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Seafloor Massive Sulfides: Their Role in Biodiversity of the Abyssal Ocean and the Threat of Deep-Sea Mining

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Abstract

Seafloor massive sulfides (SMS) at hydrothermal vents present huge opportunity for deep-sea mining (DSM) due to their abundance and high mineral grade. Little is known about the deep-sea; however, hydrothermal vents are some of the most biologically active deep-sea ecosystems, providing significant biodiversity and other ecosystem services that maintain the entire planet. The mining of SMS, which may commence within the decade (2020s), poses serious risk to hydrothermal vents as mining methods will likely require the destruction of active and/or nonactive vents, which will in turn affect these ecosystems and their services. The environmental impacts of mining SMS deposits must be carefully considered alongside the benefits from moving away from terrestrial mining before DSM is allowed to commence on the largescale.

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Acronyms

Ag	silver
As	arsenic
Au	gold
Ba	barium
$CaSO_4$	calcium sulfate
Cd	cadmium
Cu	copper
DSM	deep-sea mining
EEZ	Exclusive Economic Zone
Fe	iron
FeMn	ferromanganese
Ga	gallium
Ge	germanium
In	indium
ISA	International Seabed Authority
LCD	liquid-crystal display
LCE	low-carbon economy
Mn	manganese
Ni	nickel
Pb	lead
REE	rare earth element
Sb	antimony
Se	selenium
SMS	seafloor massive sulfides
Zn	zinc

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1. Introduction

The oceans cover almost 75% of the Earth's surface and contain over 97% of the Earth's total water (1). The deep-sea, which is considered ocean beyond the typical shelf break at 200m, is consequently the largest continuous ecosystem, covering 65% of the Earth's surface (2). However, the deep-sea is also the most remote ecosystem on earth, and remains the least understood to scientists (3). Regardless, the ocean and deep-sea provide to society abundant natural resources such as energy, food, fuel, and minerals, as well as cultural services like tourism and recreation.

Mineral deposits of several forms can be found on the ocean floor in large amounts, including polymetallic manganese (Mn) nodules, ferromanganese (Fe-Mn) crusts, and seafloor massive sulfides (SMS, sometimes referred to as polymetallic sulfides). Submarine deposits represent some of the largest known sources of many minerals including some critical minerals (minerals essential to the manufacturing of green technology and other important industries), and present huge opportunity for exploration and extraction (4, 5).

However, the exploitation of these resources, which as of 2022 has yet to commence at commercial levels due to technological and funding obstacles, is riddled with controversy, not least due to anticipated adverse environmental impacts. Even so, deep-sea mining (DSM) is expected to commence in international waters within the decade (6).

2. Deep-Sea Ecosystems

The deep-sea (see below, including the bathyal, abyssal, and hadal zones) is the lowest layer of the oceans, extending from a depth of around 1,800m to over 10,000m (Fig. 1) in some areas (7). This section first covers characteristics and ecology of the abyssal plains, and then discusses ecology related to hydrothermal vents and SMS, including structure and mineral content, ecosystems, and contribution to biodiversity.

2.1 The Abyss

Most deep-sea terrain is ‘abyssal plain’—expansive flat seabed approximately 3,000-6,000m below the surface (Fig. 1) (9). Most of this area is covered by smooth sediment, although bare rock (e.g., seamounts, ridges) is exposed in some regions (2). At these depths, sunlight does not penetrate, and ecosystems exist in total darkness; similarly, the deep is characterized by other extreme conditions such as low temperatures, high pressure levels, slow currents, and minimal food availability (Table 1) (9, 10).

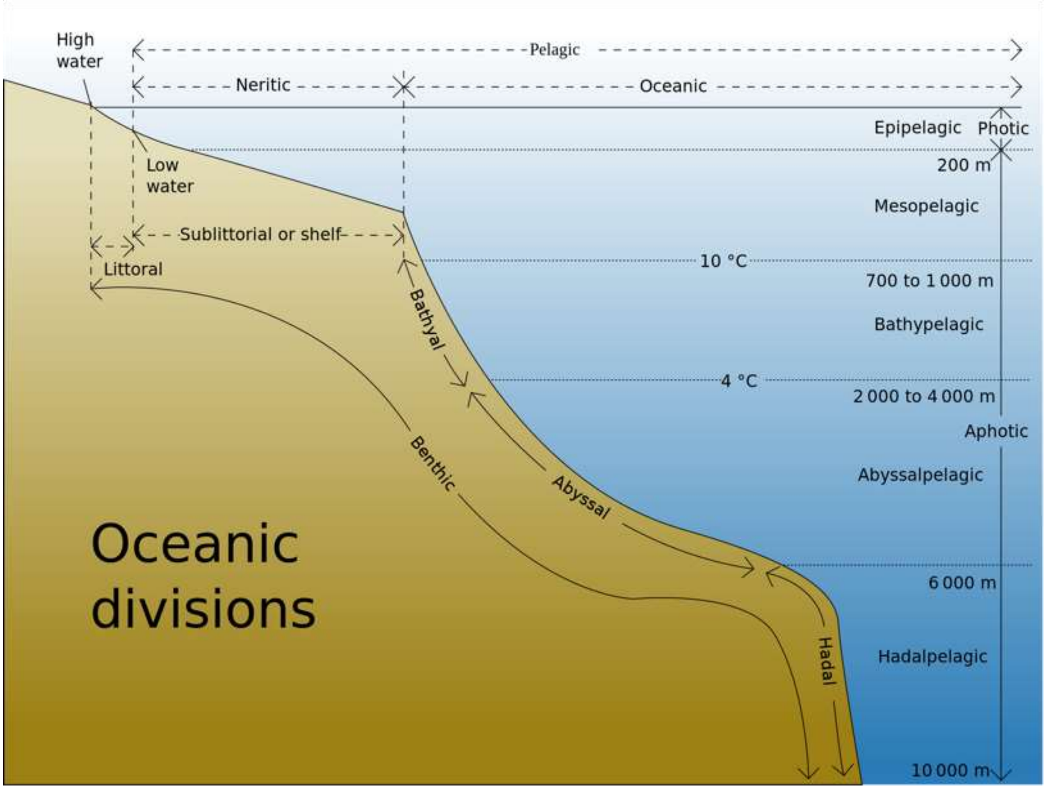


Figure 1: Key divisions of the ocean.

The deep sea (~1,800m and deeper) includes the bathyal, abyssal, and hadal zones (8).

Because of the extreme conditions presented by the deep-sea, the abyss typically experiences low levels of productivity and thus low biological density and species richness

(11, 12). However, despite the relatively low abundancy of life, these abyssal plain environments host substantial biodiversity, similar to that of shallower depths (13). This is largely due to the consistency of environmental variables leading to physically stable environments (2).

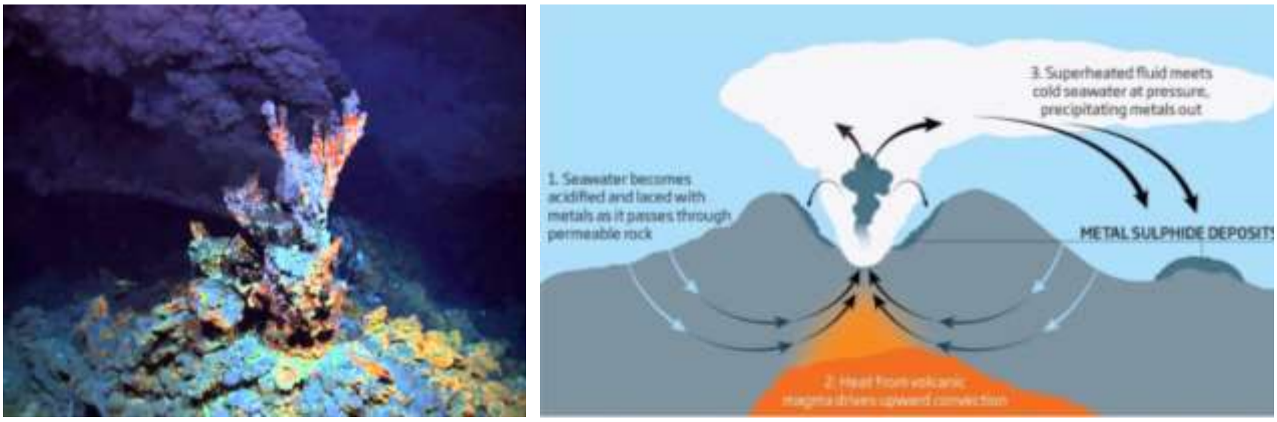
	Abyssal Plains	**Hydrothermal Vents**
Floor material	Sediment--soft clay, siliceous or carbonaceous oozes [a]	Metallic, sulfur-rich precipitates [b]
Sediment/mineral deposition rate	mm-cm/1,000 years [a]	30cm/day (maximum), intermittently [a c]
Organic content of sediments	<0.1% (under oligotrophic waters), >0.5% (under productive waters) [a]	6.3-23.1% [d]
Temperature	1-2°C [a]	250-400°C [e f]
Pressure	300atm [a]	300atm [a]
Currents	1cm/sec or <1km/day (sluggish) [a]	1-5cm/sec or <5km/day (sluggish) [g]
Tidal component	Present [a]	Present [h]
Salinity	3.48% (oceanic) [a]	2.9-5.6% (oceanic to high salinity) [i]
O_2 concentration	5-6 ml/l (near saturation) [a]	0.0010-0.0056 ml/l (hypoxic) [j k]
Light (solar)	None [a]	None [a]

Table 1: Environmental characteristics of the deep-sea habitats of abyssal plains and hydrothermal vents. Adapted from (9)[a]; additional data from (14)[b], (15)[c], (16)[c], (17)[e], (18)[f], (19)[g], (20)[h], (21)[i], (22)[j], and (23)[k].

2.2 Seafloor Massive Sulfides

Seafloor Massive Sulfides (SMS) deposits are found on deep ocean hydrothermal vents. Vent sites are seafloor fissures where hot geothermal water and other fluids flow into the ocean via ‘chimney-like’ columns from beneath the earth’s crust (Fig. 2a), and are located at volcanic arcs, ocean ridges, subduction zones, and other tectonically active sites (14, 26).

There are hundreds of thousands of kilometers of these submarine tectonic settings (e.g., 60,000 km of mid-ocean ridges, 22,000 km of volcanic arcs); consequently, there may be thousands of active, inactive, and extinct hydrothermal vents (for definitions, see Section



a *b*

Figure 2: Image of a deep-sea hydrothermal vent (a) by Oregon State University (24). Diagram representing the formation of mineral deposits via hydrothermal vents (b) which can then be harvested from surrounding areas (25).

2.2.2.) in the oceans, though only 721 have been identified by the InterRidge vents database at the time of this writing (Fig. 3) (InterRidge is an international academic organization that promotes research of oceanic spreading centers) (14, 27). There are likely many more in uncharted waters, as only 6.5% of the seafloor has actually been surveyed (as of 2011) (28). Plus, only 5% of oceanic ridges have been surveyed, leaving 57,000 km of mid-ocean ridges remaining to be surveyed in any detail (29).

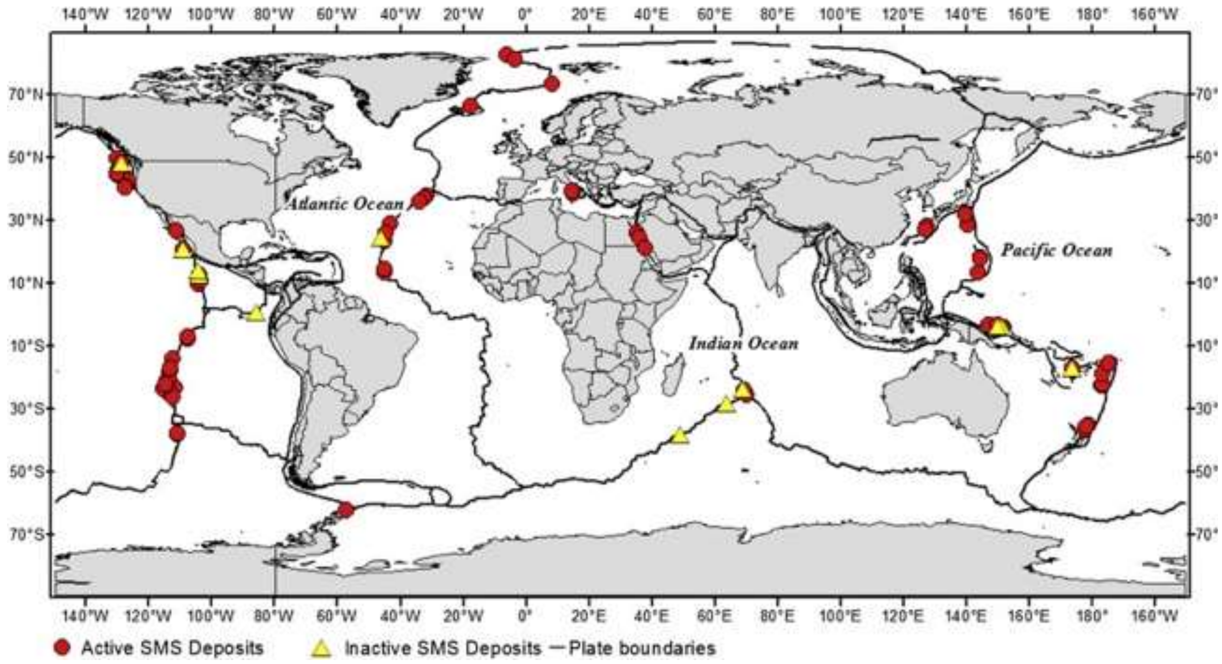


Figure 3: Distribution of SMS deposits around the globe (30). Red circles indicate active SMS deposits and yellow triangles indicate inactive SMS depositsthe black lines throughout the oceans represent tectonic plate boundaries. More deposits are known than are shown on the above map as their locations are not currently available for mapping.

A 2011 study estimated that SMS deposits occurred every 100 km along submarine tectonic plate boundaries, as not all hydrothermal vents are known to have significant SMS mineralization (31). These deposits can also be found across a wide range of depths (e.g., 2,000-6,000m deep), with the shallower sites more likely to be mined first due to accessibility and thus economic viability (30, 32, 33).

2.2.1 Mineral Content and Abundance

When hot (>250ºC) metal- and sulfur-rich fluids discharged from a hydrothermal vent accumulate and precipitate with cold seafloor ocean water, SMS deposits can develop (Fig. 2b) (35). In some cases, minerals—such as copper (Cu), zinc (Zn), gold (Au), silver (Ag), iron (Fe), and lead (Pb)—may precipitate over large areas in high concentrations, making them attractive sources for mineral extraction (Fig. 4) (14, 36).

Even so, the concentrations of metals differ depending on location and type of tectonic setting, a result of the metals' volcanic source rocks (29).

Aside from metal-rich deposits, minerals from hydrothermal plumes modify the composition of the oceanic crust, influence ocean chemistry, and provide energy to the deep-sea (37).

Figure 4: Cross-section of a SMS deposit from a hydrothermal vent. Minerals in this deposit include chalcopyrite (or copper iron sulfide, $CuFeS_2$), sphalerite (or zinc sulfide, ZnS), and anhydrite (or calcium sulfate, $CaSO_4$) (34).

Estimates from the International Seabed Authority (ISA) on the mineral tonnage of SMS deposits on mid-ocean ridges vary from 1-100MT; much of this uncertainty results from the fact that little can be known about the thickness of SMS deposits without actually dissecting or manipulating them in some way (29). However, other studies suggest quantities much higher, with a 2011 study estimating up to 143MT from only 165 sites (31). Additionally, subsea mineral deposits typically host relatively high grades of ore; for example, Cu grades from SMS deposits have been found with up to 12% Cu, whereas current land-based grades are typically around only 0.5% Cu (4). Indeed, the largest reserves on earth of many critical minerals, rare earth elements (REEs), and other metals are found on the seabed, establishing huge opportunity for exploitation (4, 5). Deep-sea mineral deposits host a high tonnage of REEs, and certain SMS deposits are known to host certain critical metals such as selenium (Se), barium (Ba), and indium (In) at abundances many times greater than average continental crust amounts (216, 100, and 26 times higher accordingly) (5).

Despite the vast mineral resources provided by seafloor deposits, SMS mining is not yet economically feasible on the large-scale. Deposits that are likely to become economically viable in the near future include those that are in relatively shallow (<2,000m deep) waters close to land (e.g., within nations' Exclusive Economic Zones (EEZs) of 200 nautical miles adjacent to territorial seas), and containing high grade base metals (29). Furthermore, significant funding and technological advances must be made, as submarine conditions and mining methods require expensive, complex machinery and technology (30, 38).

2.2.2 Ecosystems and Biodiversity

Active, inactive, and extinct hydrothermal vents all host different biological communities. Simply defined by a 2020 study, active vent fields (a geologically continuous range of vents) are those currently exhibiting hot (above ambient seawater temperature (Table 1)) fluid flow, and inactive (or dormant) vent fields are those that are not currently exhibiting hot fluid flow but are likely to become active again; in contrast, extinct vent fields are those not expected to become active again (36). Of the 721 hydrothermal vents identified by the InterRidge database, 666 are listed as 'active' and only 55 'inactive' (27). This database has no vents documented as 'extinct', although 'extinct' vents are likely combined with 'inactive' vents as 'extinction' of vents is a relatively new concept (although this is not directly stated within InterRidge). Furthermore, the small number of documented inactive and extinct (hereby collectively referred to as nonactive) vents can be largely explained by the predominant exploration tool for SMS deposits—detection of hydrothermal plumes—which are not exhibited by nonactive vents (36).

Several studies suggest that nonactive vents will be the target of SMS mining, at least initially; despite this, a 2020 study points out that all current ISA contracts for exploration (31 total) include areas with active hydrothermal vents (36, 39). Additionally, there are seven contracts for SMS exploration specifically, including in the South West Indian Ridge, the Central Indian Ridge, and the Mid-Atlantic Ridge (40).

Consequently, it is important to consider the biological communities that are hosted by different vent settings. Active hydrothermal vents present one of the most extreme environments on earth. Waters surrounding vents can reach up to 400ºC, are extremely acidic (pH 3-5, where pH 7 is neutral between alkaline and acidic, and 0 is the most acidic value on the scale), and completely devoid of all sunlight (and thus photosynthetic processes) (Table 1) (9, 17). Therefore, many species (e.g., giant tube worms, eyeless shrimp) that live in these benthic conditions (Fig. 5) are endemic or otherwise extremely specially adapted (including for chemoautotrophic primary production); these biological and geochemical contexts can also vary between vent fields, suggesting that conservation and management as a result of DSM will need to be specific for each area (30, 43-45).


a *b*

Figure 5: Giant tube worms (a) near a hydrothermal vent (41). Various shrimp species (b) on a hydrothermal chimney (42).

Nonactive vents are largely inhabited by suspension-feeders (e.g., corals, sponges, barnacles) that rely on proximate active vents for chemosynthetic primary production (46). Even so, virtually nothing is known about biological structure and function at nonactive vents anywhere in the oceans (44).

Due to the extreme conditions, knowledge on biodiversity and species composition at even the most well-studied active hydrothermal vents is insufficient. In fact, as of 2015 less than 1% of deep-sea habitat has been sampled; recent studies suggest that species discovery is far from complete and that estimations of undiscovered species are uncertain at best (47, 48). Scientists continue to discover new species of flora and fauna at hydrothermal vents at an average rate of two species per month (32). However, what we do know tells us that populations (and species) at both active and nonactive vents remain vulnerable to significant disturbances such as mining and will likely take a relatively long amount of time to recover (if possible at all) (30, 49).

3. Deep-Sea Mining for Seafloor Massive Sulfides

3.1 Methods

Because SMS exist in extremely hot, dark, and high-pressure environments, and are firmly attached to the rocky substrate of the seafloor, conceptual mining methods require highly specialized machinery and vehicles. In general, all DSM operation concepts include a surface support vessel, a seabed remote-operated resource collector, and a lifting system between the two (Fig. 6) regardless of deposit type (51). However, SMS mining will require additional seafloor vehicles to physically separate the deposits from the substrate using methods such as fragmentation, vibration, suction, or water-jet stripping (Fig. 7) (52, 53).

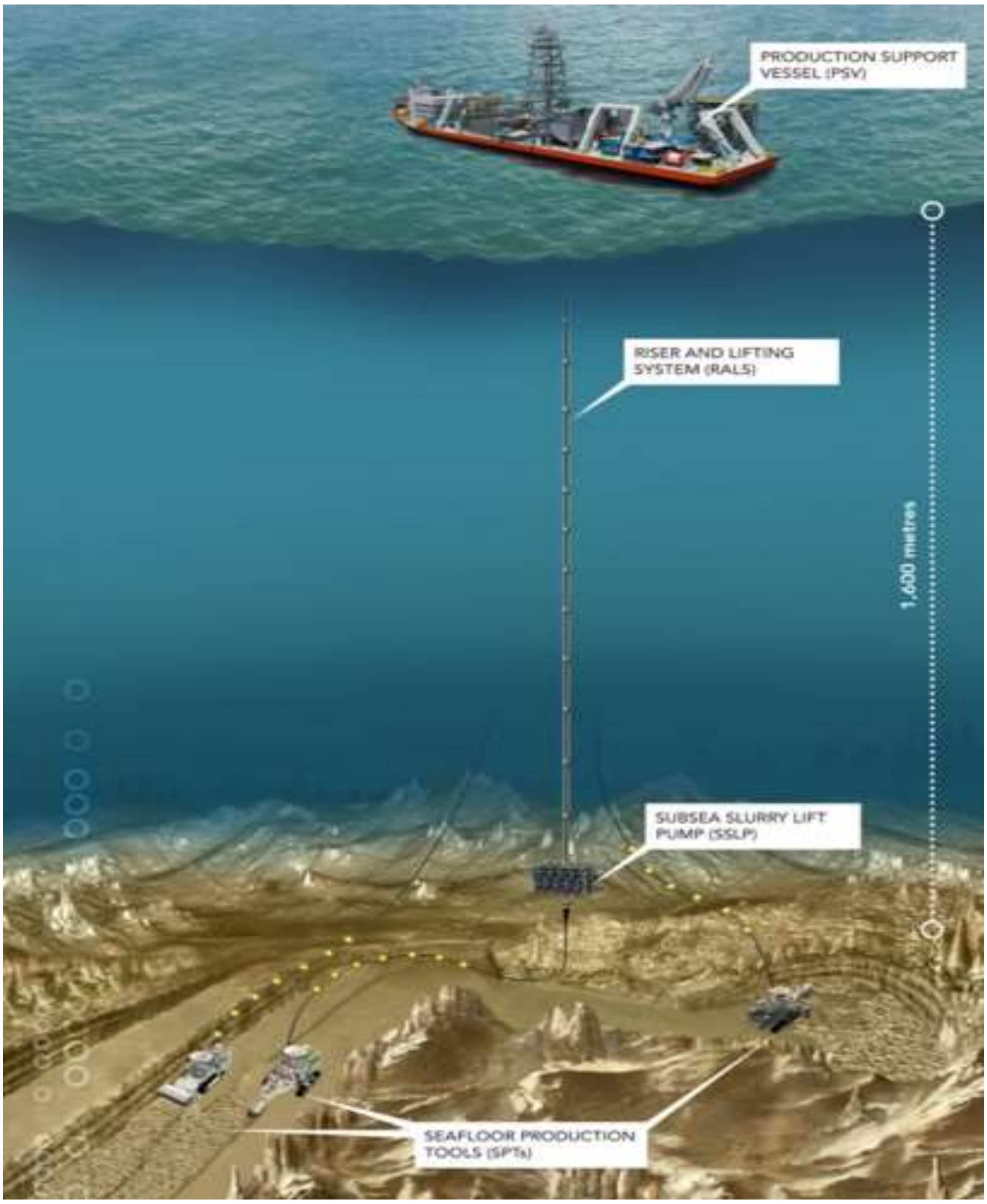


Figure 6: Conceptual image of a mining system (via Deep Sea Mining Finance Ltd), including a surface production support vessel, a riser and lifting system, a subsea slurry lift pump, and seafloor production tools (not to scale) (50).

Figure 7: Mining of SMS will require the physical separation of deposits from the seafloor substrate (54). Specific methods are still being researched and develoureped.

Moreover, DSM concepts typically assume that once recovered from the seabed, ore will be transported to land-based processing sites; mineral processing onboard the support vessel is expected to be limited as dewatering the ore and returning this wastewater to the water column will take priority (52). However, some studies have explored seafloor mineral processing (as opposed to land-based) so as to downsize the scale of production vehicles and tools, and further reduce cost (55).

3.2 Environmental Impacts

There will be environmental impacts of DSM for SMS along the entire value chain, from exploration to production. However, for the purposes of this paper, impacts discussed will include only those specific to deep-sea operations (and not land-based processing and refining) as those impacts will parallel terrestrial mining and are not unique to DSM.

One of the most prominent impacts will be destruction of the hydrothermal vent systems. In many cases, SMS deposits will be directly removed, immediately changing seafloor topography (51). SMS mining is likely to result in flattening of the seabed after vents are drilled, removed, or otherwise manipulated. Studies show that deep-sea biodiversity and ecosystem services benefit from seafloor terrain heterogeneity, and the razing of vents could threaten these functions (56). Some studies suggest, however, that the physical mineral structures of these vents could reform quickly (e.g., within several months to as long as centuries) if the vent remains active; however, this does not account for the recovery of associated species and ecosystems, and cannot be extended to nonactive vents (39, 44). Seabed mining vehicles may also cause the compaction of nearby sediments and other soft substrates, temporarily or indefinitely affecting the terrain surrounding vents (51, 57).

Directly related is habitat loss and fragmentation caused by SMS deposit removal (39). The brunt of these effects will be felt by sessile organisms, as they will be harmed or killed due to their stationary nature; in contrast, motile organisms may migrate away from disturbed areas, although the complete avoidance of all impacts by these organisms is likely impossible (51). As mentioned above, many deep-sea and hydrothermal vent species are endemic, so physical disturbance in one area can lead to local and even global extinction (6).

Increased sedimentation and sediment-rich plumes created from mining activity pose another serious issue. The physical disturbances caused by operations may circulate sediments (consisting of silt, clay, microbes, minerals, and other suspended particles) nearby the vents, creating plumes around the ecosystems (6). Some studies suggest that these plumes may release potentially toxic metals that pose risk to flora and fauna; however, many hydrothermal species have adapted to their metal-rich environment, suggesting that certain organisms may be able to withstand additional metals to a certain capacity (30, 39, 58). Even so, any increase in suspended particles risks the smothering and clogging of filter-feeders such as sponges, bivalves, and certain species of fish (51, 59).

Significantly, impacts due to sedimentation and plumes may be felt not only in the direct mining area, but also in the ‘far field’ (over 10km away from the original site) and all along the water column (51). For example, there are concerns that sediment plumes may drift towards continental shelves, coastline, between EEZs, and even into international waters (60). On top of this, dewatered waste that is returned to the ocean will contain these sediments; because discharge is not always returned to the same location, this allows for adverse sediment-related harm throughout the water column from potentially toxic and nutrient-rich waste waters (39, 61).

Beyond these effects, SMS mining will inevitably create various pollutions in the deep-sea: noise, light, temperature, and chemical. Organisms experience relative silence in the deep-sea environment and induced noise from mining operations will increase ambient noise, thereby affecting deep-sea species, many of which communicate, navigate, and/or detect food using sensitive sound frequencies (18, 51). Similarly, the deep-sea is characterized by complete darkness and increased light from mining vehicles can damage organisms (e.g., blindness, disruption of bioluminescence) as well as cause emigration (18, 62). In the same way, induced vibration and increased water temperature due to mining operations will affect deep-sea organisms, along with the potential for spills of hydraulic fluid and other fuels (6, 32, 51, 63).

4. Discussion

The gradual transition from the bathyal to the abyssal environment represents the strongest biological gradient in the deep-sea, as biodiversity exponentially decreases with depth and distance from land (64). As detailed above, hydrothermal vents represent biodiversity hotspots, characterized by pockets of biologically dense and diverse communities, especially in comparison to surrounding abyssal seafloor (65, 66).

Despite their remoteness, hydrothermal vents provide ecosystem services beyond biodiversity that impact the whole world, including food and habitat provisioning; nutrient cycling; carbon sequestration; water circulation; climate and greenhouse gas regulation; pollutant detoxification; and recreation (10, 67, 68). Hydrothermal vents specifically provide the most intense secondary production of the deep-sea because of the chemoautotrophic primary production and hard substrate (69). Consequently, the total biomass (Fig. 8) of vent ecosystems greatly exceeds that of the abyssal seafloor, with biomass exceeding 70kg/m in active vent fields (70). Studies show that biodiversity loss in the deep-sea is associated with the exponential reduction of ecosystem functioning, which in turn threatens the entire global ecosystem (71, 72).

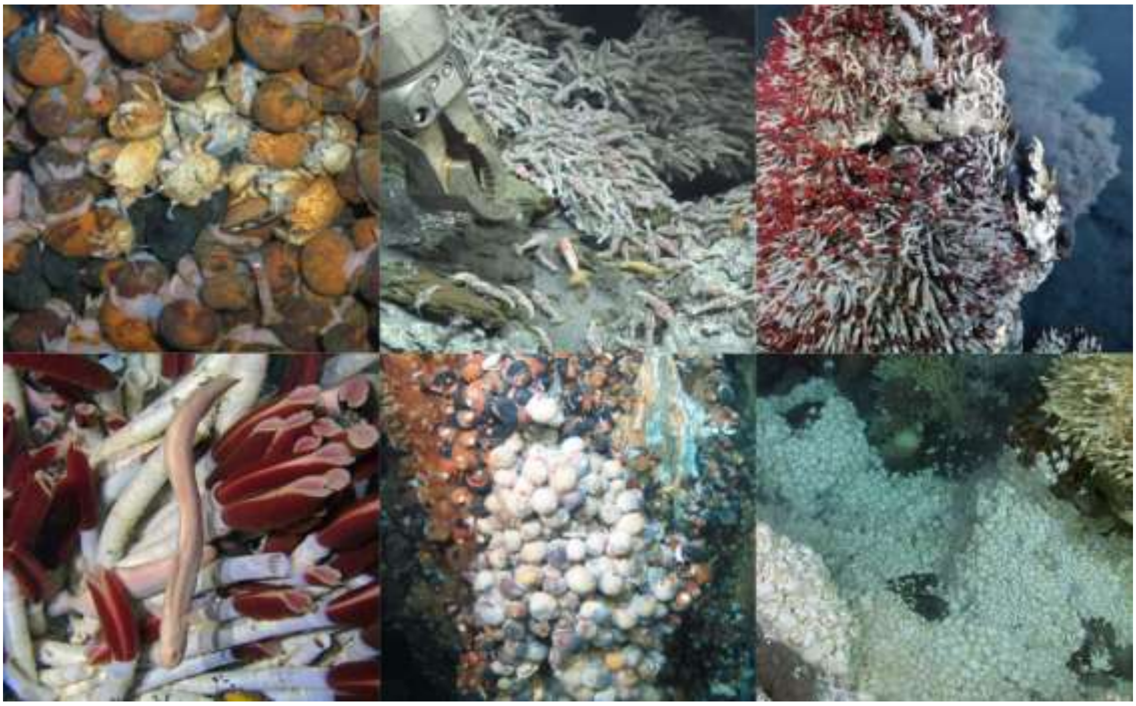


Figure 8: Biodiversity (and biomass) of hydrothermal vent ecosystems (74). From top left, clockwise: hairy-chested Hoff crabs in the Indian Ocean, eyeless shrimp along the Mid-Atlantic Ridge, tube worms in the Juan de Fuca Ridge, Hoff crabs and stalked barnacles in the Southern Ocean, various gastropods in the southwest Pacific, tube worms and zoarcid fish in the East Pacific Rise.

…

Because we do not currently know the full environmental impacts of SMS mining, these ecosystem services and biodiversity benefits risk being seriously affected. It may be impossible to completely understand the impacts until mining is physically carried out; however, by then it may be too late to mitigate the adverse effects. It will be important for deep-sea operators to proceed with a precautionary approach during initial exploration and extraction. The precautionary principle suggests that if an action risks environmental harm without scientific certainty that it does not, the proponent of said action is required to provide this certainty or proof (73).

Marine biology is at a unique place in this context in that science can study and prevent the environmental impacts of this human exploitation before it occurs—historically, exploitation has occurred first, and environmental research has come second. Clearly, hydrothermal vents (both active and nonactive) are important ecosystems of the deep-sea and the entire ocean. However, the destruction of hydrothermal vents by DSM could adversely affect much more than just localized vent fields.

As seen by the ecosystem services that they contribute to, SMS mining could cause significant environmental impacts around the world, many of which may be irreversible. Several scientific studies have even endorsed the complete abandonment of DSM efforts due to the large-scale, long-term risk posed to oceanic ecosystems (61).

Despite these alarming environmental impacts, DSM is still being considered for future mineral exploitation. In some contexts, DSM may be seen as a preferred alternative to terrestrial mining.

4.1 Seafloor Massive Sulfides versus Terrestrial Mining

Despite the wide-reaching environmental impacts anticipated from DSM, there are potential benefits that keep the idea alive. As described in Section 2.2.2., there is an abundance of mineral resources on the seafloor (Fig. 9). In fact, submarine deposits provide some of the largest deposits of many metals, including Mn, Cu, nickel (Ni), and various REEs (4).

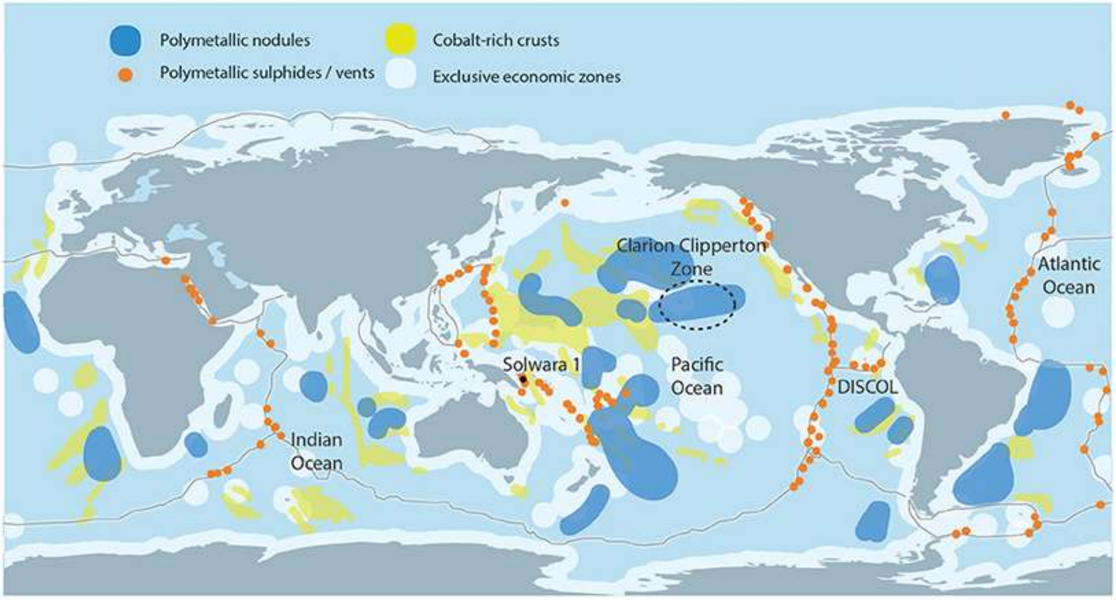


Figure 9: Map of the oceans showing the locations of the three most abundant types of submarine mineral deposits: polymetallic Mn nodules (blue), cobalt-rich FeMn crusts (yellow), SMS (orange); as well as the EEZs of world nations (light blue) (53). Original data from (75).

Furthermore, the metallic grades of several elements of economic interest at SMS (e.g., Cu, Zn, Au, Ag) are significantly higher than their land-based counterparts; rare elements that can be found in SMS deposits include cadmium (Cd), gallium (Ga), germanium (Ge), In, arsenic (As), antimony (Sb), and Se (75). Many of these metals will continue to be needed in greater amounts and higher grades as the demand for 'green' technology increases as we transition to a low-carbon economy (LCE). For example, In is used to make liquid-crystal display (LCD) screens and Sb is used in batteries (76).

SMS mining may also alleviate some of the environmental and social impacts typically experienced from terrestrial sulfide mining. As with most land-based mining operations, sulfide mining typically requires the razing and deforestation of ecosystems to create space for exploration, development, and transportation; similarly, drilling can lead to surface and aquifer contamination, and deposit removal can lead to erosion, acid mine drainage, and toxic sedimentation (both airborne and suspended in water) (77). Socially, terrestrial sulfide mining can be associated with the disruption and abuse of indigenous and other communities, human health risks, and economic burdens associated with reclamation, loss of resources, and ecosystem damage (78, 79). However, while many of these social impacts are avoided by switching to DSM, other adverse environmental (Section 3.2.) and social impacts emerge in their place.

Indeed, the question when contrasting terrestrial and marine sulfide mining is not which approach produces no environmental (or social) harm, but rather which one's impacts can be mitigated best to socially and legally accepted levels. The full extent of SMS mining's environmental impacts is not yet known; however, based on the biodiversity and endemicity provided by deep-sea hydrothermal vents as well as the complex technological and financial challenges created by mining in the deep ocean, SMS DSM is not yet a viable alternative to terrestrial mining.

Despite this fact, the first license for commercial exploitation of deep-sea mineral resources was issued by the ISA in 2011 for within the territorial waters of Papua New Guinea (80). Furthermore, some studies estimate that DSM may commence in international waters by 2025 (6). It is reasonable to expect that if the first DSM efforts are successful, a wave of DSM projects may result, stimulating widespread research, technological development, exploration, and exploitation.

5. Conclusion

The prospect of DSM holds significant opportunity for several different industries as we transition to the LCE. The deep-sea is likely to be the earth's last untapped reservoir of many critical minerals with high volumes and grades. SMS deposits formed at hydrothermal vents oftentimes boast large amounts of Cu, Zn, Au, Ag, Fe, and Pb, of which mining may become feasible and economical within the next decade. However, hydrothermal vents are delicate, productive deep-sea ecosystems that if destroyed by mining operations, could have effects that echo throughout the ocean and even the entire world. The adverse environmental effects of SMS and other submarine deposit mining need to be carefully considered against the benefits and approached with the precautionary principle before commercial DSM commences at a large scale.

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