The effects of Deep-Sea Mining sediment plumes on the marine ecosystem

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Abstract

From the onset, deep-sea mining has raised concerns surrounding its environmental impacts on fragile and poorly studied marine ecosystems such as hydrothermal vents, seamounts, and polymetallic nodule fields. Most research on the topic centres around the effects of habitat degradation on benthic communities inside the mining perimeter, but ore extraction and processing are also expected to generate extensive plumes of resuspended sediments. Benthic communities inhabiting a wide radius around the mining site as well as midwater fauna in the overlaying water column could be affected by an increase in suspended sediment concentration as well as the upheaval of toxic metals from the ocean's crust, resulting in much more widespread environmental damage than previously imagined. In this review we will discuss the effects of sediment plumes on the marine ecosystem: their origin, composition, spatial extent, as well as the environments and species that will be most affected by them. We will conclude with an overview of the strategies that have been proposed to minimize such effects and the knowledge gaps surrounding the deep sea that prevent us from obtaining a comprehensive picture of the true environmental impact of deep-sea mining.

Keywords: abyssal plains, deep-sea mining, disturbance, hydrothermal vents, seamounts, sediment transport, toxicology

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1. Introduction

The discovery of mineral deposits in the deep sea can be traced back to the voyage of the *HMS Challenger* in the 1870s, in the form of ferromanganese nodules dredged from the seafloor [1, 2]. These peculiar formations were filed as an interesting geological novelty [1], but in the second half of the 20th century, using more modern techniques, further analysis of these nodules revealed high concentrations of other ores such as Nickel, Cobalt, and Copper: important resources for the creation of high-performance alloys, high-tech batteries, and microchips [1, 3]. At the same time, the development of state-of-the-art ocean mapping technology allowed researchers to discover that the seafloor of most areas of the globe was home to extensive ore deposits containing these sought-after minerals [1]. In recent years, thanks to technological innovations in deep-sea extractions by the oil & gas industry and a fragile political climate around equivalent land mining sites, deep-sea mining (DSM) is becoming a reality [3], with full-scale operations set to begin in 2023 [4].

Just like on land, seafloor mining activities have called attention to the significant environmental impact they are expected to cause, especially considering our general lack of knowledge of the deep sea, which stems from its inaccessibility [5], and the complex legal framework that surrounds many of the proposed mining sites, located in international waters [6]. In areas beyond national jurisdictions (ABNJ, known as "The Area"), the extraction of seafloor mineral resources is managed by the International Seabed Authority (ISA), an organization established by the United Nations Convention on the Law of the Sea (UNCLOS) to organize, regulate, and control seabed mining, with a principle that holds the seabed in the Area to be the Common Heritage of Mankind. This crucial principle requires any development to benefit mankind as a whole, by sharing the benefits of deep-sea exploration and exploitation, including monetary profits and access to technology [1]. In accordance with UNCLOS, the ISA must, among other obligations, prevent "serious harm" and ensure "effective protection of the marine environment" from the harmful effects of seabed-mining activities [7]. UNCLOS also specifies that environmental protections for seabed mining within waters of national jurisdiction (a country's "exclusive economic zone", or EEZ) should be "no less effective" than those developed by the ISA [7] (**Fig. 1**).

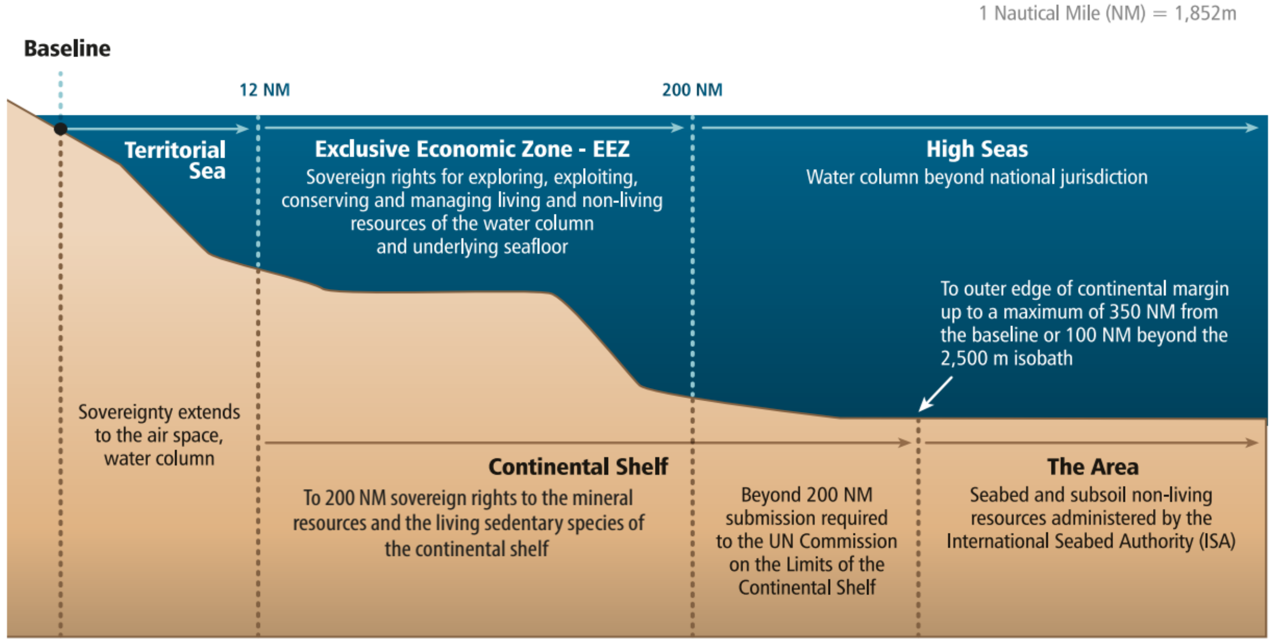

Figure 1: *Subdivision of ocean zones by UNCLOS. Coastal states own mineral resources in their EEZ and Continental Shelf, while the Area beyond is Common Heritage of Mankind [1].*

The disturbances generated by mining take on a novel nature, strength, and persistence in an oceanic setting, especially considering the greater spatial and temporal scales at which deep sea ecosystems operate. The most direct impacts include mortality and removal of fauna living on the mined substrate, habitat loss by substrate removal, habitat fragmentation, habitat modification (change in mineral and sediment composition, topography, chemical regimes) as well as sound and electromagnetic radiation by mining instruments [8]. One of the main distinctive and often overlooked differences between land mining and seabed mining is the three-dimensional nature of the latter, since the effects of mining activities can extend beyond the immediate seafloor disturbed by the extraction of minerals [9]. In particular, the extraction process is expected to raise significant quantities of sediment, which can be carried by ocean currents and negatively affect not just the surrounding seafloor as it settles, but also the water column [10].

To better understand the causes that lead to the formation of sediment plumes, it is important to first introduce the mining process. Deep-sea mining technology is still in its infancy [11], but the overall layout has been consolidated as follows [12] (**Fig. 2**):

- A series of remotely operated mining machines moving horizontally on the seafloor. The precise method of ore recovery will vary depending on the mineral deposit, but the extracted material will be comprised of a watery slurry containing the ore itself mixed with ground-up crust or sediment particles coming from the disturbed seafloor.
- A vertical riser pipe system, designed to connect the seafloor miners to the surface mining platform and transfer the slurry using a series of hydraulic pumps.
- A mining platform at the surface, consisting of a large vessel that serves as a centralized control centre for ore recovery and a pre-processing plant. Here, the mineral-rich rocks are separated from the slurry and shipped to shore for further processing. The vessel is also responsible for maintaining the correct positioning of the whole infrastructure, following the track of the underwater miners below to avoid stressing the riser pipe.
- A wastewater recirculation system, designed to get rid of the slurry after the ores have been extracted by discharging the unwanted material in the water column.

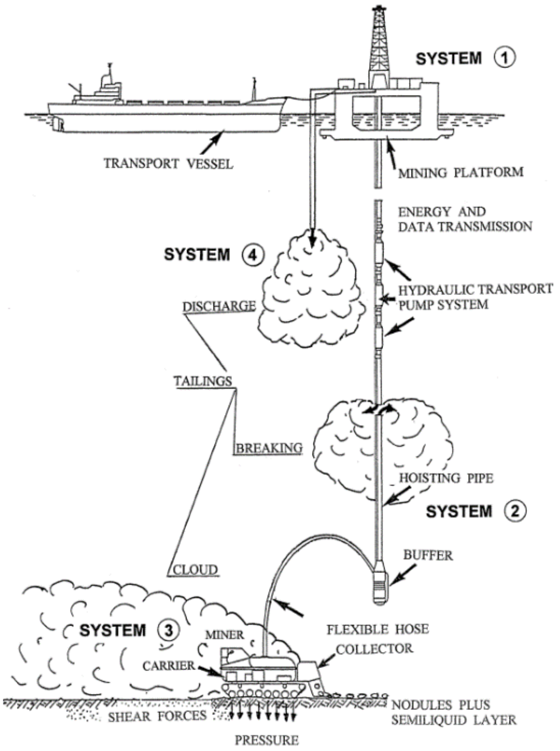

Figure 2: *Manganese nodule mining concept, consisting of a surface mining platform (System 1), vertical riser pipe (System 2), remotely operated miner (System 3), wastewater recirculation pipe (System 4). Benthic and midwater plumes are also shown [12].*

From this description, it is possible to infer that sediment plumes will be generated in two separate occasions: the first being at the seafloor, as the mining vehicle crushes the crust or disturbs the sediments to collect the ores (Benthic plumes), and the second being in the water column, as a result of wastewater discharge (Midwater plumes).

2. Environment, fauna, sediment composition

The impact of mining plumes on the marine ecosystem depends on the composition of the resuspended sediment, the environment where resuspension and redeposition occur, and the fauna inhabiting that environment. Here we will focus on setting the stage for the various habitats that will be affected by mining operations and the biodiversity that they host.

2.1. Polymetallic nodule fields

Polymetallic nodule fields occur in most oceans in the highest concentration at depths of 4000-6000 m [2]. The most commercially important area for nodule extraction is a 6000000 Km^2 area in the eastern Pacific Ocean: The Clarion Clipperton fracture zone (CCFZ) (**Fig. 3**). Being situated in international waters, it is administered by the ISA [6].

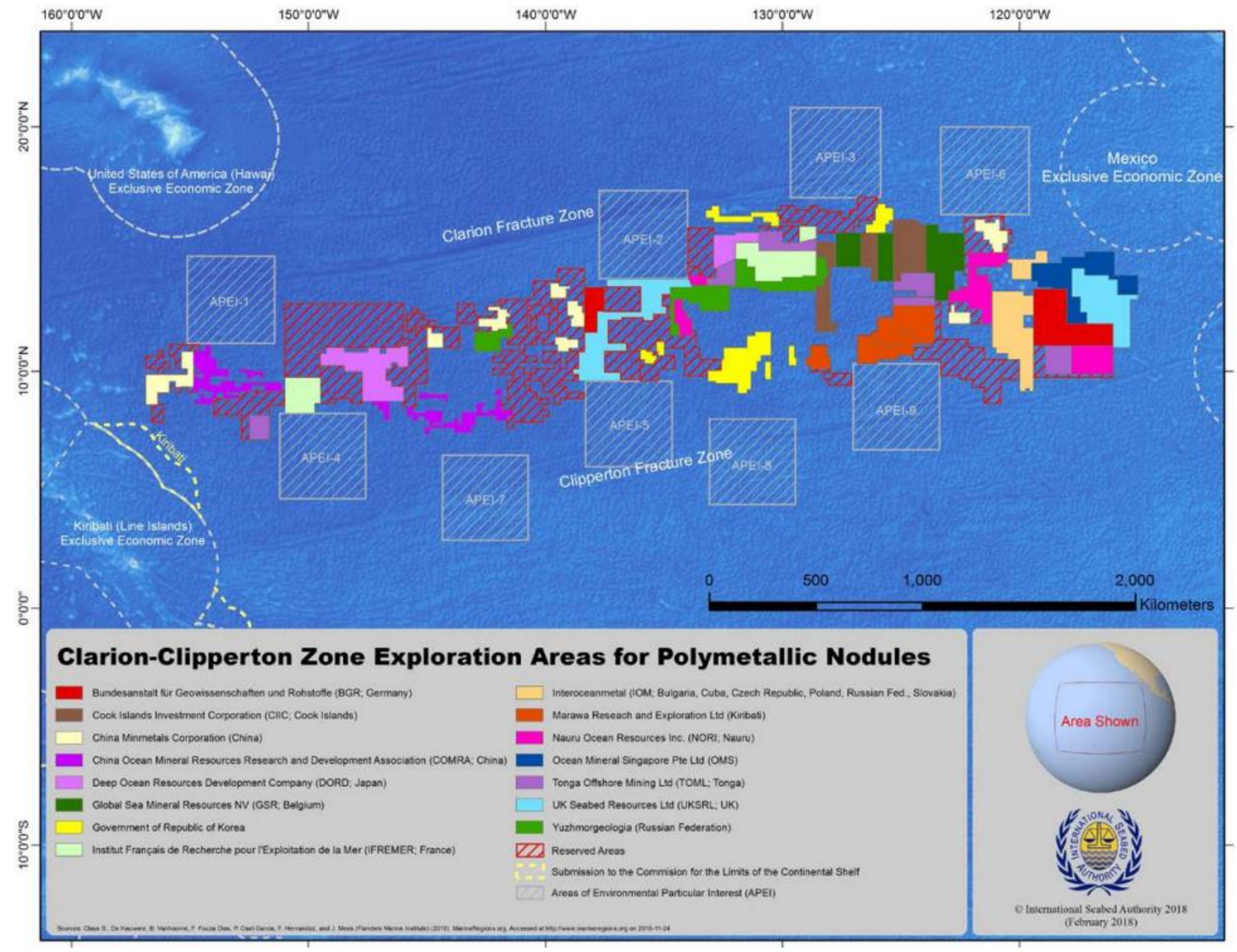

Figure 3: Geographic location of the Clarion-Clipperton Fracture Zone (CCFZ) [1].

This far offshore oligotrophic environment is dominated by expansive abyssal plains where sediment deposition is minimal, since the only clastic input comes from fine aeolian dust transported from the continents (red clay), or mineralized tests of organisms from the water column (Globigerina ooze). Ferromanganese nodules tend to be most prevalent in pelagic red clay [13]: The red colour is, in fact, determined by the high amounts Mn2+ and Fe found in the calcite and hematite composing these beds [14]. Additionally, refractory organic matter (OM) coming from the water column above can adsorb trace metals such as Mn, Fe, Cu and Ni during its descent [15]. Oxygen-rich conditions, such as the ones found in the top few cm of the seafloor [14], can oxidise the OM and release these metals [16] in the interstitial waters [15]. High metal concentration can subsequently lead to their precipitation inside the sediments around a hard substrate, forming diagenetic nodules, or combine with dissolved metals in the water column and precipitate on the sediment surface to form hydrogenetic nodules [1] (**Fig. 4**).

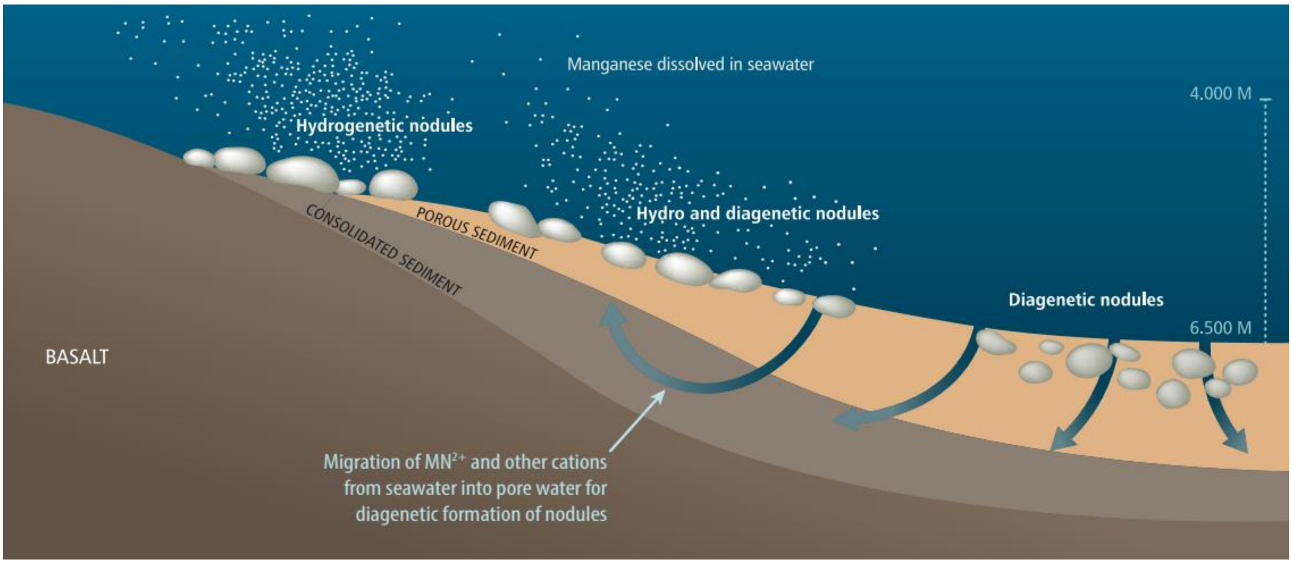

Figure 4: *Formation of Hydrogenetic and Diagenetic polymetallic nodules [1].*

This results in vast expanses of soft sediments dotted by potato-sized nodules that provide the almost exclusive instance of hard substrate in abyssal plains. Biodiversity is much higher than surrounding areas, despite many species being rare [17]. Soft sediment meiofauna (size retained in 63 µm mesh) is dominated by nematodes and harpacticoid copepods [17], but sampled specimen belong to 23 animal groups across 13 phyla [18]. Polychaetes and isopods are the most abundant macrofauna (size retained in 500 µm mesh), while megafauna (any fauna visible with the naked eye or in photographs) is composed of ophiuroids, holothurians, fish, large komokiaceans and xenophyophore protists [18, 19]. Hard-substrate nodules tend to be colonized by sessile organisms like cnidarians, xenophyophores [18], and hexactinellid stalked sponges like *Hyalonema sp.*, which can themselves act as substrates for other taxa (Ophiurida, Actiniaria, Cirripedia, Amphipoda, Brisingida, Ophiacanthida) [20]. Epifauna densities seem to be positively correlated with nodule cover, and the food web hinges on non-trophic interactions [20], since the main source of nutrition for most species comes from filtering the small input of marine snow drifting down the water column [10].

2.2. Seafloor massive sulphides

Seafloor massive sulphides (SMS) are mainly found in volcanically active areas like back arc basins, oceanic hotspots, plate boundaries, and mid ocean ridges [1, 21]. These mineral deposits form when hydrothermal fluids inside the oceanic crust are superheated up to 400°C at high pressures by the underlying magma and rise to the seafloor carrying dissolved metals (mainly Zn, Pb, Au, Ag, Ba, Cu), forming a hot plume. The sudden contact with cooler bottom waters precipitates these metals locally in sulphide-rich chimney structures, or in the surrounding sediments [21] (**Fig. 5**). Many SMS occur in waters shallower than 2000 m within the jurisdiction of national EEZ [21, 22]. Important deposits are found along the slow spreading ridge of the Red Sea [22, 23] but the most famous site is arguably Solwara 1 in Papua New Guinea, the site of choice for the now defunct Nautilus Minerals Inc. [11].

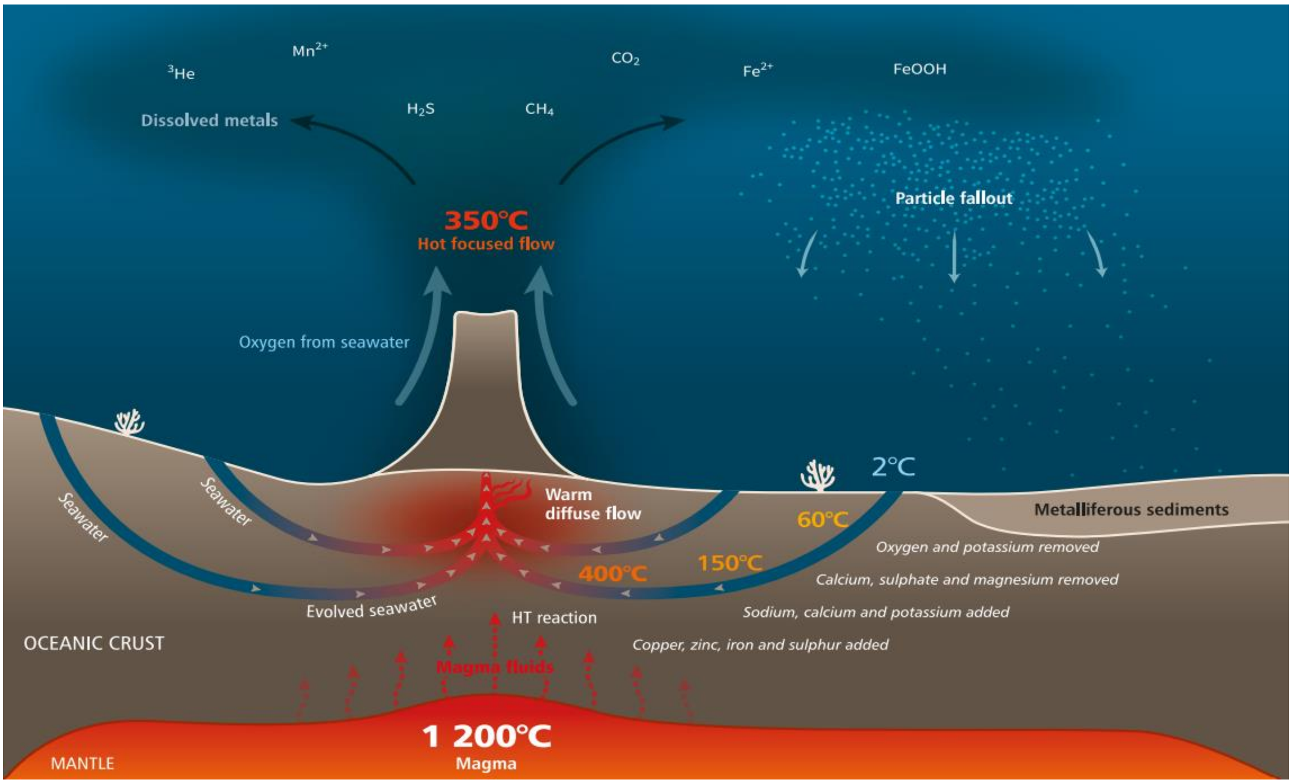

***Figure 5:** Formation of polymetallic chimneys (smokers) and seafloor massive sulphide deposits [1].*

Active vent fauna has been extensively studied in many locations [23]: the entire community is supported by chemosynthetic bacteria that rely on methane or sulphide-rich fluids for primary production [24]. This results in the presence of many specialized mega and macrofaunal sessile species in symbiosis with these chemosynthetic bacteria that can only survive near the vent. Over 500 species have been identified in active vent ecosystems. Megafauna taxa include mussels, snails, shrimps, and polychaetes, whereas dominant macrofauna taxa are limpets, crabs, amphipods, and polychaetes [17]. Vent fauna tends towards high biomass and low diversity [25] compared to the background fauna and can resist high temperatures and toxic metal concentrations [23]. Clear zonation is present around the vent site, as vent-specific fauna is taken over by a more typical seamount fauna, consisting of sessile, filter-feeding, long-lived and slow-growing taxa such as sponges, hydroids, corals, anemones, squat lobsters, ophiuroids and holothurians that also take advantage of the hard substrate provided by inactive SMS deposits [26, 27, 28]. Since vents have a patchy distribution, larval dispersal between chains of vents seems to be the dominant method of connectivity [29].

2.3. Cobalt-rich crusts

The slopes and summits of seamounts, ocean ridges and the plateaux on top of guyots are the most common locations of oxidized deposits of cobalt-rich ferromanganese crust. The most commercially important deposits occur in the equatorial Pacific Ocean, the EEZ of islands like Hawaii and Johnston Island (USA), the Marshall Islands, the Federated States of Micronesia, and international waters [30]. At depths of 400-4000 m, the geophysical characteristics of seamounts accelerate water currents, maintaining their surface free of any sediments, and allowing minerals (Ti, Ce, Ni, Pt, Mn, P, Tl, Te, Zr, W, Bi, and Mo) to precipitate onto the rock surface, likely with the aid of bacterial activity, forming pavements up to 26 cm thick [17]. Seamounts are important hotspots of biodiversity thanks to high current-induced primary productivity, supporting a large biomass of megafauna including demersal species important for the fishing industry [31] and benthic filter feeders, such as cold-water corals and sponges [17]. Very little is known about macro and meiofauna, since <1% of seamounts have been sampled, other than the striking variability in faunal composition even between neighbouring seamounts [30], and the slow-growing nature of their benthic assemblages [17].

2.4. Midwaters

Despite not being of commercial interest to the deep-sea mining industry, midwater ecosystems will be directly affected by the extraction of all aforementioned mineral deposits through the discharge of sediment plumes. Representing more than 90% of the biosphere [32], they offer invaluable ecosystem services but are also among the least studied regions of the planet [33]. Midwater ecosystems are defined as the water column from 200 m deep to the seafloor [32], encompassing the mesopelagic, bathypelagic, and abyssopelagic zones. They are characterized by a lack of light penetration beyond 1000 m in the clearest waters and the absence of any kind of substrate. As a result, the poorly studied midwater fauna includes transparent, gelatinous, and bioluminescent plankton and nekton, many of which can filter feed by trapping drifting organic particles using sticky appendages or mucus nets [10]. The water column above the CCZ is characterized by high surface primary productivity throughout the year, a thick oxygen minimum zone (OMZ) and a median particulate organic carbon (POM) size of only 77 µm. This means that despite large amounts of organic material, the sinking speed is low, and the POM has a longer residence time in the water column. This allows for more microbial degradation or plankton grazing, resulting in low sedimentation rates on the seafloor [34].

3. Modelling plume dynamics

Since no full-scale mining operations have taken place yet, several modelling approaches have been utilized to simulate the scale of sediment plumes and inform mitigation strategies from the onset wherever possible. In general, small-scale mining plume dispersion field data was gathered to Provide computer model validation data, akin to what would be done during the environmental impact assessments (EIA) of mining operations [35].

3.1 Benthic plumes

The operation of mining tools (raking, cutting, scraping), the pre-processing of ores (grinding, crushing, washing) and the movement of collectors on the seafloor will generate benthic, or operational, sediment plumes. The plumes, which comprise inorganic particles and refractory organic material, may reach several tens of metres above the seafloor [8]. Depending on particle size and settling velocity, the suspended material will be re-deposited at different distances from the mining site. We will mostly focus on polymetallic nodule mining scenarios, since the sedimentary particles resuspended are generally finer than the crushed rock of SMS or cobalt-rich crusts. Gillard et al., 2019 [36], recorded 28% of the sediment from the German CCZ contract area to have a grain size < 10 µm, 57% between 10 and 63 µm, and 15% > 63 µm. The nodule mining process is expected to occur at a rate of 30,000 m^2 of seabed per hour, resulting in the extraction of 300–400 tons of nodules – equivalent to mining an area of 200 km^2 to recover 2–3 million tons of ore per year [37]. The ejection of benthic plumes will occur at a height of 5 m above the seafloor based on current designs [38]. Considering that known pre-prototype miners have a seabed mining depth of 6 cm, the process will displace around 1800 m^3 of sediment (particles and porewater) per hour [37]. The resuspended sediment is initially expected to be highly concentrated inside the plume [37]. This can have a positive impact on sedimentation speed by means of flocculation, which is the process through which smaller particles coalesce into larger aggregates with greater sinking speed, localizing negative plume effects. The shear rate of bottom currents and eddies, conversely, can have a disruptive effect on these aggregates [39]. The results obtained by Gillard et al, 2019 [38], indicated that the discharge of elevated plume concentrations (500 mg/L), even under an increased shear rate ($\geq 2.4\ s^{-1}$) generated by movement of the mining vehicle, would result in improved efficiency of sediment flocculation. Furthermore, particle transport model results suggested that even under typical deep-sea flow conditions (shear rate $0.1\ s^{-1}$), rapid deposition of particles could be expected (in a scale of days), which would restrict heavy sediment blanketing (several cm) to a smaller fall-out area near the source. That said, Purkiani et al., 2021 [39], showed that even if slopes in the mining area are very gentle, the deposition patterns and the extent of low deposition contours (< 0.07

mm) are significantly affected by these variations. In addition, when sediment release coincides with a period of strong mixing in the deeper water column, the suspended sediment plume may rise tens of meters above the seafloor, increasing horizontal dispersion of the sediment plume and far-field deposition.

The effects of elevation and topography become even more important in the modelling of plumes generated on seamount slopes, where strong currents tend to prevail over sedimentation [35]. Spearman et al., 2020 [35], Through a combination of numerical dispersion modelling and in situ measurements at the Tropic seamount (300 nautical miles SSW of the Canary Islands), showed that plumes composed of resuspended sediments and ground crust fragments tend to remain in proximity (1.4 Km radius) to the summit, following a semidiurnal tide-generated current that rotates clockwise around the seamount itself (Taylor cap) (**Fig. 6**). This would localize the potential impact area on the seafloor where flocculation and sedimentation occur. Flocculation, in turn, was observed to be enhanced by the activity of bacteria and excreted polymers.

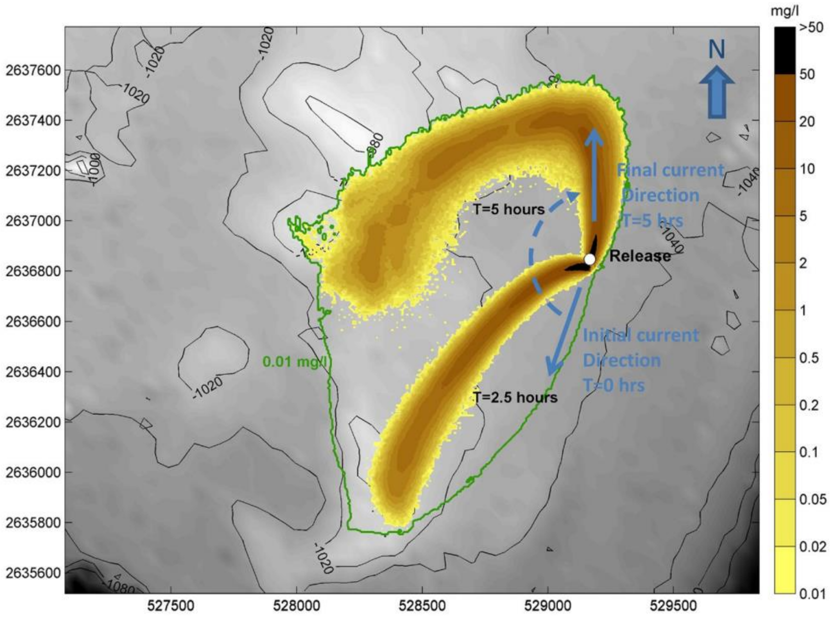

Figure 6: *Effect of a seamount's Taylor cap on benthic plume dynamics at +2.5hours and +5hours. Envelope of increases greater than 0.01mg/l over whole of simulation indicated by green line [35].*

3.2. Midwater plumes

To date, no specific regulations have been set by the ISA regarding the discharge depth of midwater plumes [5], complicating the analysis. Expected sediment discharge rates of commercial mining are estimated to be 10 kg/s for the whole duration of the operation. Upon release, the sediment-rich fluid will quickly lose its initial momentum and transition into a buoyancy-driven phase [40]. In these conditions, where density is the only factor taken into consideration, midwater plumes in many ways act like an inverted volcanic cloud [41] (**Fig. 7**). With a uniform stratification of the water column, a particle-laden plume is gradually arrested by the mixing and entrainment of the ambient fluid through which it descends after travelling an initial distance conventionally labelled as H, where it reaches the same average density as the surrounding water layer. Once this height is reached, some particles continue to descend, while the remaining fluid, a mixture of the source fluid that now contains fewer particles and the fluid entrained from the environment, rises back to a shallower neutral buoyancy height. When all particles separate from the flow as fallout, the density of the remaining fluid is equivalent to that of the fluid a distance 5H/8 below the source, as demonstrated by Mingotti & Woods, 2019 [42]. Upon reaching this depth, the now clarified fluid will remain stationary. In the case of oceanic water masses, where there is a clear difference in density between an upper and a lower well-mixed layer, the plume reaches the density boundary, entraining a small amount of the denser fluid below and then intruding at the thermocline. In this case, as particles settle from the spreading intrusion, the fluid will tend to remain at the thermocline as it will have a density intermediate to the two layers. The stratification in the deep ocean is very weak, so the convective downflow of particles may form a weak descending plume. Deeper below the interface, as entrainment begins to dominate, the plume will start to grow in radius until it reaches the bottom. For larger stratification, as the plume entrains the shallower less dense fluid, it may be arrested by the stratification, leading to a second intrusion in the deeper layer from which the particles will then sediment. With even stronger stratification, the plume will not fully develop, but a cylinder of descending particles will form [41].

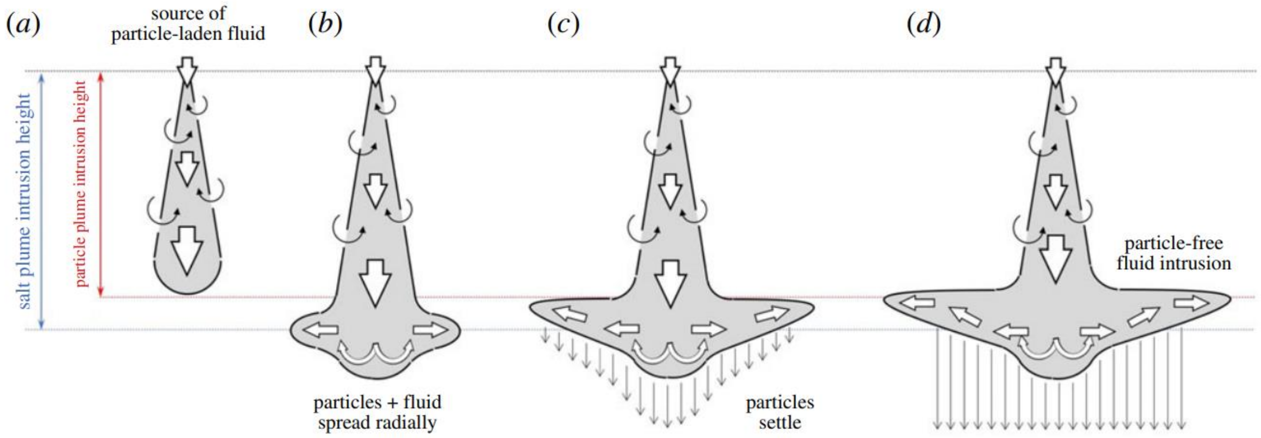

Figure 7: *Behaviour of a sediment plume descending through a stratified water column. (a) Particles form a turbulent descending plume which entrains ambient fluid; (b) upon reaching the neutral buoyancy level, the mixture of particles and fluid spreads radially; (c) particles settle from the intruding fluid; (d) the remaining fluid, depleted of particles, rises to its new neutral buoyancy level, forming a shallower intrusion [41].*

The volume of water that will be impacted by midwater discharges will be much greater than their actual extent. As it develops, water parcels moved by currents at different depths are going to pass through the settling plume, exposing their drifting fauna to increased sediment loads, while at the same time passively transporting and diluting portions of the plume [40]. In this phase, when buoyancy plays a lesser role, the evolution of the plume's concentration is controlled by a combination of physical processes. Advection by background currents will primarily create a meandering path of particles originating at the intrusion site. Turbulent diffusion caused by small-scale eddies will progressively dilute the sediment away from the intrusion area, resulting in a wider and taller plume of decreasing concentration. Finally, differential settling of sediments will stretch the plume vertically, as large particles settle faster than smaller ones (**Fig. 8**). For a midwater plume in the CCZ, it could take several years for all particles to reach the seabed, while impacting a volume of water up to 483 km^3 with particulate concentrations predicted to be above safe thresholds for midwater fauna [40].

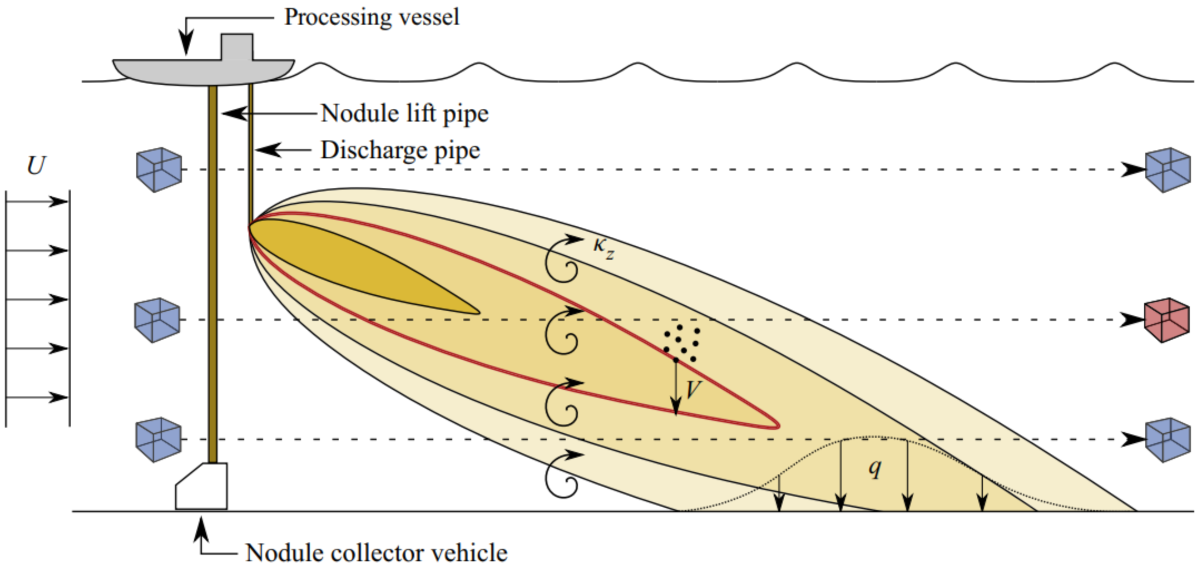

Figure 8: *Sketch of the dynamics of a settling deep-sea mining midwater plume as water parcels travel through the plume and dilute it. Due to turbulent diffusion, the plume expands vertically and horizontally, while due to the settling of sediment, the plume eventually reaches the seabed with a variable sedimentation rate "q". The volume of water with sediment concentrations above safe thresholds for midwater fauna is highlighted in red [40].*

One of the few field experiments on midwater plume discharge dynamics was carried out by Muñoz-Royo et al., 2021 [43], in the Pacific Ocean 50 km off the coast of California. A pumping system was configured to draw water from the ocean surface onto the research vessel, combine it with a highly concentrated mixture of sediment laden saltwater with Rhodamine dye, and then discharge the mixture at depth through a pipe for 45 minutes. After the discharge period had ended, the resulting plume was tracked and monitored by towing a CTD behind the vessel while cycling it through the water column (tow-yo profiling), with the support of a dynamic particle dispersion model. Although plume depth and dilution were aligned with the aforementioned models, no flocculation was observed, since the turbulence levels of open waters is sufficient to disaggregate the sediment upon discharge. As it descends, the disaggregated sediment rapidly dilutes, so the ability for individual particles to aggregate is greatly reduced. In the long term, this can increase the residence time of the midwater plume from what was previously predicted.

4. Effects of sediment plumes on deep-sea fauna

Now that the scale at which mining operations affect the deep sea has been explored, we will focus on how sediment plumes interfere with the survival and resilience of deep-sea fauna by increasing suspended sediment loads and toxic metal concentrations. In the final section, we provide a summary of field data gathered from disturbance experiments.

4.1 Increased suspended sediment load

The particles suspended in both benthic and midwater sediment plumes will have a negligeable contribution to the nutrition of deep-sea fauna because their organic content is lower by nearly two orders of magnitude than naturally sedimenting marine snow [44]. Additionally, according to Christiansen et al., 2020 [8], the increased load of these mostly inorganic particles in the near bottom water layers may directly affect the benthopelagic fauna in various ways:

- Burying/smothering is a main concern, especially for less mobile demersal species or benthic animals close to the source, where massive sedimentation is expected to occur, but scarce empirical data is available.
- Respiration may be impaired through the obstruction of gills, while congestion of the filtration apparatus with unpalatable particles may hamper feeding in many species, for example copepods. Additionally, the clogging of mucus nets in flux feeders, like pteropods, could lead to enhanced weight and sinking speeds and reduce the availability of proper food items.
- The competition between unpalatable particles and organic food particles will result in greater energy expenditure for feeding. The ingestion of particles of little or no nutritional value may lead to starvation and reduced growth rates in the near-bottom zooplankton, which will probably result in a cascading effect to higher trophic levels [45, 46, 47].
- The olfactory system is highly developed in benthopelagic scavengers to find food [48]. Sediment plumes will interfere with odour trails released from food falls, resulting in lower detection rates and generally lower food availability and consumption for scavengers.
- Many deep-sea organisms are capable of bioluminescence, which they employ, among other uses, for communication and mate finding [49]. Enhanced turbidity inside sediment plumes will attenuate light transmission and largely decrease the visibility of light emissions, leading to reduced probability of finding a mate and thus lower reproduction rates in an environment with extremely low abundances and encounter rates.
- Since vision is limited in the deep sea, chemosensory is also thought to be important for reproduction. Although no data is yet available for deep sea organisms, inferences on this matter have been made using shallow-water counterparts [50]. A sediment plume would interfere with such chemical trails and lead to a decrease in reproductive success.

Studies on the effect of increased suspended sediment concentration (SSC) on deep sea fauna do not abound, mainly because of logistical difficulties that arise when handling species adapted to locations and conditions that are often hard to sample and incompatible with standard laboratory practices. The few studies that exist focus on filter-feeding benthic animals such as cold-water corals and hexactinellid sponges, in the context of drill cutting exposure due to oil & gas prospecting and sediment resuspension from bottom trawling [51, 52]. Wurz et al., 2021 [51], reported that The Hexactinellid Deep-Water Sponge *Vazella pourtalesii*, though capable of coping with temporary (7-14 days) elevated concentrations of indigestible suspended particles, significantly lowered in clearance rates after 14 days of exposure, suggesting an inability to cope with long-term persistence of increased sediment load. T. Kutti et al., 2015 [53], found similar short-term adaptations in the sponge species *Geodia barretti*. Scanes et al., 2018 [52], investigated the effect of suspended sediment (10 mg/L) on the gorgonian coral *Primnoa resedaeformis* and the demosponge *Geodia atlantica* in a factorial mesocosm experiment for 40 days. In *G. atlantica*, similarly to the other experiments, chronic exposure to elevated suspended sediment reduced metabolism, supressed silicate uptake and induced cellular instability, suggesting an inability to cope with increased load over long periods of time. For the coral *P. resedaeformis*, increased SSC reduced O:N ratios after 40 days, however the effect was minimal compared to other disturbances investigated in the same study. To understand the effects of different grain sizes on deep sea fauna, M. Pinheiro et al., 2021 [54], utilized the mussel *Mytilus galloprovincialis*, a species known to withstand high pressures [55], as a proxy for benthic filter-feeding organisms. The results showed that smaller sized particles, which are also characterized by their high dispersion potential and longer suspension periods, are the ones leading to more severe effects, such as a decrease in filtration rate and antioxidant enzyme production. Other similar studies have tried to utilize different shallow water organisms as proxies, finding similar responses to increased SSC irrespective of habitat of origin [56]. Helpful as they may be at offering an indicative inference of how deep-sea fauna is expected to react, data on deep sea species will still be needed to corroborate their findings.

4.2. Toxicity

The metalliferous nature of deep-sea deposits is an additional cause for concern. The mining process has the potential to release throughout the water column significant amounts of toxic metal mixtures in both dissolved and particulate states. Copper, cadmium, zinc, and lead, as well as rare earth elements, can disrupt organism physiology and performance. If released on the scale expected from deep-sea mining, they could impact whole populations and lead to ecosystem-scale effects, including bioaccumulation in higher trophic levels of food chains [57] (**Fig. 9**). The toxicity of many of these metals has been individually tested in standard laboratory conditions: the US EPA ECOTOXicology Database (ECOTOX, [58]), for example, summarizes all available metadata included within each ecotoxicology publication, conventionally set at a temperature of 20°C and a pressure of 0.1 MPa. These measures are often in the form of LC50, as in the concentration of metals which are either lethal, or "effective," for 50% of the exposed population over a designated period, conventionally 72 or 96 h [57]. The context of the deep sea, however, presents additional challenges in determining the actual effect on its fauna. The low temperatures (down to 2°C), high hydrostatic pressures (up to 60 Mpa) and potentially altered pH that define these environments make it difficult to apply toxicological thresholds recorded for shallow water organisms, since they may differ biochemically and physiologically from deep-sea fauna [57]. To address some of these uncertainties, Brown et al., 2017 [59], contrasted the effects of low temperature (10°C) and high hydrostatic pressure (10 MPa) on lethal and sublethal (respiration rate, antioxidant enzyme activity) toxicity in acute copper and cadmium exposures, using the shrimp *Palaemon varians* as a model organism. *Palaemon varians* is a shallow-water species with a close phylogenetic relationship to hydrothermal vent shrimps [60]. The experiments showed that both copper and cadmium toxicity were significantly reduced at low temperatures, but the effects of pressure were more complex: copper significantly increased in toxicity at high hydrostatic pressures and cadmium, while not increasing in toxicity, had a potentiating effect on copper toxicity. Similar results were found in other studies, such as Mevenkamp et al., 2017 [61], which investigated copper toxicity on the nematode *Halomonhystera disjuncta*, a closely related species to deep sea nematodes. These studies, however, do not consider the complex composition of deep-sea metalliferous deposits, which can be both site-specific and subject to changes via mineral weathering, especially considering possible potentiating effects of metals on each other, as was the case with copper and cadmium [59]. The only option, then, is to conduct ecotoxicological analyses using samples from proposed mining sites, preferably on deep sea model organisms. Carreiro-Silva et al., 2022 [62], investigated the effects of suspended polymetallic sulphide (PMS) particles from inactive chimney rocks of the Lucky Strike vent field on the octocoral *Dentomuricea* aff. *meteor*. This filter-feeding species forms extensive coral gardens in the Azores seamounts between 200 and 400 m depth that can be affected by the horizontal and vertical dispersal of mining plumes, making it a fitting model organism. The results showed not only that the accumulation of toxic metals (mainly Cu) was higher than those measured with experimental copper exposure, but also that PMS particles themselves, being sharper and finer than inert quartz fragments and coated in toxic metals, contributed significantly to coral mortality by means of rapid accumulation and damage in their tissues. In addition, an increase in cellular oxidative stress biomarkers and respiration rate before the polyp's death signalled rapid tissue deterioration due to Cu exposure. The experiment, however, did not take into account the effect of temperature or pressure, as the octocoral was acclimatized to standard laboratory conditions, making the results difficult to translate directly to a deep-sea scenario. Finally, A. Brown et al., 2017 [63], revealed similar avoidant behaviour between shallow water and deep-water holothurians (*Holothuria forskali* and *Amperima* sp. respectively) when exposed to artificially produced Cu-spiked sediments meant to replicate SMS grain and ore content. Since holothurians are vagile species, a flight response was observed, with little to no metabolic response, which could prove an unsuccessful strategy in an expansive DSM setting. This experiment had the advantage of overcoming the pressure/temperature problem by investigating the behaviour of deep-sea holothurians in situ (the DISCOL experiment area southern reference site, more on it in the next paragraph) using a ROV, however the artificial makeup of the sediments excludes the potentiating effects of complex metal mixtures. It is clear, then, that extensive knowledge gaps still exist regarding the effects of metal exposure on fauna affected by DSM activities, and ecotoxicological studies have yet to capture the full scope of the issue.

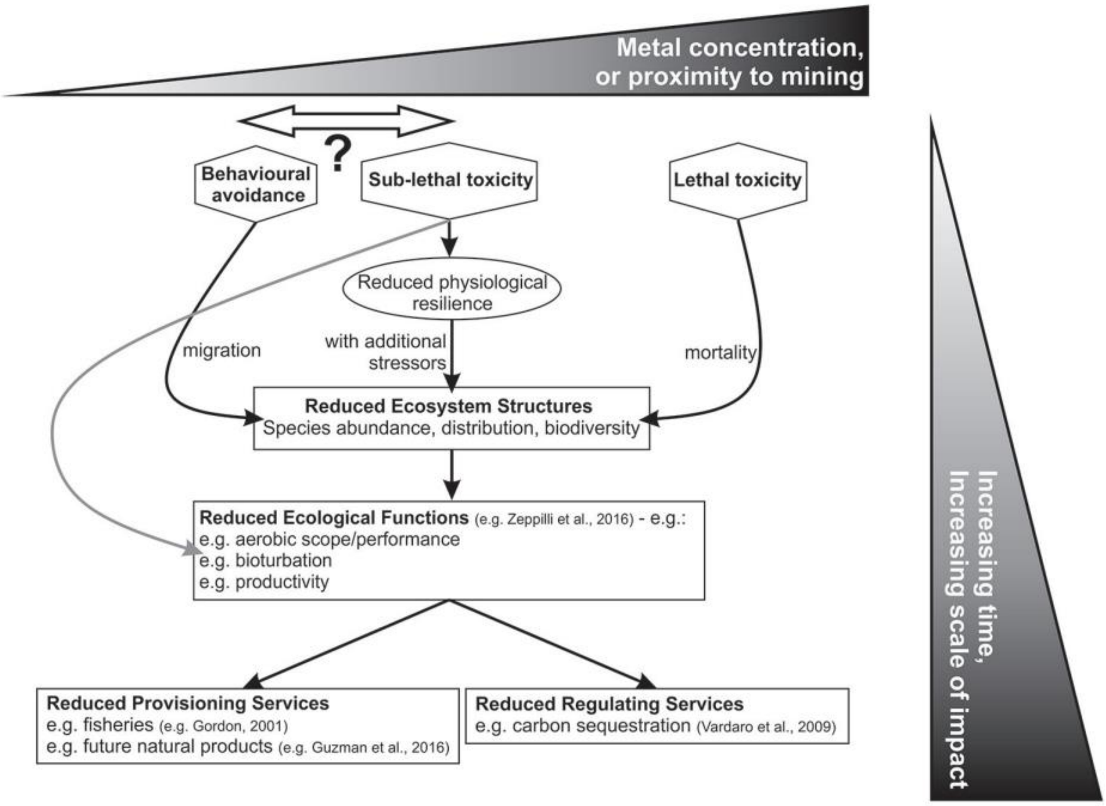

Figure 9: *Representation of how behavioural, sub-lethal and lethal impacts of metal exposure can scale to produce Ecosystem-scale impacts. From left to right is the effect of increasing metal concentration, or increased proximity to the metal release. Behavioural modifications or sub-lethal effects will occur at low metal concentrations or far from a mining site. Lethal impacts will occur at high metal concentrations or locations close to metal release. Sub-lethal exposure can result in a reduction in organism performance that cause direct impacts to Ecological Function (grey line) or result in organism mortality that cause direct impacts to Ecosystem Structures [57].*

4.3. Empirical field data on mining impact

From the 1970s to the late 1990s many small-scale sediment disturbance experiments have been carried out to empirically assess the long-term effects of nodule mining on the benthic fauna [64]. The most extensive of these experiments was the “DISturbance and reCOLonization experiment” (DISCOL), conducted in the Peru Basin in 1989 in what is known as the DISCOL Experiment Area (DEA, 1100 ha) (**Fig. 10**). Despite the rather tame nature of the sediment disturbing device (an 8 m wide plough-harrow) compared to a full-scale mining operation, the effects on the benthic fauna have been greater than previously expected, and even after 26 years the biological community has not returned to pre-disturbance conditions [65]. Areas surrounding the plough track received up to 30 mm of resuspended sediment, and most taxa visible through AUV surveys are mobile benthic deposit feeders that likely colonized the area after the experiment had taken place to capitalize on newly available organic matter [65]. In fact, megafauna densities demonstrated high variability in recovery rates among taxa, ranging from only 11% in Anthozoa to 167% in Holothuroidea, and major changes in community composition [17]. Macrofauna density in sediments recovered more quickly, reaching mean recovery of 85% after 7 years [66]. Mean meiofauna densities recovered to 90% after 26 years [17]. As expected, Suspension feeders, particularly Anthozoa, consistently showed the highest sensitivity to impacts, exhibiting substantial reductions in standing stock. Commercial-scale mining in the CCZ may exert an even greater impact on the structure and function of megabenthic assemblages than what was observed in DISCOL, since the proportion of suspension feeders in the CCZ, where nodule-attached Anthozoa and Porifera often dominate the megabenthic community, is much higher than in the Peru Basin [65].

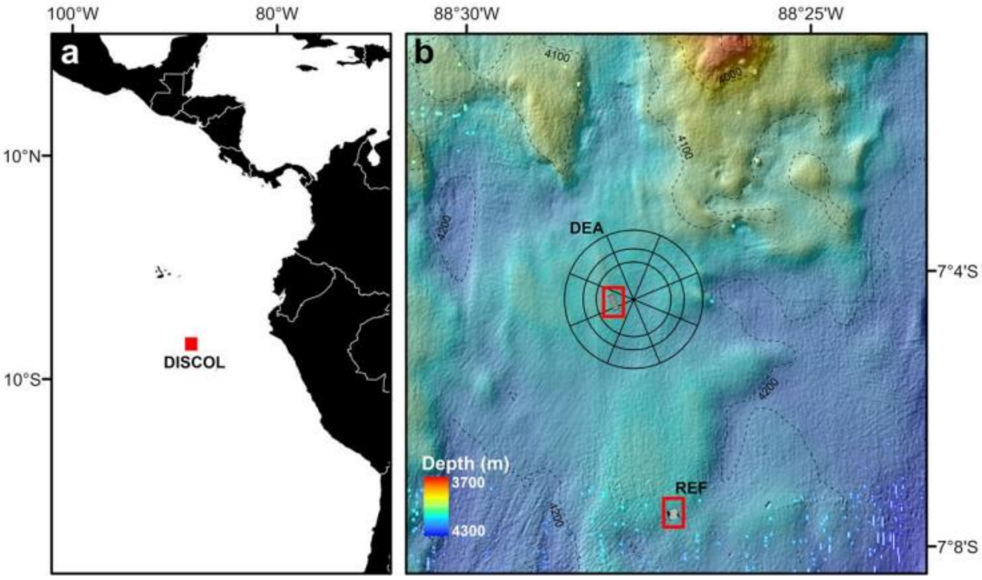

__Figure 10:__ Geographic location of the DISCOL Experiment Area (DEA) and the DEA Reference site (REF) [65].

Equivalent small-scale disturbance experiments have not been carried out for SMS deposits, and most of the faunal resilience and recolonization data comes from measurements of recovery from volcanic eruptions at active hydrothermal vents on fast-spreading ridge centres [17]. According to Gollner et al., 2017 [17], recovery in these conditions differ among taxa, but can be relatively rapid since vent communities at fast-spreading centres seem to be more resilient to metal-rich environments and adapted to such natural events. Abundance and biomass values reach pre-disturbance values within a few years, but diversity and composition often remain different, displaying clear faunal succession. The drivers of vent community resilience are diverse and include availability and constitution of hydrothermal plume fluids, species-specific factors of dispersal and connectivity, and interactions of competition and predation. However, the use of local natural occurrences as a proxy is hardly applicable to SMS deposits vastly different in location and mineral background, and subject to anthropic disturbances that are unlike any spontaneous event. Whereas volcanic eruptions pave over areas, mining machines are expected to scrape and excavate the crust generating extensive sediment plumes not comparable in composition with volcanic plumes. It is currently unknown to what extent these changes in substrate surface area and SSC may delay or prevent recovery of vent communities (disruption of larval dispersal, mortality of larvae, success of larval settlement), and the same can be said for the fauna of inactive vents [23].

Certain seamounts are already experiencing severe anthropic pressures in the form of bottom trawl fishing, which can deplete the substrate of important slow-growing, habitat-forming cold-water corals and sponges, thus also simulating the removal and upheaval by mining equipment [17]. Seamounts subject to high trawling can support half the overall benthic biomass and species richness than unfished seamounts [67], most of them having corals reduced below 30-50% of the cover estimated as necessary to maintain habitat viability [68]. Data on recovery after the cessation of fishing activity is scarce and limited to megafauna only [17]. The lack of data is exacerbated by the fact that the uniqueness of each seamount and its communities hampers generalized comparisons, since differing environments lead to different faunal responses to disturbance. Thus, only seamounts with similar conditions and near each other can be successfully compared. Recovery of seamount megafauna shows large variations depending on taxa [17], indicating significant changes in community composition following disturbance in what could be considered an early stage of succession [69]. Return to a pre-disturbance state is expected to take place rather slowly, given the geographical isolation of seamounts and the slow growing nature of its climax species [70].

No data is currently available on the effects of anthropic disturbances on midwater fauna.

5. Discussion and conclusions

5.1. Expanding our knowledge

Until recently, technical challenges have prevented a thorough scientific exploration of the oceans. The advent of deep-sea mining has caused an immediate need to expand our knowledge on a global scale to understand the effect that this industry will have on the biosphere before it is too late. Sediment plumes are likely to have the most far-reaching consequences outside the mining region and cross stakeholder borders [10]. It is therefore important to focus on the following issues:

- Describe deep-sea fauna and estimate their abundances, especially in midwater ecosystems, which are critically understudied [33].
- Understand the responses of this fauna to increased sediment load and toxic metal concentrations in situ without relying on educated guesses based on shallow-water species [56].
- Study the complex interactions between metal species that comprise deep-sea deposits, which can create a potentiating toxic effect [59].
- Delineate the processes that influence larval dispersal between biological hotspots like hydrothermal vents and seamounts, as well as the interactions between the seabed, midwaters, and the epipelagic zone (migration, nutrient cycling etc.) to improve our knowledge on the resilience of these ecosystems [32].
- Consider the interaction of mining plumes with commercially important and overexploited marine species [31].
- Gather more data from disturbance experiments to improve plume dispersion models [10].

Scientific research is challenging, time and resource-intensive, therefore closing these knowledge gaps is likely to require substantial time and a coordinated effort [5]. At this moment the ISA, following an outcome-based approach, does not impose strict binding rules on mining companies as to how their research should be conducted, published, and implemented in the extraction process, so long as the results do not cause “serious harm” to the marine ecosystem and meet ISA standards [37]. This has made it difficult to access many important details regarding the design of mining vehicles, pipeline systems and ore processing strategies, as they have been kept under trade secret, severely limiting our understanding of DSM environmental impacts. Since the ABNJ was declared by UNCLOS to be common heritage of mankind, it seems only fair for the ISA to both demand every relevant mining and research data to be publicly available, and to set standardized guidelines for conducting research in the Area, so that all data can be easily gathered and compared [5]. This would also force mining companies to be more transparent about their industry standards, and possibly serve as a deterrent against corporate propaganda and coverups that seek to misinform the public, which in the case of sediment plumes have already been reported from Nautilus Minerals inc. [9] and The Metals Company (TMC) [71].

5.2. Recommendations

Despite these persisting knowledge gaps the scientific community has already put forward many recommendations to minimize the impact of DSM sediment plumes and improve the research and regulations that surround this topic.

- Existing ISA regulations for seabed mineral exploration provide only a vague definition for “serious harm to the marine environment”, defined to mean “*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*". Such standards are to ensure the application of "best environmental practices and the precautionary approach", but unless mining proponents and decision-makers have clear and comprehensive parameters for what constitutes effective protection against "serious harm" and associated significant adverse change to the marine environment, there will be a risk that seabed mining could cause unacceptable impacts. In particular, the definition of "serious harm" needs to include the additive capability of damage that can arise from individually non-significant impacts [7].

- The effect of changes in toxic metal concentration on deep-sea fauna is higher in individuals at the larval stage [57]. This is also the most important life stage for dispersal and colonization and needs to be given special attention. The highly specialized fauna of hydrothermal vents relies on the dispersal of larvae between island-like ecosystems of distant vents to maintain connectivity and colonize new vent fields [29]. Key source populations need to be identified and protected from any disturbance, prioritizing the mining of less connected vent sites that host sink populations.
- Different deep-sea species will produce different responses to increased SSC and toxic metal concentration. Research on physiological responses to these conditions should focus on finding "canary species" that can serve as a universal benchmark for testing the effects of toxicity [57]. These same species can then be referenced by policymakers to set fact-based boundaries on the maximum allowable sediment and metal concentrations around DSM sites.
- Benthic plumes are caused by the interaction of mining vehicles with the seafloor. Since the design of the collector vehicle is one of the variables that can be most easily optimized in the mining process, companies should implement size-scaled vehicles to assess which design parameters correlate with plume spread and impact. For example, volume of sediment and water collected and ejected per unit area mined; height of exhaust above seabed; shape of exhaust and direction of outflow; potential use of artificial flocculants. These parameters will have a relationship to natural flocculation capable of reducing plume spread, or the formation of gravity flows. The analysis should also encompass the quantity and ratio of sediment and water entrainment during the ore collection process, enabling more favourable plume release conditions for minimised dispersion. Such a process is especially important in this preliminary phase, since there may be several different competing designs in the early years of mining, some of which may cause more impact than others [37]. Based on the experience of the dredging industry, it has been suggested that nodule mining vehicles should be as wide and slow as possible to minimize sediment shear rates without sacrificing nodule recovery rate [72].
- Midwater ecosystems have been understudied by the scientific community because its organisms are difficult to sample and analyse, sparsely distributed, elusive, often fragile, and live at pressures up to 100 atmospheres: all major problems for laboratory-based investigations [33]. However, the investigation of midwater faunal assemblages in the context of a DSM exploratory phase could benefit from their sparse distribution and vast habitat, since this means that a large area like the CCZ could be described with acceptable detail by only focusing on a few target regions following their intersection with the mesopelagic ecoregions [10] proposed by Sutton et al., 2017 [73] (**Fig. 11**).
- Midwater ecosystems have also been severely neglected by mining companies in their environmental impact assessments [32], and by the ISA in their lack of directives concerning wastewater discharges [5]. Pending future policies, it is advisable to discharge midwater plumes as close to the seafloor as possible to limit plume dispersion [10]. If feasible, the discharge pipe could be incorporated around or directly next to the riser pipe, so as to lay the contents of the midwater plume on top of the seafloor eroded by the mining vehicles, as it has been observed that sedimented areas tend to recover relatively more quickly than eroded areas [6]. In the eventuality that the best available techniques did not allow for discharge close to the seafloor, it

is recommended for the wastewater slurry to be artificially oxidised before release to avoid an increase in oxygen demand in the mesopelagic zone and thicken the already present OMZ [10].

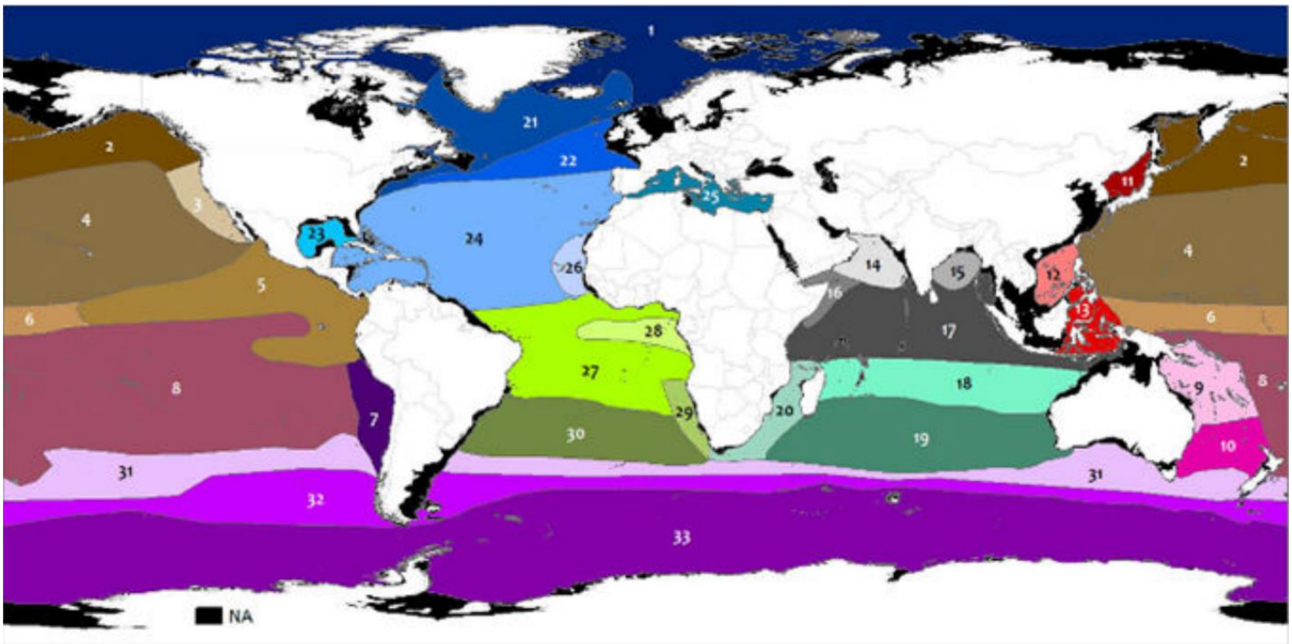

Figure 11: *The mesopelagic ecoregions or biogeographic provinces of the world's oceans proposed by Sutton et al. (2017) [10].*

5.3. Final thoughts

The current state of the DSM industry is extremely delicate: on one hand, since no commercial mining activities have taken place, scientific research of its effects on the marine environment has had very little tangible data to work with. This means that current predictions cannot be tested unless mining has already begun. On the other hand, if mining companies get the green light to start mining the seafloor without proper knowledge of the consequences, we risk following the footsteps of our previous generations towards yet another environmental disaster. The consensus of many researchers [10] is that a full-scale pilot mining test for every mineral deposit type needs to be conducted using the best available techniques, and closely monitored in all its phases to assess the viability of the industry as a whole. This monitoring program would include a thorough assessment of long-term environmental impacts in the mining area, seafloor, and water volume affected by resuspension-redeposition of plume material. It has not escaped our notice that a full-scale test with such an uncertain outcome would be prohibitively expensive for any mining company [10]. This is why we propose this pilot project be funded and developed by a consortium of all mining companies that seek to extract minerals from the seafloor, in which the (currently secretive) best available technologies can be selected, and result in the most favourable outcome for the mining companies, both in terms of efficiency and environmental safety. The Area is declared to be common heritage of mankind: if the ISA is determined to uphold this principle, mining companies need to be compelled to share their technologies and practices, otherwise doubts could arise regarding their ability to share the product of their service to benefit humanity.

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