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Research is needed to inform environmental management of hydrothermally inactive and extinct polymetallic sulfide (PMS) deposits

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ABSTRACT

Polymetallic sulfide (PMS) deposits produced at hydrothermal vents in the deep sea are of potential interest to miners. Hydrothermally active sulfide ecosystems are valued for the extraordinary chemosynthetic communities that they support. Many countries, including Canada, Portugal, and the United States, protect vent

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ecosystems in their Exclusive Economic Zones. When hydrothermal activity ceases temporarily (dormancy) or permanently (extinction), the habitat and associated ecosystem change dramatically. Until recently, so-called "inactive sulfide" habitats, either dormant or extinct, received little attention from biologists. However, the need for environmental management of deep-sea mining places new imperatives for building scientific understanding of the structure and function of inactive PMS deposits. This paper calls for actions of the scientific community and the emergent seabed mining industry to i) undertake fundamental ecological descriptions and study of ecosystem functions and services associated with hydrothermally inactive PMS deposits, ii) evaluate potential environmental risks to ecosystems of inactive PMS deposits through research, and iii) identify environmental management needs that may enable mining of inactive PMS deposits. Mining of some extinct PMS deposits may have reduced environmental risk compared to other seabed mining activities, but this must be validated through scientific research on a case-by-case basis.

1. Introduction

Polymetallic sulfides (PMS; also called Seafloor Massive Sulfides) are produced at active hydrothermal vents on the seafloor and can contain commercially important metals such as copper, zinc, gold, and silver. The volume of PMS that accumulates at a vent site is correlated with the duration of active venting of metal- and sulfide-rich fluids. Hydrothermal vents on the East Pacific Rise, for example, may persist for years to a decade or so, with relatively little accumulation of PMS, whereas vents on the Mid-Atlantic Ridge may persist for 100's of thousands of years and produce large accumulations of PMS [1]. Accumulations of PMS of sufficient size and quality are of interest to seabed miners and are referred to as PMS deposits, while minor accumulations of sulfides are referred to as occurrences [2].

Hydrothermally *active* vent ecosystems typically support dense populations of invertebrates and microbial life that comprise oases of chemosynthetically sustained life in the midst of what is often a low-biomass deep-sea benthos [3,4]. These ecosystems are often associated with PMS (as occurrences or deposits); they can also be associated with diffuse hydrothermal flow emanating from cracks and fissures in rocks. Scientists studying hydrothermally ecosystems follow a voluntary code of conduct designed "to preserve their outstanding beauty for future generations" [5]. Ecosystems associated with hydrothermally active PMS deposits and other geological settings are recognized as rare and vulnerable biodiversity hotspots with intrinsic value [6–8]. Measures to protect hydrothermal-vent ecosystems are already in place within some Exclusive Economic Zones, on Extended Continental Shelf Claims of some coastal States [8,9], and through regional sea conventions (e.g., [10]).

PMS deposits produced at hydrothermal vents may become hydrothermally *inactive* through reorganization of fluid flow. Such reorganization may be the outcome of processes such as clogging of conduits by mineralization [11] or "capping" of the hydrothermal system by minerals and (or) sediment as the underlying heat source cools [12]. Inactive PMS deposits remain linked through fluid-flow pathways to the underlying heat source and may become reactivated through natural (e.g., tectonic activity) or anthropogenic (e.g., drilling, mining) processes. Ultimately, PMS deposits become *extinct*, cut off from the heat source, inexorably migrating with the ocean floor as it moves away from the volcanic spreading axis. Jamieson and Gartman (2020) put forward the case that the terms active, inactive, and extinct PMS deposits only make sense when used at the scale of a vent field, where spatially associated PMS chimneys, edifices and mounds are (or were) linked by a common heat-hydrothermal source [11]. Inactive PMS deposits will be co-located with hydrothermally active PMS deposits or occurrences (i.e., within the same hydrothermal vent field), whereas extinct PMS deposits will not occur within an active hydrothermal vent field [11]. Inactive and extinct PMS deposits may be the most likely seafloor PMS to be mined in the future [13].

The International Seabed Authority (ISA) has regulatory authority over mineral resources of the seabed, legally defined within the 1982 United Nations Convention on the Law of the Sea (UNCLOS) as the "Area" (UNCLOS, article 1). Of the 30 mineral *exploration* contracts awarded to date by the ISA, seven are for PMS on the Mid-Atlantic and Indian Ocean ridges (https://www.isa.org.jm/deep-seabed-minerals-contractors; accessed January 21, 2020). To our knowledge, no regulatory distinction between active, inactive, or extinct PMS deposits has yet been made by the ISA with regard to their exploitation. The ISA does, however, offer formal definitions of active and inactive sulfides, including the concept of dormant PMS deposits that have potential to be reactivated (Box 1). From an ecological perspective, hydrothermally inactive and extinct PMS occurrences and deposits are habitats distinct from active hydrothermal vents. Hydrothermally inactive and extinct sulfide occurrences may represent more than one type of habitat, given, for example, differences in the geochemistry of and microbiology associated with sulfide minerals as they age.

While there is much discussion in the scientific literature about potential impacts of mining hydrothermally active PMS deposits [14–18], the present contribution focuses on environmental management needs related to inactive and extinct PMS deposits and seabed mining. First, we provide a brief overview of abiotic and biotic indicators of hydrothermally inactive and extinct PMS deposits, and then highlight research that may enable effective environmental management planning for mining of inactive or extinct PMS deposits.

2. Environmental indicators of hydrothermally inactive/extinct PMS deposits

Hydrothermally inactive/extinct PMS deposits exhibit no detectable fluid flow or temperature anomaly. In reality, there is a continuum of decreasing hydrothermal activity from high-temperature 'black-smokers' to complete absence of venting fluids. This continuum is informed by increasing sensitivity of methods to detect diffuse, low-temperature fluid fluxes and by the reference frame against which a temperature anomaly is measured.

For environmental management, a suite of relatively simple indicators of hydrothermal activity may be used for an initial assessment of whether a PMS deposit is hydrothermally active or inactive/extinct. Remote sensing of chemical (e.g., redox anomalies), and physical (e.g., temperature, optical backscatter) anomalies in the water column and at the PMS deposit itself [19] can be used to assess hydrothermal activity. Remote imaging may be used to examine surficial PMS deposit for the white mineral anhydride (calcium sulfate). This mineral is deposited at high temperatures and dissolves at lower temperatures, so its presence indicates ongoing high-temperature hydrothermal activity [20]. In practice, characterization of the biota associated with a PMS deposit—specifically the presence or absence of vent-endemic taxa and invertebrate-microbe symbioses that depend on dissolved, reduced chemicals (e.g., H_2S, CH_4, H_2) in diffuse-flow fluids—is likely to be a key determinant in the initial classification of PMS deposit as active or inactive/extinct. Microbial communities within and on PMS deposits also change dramatically in composition and function during the transition from a hydrothermally active to hydrothermally inactive PMS habitat [21,22]. Microbial communities of hydrothermally inactive sulfide habitats include free-living autotrophic bacteria that derive energy from oxidation of sulfide minerals [23,24]. Inactive and extinct PMS deposits lack dense populations of invertebrate taxa dependent on chemosynthetic symbionts characteristic of hydrothermally active vent ecosystems [2], since without fluid flow there is no ready supply of dissolved reduced compounds to fuel these symbioses. It is not known if any taxa associated with inactive sulfide habitats are nutritionally dependent on autotrophic microorganisms that use mineral sulfides as a source of reducing power for chemosynthesis.

Complete cessation of fluid flow is expected to result in mass mortality of vent-flux dependent micro- and macro-organisms within a relativelt short timeframe (days to weeks to months?), accompanied by a transient pulse of scavengers. Over time (months to years?), inactive and extinct PMS deposits may be colonized by epifaunal invertebrate species and species assemblages—including hexactinellid (glass) and cladorhizid (carnivorous) sponges, sea anemones, hydroids, brisingid seastars, and soft, black, gorgonian and stony corals—that also occur on other types of hard substrata [2]. Such taxa are presumed to be susceptible to the toxic qualities of vent fluids and are only able to colonize a site once concentrations of dissolved metals and sulfide are below toxic thresholds [3]. Ecosystem characteristics of inactive or extinct PMS deposits that are buried (sediment-covered) are essentially unknown (but see Ref. [25,26] for microbial studies of such systems).

While taxa endemic (obligate) to the inactive sulfide habitat may yet be discovered, there is no substantive evidence of any such taxa to date [2]. However, a recent eDNA study does highlight significant differences in metazoan diversity among hydrothermally active sulfide habitats, hydrothermally inactive sulfide habitats, and peripheral, hard substratum habitats [27]. Quantitative studies of megafaunal invertebrate taxa associated with inactive sulfide habitats of the Kermadec Arc [28] and the Central Indian Ridge [29] indicate that the hydrothermally inactive sulfides do support distinctive *assemblages* of megafauna not found elsewhere in a given study area, but these studies do not report any species found exclusively on inactive or extinct sulfide occurrences. There is no knowledge regarding differences in faunas of inactive *versus* extinct sulfide habitats exposed on the seafloor, though there are likely differences between sediment-dwelling faunas associated with buried sulfide minerals and epi- and interstitial faunas of exposed sulfide habitats.

3. Research to inform environmental management of mining hydrothermally inactive PMS deposits

3.1. Basic ecological studies

Because there have been only limited studies of inactive or extinct sulfide habitats [2], it is difficult to know the extent to which the fauna of these habitats may be distinct from and (or) linked to the faunas of surrounding non-hydrothermal, non-sulfide mineral deep-sea habitats. This in turn makes it difficult to determine the extent of loss of local biodiversity and ecosystem services due to seabed mining of inactive PMS deposits. Because inactive and extinct PMS deposits may sometimes appear to be barren of megafauna [2], the seeming paucity of organisms might lead to less attention to some environmental baseline measurements during the scoping phase [30]. Baseline ecological surveys and targeted scientific research are required by the ISA during the exploration phase of mining activities to provide information on the pre-mining state of the environment [30]. These surveys and research activities include quantitative characterization of microbial and metazoan community structure, population connectivity and resilience of indicator taxa, trophic interactions, and ecosystem functions and services such as oxygen consumption, primary production, and nutrient cycling [31,32]. Environmental baseline surveys also include studies of natural variability at relevant spatial and temporal scales and environmental correlates of this variability. The precedent for such integrated environmental baseline surveys is already established for polymetallic nodule beds of the Clarion-Clipperton Zone (e.g. Ref. [33–35]) and will be essential for inactive and extinct PMS deposits as well.

3.2. Environmental risks and research needs

Potential environmental risks of deep-sea mining have been discussed extensively in the scientific literature in recent years [2,14,36–39]. The intent here is to raise awareness of certain environmental risks associated with inactive or extinct PMS deposits that may have largely escaped attention to date, and to identify critical research needs. The degree of uncertainty associated with potential environmental risks of mining inactive or extinct PMS deposits is great due to our limited knowledge about the biology of the inactive/extinct sulfide habitat.

Obligate faunal associations. If taxa obligately dependent on the inactive/extinct sulfide habitat are discovered, important research includes study of i) relationships and adaptations of these taxa to the inactive sulfide environment, ii) the vulnerability and resilience of these taxa to habitat destruction and sediment plumes, and iii) precautionary and mitigatory approaches needed to avoid serious harm to populations of these taxa.

Overburden removal. Inactive and extinct PMS deposits of interest to miners may be buried by sediment. Removal of sediment and (or) hard-rock overburden is an environmental management consideration particularly relevant to these deposits. The approach to removal of sediment overburden may include bulldozing and (or) pumping [40]. The necessity to remove and stockpile overburden will generate a third

Box 1
International Seabed Authority definitions of active and inactive sulfides

The International Seabed Authority, which regulates seabed mining in the Area, offers the following definitions (and descriptors) for polymetallic sulfides [31]:

"*Active sulfides*: Polymetallic sulfides through which warm or hot water is flowing. Active sulfides (also called hydrothermal vents) deliver reduced compounds (e.g., sulfide, methane) to the seafloor-seawater interface where they can be oxidized or otherwise autotrophically metabolized by free-living or symbiotic microorganisms.

Inactive (or dormant) sulfides: Polymetallic sulfides through which warm water is no longer flowing into the overlying seawater (i.e., they are "cold"). Disturbance of these sulfides may result in renewal of hydrothermal fluxes into the water column, turning inactive sulfides into active sulfides (hence the concept of "dormant" sulfides)."

The ISA [31] also references.

"*extinct vents* that will remain hydrothermally inactive even when disturbed by test-mining", but does not offer a formal definition of an extinct vent in the glossary of terms. In practice, it is not easy to predict whether a sulphide deposit would or could become active again.

"Active" and "inactive" modifiers as used here reference hydrothermal fluid flux; sulfide minerals themselves react with each other and with seawater, and thus might always be considered active. Similarly, "inactive" sulfides are not inactive biologically; they are colonized by microbes and other organisms and are thus active ecosystems.

type of plume (and the potential for slumping and more plumes), in addition to plumes generated by mining vehicles and return water. Research is needed to i) assess whether there is a specialized community associated with an overburden habitat, and if there is, to understand the ecological characteristics, vulnerability, and resilience of this community, and ii) to assess the dispersal and contaminant characteristics of any overburden plume and its potential impact on surrounding pelagic and benthic ecosystems.

Reactivation of inactive PMS deposits and potential impacts on nearby active hydrothermal habitats. PMS deposits are three dimensional, with extensive (up to hundreds of meters) sub-seafloor expressions of mineralization [12,41,42]. Economic resource assessment (e.g., through drilling) and mining of an inactive PMS deposit have the potential to reactivate hydrothermal venting by creating new fluid pathways [11]. This could reactivate venting at the mine site and alter fluid flow and chemistry at active vent ecosystem(s) within the vent field. Technology developments may be needed to address these issues, including methods i) to map linkages between and among hydrothermally active and inactive sulfide deposits, and ii) to detect and monitor changes in fluid flux and geochemistry at active site(s). Development of such technologies may not be realistic given our current inability to map subsurface hydrothermal circulation; a precautionary approach may be to avoid mining activities within any hydrothermally active vent field.

Open-pit mining. Mining of PMS deposits has been proposed to follow open-pit benching methods using seabed crawlers, resulting in three-dimensional alteration of seabed topography and transforming seabed relief from exposed chimneys and mounds to benched depressions [40]. This seabed modification has led to concern regarding altered hydrographic regimes and depressions with stagnant water and increased sediment retention [37]. The topography of ridge flanks where sulfides occur is naturally rough, including steep-sided natural depressions where sediments are known to accumulate [43]. Because bottom currents advect large volumes of seawater and are expected to be turbulent and 'chaotic' along ridge axes [44], they may mitigate concerns about local acidification in mining pits [45]. An additional depression in a region may not impose significant harm to the environment, though this might need to be investigated through modeling of single and multiple mine pits in a region as part of an assessment of cumulative risk from mining operations.

Innovative mining methods and technologies may create different environmental impacts. For example, some equipment manufacturers are investigating a vertical approach to PMS mining [46]. Vertical trench cutter systems are still under development and the environmental impacts have not been determined [46]. However, it has been suggested that vertical mining may entail less sediment disturbance [46], which may reduce plume generation and associated environmental impacts at and near the seafloor. To conduct realistic assessments, more information is needed on the mining technologies to be employed, alongside additional information on the seafloor habitats that may be impacted by these technologies.

Metal toxicity. Mining of sulfide deposits is expected to have a greater potential for metal toxicity than mining of either nodules or crusts, due to the chemically reduced state and high oxidation potential of sulfide minerals compared with fully oxidized polymetallic crust and nodule material. Natural metal-rich fluids and plumes are a characteristic of active hydrothermal vents, but are absent from inactive and extinct PMS deposits. During mining of inactive or extinct PMS deposits, metals that might be in concentrations toxic to invertebrates (e.g., copper, cadmium) are likely to be released as fine particulates, with potential for sublethal and lethal effects on ingestion by pelagic and benthic organisms [47,48]. The ecotoxicology of inactive sulfide mining products (mining plumes, shipboard processing "return" plumes, overburden-removal plumes) at relevant spatial and temporal scales, including bioaccumulation of metals and metal toxicity in benthic and pelagic ecosystems, remains an important area for field and experimental studies [47]. There is also need for further development and testing of new techniques (e.g. *in situ* sensors) to monitor concentrations of bioavailable metals in the environment [e.g., 49]. Chemical characterization and modeling of the fate of dissolved metals and particulate material in plumes generated by mining of inactive or extinct sulfide deposits are needed for environmental impact assessments.

3.3. Management needs

Baseline Studies. As emphasized Section 3.1 and as required for environmental impact assessments, there is need for well-designed baseline studies to understand, amongst other aspects, the diversity (including but not limited to species richness, species abundances, biogeography), ecology and resilience of ecosystems at inactive sulfide habitats. These baseline studies should include maps of the distribution of inactive and extinct sulfides and include detailed biological data from inactive and extinct sulfide habitats targeted for mining as well as those identified for protection from mining, to ensure representative habitats can be identified and conserved.

Habitat classification. A hierarchical approach to habitat classification may be especially useful for difficult-to-sample and data-poor, deep-water ecosystems such as inactive and extinct sulfide habitats [50]. The EUNIS habitat classification system [51] broadly distinguishes between active and inactive vent fields and has been used in classification of the marine space of Portugal [52]. The classification scheme for active and inactive vent fields may not provide sufficient habitat resolution to inform environmental management practices associated with deep-sea mining, including identification of ecosystems at risk of serious harm and of suitable areas to be designated as Impact and Preservation Reference Zones [53].

Monitoring. A possible risk of mining an inactive PMS deposit is an impact on fluid flow at an active sulfide ecosystem within the same vent field. This implies that environmental management by contractors and oversight by regulators will need to be at the level of an active hydrothermal vent field and not at the level of a deposit that makes up only part of a vent field. It also implies that, as noted above, development of effective tools is needed for monitoring changes in fluid flux and delivering early-warning signals of potential environmental impacts at active vents.

Restoration. Once extraction of metal-rich minerals has ceased at an inactive or extinct PMS deposit and mine-closure operations begin, restoration of the disturbed ecosystem to its pre-disturbance state may be impossible or impracticable [54,55]. Research is needed to understand if there is potential for passive (unassisted) restoration and need for active restoration (e.g., deployment of 3-dimensional structures to facilitate colonization by suspension-feeding invertebrates) following mining of inactive or extinct PMS deposits [17]. The efficacy of any restoration activity proposed in environmental management and monitoring plans submitted as part of applications for exploitation contracts would need to be tested. If restoration or rehabilitation is not practical, consideration should be given to identifying a mechanism to compensate for the intrinsic value of habitat loss [56,57], though challenging questions arise, including who should be compensated, how compensation should be distributed, and how much compensation is appropriate.

4. Risks of mining inactive or extinct PMS deposits relative to mining other seabed resources

Mining of hydrothermally inactive or extinct PMS deposits may be perceived to have lower environmental risks than mining hydrothermally active PMS deposits. For example, through research, it may be demonstrated that there are species, populations, assemblages, and ecosystem functions and services in a region (e.g., on basalt outcrops) that are similar to those at inactive or extinct sulfide habitats, reducing the likelihood of significant loss of biodiversity or ecosystem function on a regional scale. Even where such similarity may be demonstrated, recommended conservation targets for protection of representative habitats in a region (i.e., inactive or extinct PMS deposits in this case) are on the order of 30–50% [58,59]. This level of protection would contribute to a precautionary approach. Such an approach has been pursued by the ISA in other mineral provinces, as, for example, through the placement of Areas of Particular Environmental Interest in the Clarion-Clipperton Zone [60]. If species richness, abundance, and biomass are low at inactive and extinct PMS deposits, the impact of habitat loss and other measures of ecosystem health may *appear* to be minimal, increasing the possibility that a social license to mine may be obtained [61], in addition to an exploitation contract being issued by the ISA. Mining inactive and extinct PMS deposits might deflect demand to mine hydrothermally active PMS deposits that support hydrothermal-vent ecosystems. Accessible (i.e., not deeply buried) inactive and extinct PMS deposits are suggested to be more abundant and larger than active PMS deposits [62], which may make it possible to locate inactive and extinct PMS deposits that could serve as Preservation Reference Zones and Impact Reference Zones for environmental monitoring requirements [53]. In contrast, these management zones seem challenging to identify for active hydrothermal vents [6]. Mining inactive PMS deposits will also be technologically less challenging than mining hydrothermally active PMS deposits, where high-temperature (350 °C) and acidic fluids are present.

The need for caution, however, is paramount. The potential for lower environmental risk at inactive and extinct PMS deposits compared to potential environmental risks for other seabed resources has not been validated, particularly given the relative absence of knowledge about faunas associated with inactive/extinct sulfide habitats. For inactive PMS deposits, the possibility of generating impacts at active vents within the same vent field has the potential to be a serious risk to populations of vent-endemic organisms. The lack of data underpinning potentially reduced environmental risks of mining at inactive and extinct PMS deposits will likely motivate research to increase knowledge of the ecology of inactive/extinct PMS habitats and address many of the gaps identified here.

5. Conclusions

Inactive and extinct PMS deposits may offer opportunities for mining, but significant impacts could arise through, for example, impacts to active sulfide ecosystems should an inactive PMS deposit be reactivated within a vent field, or through risks associated with metal toxicity or overburden removal. A clarion call is put forth to the scientific community and marine minerals industry to build new knowledge about ecosystems of hydrothermally inactive and extinct PMS deposits through research and technology development. Baseline data arising from field studies of inactive and extinct PMS deposits will help to fill immense knowledge gaps regarding these habitats.

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Declaration of competing interest

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