 2014). Topographically, much of the deep ocean floor is abyssal plain at depths exceeding 3,000 m with features that include submarine canyons, oceanic trenches and ridges, hydrothermal vents and seamounts. Yet the vast majority of the deep-sea environment is unexplored and much remains to be discovered about the distinctive biodiversity associated with the deep seabed. Only a fraction of the deep sea has been scientifically studied and there are many valid concerns relating to seabed mining, one of which is the disturbance to as-yet-undescribed biota. In the past 20 years, for example, newly reported species range from invertebrates, such as a yeti crab, to large marine vertebrates including elusive beaked whales (Ramirez-Llodra et al., 2011; Thompson et al., 2012; Dalebout et al., 2014; Thatje et al., 2015; Araya, 2016; Vanreusel et al., 2016). Some deep-sea species with long life spans are vulnerable to physical disturbance because of their slow growth rates. For example, the Greenland shark (*Somniosus microcephalus*) dives to around 1,200 m and is described as the longest living vertebrate, reaching maturity at 156 ± 22 years with a lifespan of at least 392 ± 120 years (Neilsen et al., 2016). The black coral (*Leiopathese* spp.), a deep ocean species found off the Azores, is known to have a colony lifespan of up to 2,320 ± 90 years, arguably one of the longest living organisms on Earth (Carreiro-Silva et al., 2013).

In this review, we respond to the growing interest in exploitation of deep-sea mineral resources by drawing together information from peer-reviewed and other technical literature on developments within this industry. Here, we explore three broad aspects relating to the exploration and exploitation of seabed mineral resources: (1) the current state of development of such activities in areas both within and beyond national jurisdictions, (2) possible environmental impacts both close to and more distant from mining activities and (3) the uncertainties and gaps in scientific knowledge and understanding which render baseline and impact assessments particularly difficult for the deep sea. We also consider whether there are alternative approaches to the management of existing mineral reserves and resources, which may reduce incentives for seabed mining.

THE LOCATIONS OF MARINE MINERAL RESOURCES AND GAS HYDRATES

Mineral extraction from sediments and structures across the deep sea has been proposed at several habitat types—the abyssal plains, hydrothermal vents and seamounts along the mid-ocean ridges. Three main resources are of commercial interest: manganese nodules (MN) on the abyssal plains, particularly in the Pacific Ocean; SMS at hydrothermal vents, including off the coast of Papua New Guinea; and cobalt-rich crusts (CRC), which are found at seamounts worldwide with the largest deposits in the Pacific Ocean (**Figure 1**). In addition to metal-rich deposits, there is interest in extracting methane from gas hydrates associated with marine sediment on continental slopes and rises (in addition to beneath terrestrial permafrost). Other continental shelf resources of commercial interest include diamonds, ironsands (rich in titanomagnetite and lime-soda feldspars for steel production), and phosphorites. Shallow seabed mining for diamonds has been taking place off the coast of Namibia since 2001 by Diamond Fields International Ltd.

Manganese (Polymetallic) Nodules of the Abyss

Manganese nodules form on vast deep-water abyssal plains and comprise primarily of manganese and iron, though significant amounts of other metals are also found in these structures (**Figures 2A,B**). Nodules are potato-like in shape, 4–10 cm in diameter, and are thought to form in a process that takes millions of years in which manganese in seawater adsorbs to a nodule substance that is oxidized by bacteria and becomes nodule matrix (Blöthe et al., 2015; Vanreusel et al., 2016). The main constituents of interest in addition to manganese (28%) are nickel (1.3%), copper (1.1%), cobalt (0.2%), molybdenum (0.059%), and rare earth metals (0.081%) (Hein et al., 2013). Nodules also contain traces of other commercially relevant elements including platinum and tellurium, which are important constituents of technological products such as photovoltaic cells and catalytic technology (**Table 1**) (Hein et al., 2013; Antoni et al., 2017; Ojo and Dharmadasa, 2017).

Nodule accumulations of economic interest have been found in four geographical locations: the Clarion-Clipperton Fracture Zone (CCZ) in the north-central Pacific Ocean; the Penrhyn Basin in the south-central Pacific Ocean; the Peru Basin in the south-east Pacific; and the center of the north Indian Ocean. In the Pacific Islands region, the manganese nodule deposits with the greatest abundance and concentration of metals are found in the EEZ of Rarotonga (the Cook Islands). Other areas with high abundance are the two eastern island groups of the Republic of

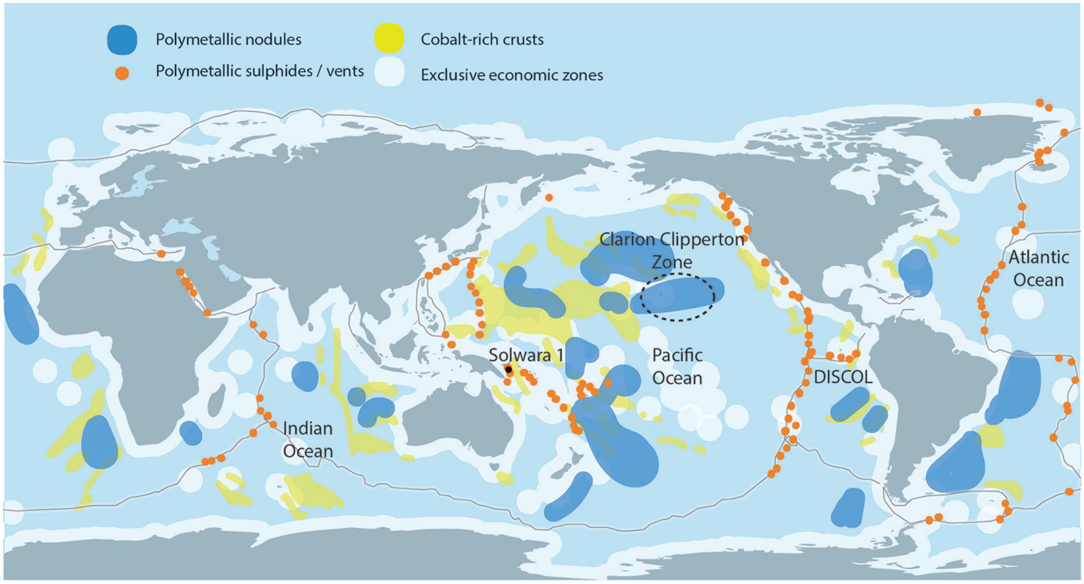

FIGURE 1 | A world map showing the location of the three main marine mineral deposits: polymetallic nodules (blue); polymetallic or seafloor massive sulfides (orange); and cobalt-rich ferromanganese crusts (yellow). Redrawn from a number of sources including Hein et al. (2013).

Kiribati (Phoenix and Line Islands), to a lesser extent the western Kiribati group (Gilbert Islands) and within the EEZ of the island nations Tuvalu and Niue (Secretariat of the Pacific Community, 2011).

Polymetallic nodules grow extremely slowly, at a rate of only rate of several mm to several cm per million years (Halbach et al., 1980; Gollner et al., 2017). Very few studies have investigated nodule fauna because of their inaccessibility on the abyssal plains, but they have been reported to provide some of the only hard substrate for marine species at those locations and therefore removal may result in significant habitat loss (Glover and Smith, 2003; Veillette et al., 2007; Vanreusel et al., 2016). Certain sponges and molluscs are unique to the surfaces of nodules, and nematode worms and crustacean larvae have been found within crevices (Thiel et al., 1993). Vanreusel et al. (2016) report higher densities of both sessile and mobile fauna living on or near manganese nodules than in nodule-free areas of the abyssal plains—in nodule-rich areas, a recorded 14–30 sessile individuals per 100 m^2, and 4–15 mobile individuals per 100 m^2; while in nodule-free areas there were up to 8 sessile individuals per 100 m^2 and 1–3 mobile individuals per 100 m^2.

Seafloor Massive Sulfides at Hydrothermal Vents

Seafloor massive sulfides (SMS), which are associated with both active and inactive hydrothermal vents along oceanic ridges, have a high sulfide content but are also rich in copper, gold, zinc, lead, barium, and silver (**Figure 2C**; Hein et al., 2013). More than 200 sites of hydrothermal mineralization occur on the seafloor and, based on previous exploration and resource assessment, around 10 of these deposits may have sufficient tonnage and grade to be considered for commercial mining. The technological viability to explore and extract marine mineral deposits is determined by the depth at which the minerals are found (Boschen et al., 2013, 2016).

Deep-sea vents are primarily concentrated along Earth's mid-oceanic ridge systems in the Pacific, Atlantic, Arctic, and Indian oceans (Van Dover et al., 2002). Ongoing exploration and resource evaluation indicate that polymetallic seafloor massive sulfide deposits in the Pacific have high copper concentrations with significant enrichment in zinc, gold and silver and are located in comparatively shallow water (<2,000 m; Secretariat of the Pacific Community, 2011; Hein et al., 2013).

Hydrothermal vent communities were first described in 1977, but since then only ~10% of the deep ridge habitat has been explored (Ramirez-Llodra et al., 2010). In the past decade, ridge habitats have attracted attention from research teams trying to understand ecosystem dynamics and also by companies interested in exploiting minerals for commercial purposes (Beaulieu et al., 2015). Hydrothermal vents are found at 1,000–4,000 m depth and are characterized by temperatures up to 400°C and high acidity (pH 2–3), yet they support vast communities of organisms (Ramirez-Llodra et al., 2007). Chemosynthetic bacteria form the basis of vent ecosystems, and in turn support a large biomass of invertebrates that include molluscs, annelid tube-dwelling worms, and crustaceans (Van Dover et al., 2002). Some researchers think that life of Earth originated at hydrothermal vents (Martin et al., 2008). Around 85% of vent species are considered to be endemic (Ramirez-Llodra et al., 2007) with an average of two new vent species described every month in the 25-year period following their discovery (Van Dover et al., 2002). Within

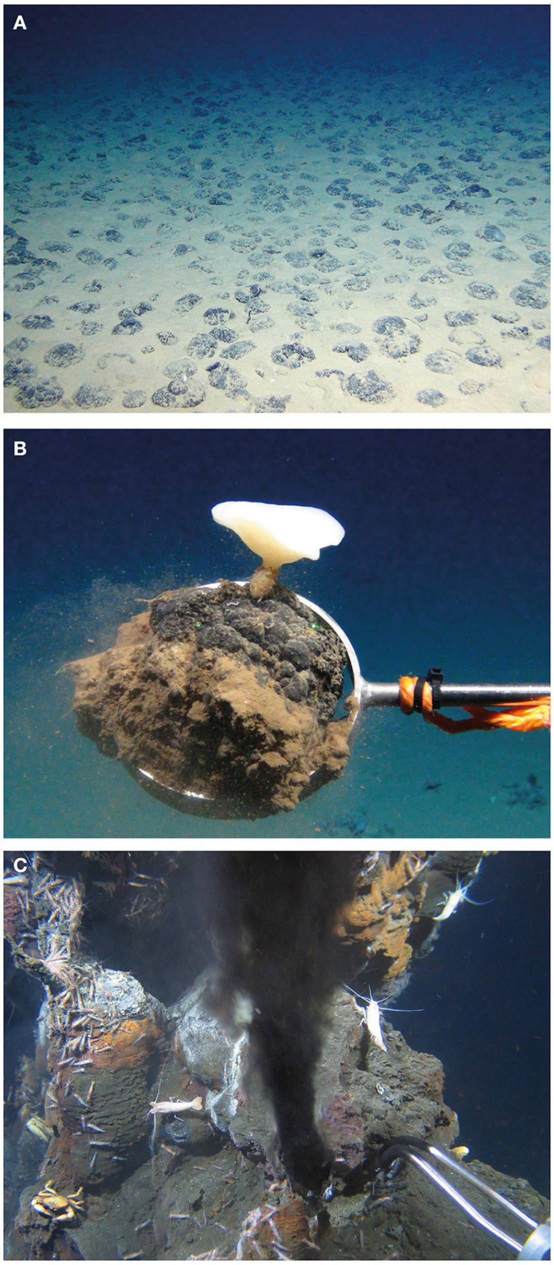

FIGURE 2 | Types of mineral deposit. **(A)** Manganese nodules in the Clarion Clipperton Zone, Pacific Ocean, **(B)** ROV KIEL 6000 holding a manganese nodule with associated fauna, **(C)** Black smoker (vent) on the mid-Atlantic ridge with deep sea shrimps and temperature measuring device. Photo taken by ROV KIEL 6000 during cruise M78/2. Copyright ROV Team; GEOMAR Helmholtz Centre for Ocean Research, Kiel.

the past decade, newly described species include a yeti crab (*Kiwa* spp.) that lives 2,600 m deep near hydrothermal vents in the Antarctic Ocean and farms chemosynthetic bacteria on its claws (Thurber et al., 2011; Thatje et al., 2015), and four species of deep-sea worm that live near vents in the Pacific Ocean (Rouse et al., 2016). Goffredi et al. (2017) found a high diversity of fauna inhabiting vents in the southern Gulf of California, reporting that only three of 116 macrofaunal species that they observed or collected were found on all four of the vent fields they studied. The research team's findings have implications for seafloor massive sulfide mining because destroying a discrete community at one vent could have connectivity implications for communities at nearby vents. Conservation issues could arise if recolonization of a mined vent is by species from a neighboring vent rather than by species that had colonized the vent before mining had taken place.

Cobalt-Rich Crusts at Seamounts

Cobalt-rich crusts, also referred to as ferromanganese crusts, form on the slopes and summits of seamounts and contain manganese, iron and a wide array of trace metals (cobalt, copper, nickel, and platinum; Hein et al., 2013). Based on grade, tonnage and oceanographic conditions, the central equatorial Pacific offers the best potential for crust mining, particularly within the EEZ of Johnston Island (USA), the Marshall Islands and international waters in the mid-Pacific seamounts. The EEZs of French Polynesia, Republic of Kiribati and the Federated States of Micronesia are also considered as potential locations to exploit cobalt crusts; smaller reserves have been recorded in Tuvalu, Samoa and Niue. Cobalt-rich crust mining is more technologically challenging than harvesting manganese nodules from abyssal plains because crusts are attached to rock substrates. Cobalt is of economic interest because the metal has wide-ranging uses that include those in superalloys, such as in jet aircraft engines, and in battery technology (Hein et al., 2013).

Globally, there are estimated to be more than 33,400 seamounts rising 1,000 m or more from the seafloor, and more than 138,000 smaller features known as knolls (rising 500–1,000 m) and hills (rising $<$ 500 m; Pitcher, 2007). Yesson et al. (2011) estimated that seamounts occupy an area of ~17.2 million km^2 or 4.7% of the global ocean floor. The physics of currents associated with seamounts create oceanographic upwelling that delivers nutrients to surface waters that promote the growth of animals including corals, anemones, featherstars, and sponges (Koslow et al., 2001; Yesson et al., 2011).

Rowden et al. (2010) describe seamounts as oases on the abyssal plains because they often support higher epibenthic species diversity and biomass than nearby slopes. The oases hypothesis appears to depend on the geophysical context in which the seamount exists. Seamounts, in tandem with persistent hydrographic features such as oceanic fronts, have been shown to support high levels of primary productivity and provide a habitat for pelagic species. In such circumstances, seamounts can connect benthic and pelagic ecosystems. For example, fish and marine mammals are known to aggregate over seamounts, using them either for foraging or resting (Garrigue et al., 2015; Morato et al., 2016). Reisinger et al. (2015) tagged and tracked killer whales (Orcinus orca) and found that they spent time hunting over certain seamounts, which suggests that these oceanic features are a source of prey for these mammals. As well as supporting marine fauna including cetaceans, pinnipeds, and turtles for feeding, seamounts are thought to be navigational features during migrations and as breeding grounds (Yesson et al., 2011).

TABLE 1 | A summary of the uses of major resources found on the seabed.

Resource	Symbol	Uses	References
Copper	Cu	Electricity production/distribution – building wires and telecommunication cables/circuit boards. Transport sector—vehicle brakes, radiators and wiring, copper-nickel alloys are non-corrosive and provide material for the hulls of ships. Ecorys (2012) classes mid-ocean ridge copper deposits as areas of "high" economic interest.	British Geological Survey, 2007 Goonan, 2009 Ecorys, 2012 United States Geological Survey, 2012b
Silver	Ag	Mobile phones, PCs, laptops and batteries currently use the largest volumes of silver, many of the newer uses of silver focus on its antibacterial properties. Silver used domestically in mirrors, jewelery and cutlery. Ecorys (2012) classes mid—ocean ridge silver deposits as areas of "high" economic interest.	Ecorys, 2012
Gold	Au	Predominantly jewelery, although has also been used in electrical products. However, the total amount of material used for electricity is decreasing as base metal-gold alloys are increasingly providing a cheaper alternative to pure gold in electrical products. Ecorys (2012) classes mid—ocean ridge gold deposits as areas of "high" economic interest.	Ecorys, 2012 British Geological Survey, 2007 United States Geological Survey, 2012a
Zinc	Zn	Galvanizing steel or iron to prevent rusting, also commonly used as an alloy in the production of brass and bronze. Zinc is also used in the production of paint, as well as pharmaceutical products as a dietary supplement. Ecorys (2012) classes mid—ocean ridge zinc deposits as areas of "high" economic interest.	British Geological Survey, 2004 Ecorys, 2012
Manganese	Mn	Mainly used in construction industry due to its sulfur fixing, deoxidizing, and alloying properties. It is preferred over other more expensive alternatives. Ecorys (2012) classes manganese crusts and nodules at intraplate seamounts as areas of "low" economic interest.	Ecorys, 2012 Geoscience Australia, 2012 Blöthe et al., 2015
Cobalt	Co	Primarily used in production of super alloys with exceptional resistance to high temperatures, for example those used to make aircraft gas turbo engines. Also used in rechargeable batteries—notably lithium-ion batteries used in hybrid electric vehicles. These batteries contain high proportions of cobalt as 60% of the cathode in lithium-ion batteries is composed of lithium-cobalt oxide. Ecorys (2012) classes deep sea and intra plate seamount deposits of cobalt as areas of "moderate" and "low" economic interest, respectively. Cobalt is also found in manganese nodules.	British Geological Survey, 2009 Ecorys, 2012 United States Geological Survey., 2012c
Rare Earth Elements	REEs	Set of 17 elements including the 15 in the lanthanide series, plus scandium and yttrium. Used in the widest group of consumer products of any group of elements and have electronic, optical, magnetic and catalytic applications. Trends suggest that "green"—carbon reducing—technologies such as hybrid and fully electric cars, catalytic convertors, wind turbines and energy efficient lighting are key growth areas for REEs in the future. Demand for rare earth elements is increasing by 5–10% annually. Ecorys (2012) classes intraplate seamount deposits of REEs and yttrium as areas of "low" and "moderate" interest, respectively.	British Geological Survey, 2011 Ernst Young., 2011 Ecorys, 2012MIDAS, 2016
Tin	Sn	Used in the high-tech industry for manufacture of items such as smartphones and laptops in which the metal is used in solder. Also found in tinplate and in compounds that are used to make plastics, ceramics and fire retardants.	Geoscience Australia, 2016
Gas Hydrates		Gas hydrate is a solid ice-like form of water that contains mainly methane gas molecules in its molecular cavities. Methane from gas hydrates may constitute a future source of natural gas. Note that the high methane content of these hydrates and their potential adoption as a fuel resource could make them key sources of Carbon emission. According to the United States Geological Survey, the world's gas hydrates may contain more organic carbon than the world's coal, oil, and other forms of natural gas combined. Estimates of the naturally occurring gas hydrate resource vary from 10,000 trillion cubic feet to more than 100,000 trillion cubic feet of natural gas.	Sloan, 2003 Kretschmer et al., 2015

Some specific information on economic interest in these resources in European waters has been provided where available.

Gas Hydrates

Gas hydrates are ice-like solid crystalline structures that form when water molecules create a cage-like structure around a gas molecule at low temperature and high pressure. Although gas hydrates are not seabed mineral deposits, they have been included in this review because their exploitation is also close to becoming a reality, and could in itself result in substantial impacts on surrounding deep-sea ecosystems. Gas hydrates may contain methane, ethane, propane or butane, though methane hydrate is the most common that occurs naturally. Potentially large quantities of gas hydrates are available—for example, 1 m^3 methane hydrate can yield 164 m^3 methane gas (Makogon et al., 2007; Duan et al., 2011) but commercial extraction of natural gas has not yet taken place because the process is technologically complex and costly. Estimates of the global mass of marine methane hydrates vary: Piñero et al. (2013) estimate in the region of 550 Gt C, but Kretschmer et al. (2015) suggests the higher figure of 1,146 Gt C. Reserves of gas hydrates are widely distributed and ∼220 deposits have been identified across the globe in the sediment of marine continental slopes and rises and on land beneath polar permafrost; continental shelf margins contain 95% of all methane hydrate deposits in the world (Demirbas, 2010; Chong et al., 2016).

Formation of gas hydrates depends upon a number of factors including accumulation of particulate organic carbon at the seafloor, the microbial degradation of organic matter and its related generation of methane, and composition of the gas (Makogon et al., 2007; Piñero et al., 2013). Methane hydrates are most commonly found at seawater depths of 1,000–3,000 m; they do not usually form in water <600 m deep because the water is too warm, but in the Arctic hydrates may form in shallow waters of around 250 m, where water temperature at the seabed is as low as −1.5°C (Buffett and Archer, 2004).

REGULATION AND MANAGEMENT

The legal framework governing anthropogenic activity on the ocean depends upon distance from land. A coastal state's territorial sea, in accordance with the 1982 United Nations Convention on the Law of the Sea (UNCLOS), extends to 12 nautical miles (22 km) from its coastline and includes the air space, the water body to the seabed and the subsoil (United Nations Convention on the Law of the Sea, 1982). Coastal states have exclusive rights and jurisdiction over the resources within their 200-nautical mile (370 km) exclusive economic zone (EEZ). Some states have an extended continental shelf beyond the EEZ within which they have sovereign rights over the seabed and any mineral resources, though not over the water column (**Figure 3**). Further out to sea is the area beyond national jurisdiction (ABNJ), which is a term used to describe both the seabed "Area" and the high seas water column above. UNCLOS designates the "Area" as the common heritage of mankind. The legal framework for the Area is provided by UNCLOS. The responsibility for the regulation and control of mineral-related activities in the Area is with the International Seabed Authority (ISA), comprised of the States Parties to UNCLOS.

Three sections in UNCLOS are particularly relevant to deep-sea mining: Article 136, Article 137.2, and Article 145, which respectively cover the common heritage of mankind, resources and the protection of the marine environment.

UNCLOS Article 136—Common Heritage of Mankind

The Article states that:

> "The Area and its resources are the common heritage of mankind."

Jaeckel et al. (2017) note that the principle of the common heritage of mankind in relation to the marine environment needs to be developed by the ISA. As well as sharing the benefits of marine resources for current and future generations, the common heritage of mankind principle also includes environmental conservation and preservation of the Area. As interest in commercial seabed minerals mining escalates, exploitation regulations will need to be refined and agreed upon by all interested parties. Setting conservation targets that incorporate research will help to determine the necessary measures to provide effective environmental protection.

UNCLOS Article 137.2—Legal Status of the Area and Its resources

The Article states that:

> "All rights in the resources of the Area are vested in mankind as a whole, on whose behalf the Authority shall act. These resources are not subject to alienation. The minerals recovered from the Area, however, may only be alienated in accordance with this Part and the rules, regulations and procedures of the Authority."

UNCLOS Article 145—Protection of the Marine Environment

The Article states that:

> "Necessary measures shall be taken in accordance with this Convention with respect to activities in the Area to ensure effective protection for the marine environment from harmful effects which may arise from such activities.
>
> To this end the Authority shall adopt appropriate rules, regulations and procedures for *inter alia*:
>
> (a) The prevention, reduction, and control of pollution and other hazards to the marine environment, including the coastline, and of interference with the ecological balance of the marine environment, particular attention being paid to the need for protection from harmful effects of such activities as drilling, dredging, excavation, disposal of waste, construction and operation or maintenance of installations, pipelines and other devices related to such activities;
>
> (b) The protection and conservation of the natural resources of the Area and the prevention of damage to the flora and fauna of the marine environment."

With reference to part (a) of Article 145, control of pollution and other hazards in the marine environment also includes protection of the coastline, indicating that the regulations are not limited to protecting only the Area.

In relation to (b), there is currently discussion among the scientific community, specialists in maritime law and other interested parties to define the measurement or threshold of

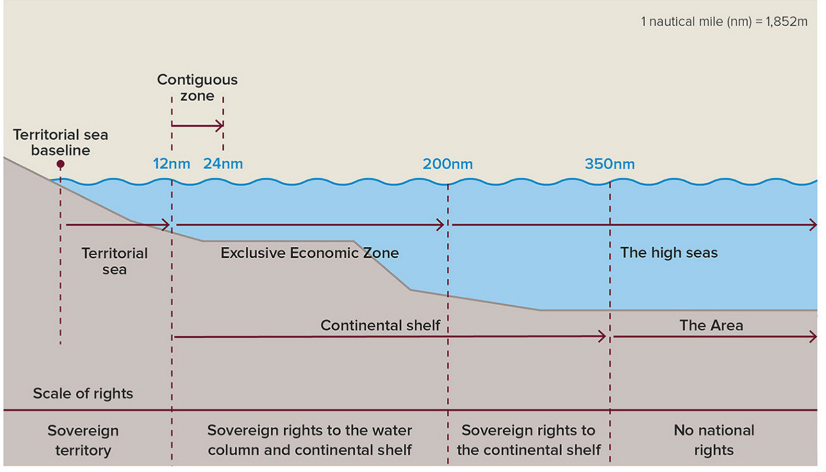

FIGURE 3 | A schematic showing jurisdictional zones from a nation's coast. Courtesy: The Royal Society, London.

harmful effects and what might constitute "acceptable harm" to an ecosystem from seabed mining. Levin et al. (2016) stress that it is crucial to understand marine biodiversity and define what effects would be harmful to the deep-sea environment to enable effective regulation of mining activities.

The International Seabed Authority

The ISA was established in 1982 by UNCLOS and is an autonomous intergovernmental body with 167 members. The ISA is responsible for the mineral resources and the marine environment in the Area. The ISA considers applications for exploration and exploitation of deep-sea resources from contractors, assesses environmental impact assessments and supervises mining activities in the Area.

To date, the ISA has approved 27 exploration contracts (www.isa.org.jm/deep-seabed-minerals-contractors). To compare with past years—17 contracts were active in 2013 and 8 were active in 2010 (**Table 2**). Contractors who have been granted exploration contracts are entitled to explore for minerals over a designated area of the seabed. Contracts are valid for 15 years, after which the contract can be extended for a further 5 years. Exploration contracts for polymetallic nodules cover up to 75,000 km^2, for SMS cover up to 10,000 km^2, and for cobalt-rich ferromanganese crusts cover a maximum 20 km^2. Seventeen contracts for exploration of seafloor massive sulfide deposits have been awarded to 16 contractors, 7 of which are national government bodies and 8 of which are companies with a sponsoring state. All six contracts for exploration relating to SMS and all four contracts to explore CRCs have been awarded to national governments. Exploitation regulations are currently under development but the ISA expects them to be finalized in the next 2 years. Accordingly, exploitation regulations were discussed at the authority's 23rd session, with calls from non-governmental observer organizations for greater transparency and for establishment of a separate environment committee. The session also included discussions on contractor compliance or non-compliance, on the need for the ISA to increase efforts to ensure environmental protection and on the establishment of a measure of "acceptable harm" to the environment from mining activity. Also discussed was the need to consider vulnerable marine ecosystems (VMEs) and ecologically or biologically significant marine areas (EBSAs) when issuing contracts, and how the ISA would justify biodiversity loss when its remit is to manage the Area on behalf of mankind (ENB, 2017).

Minerals exploration is also taking place within national waters and licenses to exploit the seabed for minerals in the exclusive economic zones (EEZ) have been issued by Papua New Guinea and Sudan/Saudi Arabia (**Table 3**). The most advanced project, which is closest to commercial exploitation, is in Papua New Guinea by Canadian registered Nautilus Minerals Inc. (hereinafter Nautilus Minerals).

An environmental permit and mining lease have been granted by the government of Papua New Guinea (Nautilus Minerals, 2011) though environmental concerns have been raised by indigenous communities, suggesting that mining will cause irreversible damage, disrupt their cultural practices and affect food sources (FSRN, 2017).

Regional Seabed Mining Guidelines

In addition to the ISA, regional guidelines that focus on the management of seabed mining are currently under development. One example is the MIN-Guide initiative in the European Union (http://www.min-guide.eu/mineral-policy). The MIN-Guide initiative is an online repository for information on minerals and related policies for Member States. In the Pacific, the Deep Sea Minerals Project was a collaboration between the Pacific Community and the European Union initiated in 2011. The Deep Sea Minerals Project aimed to

TABLE 2 | A summary of mineral exploration contracts in the Area approved by the ISA as of June 2017 including the start and end dates for these contracts.

Exploration contract holder	Sponsor	Location	Resource	Contract start date	Contract end date
China Minmetals Corporation	Government of China	CCZ	Polymetallic nodules	May 12, 2017	May 11, 2032
Cook Islands Investment Corporation	Government of Cook Islands	CCZ	Polymetallic nodules	July 15, 2016	July 14, 2031
UK Seabed Resources Ltd.	Government of United Kingdom of Great Britain and Northern Ireland	CCZ II	Polymetallic nodules	March 29, 2016	March 28, 2021
		CCZ I	Polymetallic nodules	February 8, 2013	February 7, 2028
Ocean Mineral Singapore Pte Ltd.	Singapore company majority owned by Keppel Corporation. Minority shareholders: Seabed Resources Ltd. (Lockheed Martin UK Holdings Ltd.); and Singapore-based Lion City Capital Partners Pte. Ltd.	CCZ	Polymetallic nodules	January 22, 2015	January 21, 2030
G-Tec Sea Minerals Resources NV	Government of Belgium	CCZ	Polymetallic nodules	January 14, 2013	January 13, 2028
Marawa Research and Exploration Ltd.	State enterprise of the Republic of Kiribati	CCZ	Polymetallic nodules	January 19, 2015	January 18, 2030
Tonga Offshore Mining Limited	Government of Tonga. Subsidiary of Nautilus Minerals Inc.	CCZ	Polymetallic nodules	January 11, 2012	January 10, 2027
Nauru Ocean Resources Inc.	Government of Nauru	CCZ	Polymetallic nodules	July 22, 2011	July 21, 2026
Federal Institute for Geosciences and Natural Resources of Germany	Government of Germany	CCZ	Polymetallic nodules	July 19, 2006	July 18, 2021
Government of India	n/a	Indian Ocean	Polymetallic nodules	March 25, 2002	March 24, 2017
Institut français de recherche pour l'exploitation de la mer (IFREMER)	Government of France	CCZ	Polymetallic nodules	June 20, 2001	June 19, 2016
China Ocean Mineral Resources Research and Development Association	Government of China	CCZ	Polymetallic nodules	May 22, 2001	May 21, 2016
Government of the Republic of Korea	n/a	CCZ	Polymetallic nodules	April 27, 2001	April 26, 2016
Yuzhmorgeologiya	Russian Federation	CCZ	Polymetallic nodules	March 29, 2001	March 28, 2016
Interoceanmetal Joint Organization	Governments of Bulgaria, Cuba, Czech Republic, Poland, Russian Federation and Slovakia	CCZ	Polymetallic nodules	March 29, 2001	March 28, 2016
Government of India		Central Indian Ocean	SMS	September 26, 2016	September 5, 2031
Institut français de recherche pour l'exploitation de la mer	Government of France	Mid-Atlantic Ridge	SMS	November 18, 2014	November 17, 2029
Government of the Republic of Korea		Central Indian Ridge	SMS	June 24, 2014	June 24, 2029
Government of the Russian Federation		Mid-Atlantic Ridge	SMS	October 29, 2012	October 28, 2027
China Ocean Mineral Resources Research and Development Association		Southwest Indian Ridge	SMS	Nov 18, 2011	Nov 17, 2026
Companhia De Pesquisa de Recursos Minerais (the Geological Survey of Brazil)	Government of Brazil	Rio Grande Rise, South Atlantic Ocean	CRC	November 9, 2015	November 8, 2030
Ministry of Natural Resources and Environment of the Russian Federation	Russian Federation	Magellan Mountains, Pacific Ocean	CRC	March 10, 2015	March 9, 2030
Japan Oil, Gas, and Metals National Corporation (JOGMEC)	Government of Japan	Western Pacific Ocean	CRC	January 27, 2014	January 26, 2029
China Ocean Mineral Resources Research and Development Association (COMRA)	Government of China	Western Pacific Ocean	CRC	April 29, 2014	April 28, 2029

All contract holders must either be owned by a government or sponsored by a government. CCZ, Clarion Clipperton Zones of the Pacific Ocean; SMS, seafloor massive sulfide deposits; CRC, cobalt rich crusts. Source: International Seabed Authority.

TABLE 3 | A summary of some seabed mining operations on continental shelves.

Contract holder (country of registration)	Description of contract holder	Location	Type of mineral	Project status (year awarded if known)
Nautilus Minerals Inc. (Canada)	Publically listed company	Bismarck Sea, PNG (Solwara 1 Project)	SMS	*Mining contract, active (2011)*
Diamond Fields International (Canada)	Limited company	Atlantis II Basin, Red Sea	SMS	*Mining contract, active (2010). Project currently on hold because of contractual issues with partnership company*
Diamond Fields (Namibia) a subsidiary of Diamond Fields International	Limited company	Namibia	Diamonds	*Mining contracts x4, active (2009, 2007 & 2007; 2000 is pending renewal; expected contract renewal as of November 2017)*
Diamond Fields (South Africa),	Limited company	Western Cape, South Africa	Phosphorites	Prospecting contract, active (2014)
Trans-Tasman Resources (New Zealand)	Limited company	South Taranaki Bight, west coast of North Island	Iron ore sands	*Three projects with an exploration permit, a mining permit and a prospecting permit.*
Trans-Tasman Resources (New Zealand)	Limited company	Westland sands, Ross to Karamea, west coast of South Island	Iron ore sands	Prospecting contract, active (2016)
Chatham Rock Phosphate (New Zealand)	Limited company	Chatham Rise, east side, South Island	Phosphorites	*Mining contract, active (2013). Company refused environmental mining consent approval (2015).*
Bluewater Minerals (Solomon Islands) Ltd. (Solomon Islands)	Limited company	Temotu and Western provinces, Solomon Islands	SMS	Prospecting contract, active (2007)
Green Flash Trading 251 (South Africa)	Limited company	Groen River to Cape Town, South Africa	Phosphorites	Prospecting contract, active (2014)
Green Flash Trading 257 (South Africa)	Limited company	Cape Town to Cape Infanta, South Africa	Phosphorites	Prospecting contract, active (2014)
Namibian Marine Phosphate (Pty) Ltd. (Namibia)	Limited company	Sandpiper Marine Phosphate Project, Walvis Bay, Namibia	Phosphorites	*Mining contract, active (2011). Project pending EIA approval (June 2017).*

This is not an exhaustive list and text in italics indicates exploitation (active mining) contracts, all other contracts refer to exploration. SMS, seafloor massive sulfide deposits.

improve governance and management of deep-sea mineral resources across the region in accordance with international law. The project had 15 member Pacific Island countries: Rarotonga (the Cook Islands), Federated States of Micronesia, Fiji, Republic of Kiribati, Marshall Islands, Nauru, Niue, Palau, Papua New Guinea, Samoa, Solomon Islands, Timor Leste, Kingdom of Tonga, Tuvalu, and Republic of Vanuatu. In August 2012, a Regional Legislative and Regulatory Framework was launched that aimed to improve management of marine mineral resources, with particular attention paid to the protection of the marine environment and ensuring that Pacific Island countries receive appropriate financial compensation (http://dsm.gsd.spc.int/public/files/2014/RLRF2014.pdf). Mining within EEZ areas is under the jurisdictions of national governments.

The possibility of prospecting for and extraction of gas hydrates in future decades has initiated discussion concerning regulations and management policy. No coordinated international regulations are in place to cover gas hydrate extraction, but national policies have been developed by coastal states including Japan, China, the United States, India, and Malaysia (Zhao et al., 2017).

MINING TECHNOLOGY AND PROCESSES

All proposed seabed minerals mining operations are based on a similar concept of using a seabed resource collector, a lifting system and support vessels involved in offshore processing and transporting ore. Most proposed seabed collection systems envisage the use of remotely operated vehicles, which would extract deposits from the seabed using mechanical or pressurized water drills (**Figure 4**). Development of deep-sea minerals mining technology is underway, though the greater depths involved present additional challenges. Mining for SMS at hydrothermal vents would involve mechanical removal of the ore and transportation to a support vessel to extract the necessary materials. Harvesting nodules would mean retrieving the potato-sized deposits from the seafloor then pumping the collected material to a surface vessel through a vertical riser pipe (Blue Nodules, 2016; Jones et al., 2017).

Natural gas would be extracted from reservoirs of gas hydrate in marine sediment or beneath terrestrial permafrost using one of three main methods: depressurization of the reservoir; increasing the temperature; or injecting chemical inhibitors (Makogon et al., 2007; Chong et al., 2016).

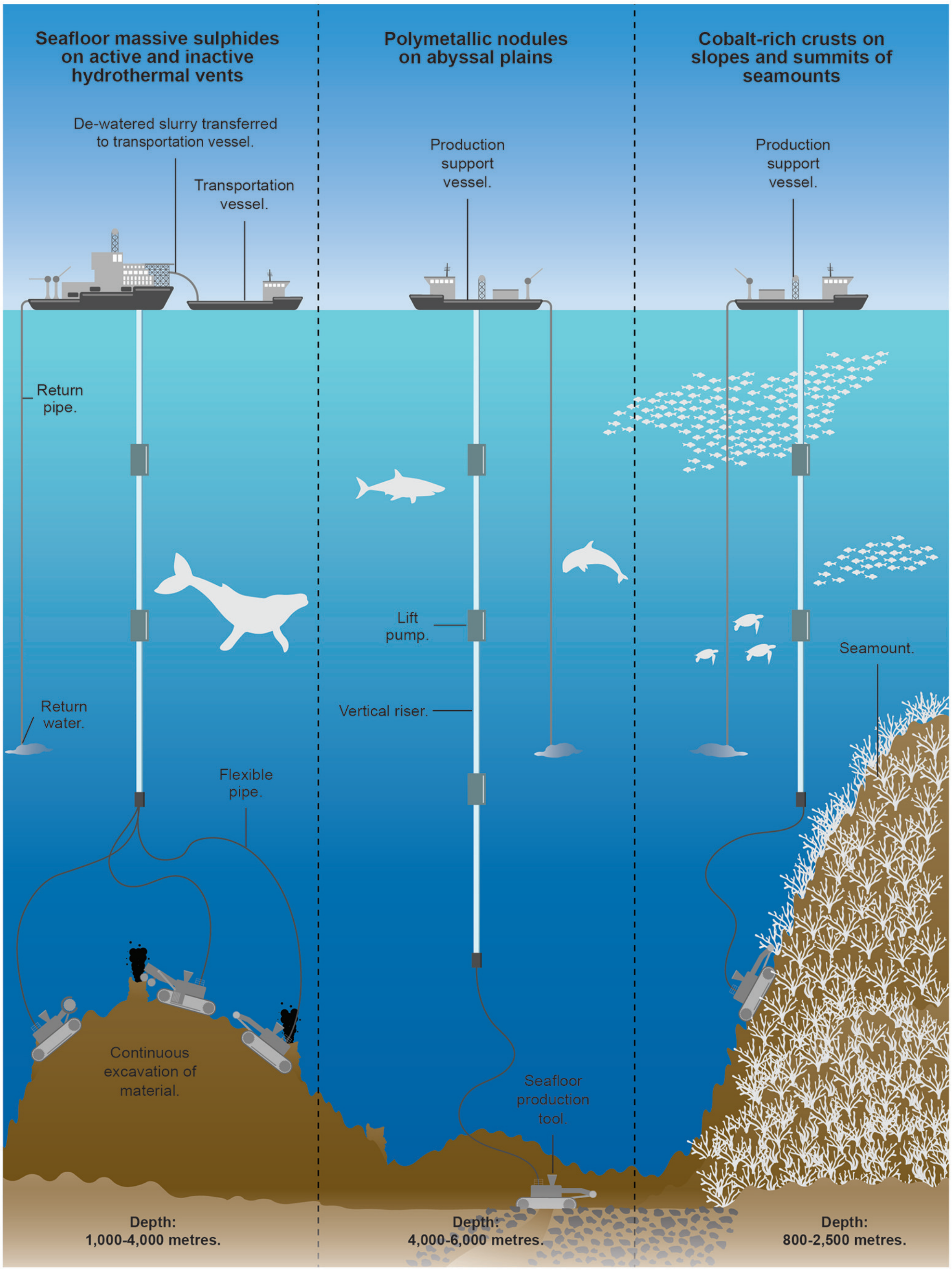

FIGURE 4 | A schematic showing the processes involved in deep-sea mining for the three main types of mineral deposit. Schematic not to scale.

Quantity and Quality of Marine Reserves of Marine Minerals

Polymetallic nodules form at a rate of several mm to several cm per million years (Halbach et al., 1980). Densely covered nodule fields (areas with >10 kg per m^2) that contain at least 1% copper and nickel are found in areas of the North and South Pacific Ocean at depths of 3,000–6,000 m in regions where there is no sedimentation from seamounts or accumulation of carbonate. Nodules are found in many areas of the Pacific Ocean, though for technical and economic reasons only a small percentage of nodules will be suitable for commercial exploitation. The composition of nodules is not uniform. Research has shown that deposits found just several 100 m apart can vary appreciably in composition—the concentration of minerals in nodules found in the North Pacific belt is greater than the South Pacific; percentage values from the former region are reported as: Mn 22–27; Ni

1.2–1.4; Cu 0.9–1.1; Co 0.15–0.25; Fe 5–9 (Halbach et al., 1980). Polymetallic nodules are also found in the Indian Ocean.

Seafloor massive sulfides are most likely to yield copper and zinc, though some also contain commercially significant grades (metal content) of gold (0–20 ppm) and silver (0–1,200 ppm; Hoagland et al., 2010). Data obtained from sampling suggest that the grades of some marine sulfide deposits, especially copper content, are higher than their terrestrial counterparts. Research suggests that seafloor sediment may also be a valuable source of rare earth elements (the lanthanides, plus scandium, and yttrium), with estimated reserves of more than 100 million metric tons (Kato et al., 2011). Most marine seafloor massive sulfide deposits are in the range 1 to 5 million (Hoagland et al., 2010). Nautilus's Solwara 1 site has an indicated seafloor massive sulfide resource of 0.87 million tons, with 1.3 million tons of inferred resource (Hoagland et al., 2010). At 90 million tons, the metalliferous muds of the Atlantis II Deep site in the central Red Sea may form the only seafloor massive sulfide deposit similar in scale to terrestrial sources (Hoagland et al., 2010; Thiel et al., 2015). Most companies focus on exploration of non-active hydrothermal vents.

Cobalt-rich crusts on seamounts can potentially yield multiple metals—manganese, cobalt, nickel, rare earth elements, tellurium, and platinum. The technology and methodologies to assess resources on seamounts is being developed but mining CRCs is not yet technologically feasible (Du et al., 2017).

The potential amount of natural gas in global reserves of gas hydrates are estimated to be around 1.5×10^{16} m^3 (at sea level) but more precise estimates are difficult because field data are scarce (Makogon et al., 2007). Countries including Japan, China, India, and the United States are investigating the resource potential of gas hydrates and in 2012, JOGMEC, the US Department of Energy and US oil firm ConocoPhillips began testing a method to extract methane by using CO_2 (Jones, 2012). Japan claimed to be the first country to successfully extract gas from methane hydrate in 2013 from an offshore location in its EEZ (BBC, 2013). In July 2016, a partnership comprising the US Geological Survey, the Government of India and the Government of Japan found a deposit of natural gas hydrate in the Bay of Bengal, India (United States Geological Service, 2016). Japan and China reportedly extracted methane hydrates in mid-2017 (Arstechnica, 2017). The German Submarine Gas Hydrate Reservoirs (SUGAR) project, launched in 2008 and financed by two federal ministries and German industries, is co-ordinated by GEOMAR and is investigating the potential of obtaining natural gas from gas hydrate reserves (GEOMAR, 2017, see http://www.geomar.de/en/research/fb2/fb2-mg/projects/sugar-i/).

Permission to Exploit Minerals

Projects in international and national waters are focusing on how feasibly to locate and extract minerals from the ocean for commercial gain. Two companies have been awarded permission for exploitation, though neither has begun commercial operations—they are Nautilus Minerals and Diamond Fields International. Both companies plan to operate in the EEZ, in the Bismarck Sea and the Red Sea, respectively. Legal terminology varies depending on the country; some countries award licenses, some award permits and others award contracts to exploit mineral resources.

The main commercial focus of Nautilus Minerals is the Solwara 1 project to extract high-grade copper and gold from seafloor massive sulfide (SMS) deposits located at depths around 1,500–2,000 m in the Bismarck Sea. In 2009, Papua New Guinea granted Nautilus Minerals an environmental permit for the development of Solwara 1 in the Bismarck Sea for a term of 25 years and then, in 2011, awarded the company its first mining lease, which covers an area of ~59 km^2 (Nautilus Minerals, 2017).

Solwara 1 covers an area of 0.112 km^2, 30 km off the coast of Papua New Guinea at a depth of 1,600 m. The project is projected to have a lifespan of 2.5 years and will focus on the extraction of copper, which has a grade of ~7%, and gold, with an average grade of 6 g per ton. During its lifetime, an estimated 1.3 million tons of material per year would be extracted from the site (Nautilus Minerals, 2008). Although commercial mining is yet to begin, in April 2012 Nautilus signed its first customer, China-based Tongling Nonferrous Metals Group Co. Ltd. (Nautilus Minerals, 2011). Nautilus Minerals's three seafloor production tools—built in the UK by Newcastle-based Soil Machine Dynamics—arrived in Papua New Guinea in early 2017. All three tools are undergoing 4-month-long submerged trials in an enclosed excavation on Motukea Island—the tools will not be deployed into the ocean and there will be no discharge of cut material into the environment. Nautilus expects delivery of its production support vessel at the end of 2018 (Nautilus Minerals, personal communication) and initial deployment and testing at Solwara 1 to begin in the first quarter of 2019, subject to financing (Nautilus Minerals, 2016a).

Diamond Fields International (DFI), together with its joint venture partner Manafa, acquired a 30-year exclusive deep-sea metal mining license, also for seafloor massive sulfide deposits, in June 2010 for activities within the Atlantis II basin in the Red Sea, ~115 km west of Jeddah. The Atlantis basin is comprised of four interlinked sub-basins lying ~2,000 m below sea level and is widely acknowledged as the largest known polymetallic marine "sedex" (sedimentary exhalative) deposit in the world. There is evidence of extensive and continuous mineralization of zinc, copper, silver, gold, lead, and other metals (Ransome, 2010). The Atlantis II project is currently on hold because of a legal dispute (Diamond Fields International, 2016).

ENVIRONMENTAL IMPACTS OF MINING AND THE POTENTIAL FOR SEABED RECOVERY

When commercial exploitation of marine resources was first suggested in the 1960s, scant regard was given to environmental consequences. Several decades on, an increasing number of commercial operations are in the pipeline and companies have been prospecting in international and national waters. In parallel with commercial interest in seabed minerals, there has been a deepening scientific understanding of marine ecosystem services and biodiversity. Increased knowledge has, in turn, highlighted the potential consequences of mining in the deep sea (**Figure 5**). In the past decade, for example, the implications of the rapid loss of marine species are becoming apparent. Biodiversity loss has led to discussions about ways to help marine ecosystems to develop resilience to climate and physical change, for example by establishing marine reserves, and studies have attempted to assess the environmental impacts of mining (McCauley et al., 2015; O'Leary et al., 2016; Roberts et al., 2017). Seabed disturbance experiments include the German project DISCOL (disturbance and recolonization experiment) and follow-up study, MIDAS (managing impacts of deep sea resource exploitation). MIDAS was a multidisciplinary programme across 11 countries partly funded by the European Commission. Its 3-year investigation was completed in October 2016 (MIDAS, 2016). Conclusions included the potential for release of toxic elements during the mining process and the difficulty of predicting the impact of release using data from laboratory experiments involving only one element. Data on deep-sea biodiversity are scarce, and investigating the genetic connectivity and ascertaining the impacts to biota will require long-term studies. With regard to the longevity of impacts following the cessation of mining, MIDAS found that seafloor habitats did not recover for decades following disturbance and concluded that it was likely that the effects of commercial mining would be evident for longer timeframes. In summary, small-scale trials cannot accurately predict the full consequences of commercial-scale mining. MIDAS worked alongside industry partners to investigate best practices, and in its conclusion to that work proposed an environmental management strategy that adopted a precautionary approach that would incorporate adaptive management.

Environmental management of the Area is by the ISA, which to date has only needed to implement regulations relating to exploration. As interest in commercial exploitation advances, the ISA is now in the process of developing a regulatory framework for exploitation. A working draft titled "Regulations and Standard Contract Terms on Exploitation for Mineral Resources in the Area" was issued in July 2016, and a discussion paper, "Regulations on Exploitation for Mineral Resources in the Area (Environmental Matters)" was made public in January 2017 (https://www.isa.org.jm/files/documents/EN/Newsletter/2017/Mar.pdf). A report from a workshop held in Berlin, Germany, in March 2017 to develop a long-term environmental strategy for the Area is available on the ISA website (https://www.isa.org.jm/document/towards-isa-environmental-management-strategy-area).

Following on from the Berlin workshop, the ISA released revised draft regulations in August 2017 titled, "Draft Regulations on Exploitation of Mineral Resources in the Area" with a short list of questions to be addressed (https://www.isa.org.jm/files/documents/EN/Regs/DraftExpl/ISBA23-LTC-CRP3-Rev.pdf).

Environmental management of exploitation in the Area will ideally involve different levels of assessment, some of which will be carried out by the ISA and some by contractors. At the time of writing, the most recent draft of the exploitation regulations does not address environmental management in detail and specific protocols have yet to be developed. Ideally, the process will involve a strategic environmental assessment and plan, overseen by the ISA, that covers activity across the entire Area. Regional environmental assessments and plans will be prepared by the ISA for smaller zones within the Area and mining contractors would commission environmental impact assessments and statements for the specific area of their contracts. However, full details of how the ISA will manage the environmental aspects relevant to exploitation have not been finalized, there is a dearth of published baseline environmental data and questions remain, including who or what body will manage and monitor areas of particular environmental interest.

Nodule Removal from the Abyss

The physical recovery of manganese nodules will take millions of years because deposition rate of new nodules is slow (Halbach et al., 1980; Gollner et al., 2017). After the removal of nodules, it is unknown whether associated biota will recover. A number of experiments have investigated the impact of nodule removal on the benthic environment in the Clarion-Clipperton Zone have shown highly variable results. For example, an experimental extraction of nodules from the CCZ was conducted in 1978 (the so-called OMCO experiment), and the area revisited in 2004 to assess the recovery of the benthic habitat. Despite the ensuing 26 years, tracks made by the mining vehicles were still clearly visible and there was a reduced diversity and biomass of nematode worms within the disturbed tracks when compared to surrounding undisturbed areas (Miljutin et al., 2011).

Experiments carried out to date have been conducted on much smaller scales than proposed commercial operations, and some tests did not involve recovery of nodules. Vanreusel et al. (2016) examined a track that had been experimentally mined 37 years ago and found that the once nodule-rich area was devoid of fauna, indicating that mining can permanently damage nodule habitat and lead to significant biodiversity loss (**Figure 6**). Tilot (2006) analyzed 200,000 photographs and 55 h of video footage (taken since 1975) to investigate the biodiversity and distribution of benthic megafauna associated with polymetallic nodules in the CCZ. The study found the polymetallic nodule ecosystem to be a unique habitat for suprabenthic megafauna.

Seafloor Massive Sulfides from Hydrothermal Vents

Remotely operated machines will inevitably cause direct physical impact to the seabed, changing its topography through suction or drilling, removal of substrate and by machinery movements. Mining that targets hydrothermal vent chimneys will remove those features entirely, leaving a flatter topography with a more uniform surface and compressed sediment in many areas that could be unsuitable for habitat recovery and recolonization. Van Dover (2010) suggests that mining will alter the distribution of vents but the mineral component of chimneys could reform over time if the vents remain active. Hekinian et al. (1983) reported physical chimney growth of 40 cm over 5 days at some locations in the East Pacific Rise. However, it is unknown how long it would take for the recovery of vent-associated species. Van Dover (2014) assessed the impact of anthropogenic activity (scientific research and commercial exploration) on

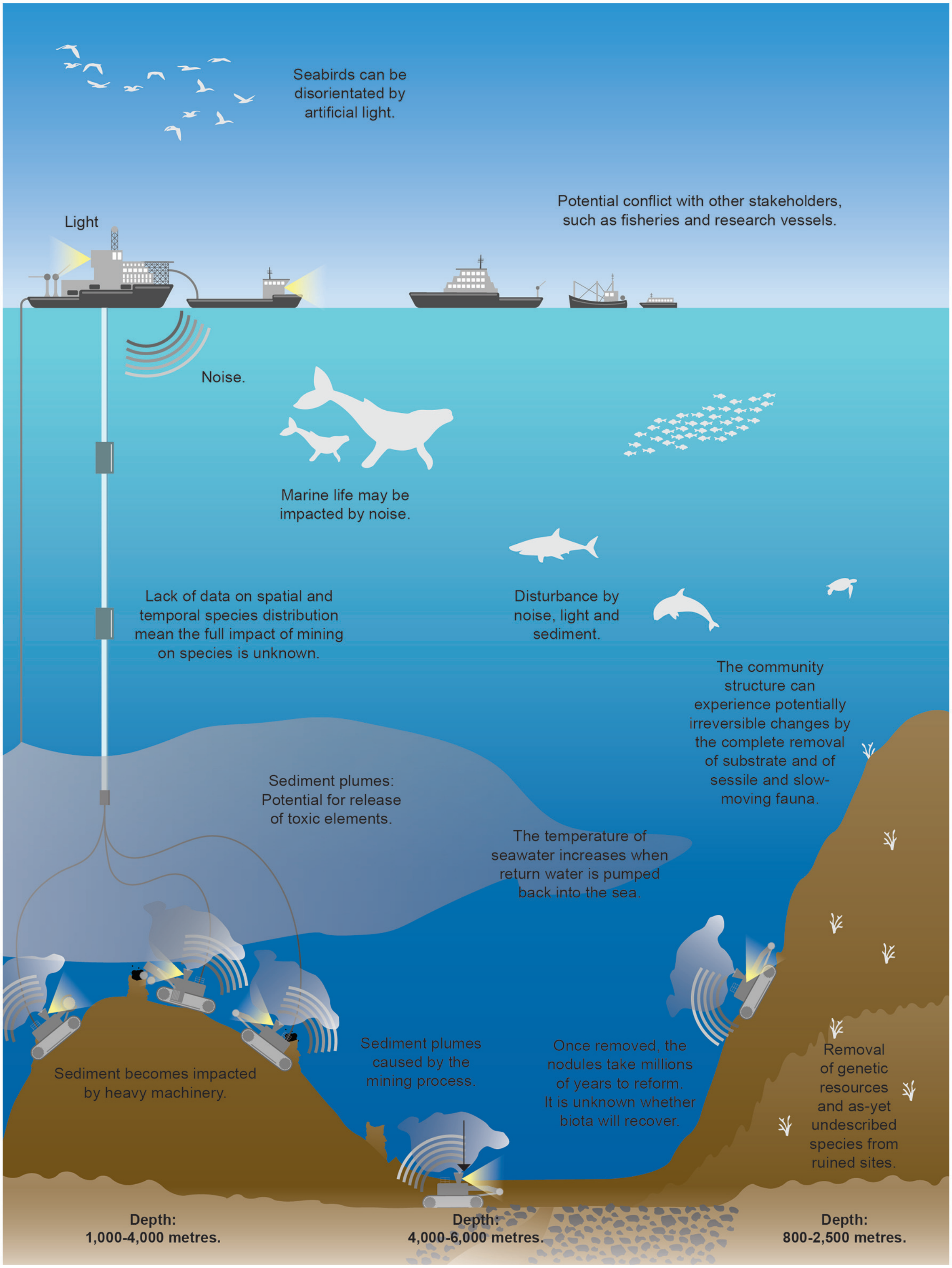

FIGURE 5 | A schematic showing the potential impacts of deep-sea mining on marine ecosystems. Schematic not to scale.

ecosystems surrounding hydrothermal vents and suggest that factors likely to impact vent communities include light and noise pollution, discarded materials, crushing seabed organisms and heavy vehicles compacting the seabed. In addition, intentional or unintentional transport of species (in ballast water, on equipment or relocation of fauna prior to mining activity) to a different

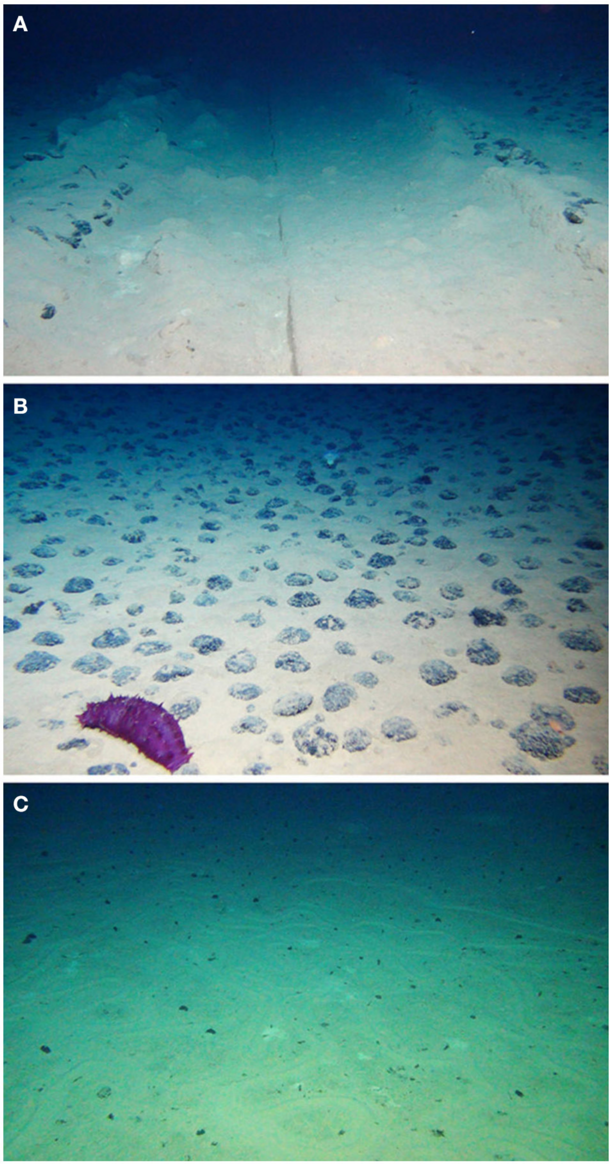

FIGURE 6 | Examples of seafloor morphology and disturbance. **(A)** Thirty-seven year old OMCO track (IFREMER license area); **(B)** Nodule landscape (IFREMER license area); **(C)** Nodule-free landscape (IOM area). Copyright: ROV Kiel 6000 Team/GEOMAR Kiel, EcoResponse cruise with RV Sonne, April–March 2015.

location can introduce potentially invasive species to habitats (Van Dover, 2014). Van Dover (2010) also refer to potentially unique communities associated with inactive vent sites and mining at these locations could permanently change community structures.

Nautilus Minerals expects its mining operations to take place 24 h a day, 365 days per year at Solwara 1. The operation will use three large robotic machines: an auxiliary vehicle will prepare and flatten the seabed by leveling chimneys and destroying habitats, a bulk cutter will leave cut material on the seabed, then a collecting machine will gather the material as slurry and it will be pumped up a rigid pipe to the production support vessel on the sea surface. Approximately 130,000 m^3 of unconsolidated sediment will be moved by Nautilus Minerals over a mining period of 30 months (Nautilus Minerals, 2008, 2016b).

Removal of Cobalt-Rich Crusts from Seamounts

Mining CRC deposits on seamounts will cause direct mortality to sessile organisms. Levin et al. (2016) suggest that such mining may also cause benthic, mesopelagic (200–1,000 m) and bathypelagic (1,000–4,000 m) fish mortality. The extent of mining on seamounts will dictate the level of impact, but it is likely that intensive mining could disrupt pelagic species aggregations due to the removal of benthic fauna, the presence of machinery and disruption as a result of noise, light and suspended sediments in the water column.

Gollner et al. (2017) discuss the potential impacts of mining in the context of what is known from activities such as fisheries, in particular trawling, that remove substrate and associated organisms from seamounts. Though there are few data on recovery of species after intensive periods of trawling, the negative impact of deep-sea fisheries on seamounts is well-documented with noted declines in faunal biodiversity, cover, and abundance (Clark et al., 2016). Many seamount species, such as the sessile corals, are thought to be slow growing (from a few micrometers to ~1 mm per year), long-lived (up to millennia), and susceptible to physical disturbance and for these reasons it has been suggested that seamounts be globally managed as VMEs (Clark and Tittensor, 2010; Fallon et al., 2014; Watling and Auster, 2017). The impact of marine mining may be more intensive than trawling because the removal of substrata will be complete. Such removal on a commercial scale accompanied by slow species recovery rates will likely lead to irreversible changes in benthic (and possibly pelagic) community structure on and around seamounts (Gollner et al., 2017).

Extraction of Gas Hydrates

Gas hydrates have attracted attention commercially as a potential future energy resource (Lee and Holder, 2001) but prospecting and any subsequent extraction of gas hydrates from seabed (or permafrost) reserves carries potentially considerable environmental risk. The greatest impact would be accidental leakage of methane during the dissociation process. Methane is a greenhouse gas that is 28 times more potent than carbon dioxide according to the assigned global warming potential over 100 years (IPCC, 2014). Other possible impacts of methane hydrate extraction include subsidence of the seafloor and submarine landslides, which could cause even greater instability in remaining hydrate deposits. Anthropogenic activity that leads to increased water temperature at seabed level could also destabilize and melt the hydrates. Dissociation of methane hydrates to form free methane could release large quantities of methane gas into the sea or atmosphere, adding to ocean acidification and/or global warming (Kretschmer et al., 2015). If increasing quantities of methane hydrate is destabilized and released, atmospheric temperature may rise leading to a positive carbon-climate feedback (Archer, 2007; Zhao et al., 2017). Concerns are also that mining could affect biota—chemosynthetic life and higher order organisms have been found on seafloor hydrate mounds. Fisher et al. (2000) noted a previously undescribed species of polycheate worm or "ice worm" (*Hesiocaeca methanicola*) that was able to burrow into sediment to reach the hydrate deposits.

Sediment Plumes

Commercial mining activity will have widespread environmental consequences. Deep-sea sediment plumes will be created by seafloor production vehicles—specifically the cutter and the collector—as well as by risers and processed material that is discharged as waste-water by the surface support vessel (Boschen et al., 2013; Van Dover, 2014; Gollner et al., 2017). Dewatering waste, side cast sediment and sediment released during the mining process are thought to be the main wastes released during mineral recovery. Dewatering waste may contain fine sediment and heavy metals that would be resuspended when discharged into the water column (Nautilus Minerals, 2008). The side-casting of sediment waste on the seafloor minimizes the need for transport to the surface or land-based storage, but would nonetheless lead to major physical alterations and would smother the benthic habitat. In relation to the proposed mining at Solwara 1, Nautilus Minerals state that their waste sediment and rock, an estimated 245,000 tons (Nautilus Minerals, 2008), will be side cast at the edge of the mining zone. Discharged return water will be returned at 25–50 m above the seabed. The returning slurry may contain suspended particles (smaller than 8 μm), be warmer than sea temperature at that depth and contain a high concentration of metals if leaching occurs from ore during mining.

The release of potentially toxic plumes is likely to impact habitats well beyond the area of mining, though details such as the volume and direction of plume travel are not yet fully understood. Some models suggest that sediment released close to the seabed may, in some circumstances, be confined to deep water and not move into the upper water column because of differences in water density (Bashir et al., 2012). However, suspended particulate matter and settlement of sediment could cover a wide area depending on discharge volume, vertical stratification and ocean currents.

According to Nautilus Minerals (2008) and Boschen et al. (2013), the release of plumes from a sulfide test-mining site at Solwara 1 resulted in sedimentation of up to 500 mm within 1 km of the discharge site and some material dispersing up to 10 km away. Records of natural sedimentation rates at hydrothermal vents range from <2 mm in some sites (Atkins et al., 2000) to <0.03 mm in others (Costa et al., 2016). Natural sedimentation rates are thought to be only few millimeters per 1,000 years in both abyssal and seamount habitats.

Making predictions of potential plume movements using models is a complex task in the absence of extensive data on plumes, upwelling, and oceanographic currents (Luick, 2012). Commercial seabed mining has not begun and therefore it is difficult to predict the impacts, but some terrestrial mining operations can help to predict potential consequences of mining operations. For example, tailings disposed of at sea from the terrestrial Lihir Gold mine in Papua New Guinea are estimated to have spread over an area of 60 km^2 from the point of discharge because of subsurface currents (Shimmield et al., 2010). Even when plumes are restricted to deep waters, impact to benthic communities cannot be avoided considering that the overall topography of the seabed could be altered and organisms will endure some extent of smothering. Such smothering will impede gas exchange and feeding structures in sessile organisms and could cause a number of other as yet unquantified impacts as a result of exposure to heavy metals and acidic wastes (Van Dover, 2010). The presence of sediment plumes could delay or prevent recolonization of mined areas through altered larval dispersal, mortality of larvae and success of larval settlement (Gollner et al., 2017).

Suggestions of technological modifications that could be employed to lessen the effect of plumes include reducing the size of the plumes and the toxicity of sediment particles, and by minimizing the accidental escape of suspended sediment during the cutting process (Boschen et al., 2013). The discharge of wastewater at the sea surface could impact marine ecosystems by causing turbidity clouds and affecting commercial fish species, as well as, in some cases, causing algal blooms (Namibian Marine Phosphates, 2012).

Increased Noise

Submerged remotely operated vehicles will increase underwater ambient noise, as will support vessels on the sea surface. Most deep-sea species generally only experience low-levels of noise, such that anthropogenic noise, particularly if occurring on a non-stop basis, will substantially increase ambient sound levels (Bashir et al., 2012). Studies on deep sea fish reveal that some species communicate using low sound frequencies (<1.2 kHz; Rountree et al., 2011) and it is thought that other benthic species may use sensitive acoustic systems to detect food falls up to 100 m away (Stocker, 2002). Anthropogenic noise is known to impact a number of fish species and marine mammals by inducing behavior changes, masking communication, and causing temporary threshold-shifts in hearing or permanent damage depending on the species, type of noise and received level (Gomez et al., 2016; Nedelec et al., 2017).

Nautilus Minerals plans to operate its seafloor production tools and offshore vessels 24 h per day, with operations on the surface and seafloor using artificial lighting. The company expects that the noise from its seafloor production tools and mining support vessels will add to ambient noise levels but precise noise characteristics of the equipment are unknown. In its environmental impact statement (EIS), Nautilus Minerals did not measure ambient noise or assess sound attenuation in relation to proposed commercial operations at Solwara 1 but referred to an older published study from the Beaufort Sea, Canada, for suggested ambient noise levels (Richardson et al., 1990). Mitigation strategies were not suggested by the company in its EIS.

Anthropogenic Light

Sunlight readily penetrates the euphotic zone (approximately the uppermost 100 m of the ocean, depending upon conditions), enabling photosynthesis, but relatively little sunlight penetrates the dysphotic zone (200–1,000 m). The aphotic zone is below the penetration of sunlight but is not completely dark: low light in the deep sea has been shown to originate from bioluminescence (Craig et al., 2011) and geothermal radiation (Beatty et al., 2005) and organisms have adapted to the conditions. Continuous mining activity that employs floodlighting on surface support vessels and seafloor mining tools would vastly increase light levels on a long-term basis and this would be a change from current conditions at proposed mining sites. For example, most of the light detected at two hydrothermal vents (one on the East Pacific Ridge, the other in the Mid-Atlantic Ridge) was near-infrared (Van Dover et al., 1996). Herring et al. (1999) found that vent-inhabiting deep-sea shrimps [*Rimicaris exoculata* and *Mirocaris* (*Chorocaris*) *fortunate*] suffered permanent retinal damage by the use of floodlights on manned submersibles surveying vent chimneys on the Mid-Atlantic Ridge.

Nocturnal artificial lighting on vessels has been shown to disorientate seabirds, particularly fledglings, leading to "fallout," in which the birds fly toward the light source and become exhausted or collide with man-made objects (Troy et al., 2013). Research is needed to determine the extent to which Beck's petrel (*Pseudobulweria becki*)—a species listed as critically endangered on the International Union for the Conservation of Nature Red List and which is native to Papua New Guinea and the Solomon Islands—would be attracted by artificial light used in proposed mining operations. If increased light levels were to persist, other mobile organisms might migrate away from the mine site. To date, there is no evidence that Nautilus has investigated ambient light levels at the Solwara 1 site or considered the likely significance of such impacts in any detail (Nautilus Minerals, 2008).

Increased Temperature

Drilling and vehicle operation during mining will release heat, as will dewatering waste that is returned to the deep sea. Steiner (2009) suggests that waste materials may be as much as 11°C warmer than the surrounding seawater, which is in line with estimates by Nautilus Minerals, which states that processed return water may result in an increase in temperature of 5.8–11.4°C (Nautilus Minerals, 2008). Very little is known about the impact of such temperature increases on deep-sea organisms, though it is thought that the deep sea has a relatively stable temperature and changes could affect growth, metabolism, reproductive success and survival of some deep-sea species (Bashir et al., 2012).

Biodiversity Loss and the Potential for Habitat Recovery

Deep-sea mining will inevitably cause loss of biodiversity on a local scale. Depending on factors such as the type of impact (for example, sediment plumes or noise), the type of mining and the ecosystem, biodiversity across a much wider area could be affected. The geographic and temporal scale of mining activities will affect the level and type of impact. For instance, extraction of SMS may target several hectares per year, whereas the area of cobalt-crust mining may range from tens to hundreds of square kilometers (Hein et al., 2009) and that of manganese nodule mining from hundreds to thousands of square kilometers per operation per year (Wedding et al., 2015). Mining activities will result in the direct mortality of organisms, removal and fragmentation of substrate habitat and degradation of the water column and seabed by sediment plumes (Van Dover et al., 2017).

The extent of habitat fragmentation because of mining is difficult to predict, given that there have been no large-scale trials. Mining large, continuous fields of manganese nodules will create a mosaic of smaller-sized fields, and mining SMS will lead to further fragmentation of an ecosystem that is, naturally, unevenly spaced but heavily dependent on association with specific and localized seabed features. The extent of resource extraction and plume dispersal will influence the size of the remaining fragments. Vanreusel et al. (2016) analyzed videos taken during test mining for nodules in the CCZ and suggest that mining removes almost all epifauna. Benthic organisms span a range of sizes with different ecological characteristics that dictate the nature and extent of their dispersal, mobility, and feeding strategies. The response of benthic organisms to the likely habitat fragmentation induced by mining will vary widely and will be challenging to predict because little is known about the life history or patterns of genetic diversity of many deep-sea species (Boschen et al., 2013).

Habitat modification may extend from the vicinity of mining operations to far-field effects, which are defined as those that are detectable more than 20 km away from the mining site. Reasons for degradation of the marine environment include drifting sediment plumes and low frequency noise propagation, which could alter species distributions, ecosystem functioning or even seemingly unconnected processes such as carbon cycling (Nath et al., 2012; Le et al., 2017).

The potential for benthic communities to recover is likely to vary substantially between locations and will be influenced by the duration of mining operations (Van Dover, 2011). Slow-growing deep-sea organisms typically have correspondingly low resilience to change (Rodrigues et al., 2001; Gollner et al., 2017). Recovery of benthic communities is difficult to estimate because colonization rates are not known for most species and there are few data on population size, reproductive biology, dispersal and, therefore, connectivity (Hilário et al., 2015). In the absence of commercial operations, recovery studies rely on study of the aftermath of natural extinction events such as volcanic eruptions or on deliberate disturbance experiments, but the spatial and temporal scales differ from commercial mining and so extrapolating results to determine ecological responses to seabed mining has limited application (Jones et al., 2017).

The extraction of manganese nodules removes the habitat for nodule dwelling organisms, making recovery of these communities almost impossible given the long time periods required for nodule formation. The first long-term disturbance and recolonization experiment (DISCOL) was established in the Peru Basin in 1989 in the southeast Pacific Ocean at a depth of 4,140–4,160 m. The experiment replicated on a small scale the disturbance that would be caused by commercially mining manganese nodules by plow harrowing a circular area of the seabed measuring 10.8 km^2. The aim of the project was to monitor recolonization of benthic biota. The experimental area was sampled five times: before, immediately after the disturbance, then after 6 months, 3 and 7 years. After 7 years, the tracks made by the plow were still visible. Mobile animals began to repopulate the disturbed area soon after the damage was caused, but even after 7 years the total number of taxa was still low when compared to pre-disturbance data (Bluhm, 2001). A recent project conducted under the JPI Oceans initiative, Ecological Aspects of Deep-Sea Mining, revisited the DISCOL experiment area in 2015 after a 20-year hiatus. Preliminary results and observations note that the original plow marks are still visible and there has been only a low level of recolonization, suggesting that disturbing nodules for commercial mining will cause long-term damage to the benthic ecosystem (JPI, 2016). A meta-analysis of 11 such test studies (including DISCOL) carried out by Jones et al. (2017) reports that the effects of nodule mining are immediate and severe, and note that although signs of recovery were observed within 1 year following disturbance, at most sites, there was a significant reduction in the number of recolonizing species. Few species groups recovered to pre-mining baseline conditions even after two decades and Jones et al. (2017) suggest that, even after smaller scale test mining experiments, the community-level effects of nodule mining are likely to be severe.

After mining seafloor massive sulfide deposits, vent community recovery will rely on the continuation of the hydrothermal energy source and presence of all species to enable repopulation. Community composition changes are likely due to recolonization of substrates by early successional species and the loss of species sensitive to change (Bashir et al., 2012). Mullineaux et al. (2010) reported recolonization of a vent following a natural volcanic eruption, but with a change in species composition and the presence of immigrant species from distant vent sites, possibly up to 300 km away. Shank et al. (1998) monitored a hydrothermal vent eruption and its recovery, reporting that large increases in faunal assemblages were only noted 3–5 years post-eruption and predicted that it could take up to 10 years for dominant megafauna to return. Sustained mining activity will have very different impacts to one-off natural events and the likelihood and extent of recovery of mined vent sites is highly uncertain (Van Dover, 2011). In an attempt to mitigate disturbance caused by mining, Nautilus Minerals proposes to temporarily transplant large organisms and clumps of substrate to a refuge area before mining and return them to their original position when mining ceases (Nautilus Minerals, 2008). The proposals have not yet been field-tested.

Data indicating the recovery of biota on seamounts following physical disturbance are scarce. Studies looking at seamounts that have been overexploited by trawler fishing indicate uncertainty as to whether recovery of deep-sea fish populations is possible because species are slow growing and bottom trawling (in common with mining operations) causes severe physical disturbance to the seabed. Additional challenges arise when predicting seamount recovery because seamounts vary widely in size, location and environmental conditions (Clark et al., 2010, 2012; Gollner et al., 2017).

Mining extinct vents only is anticipated to minimize impacts to vent species, because extinct sites are considered to host fewer species than active sites. Extinct vents are largely unstudied because they are difficult to locate without a hydrothermal plume (Van Dover, 2010). However, it may be challenging to determine whether a particular vent is extinct or temporally inactive; some reports suggest vent systems can be inactive for several years before reactivating (Birney, 2006). For example, vent activity was highly variable over a 3-year period of investigation at Solwara 1 (Nautilus Minerals, 2008). Suzuki et al. (2004) reported that inactive vents still supported the growth of chemolithotrophic microorganisms because there can still be sufficient hydrothermal energy. Van Dover (2010) noted that extinct vents with no detectable emissions nevertheless still hosted suspension feeding and grazing invertebrates. Such "extinct" or inactive vent systems may therefore prove to be far from extinct in relation to marine life.

Possible Conflicts

Seabed mining impacts have the potential to conflict with subsistence and commercial fishing, and shipping activities. The analysis of deep-sea biota for novel chemical compounds that could be used in medicines is another area of growing commercial interest. Legal cases could be brought if, for example, a sediment plume crosses a boundary and causes harm to the marine environment of a coastal state or to the area outside a contractor's allocated site. Disputes could arise if surface exclusion zones around seabed mining operations reduce access to fishing areas and/or change shipping or navigational routes, whether in EEZs or in the Area. For example, an exclusion zone of 23 × 9 km has been proposed in Namibian waters in relation to exploitation of seabed phosphate deposits, which would impact on key commercial fishing grounds for hake, horse mackerel and monkfish (Namibian Marine Phosphates, 2012). It is reported that fishing activities will cease in the immediate mining area and the exclusion zone due to habitat removal and increased levels of maritime traffic (Namibian Marine Phosphates, 2012). In another example, fishing companies were active opponents to a proposal for ironsand mining off New Zealand's west coast (New Zealand Environmental Protection Authority, 2017).

Armstrong et al. (2012) refers to the deep sea as the largest reservoir of genetic resources and many companies already hold patents for pharmaceuticals discovered there. For example, enzymes from deep-sea bacteria have been used in the development of commercial skin protection products by the French company Sederma for many years (Arico and Salpin, 2005). Hydrothermal vent species are of particular interest because they have unusual symbiotic relationships, are resistant to heavy metals and yield thermotolerant enzymes with a number of commercial uses (Ruth, 2006; Harden-Davies, 2017). The market for marine genetic resources is large and reached many billion US dollars by 2010 (Leary et al., 2010). Despite the significant economic value of deep-sea discoveries, there are concerns that mineral mining could destroy genetic resources before they have been fully understood or even discovered. There are also uncertainties surrounding the legal framework underpinning discoveries made in the Area (Ruth, 2006; Harden-Davies, 2017).

DISCUSSION

Interest in obtaining minerals and resources from the deep sea has gained momentum over the past decade but so too has the desire to survey, monitor, explore and understand deep-sea ecosystems. The oceans are the least explored ecosystems on Earth even though they cover 71% of Earth's surface (an area of 362 million km^2), of which 90% is considered the deep sea. Although only around 0.0001% of the deep seafloor has been investigated, it is evident that the deep ocean has particularly rich biodiversity (Tyler et al., 2003; Ramirez-Llodra et al., 2010). Advances in technology have made it possible to explore some of the deepest reaches of the ocean, leading to the discovery of hundreds of previously undescribed species but also making commercial exploitation of seabed minerals a real possibility. To date, no deep-sea commercial mining has taken place, nor have there been pilot operations to enable accurate assessment of impacts (Van Dover, 2014).

The resource closest to large-scale extraction is SMS by Nautilus Minerals at the Solwara 1 site in the national waters of Papua New Guinea, where exploitation is scheduled to begin in early 2019. The project has required significant financial investment and the company is under pressure to commence operations that will yield economic returns.

In this paper, we have outlined some of the very significant questions that surround plans for large-scale commercial minerals mining, whether within continental shelf boundaries or in the Area. When the mining of deep-sea minerals was first proposed several decades ago, knowledge of the deep-sea environment was relatively poor, as was our understanding of the potential impacts of seabed mining. Though our understanding of deep-sea biodiversity remains limited, it is evident that many species have specific life-history adaptations (for example, slow growing and delayed maturity; Ramirez-Llodra et al., 2010). Recovery from human-mediated disturbance could take decades, centuries or even millennia, if these ecosystems recover at all. Myriad impacts relate to seabed mining including the potential for conflicts with the interests of other users of the sea. At the time of writing, the ISA was in the process of developing a regulatory framework for managing mining in the Area. The details of the environmental management framework the ISA will adopt is still unclear. Key issues that need to be defined before commercial mining operations begin, including how states can meet their duty, as stipulated in UNCLOS Article 145, to effectively protect the marine environment. As understanding deepens with respect to ecosystem services and the role of the oceans in mitigating climate change, it seems wise to ensure that all necessary precautions are taken before any decision to allow deliberate disturbance that could have long-lasting and possibly unforeseen consequences.

Current activity in the Area is subject to exploration regulations by the ISA, but exploitation will have a far greater environmental impact than exploration, and because of this, biodiversity loss as a consequence of commercial operations is the topic of current debate. For example, questions are being asked such as: "What threshold of loss of biota would equate to significant adverse changes in the marine environment?" with regard to protecting the marine environment during prospecting and exploration activities, the current ISA regulations state that contractors must avoid causing serious harm to the marine environment, which the ISA defines as:

> "any effect from activities in the Area on the marine environment which represents a significant adverse change in the marine environment determined according to the rules, regulations and procedures adopted by the Authority on the basis of internationally recognized standards and practices."

The phrase "significant adverse change" has come under particular scrutiny from scientists and specialists in marine law, who are calling for clarification with empirical data thresholds to determine what constitutes "harm" (see for example, Levin et al., 2016).

Mitigation

Mitigation techniques that have been proposed to monitor the potential impacts to biodiversity and aid recovery of mined areas are untested so far. Indeed, Van Dover (2011, 2014) and Van Dover et al. (2017) stressed that we do not know how to mitigate impacts or restore deep-sea habitats successfully. Van Dover (2014) outlines a hierarchy of possible mitigation methods, including: (1) avoidance (such as by establishing protected reserves within which no anthropogenic activity takes place), (2) minimization (such as by establishing un-mined biological corridors, relocating animals from the site of activity to a site with no activity, minimizing machine noise or sediment plumes) and (3) restoration (as a last resort, because avoidance would be preferable). A fourth mitigation method is offset (the contractor would pay for the establishment of a dedicated reserve or for research), although Van Dover states that there is no such framework in place for hydrothermal systems and suggests initiating discussions on the topic among stakeholders with an interest in deep sea mining. For hydrothermal vent ecosystems, a deeper understanding of the ways in which these ecosystems are likely to be impacted and respond to commercial mineral extraction activities would help to determine the likelihood of natural recovery. An advanced understanding of hydrothermal vent ecology is necessary but that will require funding for research, long-term monitoring and thorough environmental impact assessments prior to authorizing any commercial activity (Van Dover, 2014).

In its mining code (currently only applicable to prospecting and exploration not exploitation), the ISA discusses establishing preservation reference zones (PRZ; areas in which no mining takes place) and impact reference zones (IRZ; areas set aside for monitoring the impact of mining activity). Under the current system, the ISA code requires mining companies to propose the locations and sizes of PRZs and IRZs (International Seabed Authority, 2012, 2013) but, as discussed by Vanreusel et al. (2016) with specific reference to polymetallic nodules, this situation could mean contractors apply PRZs to economically unimportant areas rather than those that are environmentally important. One point to note is that IRZs and PRZs are distinct from marine protected areas because they are intended to be tools for environmental monitoring, not for the conservation of biodiversity. Lallier and Maes (2016) recommend that the ISA mining code be developed to prioritize environmental protection through the application of the precautionary approach, but it is unclear how this would work on a practical basis, or whether protective measures would be effective. A number of countries, including Canada, the United States, Mexico and Portugal, have established marine protected areas to protect hydrothermal vents and other deep-sea features (Van Dover, 2014), but it is unclear how beneficial these will be.

Other strategies that have been suggested to mitigate the impact of deep-sea mining during the exploitation phase include reducing the area impacted by plumes; de-compacting sediment under the seafloor production tools; and leaving a proportion of nodules on the seabed (such as the largest and the smallest). However, to date there has been no large-scale deep-sea mining test and no assessment of whether any one strategy or combination of strategies would lessen any impact on biodiversity and ecosystem processes.

Some opponents of deep-sea mining imply that any mitigation measures seem futile. An article published in *Science* in 2015 called for the ISA to suspend approval for new exploration contracts and not approve any exploitation contracts until marine protected areas are designed and implemented for the high seas (Wedding et al., 2015). These authors also suggested that protected areas are designated *before* new exploration contracts are awarded.

Uncertainties, Knowledge Gaps, and Areas for Future Research

Many questions and uncertainties surround deep-sea mining, including those stemming from the complexity and scale of the proposed operations, and those arising from legal uncertainties relating to proposed exploitation in the Area and the fact that no large-scale impact trials have yet taken place. In this review, we have presented some of the key issues, but very substantial and significant knowledge gaps remain.

Data indicating the recovery of deep-sea biota following physical disturbance are scarce and thus this is an area warranting additional research. There is an absence of baseline data from potential mining sites because only a fraction of the ocean has been studied in depth due to the logistical complexity and financial constraints of accessing the deep sea. Future studies could focus on understanding deep-sea ecology (for example, local endemism, demographic and genetic connectivity relating to dispersal modes) in the proposed mining zones.

Discussions are underway to develop the legal framework to regulate exploitation, including issues of environmental protection, accountability, interactions across international and national boundaries, and also between claims, with input from marine scientists, legal specialists, and non-governmental organizations. Uncertainties surrounding deep-sea ecology and ecological responses to mining-related activities mean that environmental management strategies would need to be tailored to incorporate natural temporal and spatial variability of deep-sea ecosystems (Clark et al., 2010). The impact of noise on deep-sea organisms is not well-studied, which represents another significant knowledge gap in the management of commercial activities.

Alternatives Approaches

It is widely accepted that demand for metals for use in clean energy and emerging technologies will increase in the next decades, raising the likelihood of supply risk. In response, retrieving metal resources from seabed mining has been identified as one of five sectors with a high potential for development within the European Commission's blue growth strategy (European Commission, 2017a). The strategy aims to provide support to long-term sustainable growth in the marine and maritime sectors within the region, and the European Commission optimistically estimates that by 2020, 5% of the world's minerals could be sourced from the ocean floor (Ehlers, 2016). If technological challenges are overcome, the annual turnover of marine minerals mining within Europe could grow from zero to 10 billion Euros by 2030 (Ehlers, 2016).

However, there are alternatives to exploiting virgin stocks of ore from the seabed. Such approaches include: substituting metals in short supply, such as rare earths, for more abundant minerals with similar properties (United States Department of Energy, 2010; Department for Environment, Food and Rural Affairs, 2012); landfill mining (Wagner and Raymond, 2015); and collection and recycling of components from products at the end of their life-cycle. Other novel options include the potential to recover lithium and other rare metals from seawater (Hoshino, 2015).

A European Commission initiative, adopted in 2015, supports the transition toward a circular economy that promotes recycling and reuse of materials—from production to consumption—so that raw materials are fed back into the economy (European Commission, 2017b), though the strategy will depend on developing the necessary technology as well as changing consumer behavior. Recycling, though crucial, is unlikely to provide sufficient quantities of metals to satisfy requirements in future years which has prompted suggestions that reducing use of metals in products will be a necessary part of product design (United Nations Environment Programme, 2013a).

Increasing the longevity of technological devices and promoting responsible e-waste recycling could be achieved through manufacturer take-back schemes, in which component materials can be safely and effectively recovered for reuse. Recycling metals carries its own challenges, which include potential release of toxic substances during processing and limitations during metals recovery that mean not all components can be isolated (United Nations Environment Programme, 2013a). A shift in focus to reducing consumption and, in addition, better product design (United Nations Environment Programme, 2013b). Closing the loop on metals use is possible because in theory all metals are recyclable, though we are some years away from achieving such a system (Reck and Graedel, 2012). Improving consumer access to recycling and streamlining manufacturing processes can be a more efficient and economically viable method of sourcing metals than mining virgin ore and could greatly reduce or even negate the need for exploitation of seabed mineral resources.

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