The environmental impacts of deep-sea mining

Sea cucumber *Amperima sp* on the seabed in the eastern Clarion-Clipperton Fracture Zone. The lives and habitats of animals such as this one are at risk if deep-sea mining activities proceed without sufficient and reliable scientific knowledge.

Credit: Craig Smith and Diva Amon, ABYSSLINE Project

By Thomas Frölicher and Samuel Jaccard

To ensure the perennial protection of the fragile marine environment, a precautionary approach should be adopted when considering the pursuit of deep-sea mining activities.

To limit global warming to 1.5°C relative to preindustrial times and achieve net-zero emissions by 2050 as outlined in the Paris Agreement, transitioning to renewable energy sources such as solar and wind power is essential.[1] Yet, these technologies often rely on rare earth minerals. Mass production of personal technologies, such as mobile phones and laptops, further increases the demand for these finite, nonrenewable resources.

The accelerated need for minerals to support the green transition[2] has raised concerns about potential bottlenecks as the most readily available and high-grade ores on land may become exhausted and potentially increasingly vulnerable to geopolitical instabilities. This concern led to the possibility of opening up new mining frontiers to supply these minerals. One of the most contentious proposals involves exploiting mineral resources in the deep sea.

What is deep-sea mining?

Deep-sea mining relates to the process of extracting valuable mineral resources from the deep seabed. The occurrence of deep-ocean mineral deposits has been known for more than a century.[3] However, investigations dedicated to better documenting their genesis, geographical distribution, and resource potential have recently gained considerable traction.

Economic interest has traditionally focused on nickel, copper, and manganese for nodules; cobalt, nickel, and manganese for crusts; and copper, zinc, gold, and silver for seafloor massive sulfides. Research undertaken in the last decades has revealed that additional metals, including rare earth elements (REEs) such as lanthanum, cerium, praseodymium, neodymium, europium, gadolinium, and yttrium, are potential byproducts of mining the more traditional target metals. The metals enriched in these marine deposits are essential for a variety of high-tech, green-tech applications and may play a crucial role in the energy transition.

A brief description of the general characteristics of the three types of deposits—including their genesis, geographical distribution, and main metal resources—is outlined in the following sections. For details, see Reference 3.

Polymetallic (or manganese) nodules on the abyssal seafloor

Typical chemical composition: Mn (22–30%), Fe (5–9%), Ni (1.2–1.4%), Cu (0.0–1.4%), Co (0.15–0.25%), Li, Zr, Mo, Te, Pt, and REEs.

Polymetallic nodules occur throughout the global ocean, generally on, or below, the surface of sediment-covered abyssal plains (blue areas in Figure 1).[4,5] They cover about 38 million km^2 at water depths ranging between 3,500–6,500 m, notably in the

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Clarion-Clipperton Fracture Zone (CCZ; a 5,000 km stretch of seafloor between Hawaii and California), Penrhyn Basin (south central Pacific), Peru Basin, and the center of the north Indian Ocean.[5] Fields have also been reported in the Argentine Basin (SW Atlantic Ocean) and the Arctic Ocean, yet these areas have only been poorly explored.

The CCZ is the area of greatest economic interest due to high concentrations of nickel and copper as well as high nodule abundance. Nodule abundance in the CCZ ranges between 0–30 kg/m^3 and the total amount of polymetallic nodules within the region is estimated to be about 21 billion tons, amounting to about 6 billion tons of manganese.

Polymetallic nodules often occur as potato-shaped concretions that vary in size from tiny particles to pellets larger than 20 cm and are abundant in abyssal plains characterized by oxygenated bottom waters and low sedimentation rates (i.e., < 10 mm/kyr). Metal-rich nodules occur in areas of moderate surface ocean biological productivity. Nodules grow optimally near or below the carbonate compensation depth (CCD), which characterizes the depth at which biogenic carbonate particles raining from the surface ocean are completely dissolved. Indeed, above that depth, located at approximately 4,000–4,500 m depth in the Pacific Ocean, biogenic calcite increases sedimentation rates and dilutes sedimentary organic matter contents necessary for diagenetic reactions that release nickel and copper. The favorable combination of water depth and surface biological productivity in the CCZ leads to its seafloor being located just at or below the CCD. Areas further to the south are characterized by higher biological production in the sunlit surface ocean, leading to higher sediment accumulation. Under these conditions, widespread nodule formation is hampered.

Altogether, polymetallic nodules grow with average rates of 10–20 mm/Myr and usually have an age of several Myr. Nodule growth is one of the slowest of all known geological processes and thus Fe–Mn nodules are not considered a renewable resource.

Cobalt-rich crusts or ferromanganese crusts on seamounts

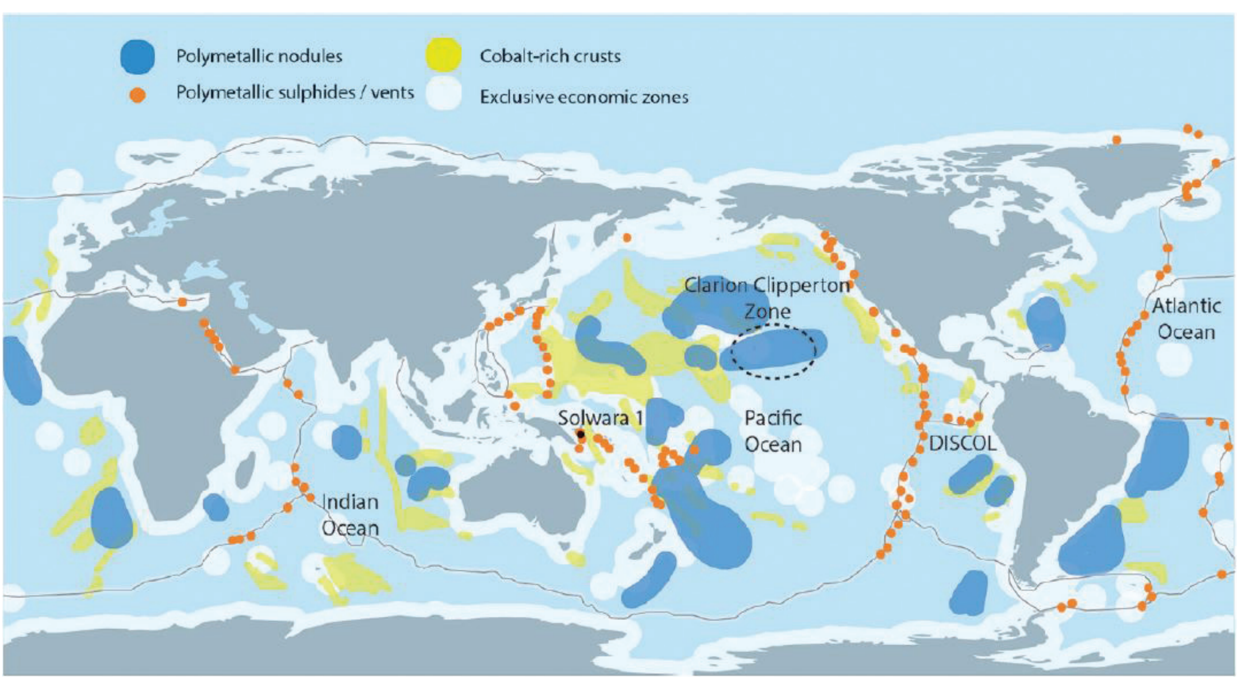
Typical chemical composition: Mn (13–27 %), Fe (6–18 %), Co (0.3–1.2 %), Ni (0.17–0.73 %), Te, Zr, Nb, Mo, W, Pt and REEs.

Cobalt-rich crusts (CRCs) are typically found at water depths ranging between 400–7,000 m, with the thickest and most metal-rich crusts occurring at depths of about 800–3,000 m.[6] Cobalt and nickel concentrations significantly decrease with increasing water depth. Cobalt-rich crust deposits are found throughout the global ocean (yellow areas in Figure 1). They occupy 1.7 million km^2 and 54% of the known crusts are in Exclusive Economic Zones.[5] The richest crust deposits are typically found in the western Pacific Ocean, where seamounts are abundant. The main settings include seamounts and submerged volcanic mountain ranges where strong abyssal currents have maintained the seafloor barren of sediments for millions of years. Fe–Mn crusts vary in thickness from less than 1–250 mm and are generally thicker on older seamounts.

In contrast to nodules, ferromanganese crusts are generally attached to a hard substrate, making them more challenging to mine. Indeed, successful crust recovery requires the Fe–Mn crusts to be detached from the substrate with minimum dilution and contamination by substrate rock material.

Seafloor massive (polymetallic) sulfides at active or inactive hydrothermal vents

Typical chemical composition: Cu (6–10%), Zn (15–22%), Co, Au, Zn, Pb, Ba, Si, and REEs.



Credit: Frölicher and Jaccard, University of Bern

Figure 1. Map outlining the location of the three main marine mineral deposits, including polymetallic nodules (blue), cobalt-rich ferromanganese crusts (yellow), and seafloor massive sulfides (orange). Modified from References 4 and 5.

Seafloor massive sulfides (SMS) represent the third and last discovered type of deep-sea mineral deposits. SMS deposits are areas of hard substratum with high base metal and sulfide content that form through hydrothermal circulation and are commonly found at hydrothermal vent sites (orange areas in Figure 1). Deep-sea vents are primarily concentrated along Earth's mid-ocean ridges and, to a lesser degree, island arc systems. Areas of potential polymetallic sulfide deposits are estimated to cover about 3.2 million km^2 globally,[7] and about 42% of the known sulfide deposits are in Exclusive Economic Zones.[5]

The composition of hydrothermal sulfide deposits varies widely depending on the geologic context and the nature of the substrate affected by hydrothermal circulation. The major minerals forming seafloor massive sulfide deposits are rich in iron, copper, and zinc as well as in gold and silver. The rare earth elements bismuth, cadmium, gallium, germanium, antimony, tellurium, thallium, and indium, which are essential for the high-tech industry, can significantly enrich some deposits.

Mining technology

All proposed seabed mining operations are based on a broadly similar concept of using a seabed collector, a vertical riser system, and support vessels involved in the processing and transporting of ore. Most proposed seabed collection systems envisage the use of remotely operated vehicles, which would extract deposits from the seabed directly using mechanical and/or pressurized water drills. The material is then transferred to a surface support vessel, where the material will undergo processing directly onboard the ship. Wastewater and sediment are returned to the ocean and the ore will eventually be transported to shore where it will be further processed.

Compared to land mining operations, there is less overburden to remove (that is, the materials that need to be eliminated to gain access to the ore of interest), and no permanent mining infrastructures are required. Indeed, marine-based mine sites do not require roads, buildings, water/power transport systems, or waste dumps that typically characterize terrestrial mines.

Further important drivers of deep-sea mining include the fact that many of the mineral deposits present at a single marine mining site contain multiple metals of interest. Thus, compared to terrestrial mining, less ore may be required to provide a given amount of metal.

In addition, acid mine drainage and stream/soil contamination will be avoided by deep-sea mining as will many other issues typically faced by terrestrial mining, such as displacement and exploitation of local populations, deforestation, and large-scale depletion of (ground) water resources.

Environmental impacts of deep-sea mining

The seabed covers 70% of Earth's surface and is home to some of the most pristine and diverse ecosystems on our planet. The ocean floor, at an average depth of 4,000 m, is characterized by high pressure, temperatures close to freezing, and no sunlight available to sustain photosynthetic productivity.

For humans, this environment is inhabitable, barely accessible, and extreme. Yet the relatively stable environmental conditions have allowed a vast diversity of taxa that are not found in shallower waters to thrive. The deep-sea ecosystems provide a broad range of critical ecosystem services, such as fish and shellfish for food, products that can be used for pharmaceuticals, climate regulation, and cultural/social value for humankind.[9]

However, these ecosystems remain poorly understood.[8] It is anticipated that mining activities on the seafloor will generate harmful, potentially irreparable environmental impacts.[5,9–14] These impacts can be divided into five categories (Table 1):[15] (1) direct removal of the resources and destruction of seafloor habitat and organisms, (2) generation of sediment plumes, (3) chemical release, (4) increase in noise, temperature, and light emissions, and (5) cumulative impacts including possible conflicts.

The recovery of deep-sea ecosystems from mining disturbances is expected to be slow, as revealed by a small-scale in-situ experiment called the "DISturbance and reCOLonization" (DISCOL) experiment.[16,17] DISCOL, which aimed to investigate the decadal-scale environmental impacts generated by deep-sea mining, began in 1989 in the Peru Basin nodule field. After 26 years, the impacts of mining are still evident in the mega benthos of the Peru Basin, with significantly reduced suspension-feeder occurrence and diversity in disturbed areas, and markedly distinct faunal assemblages. Local microbial activity was also reduced up to fourfold in the affected areas, and microbial cell numbers were reduced by about 30–50%.[17] However, it is yet unclear whether the results of the DISCOL experiment can be extrapolated.

Nevertheless, deep-sea mining disturbances are expected to be virtually irreversible because the targeted polymetallic deposits were formed over millennia and associated ecosystem dynamics may have evolved over similar timescales.[7] Moreover, deep-sea mining will compound with further anthropogenic stressors including climate change, bottom trawling, and pollution, further reducing the likelihood of recovery.

As mined deep-sea habitats are unlikely to recover naturally, habitat restoration may provide an alternative. However, the costs of habitat restoration could be exorbitant and possibly still be inadequate to prevent large-scale species extinctions. Additionally, the recolonization of abyssal communities is very slow, making it difficult to monitor the effectiveness of restoration approaches.

Understanding the long-term impact of mining on deep-sea biological communities is challenging due to the lack of continuous long-term baseline timeseries.[18] Data collection in the deep sea is often lacunar, making it impossible to know what happened between sampling campaigns. To address this lack of data, there is a need for intensified, high-resolution observation systems of deep-sea ecosystems and appropriately resolved timeseries.

Key knowledge gaps

The scientific knowledge gaps that need to be closed to inform decision-making related to seabed mining can be subdivided into two main categories: (1) a paucity of environmental baseline data and insufficient detail of the min-

Pressure	Potential impact	Affected ecosystem services	Habitat
Extraction of sea floor substrate	–Loss of benthic fauna by direct removal –Changes in sediment composition –Habitat loss or degradation –Stress induced on fauna	**Supporting** –Nutrient cycling –Circulation –Chemosynthetic production –Secondary production –Biodiversity	–Benthopelagic –Benthic
Extraction plume	–Loss of or damage to benthic species by smothering of organisms (from macrofauna to microorganisms) –Behavioral changes in animals –Changes in sediment composition –Changes in seabed morphology	**Regulating** –Carbon sequestration –Biological regulation –Nutrient regeneration –Biological habitat formation –Bioremediation and detoxification	–Benthopelagic –Benthic
Dewatering plume	–Clogging of feeding, sensorial, or breathing structure –Mechanical damage to tissues –Stress	**Provisioning** –CO_2 storage –Fisheries –Natural products	–Pelagic –Benthopelagic –Benthic
Release of substances from sediments (extraction and dewatering plume)	–Toxicity –Nutrient release –Turbidity		–Pelagic –Benthopelagic –Benthic
Underwater noise	–Disturbance of animals		–Pelagic –Benthopelagic –Benthic
Underwater light	–Disturbance of animals		–Pelagic –Benthopelagic –Benthic

Credit: Frölicher and Jaccard, University of Bern

Table 1. Seabed mining pressures, potential impacts on different habitats and ecosystem services that might be affected. Modified from Chapter 18 of the World Ocean Assessment Report II.[15]

ing operation; and (2) a general lack of comprehensive knowledge related to the cumulative (in)direct environmental impacts caused by deep-sea mining and insufficient risk assessment.

Evaluating the effects likely to arise from mining operations by means of environmental impact assessments (EIAs) is essential in ensuring that environmental considerations are considered in decision-making. The purpose of EIAs is to consider the environmental impact prior to deciding on whether to proceed with a proposed development.

Even though EIAs are a widely used and accepted approach, the processes underpinning EIAs for deep-sea mining are not yet fully developed. Therefore, there is considerable debate pertaining to the effectiveness of EAIs in the context of deep-sea mining.[19]

Further information on baseline data from potential mining sites, and improved understanding of deep-sea ecosystem structures and functions, as well as the recovery of deep-sea biomes following environmental degradation is essential for developing robust EIAs. Closing these scientific gaps related to deep-sea mining is critical to fulfilling the overarching obligation to prevent serious harm and ensure effective protection.

Given that deep-sea scientific research is challenging as well as time and resource-intensive, closing these gaps is likely to require substantial time and a capacity-intensive, coordinated scientific effort.

Recommendation

The importance of the deep sea as a habitat cannot be overstated, as it supports a substantial portion of Earth's biodiversity, much of which remains to be unraveled. The deep sea plays a critical role in Earth's climate regulation, fisheries production, and is an integral part of the common heritage of mankind. Yet, deep-sea ecosystems are under increasing stress from climate change, bottom trawling, and pollution. Deep-sea mining activities will only exacerbate these anthropogenic stressors, leading to potentially irreversible environmental consequences, including loss of biodiversity and ecosystem functioning/connectivity and habitat degradation. Furthermore, deep-sea mining activities may engender potentially deleterious consequences on carbon sequestration dynamics and deep-sea carbon sequestration.

Insufficient scientific knowledge pertaining to deep-sea ecosystems as well as the services they provide combined with a paucity of standardized, effective environmental impact assessments make it difficult to fully appreciate the risks deep-sea mining poses to biodiversity and human well-being. Nevertheless, the anticipated long-lasting environmental impacts of deep-sea mining are incompatible with (inter)national policy agendas, which aim to minimize biodiversity loss.

Given the critical importance of the ocean to our planet and its inhabitants and the potential for irreversible loss of biodiversity and ecosystem functions, a precautionary approach must be adopted to minimize the deleterious environmental consequences of deep-sea mining. Despite an increase in deep-sea research, the publicly available scientific knowledge is insufficient to enable evidence-based decision-making to effectively manage deep-sea mining activities. The absence of a robust regulatory framework and yet undefined enforcement procedures is a serious concern and calls for a precautionary approach.[8]

In the current context, we recommend that commercial deep-sea mining exploitation of mineral resources be precautionarily paused until sufficient and reliable scientific knowledge is obtained to ascertain that the environmental impacts of mining activities on marine and benthic ecosystems are minimized and strict, enforceable regulations are put into place.

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