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Scientific rationale and international obligations for protection of active hydrothermal vent ecosystems from deep-sea mining

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ABSTRACT

There is increasing interest in mining minerals on the seabed, including seafloor massive sulfide deposits that form at hydrothermal vents. The International Seabed Authority is currently drafting a Mining Code, including environmental regulations, for polymetallic sulfides and other mineral exploitation on the seabed in the area beyond national jurisdictions. This paper summarizes 1) the ecological vulnerability of active vent ecosystems and aspects of this vulnerability that remain subject to conjecture, 2) evidence for limited mineral resource opportunity at active vents, 3) non-extractive values of active vent ecosystems, 4) precedents and international obligations for protection of hydrothermal vents, and 5) obligations of the International Seabed Authority under the UN Convention on the Law of the Sea for protection of the marine environment from the impacts of mining. Heterogeneity of active vent ecosystems makes it extremely challenging to identify "representative" systems for any regional, area-based management approach to conservation. Protection of active vent ecosystems from mining impacts (direct and indirect) would set aside only a small fraction of the international seabed and its mineral resources, would contribute to international obligations for marine conservation, would have non-extractive benefits, and would be a precautionary approach.

1. Introduction

Hydrothermal vent ecosystems are natural wonders of the ocean. They exist as tiny islands in the unimaginably vast expanse of the deep sea; they are oases of vibrant and exotic life dependent on microbes that produce food using chemical energy through chemosynthesis. Biomass at active vents is dominated by species that rely on venting fluids and that can live nowhere else (Fig. 1). Active vent ecosystems are living libraries [1], sites where the sciences, arts, and humanities gain new knowledge and understanding at the intersection of Life and Earth processes. They are storehouses of endemic marine genetic diversity [2], including resources that contribute to the well-being of humans, and they catalyze research into the possibilities for, and limits of, Life itself.

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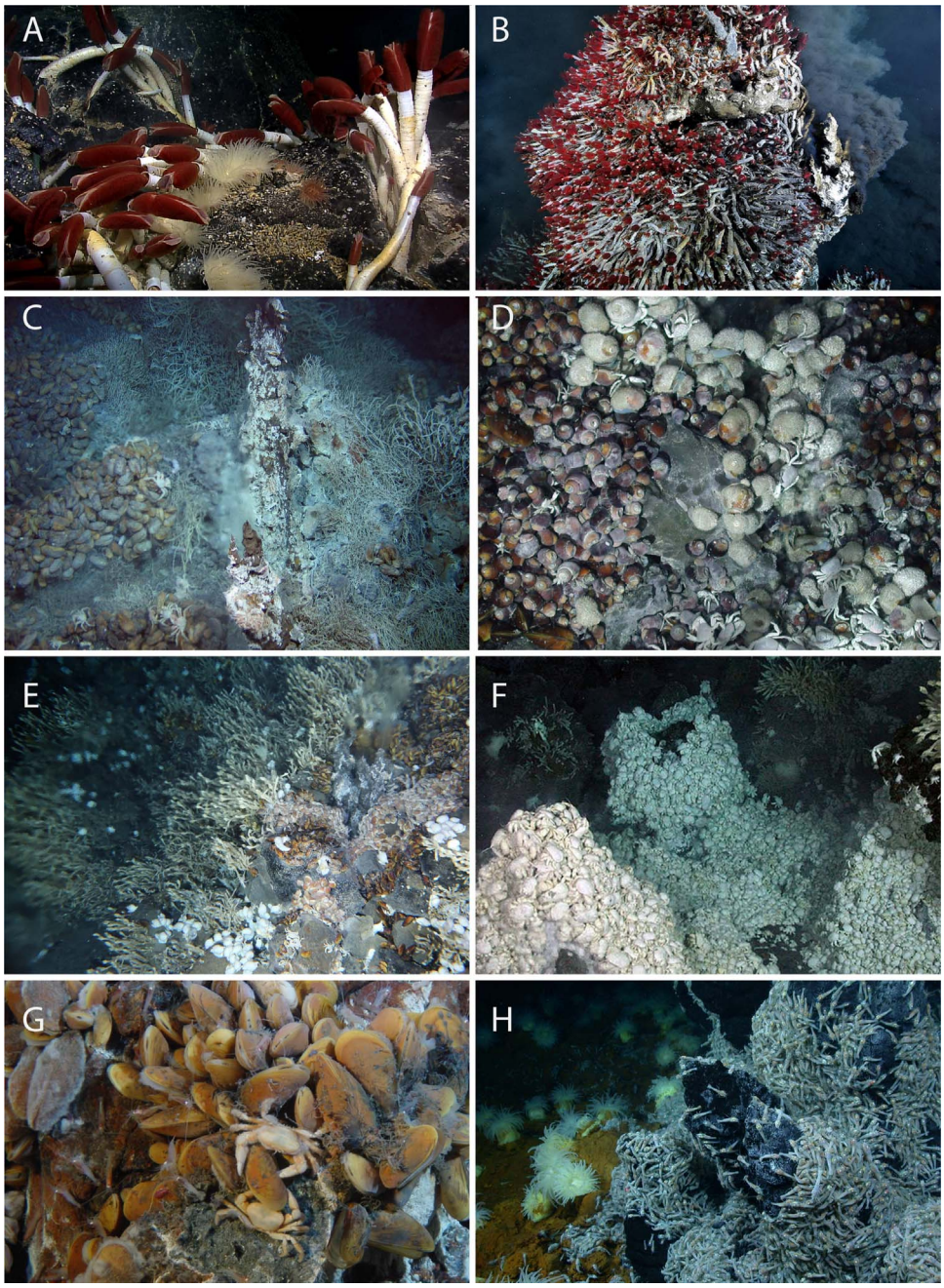

Fig. 1. Variation in the dominant, symbiont-hosting invertebrates at active hydrothermal vents around the globe. Vent communities differ widely among biogeographic regions. A key observation not evident in these regionally "iconic" photos is that different vents within a region support different assemblages of species. **Eastern Pacific Ocean:** (A) Giant tubeworms (*Riftia pachyptila*) with limpets and anemones; Galapagos Spreading Center; courtesy *Wikimedia*; B) Tubeworms (*Ridgeia piscesae*) with alvinellid polychaetes, Endeavour Hydrothermal Vents Marine Protected Area, Juan de Fuca Ridge; courtesy *Ocean Networks Canada*. **Western Pacific Ocean:** (C) Mussels (*Bathymodiolus septemdierum*) and tubeworms (*Lamellibrachia* sp*)* with lithodid crabs, Nifonea Vent Field, New Hebrides Volcanic Arc; courtesy ROV Kiel 6000, *GEOMAR*; D) Hairy (*Alviniconcha* spp.) and black (*Ifremeria nautilei*) snails with bythograeid crabs (*Austinograea alaysae*), Tu'i Malila Vent Field, Lau Basin; courtesy *Woods Hole Oceanographic Institution*. **Indian Ocean: (**E) Lepadid barnacles, scaly-foot snails (*Chrysomallon squamiferum*), mussels (*Bathymodiolus* aff. *brevior*), Solitaire Vent Field, Central Indian Ridge; courtesy *JAMSTEC*. **Southern Ocean: (**F) Yeti squat lobster (*Kiwa tyleri)*, East Scotia Ridge; courtesy *NERC ChEsSo Consortium.* **Atlantic Ocean: (**G) Mussels (*Bathymodiolus azoricus*) with bythograeid crabs, Lucky Strike Vent Field, Mid-Atlantic Ridge; courtesy *IFREMER*. **Caribbean Sea: (** H) Swarming shrimp (*Rimicaris hybisae*), Beebe Vent, Mid-Cayman Rise; courtesy *Woods Hole Oceanographic Institution*.

Active hydrothermal vents also host high-temperature (350 °C) "black smokers" that discharge metal-rich fluids. These metals precipitate at or below the seafloor to form polymetallic (especially copper and zinc) sulfides. Locations where metal-rich particulates accumulate over thousands of years are of interest to an emergent, international, deep-sea mining industry [3]. Regulations are being developed by the International Seabed Authority for the exploitation of deep-sea manganese nodules, cobalt crusts, and polymetallic sulfide deposits found in areas beyond national jurisdiction. There is thus urgency in considering whether ecological characteristics, international obligations, and other insights concerning the value of active hydrothermal vent ecosystems indicate that they should be protected, not mined.

Proposed mining of seafloor sulfide deposits will likely resemble open-cut mining on land, with removal of ore to depths of 20–30 m or more beneath the level of the natural seafloor. Our understanding of seabed mining concepts is derived primarily from pioneer documents associated with the Nautilus Minerals Niugini Limited "Solwara 1 Prospect", an area of active venting (considered to be a 'waning' system based on observations by Nautilus Minerals) that supports chemosynthetic communities [4]. While hydrothermal flux sustaining these chemosynthetic communities will not cease as a result of mining, the Environmental Impact Assessment prepared for Nautilus Minerals [5] states that *"[m]ost of the animals and their existing habitat in the path of the SMT [Seafloor Mining Tool] are likely to be removed by mining, hence the immediate loss at the local scale will be severe*" (Chapter 9, p. 24). Environmental impact assessments and management plans that only require miners to avoid and minimize environmental impacts at hydrothermal vents *where possible* [6] may not afford sufficient protection; the act of mining itself will cause severe, if not total, loss of biodiversity at the mine site.

2. Vulnerability of active hydrothermal vent ecosystems

Active vent ecosystems are "Small Natural Features" [7] with

ecological importance disproportionate to their size [8]. Active vent fields are located in narrow corridors along the 60,000-km-long path of the mid-ocean ridge axis, along 10,000 km of back-arc spreading centers, and at many volcanoes belonging to the submerged portions of volcanic arcs [9]. Most active vent sites would easily fit into a public auditorium. Even where vent fields are "large", the area of active vent ecosystems is commonly over-estimated. For example, the Pacmanus vent field in the eastern Manus Basin (Papua New Guinea), is described as 1-km long and several hundred meters wide. In reality, Pacmanus comprises a number of small sulfide mounds (e.g., Roman Ruins, Fenway, Snow Cap) and many individual active vents (a few square meters each) protruding through volcanic rocks [10], rather than a continuous expanse of vent ecosystem. The active vent ecosystem at TAG on the Mid-Atlantic Ridge—one of the largest known vent fields—covers an area not much larger than about two soccer fields (football pitches) [11]. Globally, the active vent ecosystem is a rare habitat, comprising an estimated 50 km^2, or < 0.00001% of the surface area of the planet,[1] and less than 1% of the total area of Yellowstone National Park (USA) and its hot springs. Even if this areal extent is an underestimate by one or even a few orders of magnitude, the scarcity of the vent habitat is uncontroversial and places vent ecosystems at risk.

The physical, geological, and biological consequences of mining active hydrothermal vents are uncertain, and the ability of vent ecosystems to recover from mining is open to conjecture [12]. Although scientific drilling is nowhere near as invasive or environmentally degrading as the bulk-mining envisioned by industry, the impact of scientific drilling at vents provides a glimpse into the unpredictability of responses of active vent ecosystems to major disturbances. A deep drilling operation at the Iheya North hydrothermal field (Okinawa Trough, Pacific Ocean) resulted in transformation of a vent-clam/soft-sediment habitat to a crust with higher temperature flow colonized by bacterial mat and squat lobsters [13]. In contrast, there was little perceptible change in the nature of the shrimp-dominated vent ecosystem of black smoker chimneys and the fauna of the sulfide apron at the TAG hydrothermal mound on the Mid-Atlantic Ridge following scientific drilling operations (ODP Leg 158; [14]). These different outcomes of scientific drilling underscore our inability to predict ecosystem responses to anthropogenic disturbance at hydrothermal vents.

Decadal-scale recovery of vent communities following seabed volcanic eruptions has been documented on the East Pacific Rise [15] and at Axial Volcano on the Juan de Fuca Ridge [16,17]. At NW Rota-1 on the Mariana Arc, recovery has been observed on even shorter timescales [18]. These observations are commonly used as evidence for the resilience of vent ecosystems to disturbance [12,19,20]. However, these volcanically active sites with high-disturbance regimes are not representative of active vent settings at slow-spreading mid-ocean ridges, where large ore deposits may be found and where major disturbance events are infrequent. Are species endemic to long-lived vent sites also resilient? While species may recolonize an active vent site after mining has taken place, it is not certain how much the habitability of a long-lived site will be modified, nor how many or which species would recolonize, how interactions among species might be altered, or how long recovery might take.

To predict recovery from a disturbance event, an understanding of how populations of endemic species at these small islands are connected by pelagic larval stages is essential. Even for well-studied vent species, where genetic data suggests extensive (1000 s of km) population connectivity on evolutionary time scales [e.g., *Rimicaris exoculata* on the Mid-Atlantic Ridge [21]], life-history processes that enable local populations to be maintained are not well understood, nor are there reliable recruitment models. Populations of a vent species at different sites are unlikely to contribute equally to establishment and maintenance of populations at other sites [22]. This inequality means that habitat destruction and population loss from a "source" site (that supplies recruits to other sites) will place "sink" sites at risk of loss of biodiversity [8]. Mining multiple vent sites in a region may be the only way that a company might realize a profit [3]; cumulative impacts at the seabed and in the water column from multiple mining events would exacerbate mining-related loss of biodiversity.

In theory, establishment of effective, replicated, representative networks of protected areas, currently recommended as a key conservation effort by member States to the Convention on Biological Diversity [23] and by the deep-sea scientific community [24,25], would help reduce biodiversity loss resulting from mining. But in practice, it would be challenging, if not impossible, to design replicated networks of representative sites for active vent ecosystems, given site-to-site differences in habitats and species assemblages in areas of the international seabed that are of interest to mining contractors. Between oceanic regions, differences among vent faunas are on the same order as species differences between tropical and boreal forests on different continents [26] (Fig. 1). Even within an ocean region, few vent species are shared across all vent sites (< 5% of the regional species list), with most species (~ 60%) found at only one site [27]. Vent organisms are exquisitely sensitive to nuances in fluid flux, chemical composition of vent fluids, and temperature [28,29], to the geological setting [30], and to biological interactions [31]. Species assemblages may differ markedly from one vent site to the next in the same region because habitat conditions are also markedly different [27,28,32,33].

Adaptation and response to such environmental drivers results in variable distributions of species along any geological feature that hosts hydrothermal activity [34]. Terrestrial environments such as island-chain habitats show similar species-assembly characteristics: species composition varies with size of an island, distance, habitat diversity among islands, etc. [35]. An important consequence of this pattern of natural variability in island systems is that it is difficult to designate a "representative" ecosystem in most regions. This lack of a representative ecosystem has been well documented for active vent fields of the northern Mid-Atlantic Ridge by the work of Desbruyeres et al. ([36]; see especially Table 4), wherein species composition and abundances at the Menez Gwen, Lucky Strike, Rainbow, Broken Spur, TAG, Snake Pit, and Logatchev active vents are compared. Striking differences among these sites are recorded in dominant species on sulfide chimneys, at chimney bases, and in dominant accompanying species, dominant peripheral species, and dominant carnivorous species. Important dissimilarities among the faunas of adjacent vent sites are thus viewed as the norm, not the exception.

While vent ecosystems are visually dominated by a few abundant species, many taxa at vents appear to be rare (comprising < 5% of the total abundance in samples), and some are known from only one or a few collected specimens, even where sampling efforts have been extensive (e.g., [32,4]). Rarity is likely a consequence of multiple factors within vent ecosystems, including the scarcity of habitat, the high degree of specialization to narrow niches, the disjunct nature of the habitat, and limited sampling effort. Further attention is necessary to understand the functional role of rare species at vents and their vulnerability [37].

International, regional, and state regulations call for restorative actions in degraded habitats, but there are no tested approaches to restore or rehabilitate vent ecosystems (including the overlying water column). Similar efforts on land or in near-shore ecosystems, such as seagrass beds and coral reefs, demonstrate that successful restoration is challenging in better known systems and far more tractable contexts [38,39]. Industrial-scale, active interventions to restore hydrothermal vents in the deep sea, even if logistically feasible, will likely be orders of magnitude costlier per hectare than any effort on land [40]. Scientific assessment of restoration or remediation is a critical action toward best

[1] Average active vent area estimated at ~ 30 m diameter; number of active vent sites estimated at ~ 5000 [689 known vents (InterRidge Database: https://vents-data.interridge.org/ventfields_list_all, accessed 17 June 2017) multiplied by the Baker et al. [45] estimate that 3× to 6× more active vents exist than are currently known]; total area of active vents = ~ 50 km^2; total area of planet = 510,000,000 km^2.

practices, but restoration as an environmental management tool at an industrial scale will require years to decades (possibly more) before it can be responsibly applied and reliable [40]. Further, given the biological, hydrological, chemical, and physical heterogeneity of vent ecosystems, there is no guarantee that a practice developed for one vent ecosystem would be effective in another.

3. A limited mineral resource opportunity

The prevalence of metals in modern technology, competition for mineral resources, rising metal prices, and acknowledgement of the widespread societal and ecological harm caused by some land-based mining activities fuel the search for minerals on the seabed, despite the additional cost of extracting minerals from great oceanic depths. Part of the rationale for exploitation of polymetallic sulfides seems to be based on the misconception that mining seafloor massive sulfides at active vents will contribute significantly to the global metal supply. However, a recent assessment of the global metal resource associated with sulfides at hydrothermal vent sites finds this not to be the case. Based on known and predicted vent site abundance and size along the neovolcanic zone of mid-ocean ridges and back-arc spreading centers, only 600 million tons of sulfide (containing ~ 30 million tons of copper and zinc) are likely to be found at known active and inactive vents combined – irrespective of their size [41]. In contrast, current land-based mining extracts 19 million tons of copper and 12 million tons of zinc annually [42], and the static lifetime (i.e., how long proven metal reserves will allow mining at current annual production) for these metals is measured in decades. The presence of trace metals [including so-called critical metals and even rare-earth elements [43]] at active hydrothermal vents is also used as an argument for mining seafloor sulfide deposits. Yet concentrations of these metals in vent sulfides are usually low compared to sources on land [44].

Exploration for seafloor massive sulfides in areas beyond national jurisdiction is focused on slow- and ultra-slow spreading ridges, where sulfide precipitates accumulate over very long durations (10–100 s of thousands of years). At present, there are one pending and two ISA-approved exploration contracts for polymetallic sulfides in the North Atlantic (Fig. 2), plus another four ISA-approved exploration contracts in the Indian Ocean. Exploration is mainly occurring along the neovolcanic zone, where active vent ecosystems are located. These active vents are easy to detect by prospecting for chemical and physical anomalies associated with plumes from black smokers in the water column (e.g., [45]). So-called “inactive” sulfide occurrences (also referred to as dormant, extinct, or fossil vent sites), where venting has ceased and chemosynthetic ecosystems are absent, are harder to detect, but they may contain more metals than active vent sites. Inactive sulfides on older, off-axis oceanic crust are expected to be larger than those in the axial neovolcanic zone because they have undergone a complete formation cycle [46]. Due to their age, however, off-axis sulfides will likely be overlain by meters or more of sediment. New geophysical tools currently under development may allow discovery of such large, *inactive* sulfide occurrences that could become viable future mining targets [47].

4. Other values of hydrothermal vent ecosystems

Protection of active hydrothermal vents may represent an opportunity cost for the mining industry, but would help maintain benefits for others. Extensive exploitation of sulfide deposits associated with active vent ecosystems on a regional basis could interfere with capture of other societal benefits that might accrue from these ecosystems. Such benefits include increased scientific knowledge about the deep ocean and potential applications of this knowledge [48,49]. Recent examples include electricity generated at the interface between sulfide minerals and seawater that might be used by microorganisms to fuel cellular metabolisms [87]; bioinspired materials and mechanical design principles for synthetic, multilayered structural composites as protective materials, based on the shell of the scaly-foot snail [50]; and methods to improve organ transplant preservation using the extraordinary oxygen transport and delivery properties of hemoglobin from vent tubeworms [51].

Active vent ecosystems are also valued for their genetic diversity and for the potential for discovery of marine genetic resources. Bioprospecting, when undertaken using non-harvest approaches, is environmentally friendly, and there are already examples of marine genetic resources derived from vent discoveries. These include enzymes that function under extremes of temperature, chemistry, and pressure (“extremozymes” developed from very small samples of vent organisms) that have substantial impact on society, as well as commercial value. The *Valley UltraThin™* enzyme, which increases the efficiency of ethanol production from cornstarch and is sourced from a deep-sea hydrothermal vent organism, posted annual sales value of $150M (USD) [52]. The market for enzyme products derived from all marine genetic resources has been valued at more than $50B per year [52]. The value of biotechnology products derived from active vent ecosystems may compete well against the value of polymetallic sulfide ores, estimated at $1B annually for each mining operation [53]. Exploration to discover and develop biofuel, nutraceutical, biomimetic, pharmaceutical, cosmetic, and other products from healthy, active vents could be an alternative, sustainable use of vent ecosystems.

Hydrothermal vents and their ecosystems also appeal to segments of society, generating important non-extractive use values. For example, the private, non-profit Ocean Exploration Trust broadcasts their deep-sea oceanographic explorations using telepresence. In 2016, live feeds of ROVs working on the seafloor were joined by millions of viewers, sometimes during a single dive [54,55]. James Cameron's 3-D feature films *Volcanoes of the Deep Sea* (2003) and *Aliens of the Deep* (2005), as well as segments of the BBC television series *Blue Planet* (2001), *Blue Planet 2* (2017), and *Planet Earth* (2006) deliver the wonder of hydrothermal vents to millions of children and adults in theatres, in classrooms, and at home. Aquaria and museums around the globe (e.g., New York, Paris, Athens, Moscow) feature exhibits that create a sense of place; vents represent totems for what is still unknown in natural history. Catalogs of children's books, coffee table books, and trade books list titles devoted to or inspired by hydrothermal vents, including *The Octopus's Garden* [56], *Fountains of Life* [57], *Kira's Undersea Garden* [58], *The Deep* [59], *Deeper than Light* [60], and *Alien Deep* [61]. In addition to serving as the foundation of a ‘marine wonderment’ industry, with revenues that may rival those from mineral extraction at active vents, these products signal the existence of a type of ecosystem that the public will never experience in situ, but has proven important for inspiring curiosity in future generations about science, technology, our world, and worlds beyond. It is the existence of life in active vent ecosystems on Earth that compels astrobiologists to seek hydrothermal activity and life on other ocean worlds, including Saturn's moon Enceladus and Jupiter's moon Europa [62].

5. Precedents and international obligations for protection of hydrothermal vents

Recognition of the ecological rarity and vulnerable status of active hydrothermal vent sites is not new. Key interventions for full protection of ecosystems at active hydrothermal vents have been enacted by several coastal States through establishment and management of area-based protection (Canada, Mexico, New Caledonia, Portugal, USA) [63]. Canada recently augmented its 2003 implementation of the Endeavour Hydrothermal Vents Marine Protected Area by announcing the intention to protect all hydrothermal vents sites in its waters in a large offshore area [64].

There exists a multitude of legal obligations, policy statements, and precedents for the protection of hydrothermal vents because of their rare and vulnerable (or “fragile”) characteristics. In 2004, the United

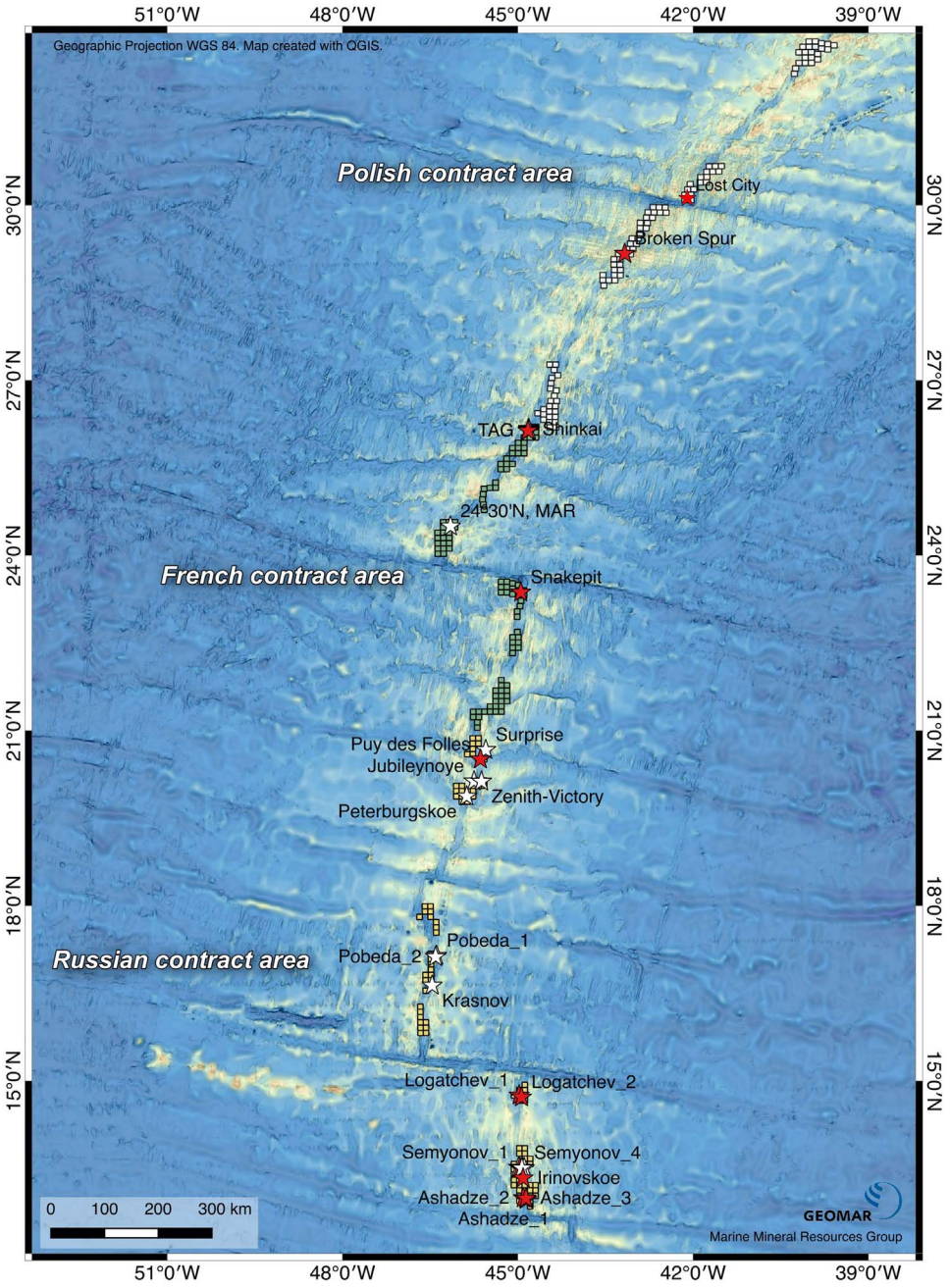

Fig. 2. Polymetallic sulfide blocks (each block is ≤ 10 km × 10 km) approved for exploration by the International Seabed Authority (ISA) in the north Atlantic (yellow blocks: Russian Federation, green blocks: France) or pending approval by the ISA (white blocks: Poland) and the locations of known active vent ecosystems (red stars) and inactive sulfide mounds (white stars). The size and distribution of blocks is prescribed by Regulation 12 (International Seabed Authority 2010): maximum exploration area per contract is 10,000 km^2, maximum area after all required relinquishment during the 15-year exploration contract is ≤ 2500 km^2; blocks must be arranged into ≥ 5 clusters, with each cluster containing ≥ 5 contiguous blocks, all within a rectangle not exceeding 300,000 km^2, with the longest dimension ≤ 1000 km. Additional requirements may apply (see Regulation 12). Background topography is the GEBCO 30 arc-second interval grid (www.gebco.net). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Nations General Assembly (UNGA) Resolution 59/24 called for States to manage risks to the marine biodiversity of hydrothermal vents and the UNGA also adopted Resolution 59/25, committing States to take action urgently to consider interim prohibitions on destructive fishing practices that have adverse impacts on vulnerable marine ecosystems including seamounts, hydrothermal vents and cold-water corals. In the same year, the Conference of the Parties to the Convention on Biological Diversity (CBD), in its Decision VII/5 (paragraph 30) agreed to the "*urgent need for international cooperation and action to improve conservation and sustainable use of biodiversity in marine areas beyond the limits of national jurisdiction*", including through the establishment of marine protected areas that include seamounts, hydrothermal vents, cold-water corals, and/or other vulnerable ecosystems. UNGA Resolution 61/105 (adopted in 2006) commits States to *"protect vulnerable marine ecosystems, including … hydrothermal vents …, from destructive fishing practices, recognizing the immense importance and value of deep sea ecosystems and the biodiversity they contain."* The Council of the European Union requires the protection of hydrothermal vents from bottom fishing through Council Regulation 734/2008, adopted by the EU to implement UNGA Resolution 61/105, wherein member States are "*committed to the conservation of marine ecosystems such as … hydrothermal vents …*", and explicitly includes hydrothermal vents in a list of vulnerable marine ecosystems ([65]; Article 2b). In 2008, parties to the CBD recognized hydrothermal vents as meeting criteria for designation as "Ecologically and Biologically Significant Areas" (EBSAs; [66,67]), where enhanced conservation and management measures may be needed. Provisions of the CBD related to States' activities regarding biodiversity protection apply beyond areas under national jurisdiction; States that currently sponsor exploration for polymetallic sulfides in such areas (India, Germany, France, Korea, Russia, China) are bound by the CBD.

The multilaterally negotiated International Guidelines for the Management of Deep-Sea Fisheries in the High Seas, adopted in 2008 to assist States in the implementation of UN General Assembly Resolution

61/105 and subsequent UNGA resolutions related to managing bottom fisheries in areas beyond national jurisdiction, list hydrothermal vents and their endemic communities as an example of a "vulnerable marine ecosystem" and should be protected from significant adverse impacts caused by bottom fishing [68]. While UNGA resolutions and International Guidelines are not legally binding, key provisions of these instruments, including criteria for identifying vulnerable marine ecosystems and requirements that such ecosystems be protected from significant adverse impacts, have become binding on States in most high seas areas through their incorporation into regulations adopted by Regional Fisheries Management Organizations (RFMOs), which have the legal competence to manage bottom fisheries in areas beyond national jurisdiction [69]. In 2016, the UN General Assembly reaffirmed and strengthened the commitment of States and RFMOs to adopt and implement regulations to protect vulnerable deep-sea ecosystems from the adverse impacts of bottom fisheries and encouraged regulatory bodies with competence over other activities potentially impacting such ecosystems in areas beyond national jurisdiction (e.g., the ISA) to consider doing the same (Resolution 71/123).

The Oslo and Paris (OSPAR) Commission for the Convention for the Protection of the Marine Environment of the North-East Atlantic recommends protection and conservation of hydrothermal vent fields as "priority habitats" [70] in the OSPAR maritime area (NE Atlantic). OSPAR also called for "*raising awareness of the importance of hydrothermal vents/fields occurring on oceanic ridges among relevant management authorities, relevant actors including industry sectors and the general public*" [71]. Protection has also been accorded to vent ecosystems by the scientific community through responsible research practices, as outlined in the 2007 InterRidge Code of Conduct [72]. These practices were reiterated by the OSPAR Commission for research activities in the northeast Atlantic [73]. The UNESCO Marine World Heritage Program also recently highlighted the *Lost City* vent ecosystem on the Mid-Atlantic Ridge as one example of a site that meets criteria for outstanding, universal value in international waters [74]. From these actions, it is evident that active hydrothermal vent ecosystems are recognized through multiple international, regional, and State interventions as natural areas in need of protection and conservation.

6. Obligations of the International Seabed Authority under the UN Convention on the Law of the Sea

Regulation of deep-sea mining and protection of the marine environment from mining activities on the international seabed are the responsibility of the International Seabed Authority (ISA), created through the United Nations Convention on the Law of the Sea (UNCLOS). The Convention was debated and drafted formally from 1973 to 1982, thus preceding by several years the discovery of active vents [75] and black smokers [76]. Given its mandate over "all solid, liquid, or gaseous mineral resources in situ in the Area or beneath the seabed, including polymetallic nodules" (UNCLOS Article 133), the ISA became, by default, the body to regulate and manage extraction of minerals deposited at vents. In the decades since the ISA was established, international policy and legal obligations for conservation of biodiversity, protection of vulnerable ecosystems, and sustainable development have evolved. It is time to ask whether active vent ecosystems *should* be mined, rather than default to mining without discussion.

The ISA, mining contractors, and sponsoring States are required to apply a precautionary approach to ensure effective protection for the marine environment from harmful effects of mining (*Regulations on Prospecting and Exploration for Polymetallic Sulfides in the Area; Regulations 33.2, 33.5*) [77,78]. This requirement entails, *inter alia*, the implementation of protective measures at an *early* stage in response to a risk of harm, even if scientific evidence as to the specific harm remains uncertain. These measures must be effective in ensuring the protection of hydrothermal vent ecosystems and must be proportionate to the risk [79]. While a moratorium on mining impacts on active vent ecosystems may be considered a far-reaching precautionary measure by some, it is currently the only known measure that would, with certainty, be effective in protecting ecosystems associated with active vents in accordance with UNCLOS Articles 145 and 194. Article 145 requires the ISA to prevent "*damage to the flora and fauna of the marine environment*" from deep seabed mining, and Article 194 requires States to take measures "*necessary to protect and preserve rare or fragile ecosystems as well as the habitat of depleted, threatened or endangered species and other forms of marine life*".

As a first step in implementing the UNCLOS obligations outlined in Articles 145 and 194, the ISA's *Mining Code* for exploration calls for application of a precautionary approach and protection of *"vulnerable marine ecosystems, in particular, hydrothermal vents…"* from serious harm (*Regulations on Prospecting and Exploration for Polymetallic Sulfides in the Area;* Regulation 33) [77]. This call for protection of vulnerable marine ecosystems is also included in draft exploitation regulations proposed by the ISA [80] and in a parallel discussion paper on environmental matters related to exploitation regulations [81]. Protection of active hydrothermal vents by the marine mining sector would be consistent with "No-Go Zones" for mining on land, where avoidance of areas characterized by high biodiversity and endemism, rare or endangered species, rare habitats, and intactness, is practiced [82].

The international community has recognized protection as a viable and proportionate option for particularly vulnerable species and ecosystems elsewhere. For example, moratoria have been applied to commercial whaling [83] and to all mineral resource activities in the Antarctic [84,85]. Protection of active hydrothermal vent ecosystems from direct and indirect impacts of mining on the international seabed would be consistent with the ISA designation of hydrothermal vents as vulnerable, the ISA's obligation to employ a precautionary approach, the obligations under UNCLOS Articles 145 and 194, and the aforementioned precedents for protection of hydrothermal vents under other international conventions. Full protection of all active hydrothermal vents would obviate the need to make difficult and incompletely informed decisions about environmental risks on a case-by-case basis, which would be a strategy fraught with potential for first-mover advantage, regulatory capture, and politically driven decision making. Further, protection of active vent ecosystems would be an important contribution by ISA member States to Sustainable Development Goal (SDG) 14, which calls for "*conservation and sustainable use of oceans, seas, and marine resources, and avoidance of significant adverse impacts*", and would be an appropriate precautionary response. Protection of all active vents from mining does not obviate the need for networks of protected areas, referred as Areas of Particular Environmental Interest (APEI) by the ISA [86]. APEIs are expected to work for broadly distributed organisms, but are likely inadequate for small, rare, and isolated habitats with idiosyncratic physico-chemical environments and with faunal assemblages endemic to and dependent on those environments.

7. Conclusion

Active hydrothermal vent ecosystems are uncommon and unusual, colonized by endemic and mostly rare species. Though vent species and ecosystems have been described as ecologically resilient, there remains uncertainty and scientific debate regarding how quickly and to what extent vent ecosystems might recover from the unprecedented damages that could be caused by mining. Even if recovery is rapid, there is uncertainty regarding how many vent ecosystems in a region could be disturbed before a tipping point is reached, beyond which species become extinct. Heterogeneity of habitats and species assemblages in vent ecosystems within and among regions makes them individually—and potentially equally—important. Active vents are recognized as vulnerable through multiple international instruments that call for their protection, and they provide important scientific and cultural benefits to society. One way to apply a precautionary approach to these

ecosystems is to protect all active vents from mining impacts, direct and indirect. This protection in areas beyond national jurisdiction would have non-extractive benefits and would set aside only a fraction of the international seabed and its mineral resources. Enactment of full protection is possible through environmental regulations for the exploitation of mineral resources – currently in draft – of the *Mining Code* of the International Seabed Authority. If and when there is scientific evidence that active hydrothermal vent ecosystems are not areas at risk of serious harm from mining activities, such a moratorium should be revisited.

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