The state of knowledge on the environmental impacts of deep-sea mining

Prof. Dr. Thomas Frölicher[1,2] *& Prof. Dr. Samuel Jaccard*[2,3]

[1]Climate and Environmental Physics, Physics Institute, University of Bern, Bern, Switzerland
[2]Oeschger Centre for Climate Change Research, University of Bern, Bern, Switzerland
[3]Institute of Earth Sciences, University of Lausanne, Lausanne, Switzerland

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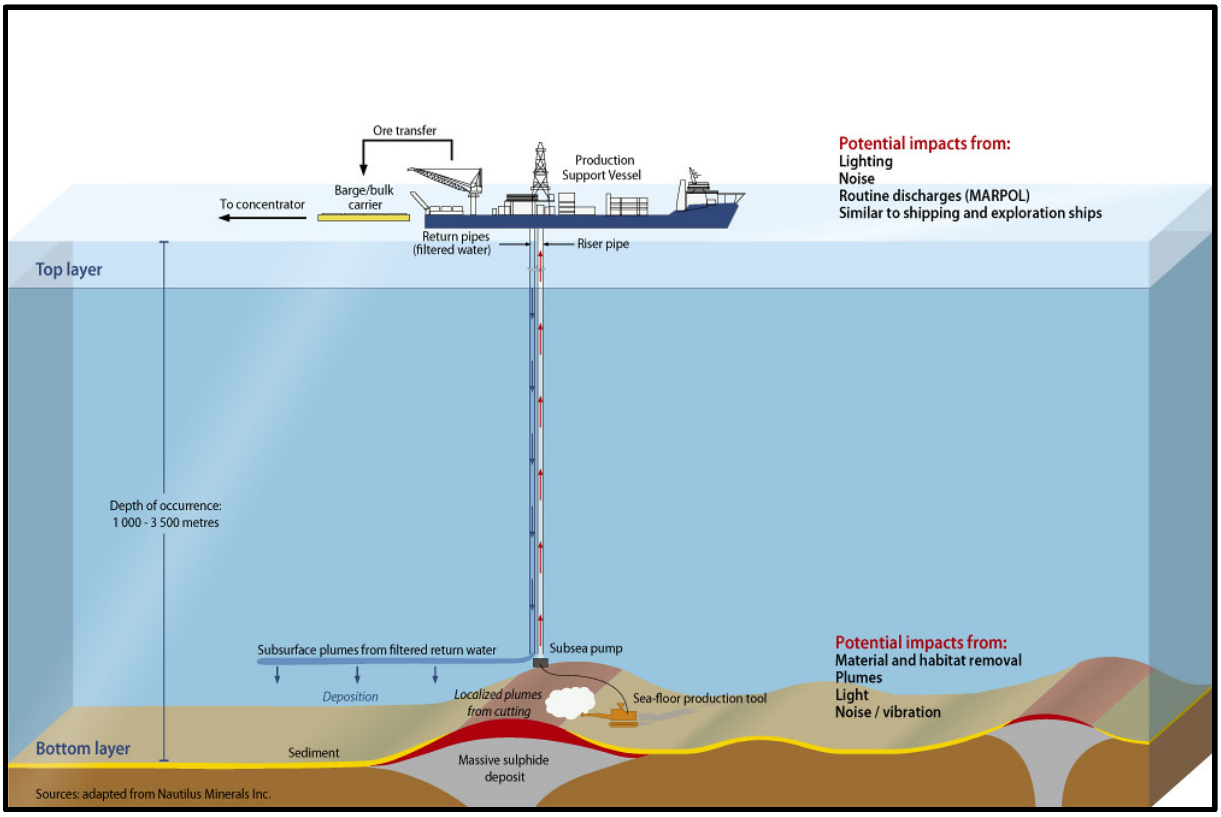

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1. Executive Summary

Deep-sea mining relates to the process of retrieving mineral resources from the deep seabed, several hundred to thousand meters below the sea surface. With the increasing demand for critical metals to sustain the energy transition as well as their growing demand steered by the green technology sector, interest in mining deep-sea mineral resources such as polymetallic nodules, cobalt-rich crusts, and seafloor massive sulfides has been growing recently. Although research and development have made continuous progress, many critical obstacles still hamper industrial-scale implementation of deep-sea mining activities, including the issue of environmental degradation. Indeed, the lack of thorough quantitative impact assessments and environmental baseline research has prevented the International Seabed Authority (ISA) from issuing exploitation permits to mine the deep sea.

The deep sea is home to some of the Earth's most pristine and diverse ecosystems, including vulnerable marine habitats hosting a variety of yet unknown organisms. Limited scientific evidence suggests that deep-sea mining activities may impose deleterious and potentially irreversible consequences on marine and benthic ecosystems and lead to habitat destruction. Moreover, the industrial removal of mineral deposits will inherently lead to environmental damage owing to the generation of sediment plumes that are enriched in harmful, bioavailable metals, with the potential to exacerbate environmental stressors associated with climate change, unsustainable fishing practices and pollution.

To ensure the perennial protection of the fragile marine environment, we recommend adopting a precautionary approach that complies with ISA's obligations to prevent ‘serious harm’ and ensure the ‘effective protection of the marine environment from harmful effects that arise from mining’. Deep-sea mining activities should be suspended until these specified obligations are met. Comprehensive environmental studies are critically needed to improve the understanding of the functional diversity and interconnections of deep-sea ecosystems, their resilience to anthropogenic activities and the vital services they provide. Additionally, alternative approaches to manage existing mineral reserves and resources on land need to be further developed to reduce incentives for seabed mining.

1. Zusammenfassung

Tiefseebergbau ist der Prozess zur Gewinnung von Bodenschätzen aus der Tiefsee, die sich mehrere Hundert bis Tausend Meter unter der Meeresoberfläche befinden. Angesichts des steigenden Bedarfs an kritischen Metallen für die Energiewende und der zunehmenden Nachfrage aus dem Sektor der grünen Technologien ist das Interesse an der Gewinnung von Bodenschätzen aus der Tiefsee, wie zum Beispiel von polymetallischen Knollen, kobaltreichen Krusten und Massivsulfiden am Meeresboden, in letzter Zeit stark gestiegen. Obwohl Forschung und Entwicklung kontinuierliche Fortschritte erzielt haben, stehen der industriellen Umsetzung des Tiefseebergbaus noch viele kritische Hindernisse im Weg, darunter auch das Problem der Umweltzerstörung. So hat das Fehlen gründlicher quantitativer Folgenabschätzungen und Umweltuntersuchungen die Internationale Meeresbodenbehörde (ISA) daran gehindert, Genehmigungen für den Abbau in der Tiefsee zu erteilen.

Die Tiefsee beherbergt einige der ursprünglichsten und vielfältigsten Ökosysteme der Erde, darunter auch empfindliche Meeresökosysteme, die eine große Vielfalt noch unbekannter Organismen beherbergen. Begrenzte wissenschaftliche Erkenntnisse deuten darauf hin, dass der Abbau von Metallen in der Tiefsee schädliche und potenziell irreversible Auswirkungen auf marine und benthische Ökosysteme haben und zur Zerstörung von Lebensräumen führen kann. Darüber hinaus wird der industrielle Abbau von Mineralvorkommen aufgrund der Entstehung von sedimentbedingten Trübungswolken, die mit bioverfügbaren Metallen angereichert sind, zwangsläufig zu Umweltschäden führen und das Potenzial haben, Umweltstressfaktoren im Zusammenhang mit dem Klimawandel, nicht nachhaltigen Fischereipraktiken und Verschmutzung zu verstärken.

Um den dauerhaften Schutz der empfindlichen Meeresumwelt zu gewährleisten, empfehlen wir einen vorsorglichen Ansatz, der den Verpflichtungen der ISA zur Verhinderung ‘ernster Schäden’ und zum ‘wirksamen Schutz der Meeresumwelt vor schädlichen Auswirkungen des Bergbaus’ entspricht. Der Tiefseebergbau sollte so lange ausgesetzt werden, bis die genannten Verpflichtungen erfüllt sind. Umfassende Umweltstudien sind dringend erforderlich, um die funktionelle Vielfalt und die Zusammenhänge der Tiefsee-Ökosysteme, ihre Widerstandsfähigkeit gegenüber anthropogenen Aktivitäten und die lebenswichtigen Dienste, die sie leisten, besser zu verstehen. Darüber hinaus müssen alternative Ansätze für die Bewirtschaftung bestehender Mineralvorkommen und Ressourcen an Land weiterentwickelt werden, um Anreize für den Abbau auf dem Meeresboden zu verringern.

1. Résumé exécutif

L'exploitation minière en eaux profondes consiste à extraire des ressources minérales des fonds marins situés à plusieurs centaines de mètres sous la surface de la mer. Compte tenu de la demande croissante de métaux critiques pour soutenir la transition énergétique et de la demande croissante de ces métaux dans le secteur des technologies vertes, l'intérêt pour l'exploitation des ressources minérales en eaux profondes, telles que les nodules polymétalliques, les encroûtements riches en cobalt et les sulfures massifs, s'est récemment accru. Bien que la recherche et le développement aient fait des progrès constants, de nombreux obstacles entravent encore la mise en œuvre à l'échelle industrielle des activités d'exploitation minière en eaux profondes, notamment la question de l'impact environnemental. En effet, l'absence d'évaluations quantitatives des impacts environnementaux et de recherche fondamentale ayant trait aux environnements pélagiques a empêché l'Autorité internationale des fonds marins (AIFM) de délivrer des permis d'exploitation minière en eaux profondes.

Les grands fonds marins abritent certains des écosystèmes les plus intacts et les plus diversifiés de la planète, notamment des écosystèmes marins vulnérables abritant une grande variété d'organismes encore méconnus. Des observations scientifiques limitées suggèrent que les activités d'exploitation minière en eaux profondes peuvent avoir des conséquences délétères et potentiellement irréversibles sur les écosystèmes marins et benthiques et entraîner la destruction d'habitats. En outre, l'extraction industrielle de gisements de minéraux entraînera par nature des dommages environnementaux en raison de la production de panaches de sédiments enrichis en métaux biodisponibles, ce qui pourrait exacerber les facteurs de stress environnementaux associés au changement climatique, aux pratiques de pêche non durables et à la pollution.

Pour assurer la protection pérenne du fragile environnement marin, nous recommandons l'adoption d'une approche de précaution conforme aux obligations de l'AIFM de prévenir les ‘dommages graves’ et d'assurer la ‘protection efficace du milieu marin contre les effets délétères de l'exploitation minière’. Les activités minières en eaux profondes devraient être suspendues jusqu'à ce que ces obligations spécifiques soient respectées. Des études environnementales complètes sont nécessaires pour améliorer la compréhension de la diversité fonctionnelle et des interconnexions des écosystèmes d'eaux profondes, de leur résilience aux activités anthropiques et des services vitaux qu'ils fournissent. En outre, il convient de développer des approches alternatives pour gérer les réserves et ressources minérales existantes afin de réduire les incitations à l'exploitation minière des fonds marins.

2. General context

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 (IPCC SR15; Masson-Delmotte et al., 2018). 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, non-renewable resources. The accelerated need for minerals to support the green transition (Wang et al. 2023) 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 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.

In ocean areas beyond national jurisdiction (i.e., beyond the Exclusive Economic Zone, EEZ), extraction of mineral resources in the deep sea is regulated by the International Seabed Authority (ISA), an autonomous intergovernmental organization established in 1994 by the UN Convention on the Law of the Sea (UNCLOS). ISA comprises 167 member States, including Switzerland as well as the European Union[1]. ISA has the mandate to prevent 'serious harm' and to ensure the 'effective protection of the marine environment from harmful effects that may arise from deep-seabed mining activities on behalf of humankind'. The seafloor below 200 m water depth is present - along with Antarctica - the only area on Earth where mineral resources are not yet extracted commercially (Sparenberg 2019).

To date, the ISA has established a regulatory framework for exploration activities relating to the three main types of mineral deposits (see section 3 for details), namely polymetallic nodules in the year 2000, polymetallic sulfides in 2010, and cobalt-rich crusts in 2012. As of today, the ISA has approved 31 contracts to explore deep-sea mineral deposits[2], covering more than 1.3 million km^2 of the international seabed (i.e., approximately 31 times the area of Switzerland). Contracts are granted to states, consortia of states and state-owned or private companies. To date, the ISA has yet to issue exploration contracts, but the authority is currently developing a regulatory framework to govern the transition to exploitation (the so-called 'mining code'). A range of mining operations is, however, already active within the 200-mile EEZ, including Papua New Guinea, the Red Sea, New Zealand and Solomon Islands (Miller et al. 2018).

In 2021, the Government of the Republic of Nauru issued a treaty provision known as the 'two-year rule' that obliges ISA to finalize and adopt regulations for deep seabed mining within 24 months so that commercial enterprises can begin extracting mineral resources from the seabed. The deadline expires in July 2023. If the ISA council fails to adopt appropriate regulations within this timeframe, ISA may accept applications for exploitation even in the absence of formal guidelines. Besides the economic benefits arising from deep-sea mining, the Republic of Nauru claims that deep-sea resource extraction is an integral part of the

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[1] Status March 24.2.2023; https://www.isa.org.jm

[2] https://www.isa.org.jm/index.php/exploration-contracts

solutions underpinning the global transition away from fossil fuels and towards renewable energy production[3].

2.1 National context

Switzerland has so far adopted an ambivalent position on deep-sea mining. In June 2021, Green Party National Councilor Nicolas Walder (GE) submitted an interpellation to the National Council to clarify the Federal Council's position on deep-sea mining with the prospect of requesting a moratorium on deep-sea mineral exploitation[4]. Walder argued that recent research indicates that the commercial exploitation of the seabed under the regulations of the ISA may not adequately protect marine and benthic ecosystems. The Federal Council noted that it will examine these new findings and is currently reviewing the possibility to call for a moratorium at the international level.

2.2 International context

In 2022, the EU published its agenda on International Ocean Governance, announcing its intention to proscribe deep-sea mining as long as the scientific understanding about the consequences of deep-sea mining on marine and benthic ecosystems has not been improved sufficiently to safely issue exploitation licenses. Chile, Costa Rica, Ecuador, Spain, Germany, Panama and Vanuatu have advocated for a precautionary pause in deep-sea mining, while France recently voted to ban deep-sea mining within its jurisdiction. In addition, a petition[5] has been signed by more than 700 international scientists and policy experts urging a ban on deep-sea mining until adequate and reliable scientific knowledge has been gathered. In a related development, BMW, Google, Samsung, and Volvo (among others) signed a call from the World Wildlife Fund (WWF) in support of a provisional ban on deep-sea mining. The companies have pledged to refrain from utilizing deep-sea minerals, which are not currently available for commercial use, in their products, supply chains, and financial operations. However, there are also concerns that a moratorium will prevent outlining specific research initiatives to thoroughly evaluate the impact deep-sea mining bears on marine ecosystems and that research efforts could plummet if a moratorium were indeed enacted[6].

In the following, we provide a brief overview of deep-sea mining and describe the different types of deep-sea mineral deposits and currently developed mining technologies (section 3). In addition, we assess the current understanding of the impacts deep-sea mining imposes on marine and benthic ecosystems (section 4).

3. What is deep-sea mining?

3.1 A short introduction to 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

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[3] http://naurugov.nr/government/departments/department-of-foreign-affairs-and-trade/faqs-on-2-year-notice.aspx

[4] https://www.parlament.ch/de/ratsbetrieb/suche-curia-vista/geschaeft?AffairId=20213633

[5] https://www.seabedminingsciencestatement.org

[6] https://eos.org/features/the-2-year-countdown-to-deep-sea-mining

century (Hein et al. 2020). 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 (Ni), Copper (Cu), and Manganese (Mn) for **nodules**, Cobalt (Co), Nickel (Ni), and Manganese (Mn) for **crusts,** and Copper (Cu), Zinc (Zn), Gold (Au), and Silver (Ag) for **seafloor massive sulfides** (SMS). Research undertaken in the last decades has revealed that additional metals, including rare earth elements (REEs; Table 1) such as Lanthanum (La), Cerium (Ce), Praseodymium (Pr), Neodymium (Ne), Europium (Eu), Gadolinium (Gd) and Yttrium (Y) are potential byproducts of mining of the other, more traditional, target metals. The metals enriched in these marine deposits are essential for a variety of high-tech, green-tech applications and play a crucial role in the energy transition (Table 1).

Resource	Symbol	Uses
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.
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.
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.
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.
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.
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.
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.
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.

Table 1: A summary of the uses of major resources found on the seabed. Table modified from Miller et al. (2018).

3.2 Types of deposits

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 (for details see (Hein et al. 2020) .

3.2.1. 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 Fig. 1). They cover about 38 million km^2 at water depths ranging between 3’500 – 6’500 m, notably in the 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 (Miller et al. 2018). 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 Ni and Cu 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 Mn.

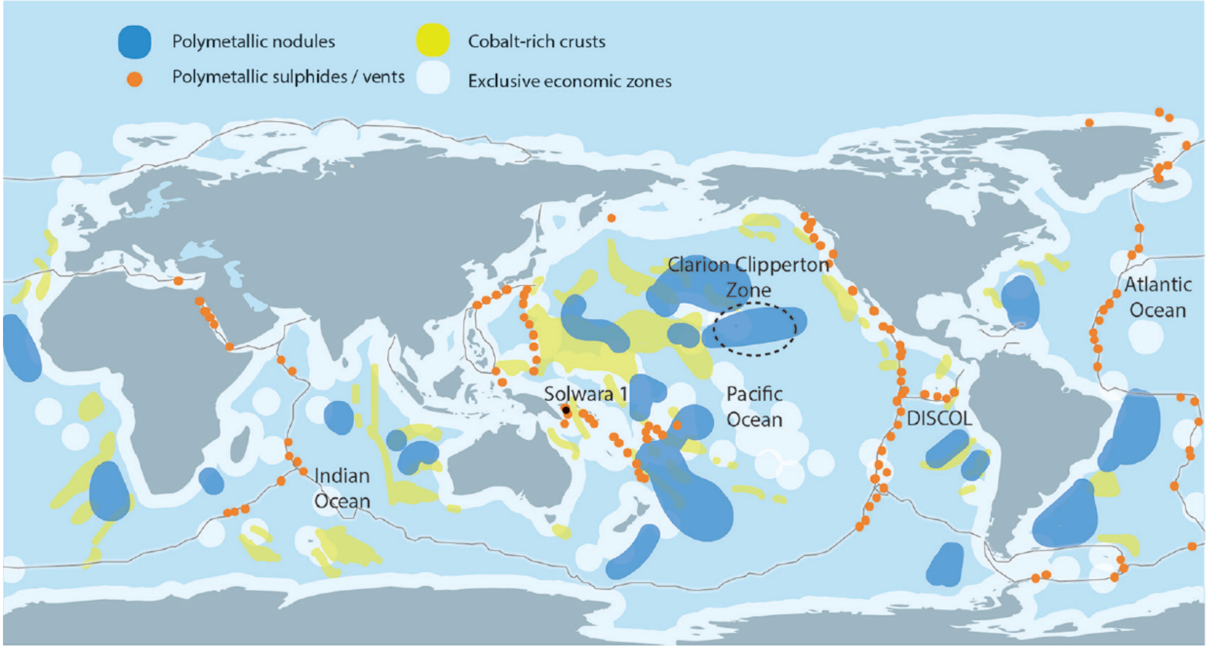

Fig. 1 Map outlining the location of the three main marine mineral deposits, including polymetallic nodules (blue), Co-rich ferromanganese crusts (yellow), and seafloor massive sulfides (orange). Figure modified from (Hein et al. 2013; Miller et al. 2018).

Polymetallic nodules often occur as potato-shaped concretions that vary in size from tiny particles to pellets larger than 20 cm (Fig. 2) 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 Ni and Cu. 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.

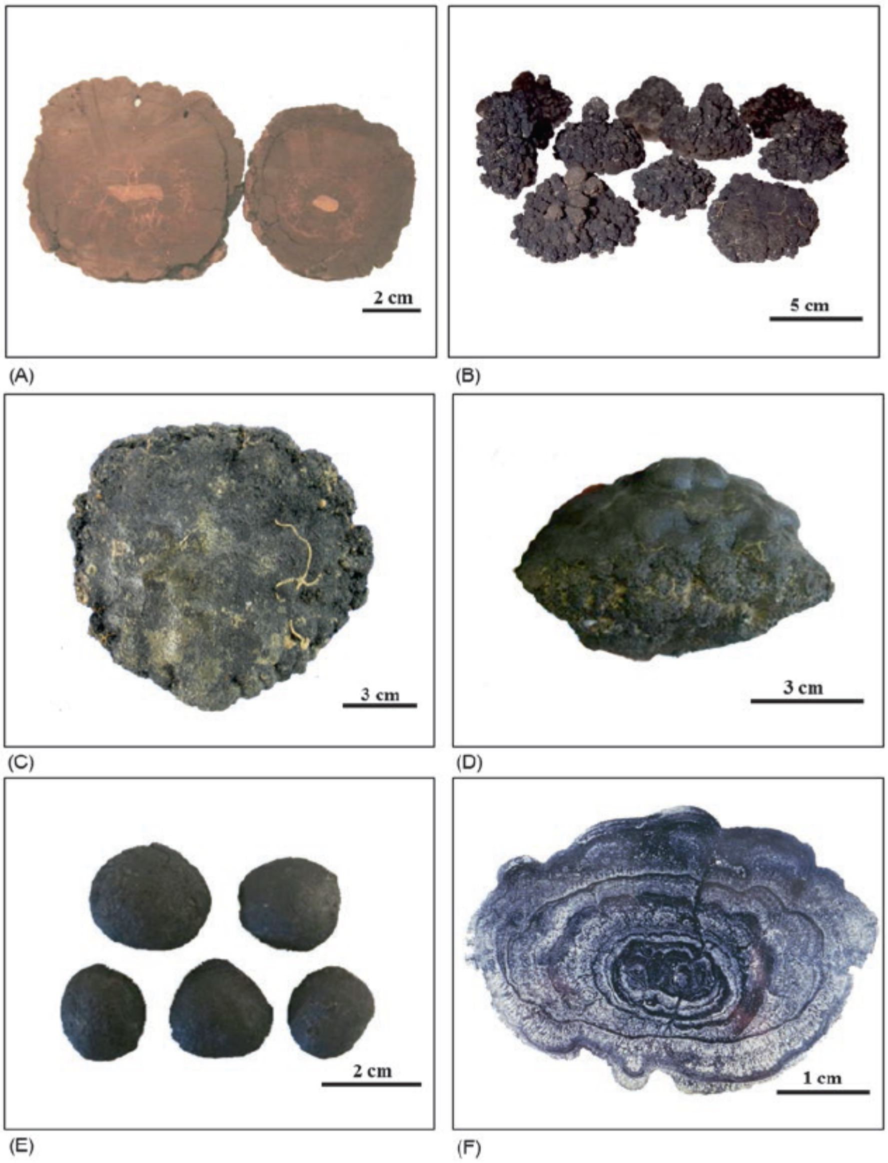

Fig. 2. Different sizes and shapes of Fe-Mn nodules. Figure modified from (Kuhn et al. 2017).

Polymetallic nodules are composed of Fe and Mn oxides that form concentrically around a nucleus (Fig. 2) by two main processes, *hydrogenetic* and *diagenetic* precipitation (Kuhn et al., 2017). Hydrogenetic precipitation is driven by the oxidation of dissolved Mn and Fe in seawater and the subsequent precipitation of Mn and Fe oxides. Diagenetic precipitation occurs within the pore space of deep-sea sediments. Oxidation (respiration) of organic matter leads to the removal of dissolved oxygen in sediments, resulting in the reduction and dissolution of Mn oxides and the release of associated elements, notably Ni and Cu. These metals diffuse upwards and in contact with oxygenated seawater are re-oxidized leading to the precipitation of thin layers of Mn-rich oxides. Ocean-floor nodules only represent the most recent generation of polymetallic nodules, and older generations of nodules are also present below the sediment surface.

The growth rate of hydrogenetic layers is typically in the range of 1 – 5 mm per million years (Myr), whereas diagenetic layers generally grow faster. 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.

3.2.2. 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 (Halbach et al. 2017). Co and Ni concentrations significantly decrease with increasing water depth. Cobalt-rich crust deposits are found throughout the global ocean (yellow areas in Fig. 1). They occupy 1.7 million km^2 and 54 % of the known crusts are in EEZs (Miller et al. 2018). 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 < 1 – 250 mm (Fig. 3) and are generally thicker on older seamounts.

Fig. 3. Co-rich ferromanganese crust covering volcanic substrate rocks. The thickness of the crust is about 80 mm. Sample collected from a seamount in the Central Pacific Basin. Picture modified from (Halbach et al. 2017).

Seamounts and ridges have characteristics that favor the development of Fe–Mn crusts. For example, local upwelling along the flanks of seamounts creates turbulent mixing that helps keep seamounts sediment free. Furthermore, upwelling supplies life-essential nutrients to surface waters, fueling biological productivity. Organic matter sinks from the ocean surface and oxidizes in the water column creating reduced, oxygen-depleted environments, which act as a reservoir for dissolved Mn and associated metals. Hydrogenetic accretion of Fe–Mn crusts is controlled by the precipitation of colloids of hydrated Mn and Fe oxides, which acquire trace metals by surface sorption processes. Growth rates are very slow and vary between 1 – 10 mm/Myr. Crust growth may be interrupted for millions of years if conditions are unfavorable for hydrogenic accretion. It can thus take up to several tens of millions of years to form thick crusts.

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.

3.2.3. 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.

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 Fig. 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 (Levin et al. 2020b), and about 42 % of the known sulfide deposits are in EEZs (Miller et al. 2018). Hydrothermal (or deep-sea) vents are the result of seawater percolating through fractures in the ocean crust in the vicinity of magmatic spreading centers. Cold seawater is heated by a magmatic source in the sub-seafloor and remerges to form the vents along a convective circulation scheme at temperatures exceeding 300 °C (Cherkashov 2017). While circulating in the ocean crust, hot, acidic fluids dissolve (lixiviate) and incorporate metals contained in the substrate. When the heated mineralized fluids, which were circulated back to the seafloor, interact with cold seawater, minerals precipitate out to form chimney-like structures - referred to as smokers (Fig. 4) – with chimney collapse forming sulfide mounds on the seafloor. Thus, for the formation of hydrothermal systems, a combination of two factors, magmatic and tectonic (which fracture the ocean crust to allow for fluid circulation) is required. There is a clear correlation between the occurrence of hydrothermal vents and spreading rates, which determine the intensity of magmatic processes, with slow- to ultraslow ridges (< 4.0 cm/year) hosting comparatively more enriched mineral resources, owing to more stable and concentrated hydrothermal activity.

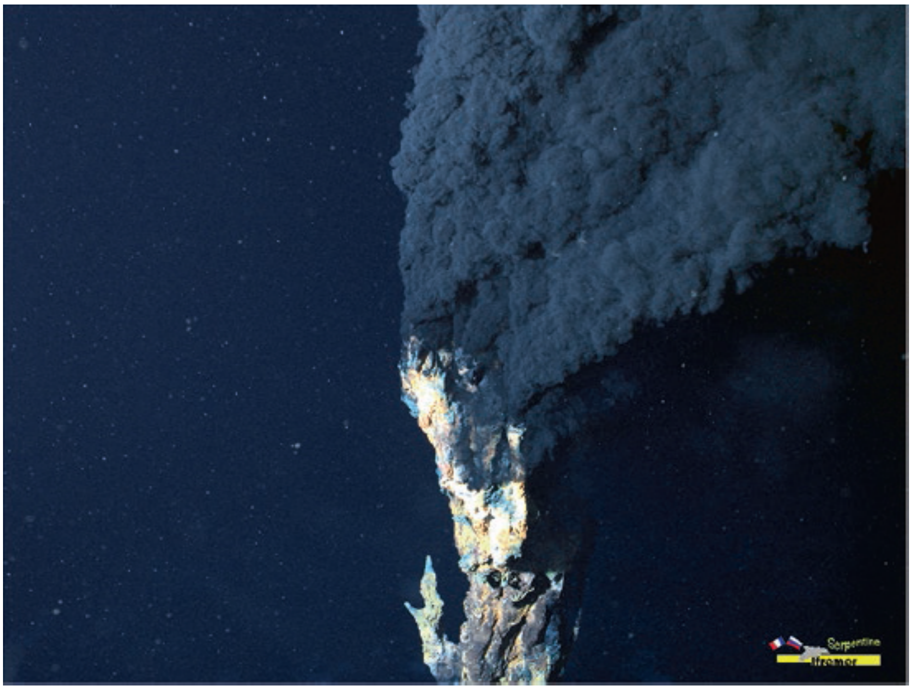

Fig. 4. Black smoker at the Ashadze-1 hydrothermal field (Mid-Atlantic Ridge). Picture modified from (Cherkashov 2017).

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 Fe, Cu, and Zn as well as in Au and Ag. The rare elements, Bismuth (Bi), Cadmium (Cd), Gallium (Ga), Germanium (Ge), Antimony (Sb), Tellurium (Te), Thallium (Tl), and Indium (In), which are essential for the high-tech industry can significantly enrich some deposits (Table 1).

3.3 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 (Fig. 5). 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 (that is the materials that need to be eliminated to gain access to the ore of interest) to remove, 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.

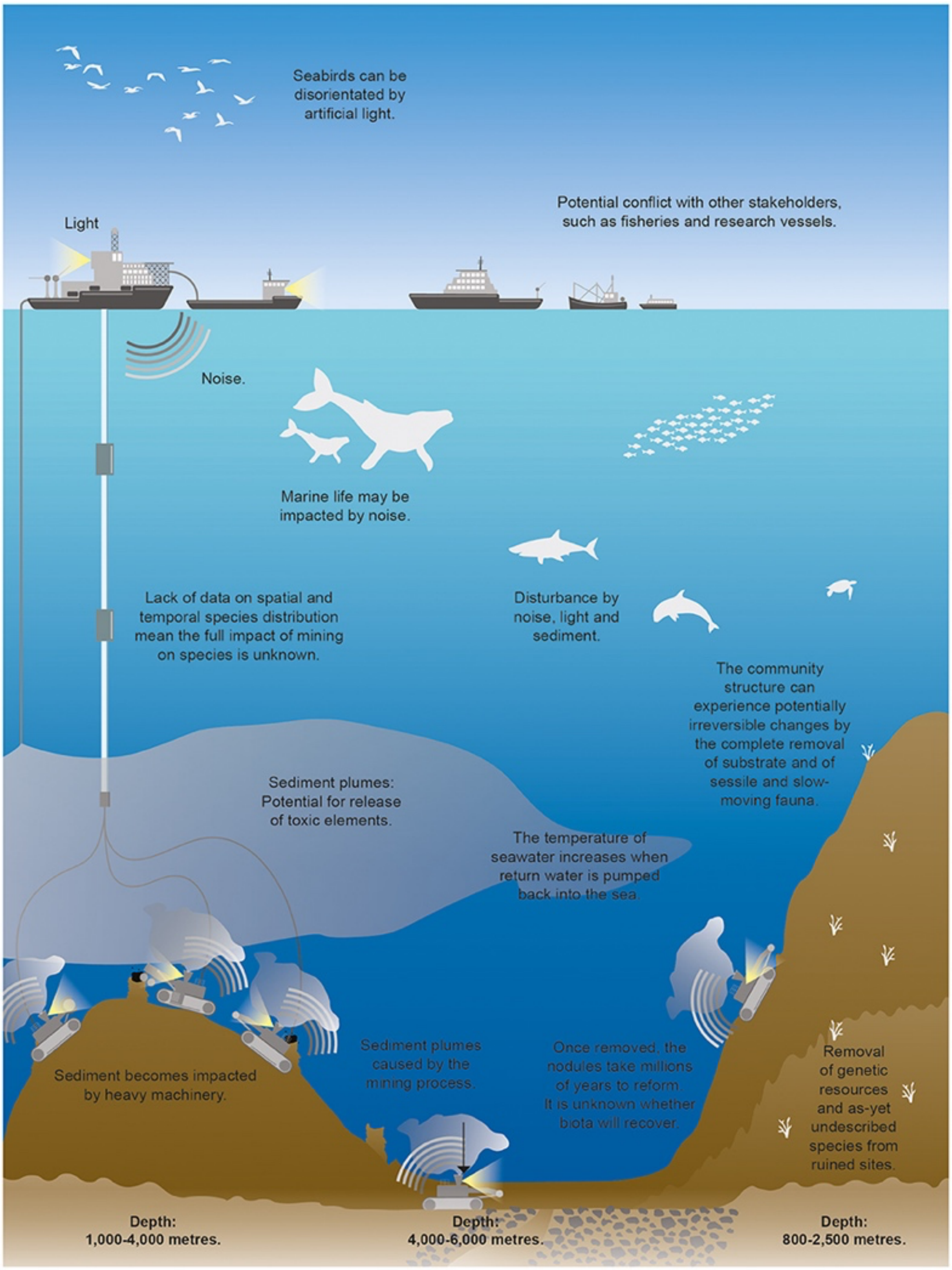

Fig. 5: A schematic showing the potential impacts of deep-sea mining on marine ecosystems. Figure modified from (Miller et al. 2018).

4. 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 strive (see Fig. 6 for some examples). 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 (Boetius and Haeckel 2018). However, these ecosystems remain poorly understood (Amon et al. 2022). It is anticipated that mining activities on the seafloor will generate harmful, potentially irreparable environmental impacts (Levin et al. 2016; Boetius and Haeckel 2018; Gollner et al. 2017; Kaikkonen et al. 2018; Van Dover 2014; Vanreusel et al. 2016; Miller et al. 2018). These impacts can be divided into five categories (Fig. 5; Table 2): (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.

Fig. 6: Deep-sea animals collected from the abyssal ocean floor in the Clarion-Clipperton Zone. Clockwise from the top left: A sea cucumber known as the ‘gummy squirrel’, a sea urchin, and two sea cucumbers. Figure taken from (Heffernan 2019).

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 **Regulating** – Carbon sequestration – Biological regulation – Nutrient regeneration – Biological habitat formation – Bioremediation and detoxification **Provisioning** – CO_2 storage – Fisheries – Natural products	– Benthopelagic – Benthic
Extraction plume	– Loss of or damage to benthic species by smothering of organisms (from macrofauna to microorganisms) – Behavioural changes in animals – Changes in sediment composition – Changes in seabed morphology		– Benthopelagic – Benthic
Dewatering plume	– Clogging of feeding, sensorial or breathing structure – Mechanical damage to tissues – Stress		– 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

Table 2: Seabed mining pressures, potential impacts on different habitats and ecosystem services that might be affected. Table modified from Chapter 18 of the World Ocean Assessment Report II[7].

4.1 Resource removal

It is expected that mining all three types of deposits outlined in section 3.2, will result in decreased habitat availability for sessile or partially sessile fauna and loss of biodiversity (Haffert et al. 2020; Miller et al. 2018; Niner et al. 2018; Vonnahme et al. 2020).

4.1.1 Removal of Fe-Mn (polymetallic) nodules from the abyssal seafloor

The removal of polymetallic nodules from the abyssal seafloor could lead to local species extinction and to a decline or loss in key ecosystem functions such as nutrient and carbon cycling (Simon-Lledó et al. 2019; Jones et al. 2017). It is also likely that the mining of nodules will cause serious harm to yet undescribed species, especially those with limited biogeographic distributions, thereby altering evolutionary potential, biodiversity, and ecosystem processes in the ocean's abyss.

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[7] https://www.un.org/regularprocess/sites/www.un.org.regularprocess/files/2011859-e-woa-ii-vol-ii.pdf

The impacts of deep-sea mining are very likely irreversible on a human timescale. The fauna that relies on the nodules may not recover over thousands of years as the nodules grow very slowly. This inference is supported by recent studies in the CCZ and Peru Basin that show reduced faunal biodiversity and altered species composition and ecosystem function still prevalent two- to four decades after a small-scale nodule removal experiment (see section 5) (Vanreusel et al. 2016; Vonnahme et al. 2020). The remotely operated seabed collector vehicles will compress seafloor sediments, adversely affecting biota living within the sediments, benthic colonization, and other specialized processes.

4.1.2 Removal of cobalt-rich crusts or ferromanganese crusts from seamounts

Seamounts host a wide diversity of species and habitats, including deep-sea corals, sponges, and other slow-growing organisms. Because seamounts are often isolated, they host unique biogeography and elevated levels of biodiversity, which make them particularly vulnerable to deep-sea mining (Jones et al. 2018; Kvile et al. 2014; Rogers 2018). Removal of crusts from seamounts may result in the mortality of corals and sponges. Mobile animals, such as fish and crustaceans, may be able to disperse, but the overall biodiversity at mining sites will be reduced to very low levels (Levin et al. 2016).

4.1.3 Removal of massive (polymetallic) sulfides from hydrothermal vents

Hydrothermal vents are also unique ecosystems that support a range of unique and endemic species. The remarkable biodiversity of hydrothermal vent communities has led to their classification as vulnerable marine ecosystems by the Food and Agriculture Organization (FAO) of the United Nations. The removal of massive sulfides from hydrothermal vents can lead to habitat loss, which can result in a decline in biodiversity. The ore removal can also disrupt the functioning of the hydrothermal vent ecosystems. Sulfides are important for nutrient cycling, and their removal can lead to changes in the physical and chemical characteristics of the vent environment, which can negatively impact the survival of the organisms that live there. There is also concern that mining could lead to fluid flow disruptions at active vent sites and the reactivation of inactive vents, subsequently altering environmental conditions and species assemblages. In addition, habitats will likely be degraded by the seabed collector vehicles, reducing habitat heterogeneity to a minimum and modifying the substratum characteristics, as well as the geochemical and hydrodynamic regimes.

4.2 Sediment plumes

Another environmental concern of deep-sea mining relates to the generation of sediment plumes that can impact the surrounding ocean environment. Two types of plumes are associated with deep-sea mining: a deep-water plume generated by the vehicles collecting minerals on the seabed and a mid-water plume caused by vessels operating at the ocean surface that discharge the water used to clean the nodules and sediments brought up with the nodules (Muñoz-Royo et al. 2021). Models and small-scale experiments suggest that such sediment plumes can travel long distances and affect the water quality, which can bear negative impacts on organisms and ecosystems (Drazen et al. 2020; Levin et al. 2020b; Amon et al. 2022). The suspended sediments from plumes may smother organisms (clogging respiratory tracts) or impair the feeding organs of suspension feeders, which make up a sizable portion of the benthic fauna. This may be especially harmful in nodule provinces as these are dominated by low-sedimentation regimes, with very clear bottom waters. Depositions from plumes will dilute food sources and may change the seabed morphology, availability of labile organic matter and bury and smother nodule habitats and benthic biota.

The sediment plumes are expected to be harmful to the ecosystems at all three deposition sources. However, the spatial scale of impacts remains unclear without a better understanding of the depth and properties of the discharge and sediment tolerances of fauna (Hein et al. 2013).

4.3 Contamination of seafloor and water column, and toxicity to marine life

Deep-sea mining can result in the release of contaminants, such as bioavailable metals, on the seafloor and in the water column (Kaikkonen et al. 2018). These contaminants remain in the water column much longer than sediment particles, raising concerns that the discharge of bioavailable metals and toxins into the mesopelagic zone may contaminate seafood. The mining of sulfide deposits is expected to bear the greatest potential for metal toxicity due to the high oxidation potential of sulfide minerals. As the assessment of toxicity and its consequences on deep-sea organisms is challenging, the response of deep-sea fauna to toxin exposure is poorly understood. However, exposure to these contaminants is expected to lead to a range of deleterious impacts, including developmental abnormalities, reproductive failure, and increased mortality (Hauton et al. 2017).

4.4 Noise, light, and temperature

4.4.1 Increased noise

The mining vehicles at the seafloor and the support vessels at the sea surface will increase underwater ambient noise levels. At the surface, the noise will arise from boat propellers and onboard machinery. The mid-water column will be filled with sounds of riser systems moving sediment from the seafloor to the surface and the motors of robots used to monitor these activities. On the seabed itself, acoustic monitoring tools will generate additional sound and seabed mining will involve drilling, dredging, and scraping the seafloor. Many of these sounds will create noise as well as vibrations that could affect marine life in areas far beyond the actual mining sites. Most deep-sea species generally experience low levels of noise, such that anthropogenic noise, particularly if occurring continuously, will substantially increase ambient sound levels (Williams et al. 2022). Anthropogenic noise is known to impact several fish species and marine mammals by inducing behavior changes, affecting communication and causing threshold shifts in hearing (Gomez et al. 2016).

4.4.2 Increased light

Little to no sunlight penetrates deeper depths of the ocean. However, the deep sea is not completely dark. Low light in the deep sea has been shown to originate from bioluminescence and geothermal radiation. Continuous mining activity that employs floodlighting on seafloor mining vehicles would vastly increase light levels, which may have an impact on the behavior and survival of marine animals. For example, some species may be attracted to or repelled by light, which can affect their feeding and breeding patterns. In addition, nocturnal artificial lighting on surface vessels has been shown to disorientate seabirds leading to fallout. Sediment plumes will also absorb light and change backscatter properties, reducing visual communications and bioluminescent signaling that are essential for prey capture and reproduction for midwater animals.

4.4.3 Increased temperature

Drilling and vehicle operation as well as dewater waste that is returned to the deep sea is expected to release heat. Some studies suggest that waste material may be more than 10 °C warmer than the surrounding seawater. Very little is known however about the impact of such a temperature increase on deep-sea organisms. Given that the deep sea has a relatively stable temperature, it is anticipated that such temperature changes could affect the growth, metabolism, reproductive patterns, and survival of some deep-sea species.

4.5. Cumulative impacts and possible conflicts

Seabed mining activities have the potential to cause conflicts with fishing, shipping and the culture and well-being of local communities (Le et al. 2017). Legal disputes could arise if, for example, sediment plumes created by mining activities harm the marine environment of a coastal state or if it diffuses into another contractor's exploitation. Additionally, disputes could arise if surface exclusion zones around seabed mining operations reduce access to fishing grounds or affect shipping and navigational routes. For instance, mining exploration claims in the northern Mid-Atlantic Ridge overlap with areas managed by the Northeast Atlantic Fisheries Commission, leading to the potential displacement or concentration of fishing efforts, and resulting in reduced catch or depletion of local fisheries (Levin et al. 2020a,b).

In addition, ocean warming, acidification, deoxygenation, and changing particulate organic carbon flux (one metric of altered food supply) are projected to affect many deep-ocean ecosystems concomitantly with increasing human disturbance and can therefore affect the recovery and resilience of ecosystems (Levin et al. 2020a). However, these additional climate change-related stressors may differentially affect hydrothermal vents, seamounts, and abyssal systems depending on their locations and water depths (Cheung et al. 2022). Nevertheless, the protection of the marine environment must involve the understanding of climate change impacts in areas targeted by deep seabed mining.

5. Recolonization after deep-sea mining

The recovery of deep-sea ecosystems from mining disturbances is expected to be slow, as revealed by a small-scale in-situ experiment (Simon-Lledó et al. 2019; Vonnahme et al. 2020). The 'DISturbance and reCOLonization experiment' (DISCOL) has investigated the decadal-scale environmental impacts generated by deep-sea mining. DISCOL is a small-scale experiment carried out in 1989 in the Peru Basin nodule field to simulate deep-sea disturbance and recolonization. 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 % (Vonnahme et al. 2020). 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. This is because the targeted polymetallic deposits were formed over millennia and associated ecosystem dynamics may have evolved over similar timescales (Levin et al. 2020b). Moreover, deep-sea mining will compound with further anthropogenic stressors including climate change, bottom trawling, and pollution reducing the likelihood of recovery.

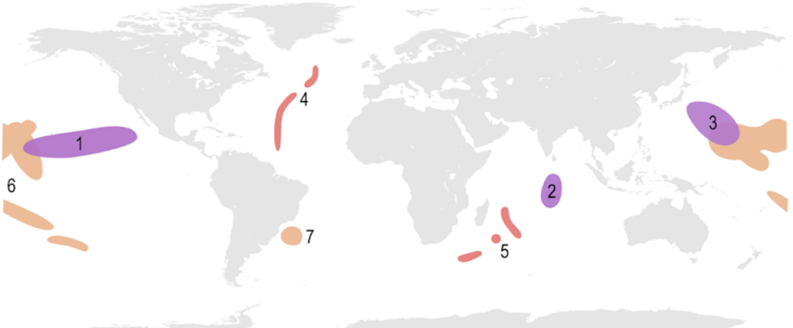
As mined deep-sea habitats are unlikely to recover naturally, habitat restoration may provide an alternative. However, the costs of habitat restoration could be exorbitant and possibly still be inadequate to prevent large-scale species extinctions. Additionally, the recolonization of abyssal communities 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 (Radziejewska et al. 2022). Data collection in the deep sea is often lacunar, making it impossible to know what happened between sampling campaigns. To address this, there is a need for intensified, high-resolution observation systems of deep-sea ecosystems and appropriately resolved timeseries.

6. Key knowledge gaps and alternative approaches

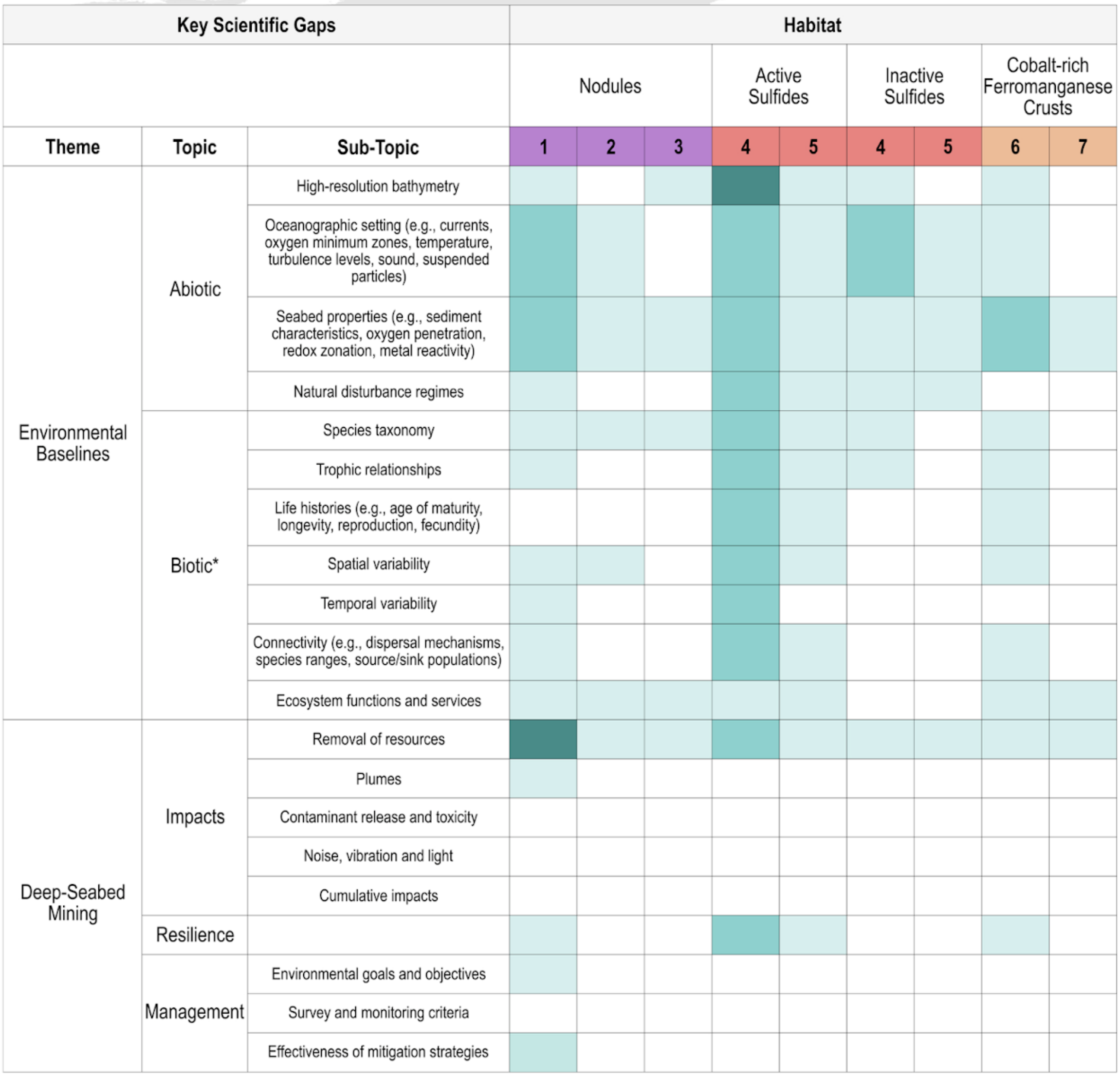
Deep-sea mining is an emerging industry that turns the deep ocean into a new industrial frontier. To evaluate whether deep-sea mining operations comply with ISA's obligation to prevent serious harm and ensure the effective protection of the marine environment from harmful effects, it is essential to expand the knowledge of deep-sea biomes and the environmental impacts of mining activities on marine and benthic habitats. Our synthesis of the publicly available, peer-reviewed literature reveals that despite an increase in deep-sea research (discussed in sections 4 and 5), the limited availability of comprehensive scientific information poses a challenge for evidence-based decision-making related to environmental management, including decisions on whether to proceed with commercial mining operations in areas where exploration contracts have been issued by the ISA.

The scientific knowledge gaps that need to be closed to inform decision-making related to seabed mining can be subdivided into two main categories (Table 3): (i) a paucity of environmental baseline data and insufficient detail of the mining operation; and (ii) a general lack of comprehensive knowledge related to the cumulative (in)direct environmental impacts caused by deep-sea mining and insufficient risk assessment.



Location
1. Clarion-Clipperton Zone
2. Central Indian Ocean Basin
3. West Pacific
4. Mid-Atlantic Ridge
5. Indian Ocean Ridges
6. West Pacific Prime Crust Zone
7. South Atlantic Rio Grande Rise

Knowledge
- ■ Scientific knowledge enables evidence-based management
- ▓ Few gaps in scientific knowledge for evidence-based management remain
- ░ Scientific knowledge gaps for evidence-based management dominate
- □ There is no or next to no scientific knowledge to enable evidence-based management



Key Scientific Gaps			Habitat								
			Nodules			Active Sulfides		Inactive Sulfides		Cobalt-rich Ferromanganese Crusts	
Theme	**Topic**	**Sub-Topic**	**1**	**2**	**3**	**4**	**5**	**4**	**5**	**6**	**7**
Environmental Baselines	Abiotic	High-resolution bathymetry	░	□	░	■	░	░	□	░	□
		Oceanographic setting (e.g., currents, oxygen minimum zones, temperature, turbulence levels, sound, suspended particles)	▓	░	□	▓	░	▓	░	░	□
		Seabed properties (e.g., sediment characteristics, oxygen penetration, redox zonation, metal reactivity)	▓	░	░	▓	░	░	░	▓	░
		Natural disturbance regimes	░	□	□	▓	░	░	░	□	□
	Biotic*	Species taxonomy	░	░	░	▓	░	░	□	░	□
		Trophic relationships	░	□	□	▓	░	░	□	░	□
		Life histories (e.g., age of maturity, longevity, reproduction, fecundity)	□	□	□	▓	░	□	□	░	□
		Spatial variability	░	░	□	▓	░	□	□	░	□
		Temporal variability	░	□	□	▓	□	□	□	□	□
		Connectivity (e.g., dispersal mechanisms, species ranges, source/sink populations)	░	□	□	▓	░	□	□	░	□
		Ecosystem functions and services	░	░	░	░	░	□	□	░	░
Deep-Seabed Mining	Impacts	Removal of resources	■	░	░	▓	░	░	░	░	░
		Plumes	░	□	□	□	□	□	□	□	□
		Contaminant release and toxicity	□	□	□	□	□	□	□	□	□
		Noise, vibration and light	□	□	□	□	□	□	□	□	□
		Cumulative impacts	□	□	□	□	□	□	□	□	□
	Resilience		░	□	□	▓	░	□	□	░	□
	Management	Environmental goals and objectives	░	□	□	□	□	□	□	□	□
		Survey and monitoring criteria	□	□	□	□	□	□	□	□	□
		Effectiveness of mitigation strategies	░	□	□	□	□	□	□	□	□

Table 3: Existing level of scientific knowledge concerning evidence-based environmental management of deep-seabed mining in regions where the ISA has granted exploration contracts. The information is based on a comprehensive synthesis of peer-reviewed literature and expert opinion. The table is taken from (Amon et al. 2022).

A key issue for any seabed mining project is the limited general knowledge of the deep-sea environment. Indeed, the environmental disturbances inherent to mid-water sediment plumes, pollution, altered noise and light levels, and cumulative impacts on deep-sea ecosystems are inadequately constrained. Even the most intensively explored deep-sea habitats, such as the active Mid-Atlantic Ridge hydrothermal systems (referred to as ‘Active sulfides’ in Table 3), lack adequate baseline information on the ecology and interconnectivity of deep-sea species and ecosystems, their roles in the provision of ecosystem function and services, as well as the scope and scale of the disturbances associated with mining operations at the seabed.

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. The many scientific knowledge gaps outlined in Table 3 indicate that all environmental management plans are inherently established in a context, characterized by inadequate knowledge. Therefore, there is considerable debate pertaining to the effectiveness of EAIs in the context of deep-sea mining (Clark et al. 2020). 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.

6.1 Alternative pathways:

Deep-sea mining is a destructive practice that will inherently lead to long-term, potentially irreversible, environmental damage. However, measures can be implemented to reduce the environmental impact of mining by minimizing its footprint, creating protected areas or refugia, and implementing engineering specifications to, for example, limit sediment plume dispersal and toxicity (Niner et al. 2018).

Recent reports suggest that terrestrial mineral reserves may in principle be sufficient, with exceptions for some metals, to support the transition to renewable technologies (Månberger and Stenqvist 2018). However, efforts should be placed on reducing the environmental and societal impact of land-based mining.

In addition, efforts should be devoted to promote a more circular economy. By reusing materials and reducing our reliance on new mineral extraction, a more sustainable economy can be achieved, and the requirement for deep-sea mining can be reduced altogether. Recycling rates of metals are currently far lower than the potential for reuse (United Nations Environment Programme 2011). However, recycling and incentives to reduce material demand will not affect the overall anticipated increase in material demand (Wang et al. 2023).

7. 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. For example, the 2020 Global Biodiversity Framework seeks to halt and reverse biodiversity loss by 2030. In addition, UN Sustainable Development Goal (SDG) 14 aims to conserve and sustainably use the oceans, seas, and marine resources, with targets to reduce pollution and increase scientific knowledge and research capacity to improve ocean health. Lastly, deep-sea mining appears to conflict with some of ISA’s guiding principles, which call to provide effective protection for the marine environment from the harmful effects which may arise from deep-sea mining activities.

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 (Amon et al. 2022).

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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