# Scientific rationale and international obligations for protection of active hydrothermal vent ecosystems from deep-s....

**Article** *in* Marine Policy · February 2018

DOI: 10.1016/j.marpol.2018.01.020



Marine Policy 90 (2018) 20–28

Contents lists available at ScienceDirect

Marine Policy

journal homepage: www.elsevier.com/locate/marpol

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

C.L. Van Dover[a,*], S. Arnaud-Haond[b], M. Gianni[c], S. Helmreich[d], J.A. Huber[e], A.L. Jaeckel[f], A. Metaxas[g], L.H. Pendleton[h], S. Petersen[i], E. Ramirez-Llodra[j], P.E. Steinberg[k], V. Tunnicliffe[l], H. Yamamoto[m]

[a] Division of Marine Science and Conservation, Nicholas School of the Environment, Duke University, Beaufort, NC 28516, USA
[b] Station Biologique de Sète, 34200 Sète, France
[c] Deep Sea Conservation Coalition, 1077KB Amsterdam, Netherlands
[d] Anthropology Department, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02142, USA
[e] Marine Chemistry and Geochemistry, Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA
[f] Macquarie Law School and Macquarie Marine Research Centre, Macquarie University, New South Wales 2109, Australia
[g] Department of Oceanography, Dalhousie University, Halifax, Nova Scotia, Canada B3H4R2
[h] World Wildlife Fund and University of Brest, Ifremer, CNRS, UMR 6308, AMURE, IUEM, 29280 Plouzane, France
[i] GEOMAR Helmholtz Centre for Ocean Research, 24148 Kiel, Germany
[j] Norwegian Institute for Water Research, 0349 Oslo, Norway
[k] Department of Geography and IBRU: The Centre for Borders Research, Durham University, Durham DH1 3LE, UK
[l] Department of Biology and School of Earth & Ocean Sciences, University of Victoria, British Columbia, Canada V8W 2Y2
[m] R&D Center for Submarine Resources, Japan Agency for Marine-Earth Science and Technology, Natushima-cho 2-15, Yokosuka, Kanagawa 237-0061, Japan

ARTICLE INFO

*Keywords:*
Polymetallic sulfides
Seafloor Massive Sulfides (SMS)
International Seabed Authority (ISA)
Convention on Biological Diversity (CBD)
Vulnerable Marine Ecosystems (VME)
Precautionary approach
Deep-sea conservation

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.

* Corresponding author.
*E-mail addresses:* clv3@duke.edu (C.L. Van Dover), sarnaudhaond@yahoo.fr (S. Arnaud-Haond), matthewgianni@gmail.com (M. Gianni), sgh2@mit.edu (S. Helmreich), jhuber@whoi.edu (J.A. Huber), aline.jaeckel@mq.edu.au (A.L. Jaeckel), metaxas@dal.ca (A. Metaxas), linwood.pendleton@wwf.org (L.H. Pendleton), spetersen@geomar.de (S. Petersen), eva.ramirez@niva.no (E. Ramirez-Llodra), philip.steinberg@durham.ac.uk (P.E. Steinberg), verenat@uvic.ca (V. Tunnicliffe), kyama@jamstec.go.jp (H. Yamamoto).

https://doi.org/10.1016/j.marpol.2018.01.020
Received 10 September 2017; Received in revised form 16 January 2018; Accepted 19 January 2018

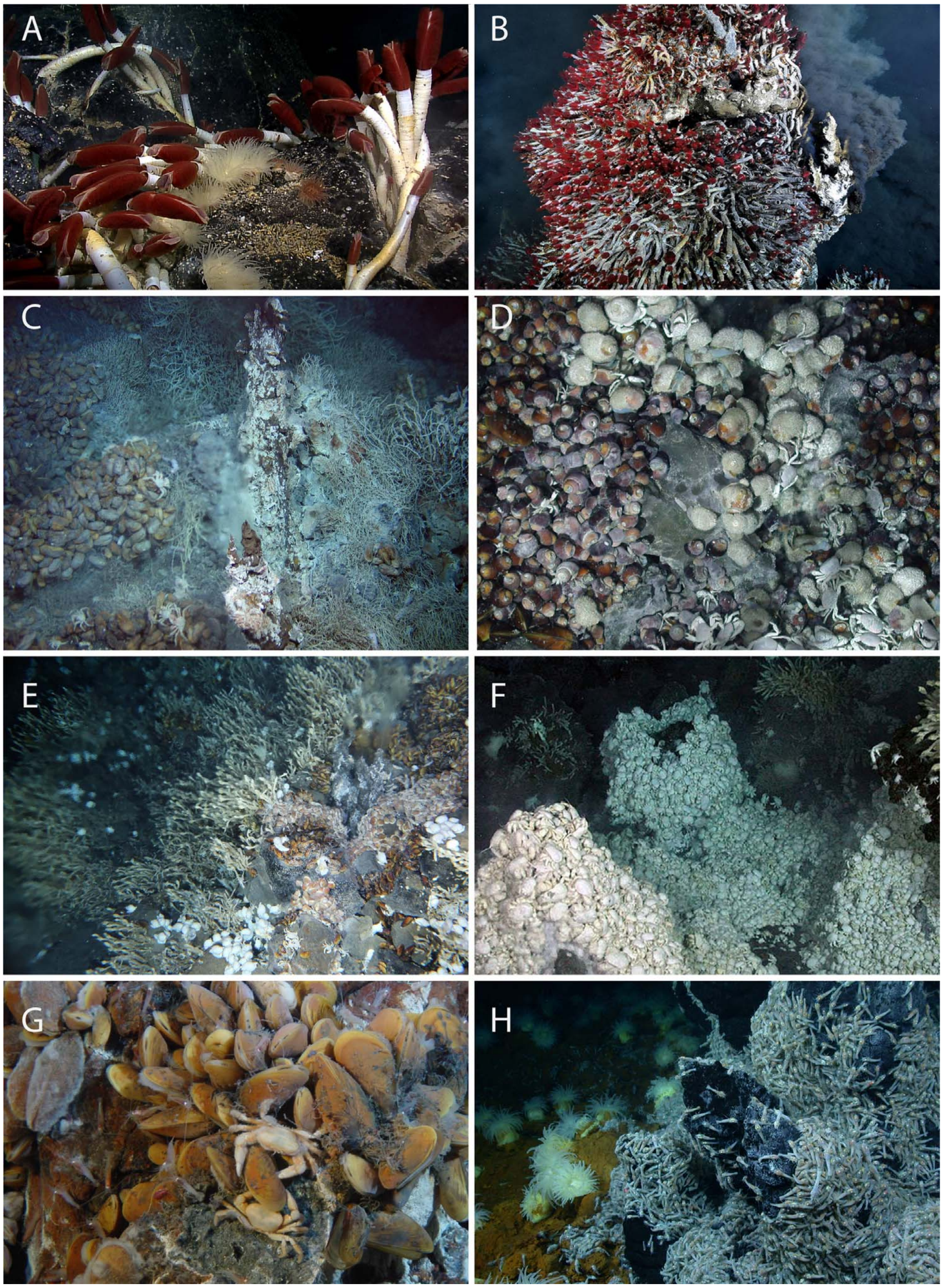


**Fig. 1.** Variation in the dominant, symbiont-hosting invertebrates at active hydrothermal vents around the globe. Vent communities differ widely among biogeographic regions. A key observation not evident in these regionally "iconic" photos is that different vents within a region support different 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

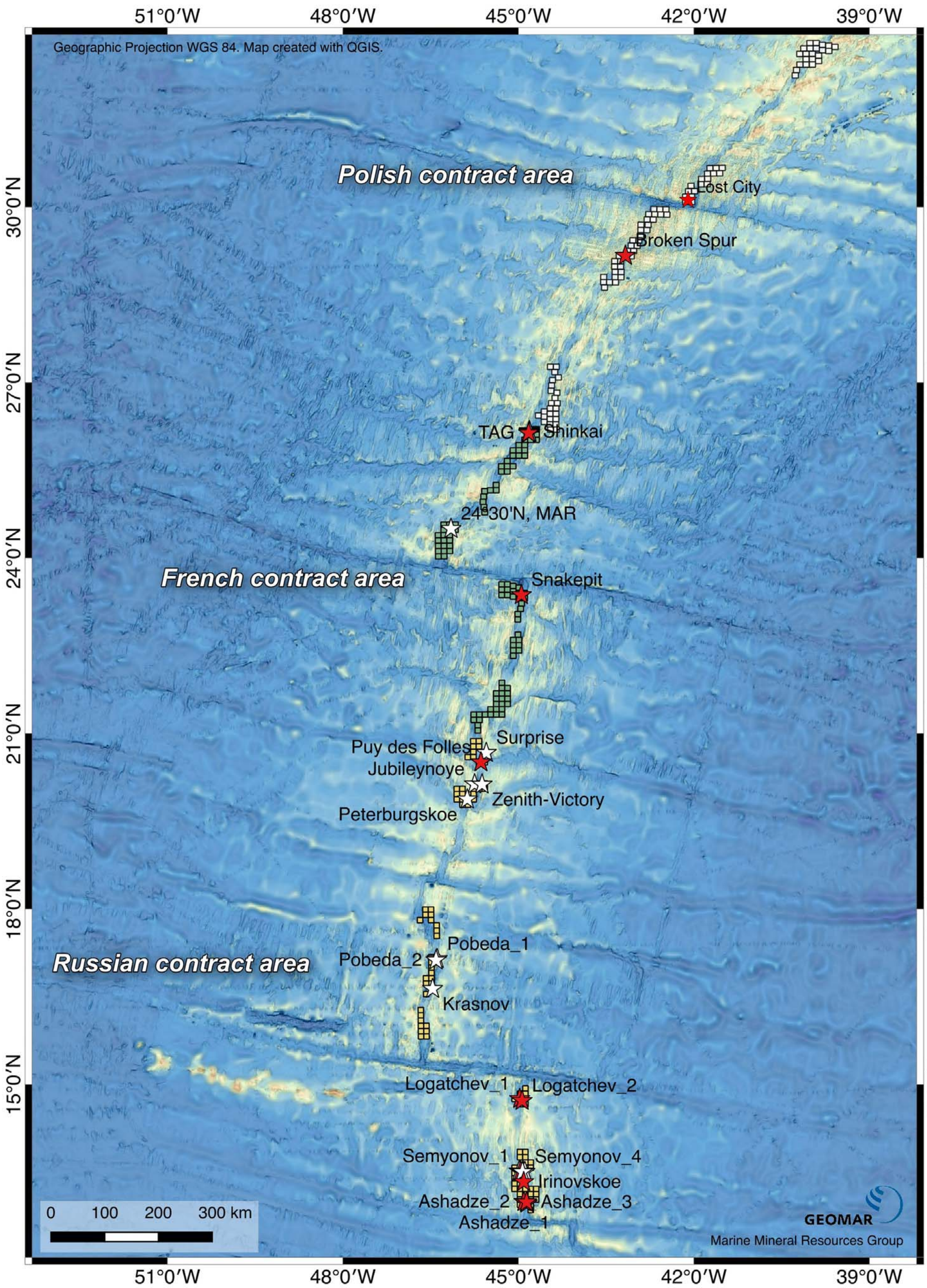


**Fig. 2.** Polymetallic sulfide blocks (each block is ≤ 10 km × 10 km) approved for exploration by the International Seabed Authority (ISA) in the north Atlantic (yellow blocks: Russian Federation, green blocks: France) or pending approval by the ISA (white blocks: Poland) and the locations of known 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.

### Acknowledgements

Cornel de Ronde (GNS Science), Craig Smith (U Hawaii), and Samantha Smith (Blue Globe Solutions) commented on an earlier draft of this paper; Hannah Lily (Commonwealth Secretariat) was consulted on legal matters. Claire Nouvian (Bloom Association) provided insight as part of a working group that met in Oslo.

### Funding sources

CLVD was supported by the Pew Charitable Trusts (Contract ID 29413), and by the Global Ocean Biodiversity Initiative through a grant from the International Climate Initiative (IKI; 16_IV_049_Global_A_Global Ocean Biodiversity Initiative GOBI). The Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB) supports IKI on the basis of a decision adopted by the German Bundestag. AM and VT acknowledge the Natural Sciences and Engineering Research Council of Canada (468437-14) for continued support. LHP was supported by the *Laboratoire d'Excellence*, LabexMER (ANR-10-LABX-19), and the European Institute of Marine Sciences (IUEM). ERLL was supported by the Norwegian Institute for Water Research and the MarMine Project (247626/O30). The NSF Center for Dark Energy Biosphere Investigations (C-DEBI; OCE-0939564) supported the participation of JAH. VT acknowledges the Canada Research Chairs Programme (996945) for support. MG received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 678760 (ATLAS), the Kaplan Fund (1579-20162011), and Oceans5. SP was supported by GEOMAR and by the European Union FP7 Project "Blue Mining" (No. 604500); this output reflects only the authors' views and the European Union cannot be held responsible for any use that may be made of the information contained therein.

### References

[1] L. Godet, K.A. Zelnio, C.L. VanDover, Scientists as stakeholders in conservation of hydrothermal vents, Conserv. Biol. 25 (2011) 214–222, http://dx.doi.org/10.1111/j.1523-1739.2010.01642.x.
[2] H. Harden-Davies, Deep-sea genetic resources: new frontiers for science and stewardship in areas beyond national jurisdiction, Deep. Res. Part II Top. Stud. Oceanogr. 137 (2017) 504–513, http://dx.doi.org/10.1016/j.dsr2.2016.05.005.
[3] S. Petersen, A. Krätschell, N. Augustin, J. Jamieson, J.R. Hein, M.D. Hannington, News from the seabed – geological characteristics and resource potential of deep-sea mineral resources, Mar. Policy 70 (2016) 175–187, http://dx.doi.org/10.1016/j.marpol.2016.03.012.
[4] P.C. Collins, R. Kennedy, C.L. VanDover, A biological survey method applied to seafloor massive sulphides (SMS) with contagiously distributed hydrothermal-vent fauna, Mar. Ecol. Prog. Ser. 452 (2012) 89–107, http://dx.doi.org/10.3354/meps09646.
[5] Coffey Natural Systems, Environmental Impact Statement, Nautilus Minerals Niugini Limitied, Solwara 1 Project Volume A, Main Report, (2008).
[6] T. Narita, J. Oshika, N. Okamoto, T. Toyohara, T. Miwa, Summary of environmental impact assessment for mining seafloor massive sulfides in Japan, J. Shipp. Ocean Eng. 5 (2015) 103–114 ⟨http://www.davidpublishing.com/⟩.
[7] C.J. Lundquist, R.H. Bulmer, M.R. Clark, J.R. Hillman, W.A. Nelson, C.R. Norrie, A.A. Rowden, D.M. Tracey, J.E. Hewitt, Challenges for the conservation of marine small natural features, Biol. Conserv. 211 (2016) 69–79, http://dx.doi.org/10.1016/j.biocon.2016.12.027.
[8] M.L. Hunter, V. Acuña, D.M. Bauer, K.P. Bell, A.J.K. Calhoun, M.R. Felipe-Lucia, J.A. Fitzsimons, E. González, M. Kinnison, D. Lindenmayer, C.J. Lundquist, R.A. Medellin, E.J. Nelson, P. Poschlod, Conserving small natural features with large ecological roles: a synthetic overview, Biol. Conserv. 211 (Part B) (2017) 88–95, http://dx.doi.org/10.1016/j.biocon.2016.12.020.
[9] S.E. Beaulieu, E.T. Baker, C.R. German, A. Maffei, An authoritative global database for active submarine hydrothermal vent fields, Geochem. Geophys. Geosyst. 14 (2013) 4892–4905, http://dx.doi.org/10.1002/2013GC004998.
[10] J. Thal, M. Tivey, D. Yoerger, N. Jöns, W. Bach, Geologic setting of PACManus hydrothermal area – high resolution mapping and in situ observations, Mar. Geol. 355 (2014) 98–114, http://dx.doi.org/10.1016/j.margeo.2014.05.011.
[11] P.A. Rona, G. Klinkhammer, T.A. Nelsen, J.H. Trefry, H. Elderfield, Black smokers, massive sulphides and vent biota at the Mid-Atlantic Ridge, Nature 321 (1986) 33–37, http://dx.doi.org/10.1038/321033a0.
[12] S. Gollner, S. Kaiser, L. Menzel, D.O.B. Jones, A. Brown, N.C. Mestre, D. van Oevelen, L. Menot, A. Colaço, M. Canals, D. Cuvelier, J.M. Durden, A. Gebruk, G.A. Egho, M. Haeckel, Y. Marcon, L. Mevenkamp, T. Morato, C.K. Pham, A. Purser, A. Sanchez-Vidal, A. Vanreusel, A. Vink, P. Martinez Arbizu, Resilience of benthic deep-sea fauna to mining activities, Mar. Environ. Res. 129 (2017) 76–101, http://dx.doi.org/10.1016/j.marenvres.2017.04.010.
[13] R. Nakajima, H. Yamamoto, S. Kawagucci, Y. Takaya, T. Nozaki, C. Chen, K. Fujikura, T. Miwa, K. Takai, Post-drilling changes in seabed landscape and megabenthos in a deep-sea hydrothermal system, the Iheya North field, Okinawa trough, PLoS One 10 (2015) e0123095, http://dx.doi.org/10.1371/journal.pone.0123095.
[14] J. Copley, P. Tyler, C. VanDover, A. Schultz, P. Dickson, S. Singh, M. Sulanowska, Effects of ODP drilling on the TAG hydrothermal vent community, 26 N Mid-Atlantic Ridge, Mar. Ecol. (1999) 291–306.
[15] T.M. Shank, D.J. Fornari, K.L. VonDamm, M.D. Lilley, R.M. Haymon, R.A. Lutz, Temporal and spatial patterns of biological community development at nascent deep-sea hydrothermal vents (9°50′ N, East Pacific Rise), Deep Sea Res. Part II Top. Stud. Oceanogr. 45 (1998) 465–515, http://dx.doi.org/10.1016/S0967-0645(97)00089-1.
[16] V. Tunnicliffe, R.W. Embley, J.F. Holden, D.a. Butterfield, G.J. Massoth, S.K. Juniper, Biological colonization of new hydrothermal vents following an eruption on Juan de Fuca Ridge, Deep Sea Res. Part I Oceanogr. Res. Pap. 44 (1997) 1627–1644, http://dx.doi.org/10.1016/S0967-0637(97)00041-1.
[17] J. Marcus, V. Tunnicliffe, D.a. Butterfield, Post-eruption succession of macrofaunal communities at diffuse flow hydrothermal vents on Axial Volcano, Juan de Fuca Ridge, Northeast Pacific, Deep Sea Res. Part II Top. Stud. Oceanogr. 56 (2009) 1586–1598, http://dx.doi.org/10.1016/j.dsr2.2009.05.004.
[18] W.W. Chadwick, R. Embley, E. Baker, J. Resing, J. Lupton, K.V. Cashman, R.P. Dziak, V. Tunnicliffe, D. Butterfield, Y. Tamura, Northwest Rota-1 seamount, Oceanography 23 (2010) 182–183, http://dx.doi.org/10.1029/2007JB005215.Embley.
[19] C.L. VanDover, Tighten regulations on deep-sea mining, Nature 470 (2011) 31–33.
[20] C.L. VanDover, Impacts of anthropogenic disturbances at deep-sea hydrothermal vent ecosystems: a review, Mar. Environ. Res. 102 (2014) 59–72, http://dx.doi.org/10.1016/j.marenvres.2014.03.008.
[21] S. Teixeira, E.A. Serrão, S. Arnaud-Haond, Panmixia in a fragmented and unstable environment: the hydrothermal shrimp Rimicaris exoculata disperses extensively along the Mid-Atlantic Ridge, PLoS One 7 (2012) e38521, http://dx.doi.org/10.1371/journal.pone.0038521.
[22] R.C. Vrijenhoek, Genetic diversity and connectivity of deep-sea hydrothermal vent metapopulations, Mol. Ecol. 19 (2010) 4391–4411, http://dx.doi.org/10.1111/j.1365-294X.2010.04789.x.
[23] D.C. Dunn, J. Ardron, N. Bax, P. Bernal, J. Cleary, I. Cresswell, B. Donnelly, P. Dunstan, K. Gjerde, D. Johnson, K. Kaschner, B. Lascelles, J. Rice, H. Von Nordheim, L. Wood, P.N. Halpin, The convention on biological diversity's ecologically or biologically significant areas: origins, development, and current status, Mar. Policy 49 (2014) 137–145, http://dx.doi.org/10.1016/j.marpol.2013.12.002.
[24] C.L. VanDover, C.R. Smith, J. Ardron, D. Dunn, K. Gjerde, L. Levin, S. Smith, Designating networks of chemosynthetic ecosystem reserves in the deep sea, Mar. Policy 36 (2012) 378–381, http://dx.doi.org/10.1016/j.marpol.2011.07.002.
[25] L.M. Wedding, S.M. Reiter, C.R. Smith, K.M. Gjerde, J.N. Kittinger, A.M. Friedlander, S.D. Gaines, M.R. Clark, A.M. Thurnherr, S.M. Hardy, L.B. Crowder, Managing mining of the deep seabed (80-.), Science 349 (2015) 144–145, http://dx.doi.org/10.1126/science.aac6647.
[26] Y. Moalic, D. Desbruyères, C.M. Duarte, A.F. Rozenfeld, C. Bachraty, S. Arnaud-Haond, Biogeography revisited with network theory: retracing the history of hydrothermal vent communities, Syst. Biol. 61 (2012) 127–137, http://dx.doi.org/10.1093/sysbio/syr088.
[27] S. Goffredi, S. Johnson, V. Tunnicliffe, D. Caress, D. Clague, E. Escobar, L. Lundsten, J. Paduan, G. Rouse, D. Salcedo, L. Soto, R. Splz-Madero, R. Zierenberg, R. Vrijenhoek, Hydrothermal vent fields discovered in southern Gulf of California clarify role of habitat in augmenting regional diversity, Proc. R. Soc. B Biol. Sci. 284 (2017), http://dx.doi.org/10.1098/rspb.2017.0817.
[28] R.A. Beinart, J.G. Sanders, B. Faure, S.P. Sylva, R.W. Lee, E.L. Becker, A. Gartman, G.W. Luther, J.S. Seewald, C.R. Fisher, P.R. Girguis, Evidence for the role of endosymbionts in regional-scale habitat partitioning by hydrothermal vent symbioses, Proc. Natl. Acad. Sci. USA 109 (2012) E3241–E3245, http://dx.doi.org/10.1073/pnas.1202690109.
[29] J. Sarrazin, S.K. Juniper, G. Massoth, P. Legendre, Physical and chemical factors influencing species distributions on hydrothermal sulfide edifices of the Juan de Fuca Ridge, northeast Pacific, Mar. Ecol. Prog. Ser. 190 (1999) 89–112, http://dx.doi.org/10.3354/meps190089.
[30] D.S. Kelley, J.A. Karson, D.K. Blackman, G.L. Fruh-Green, D.A. Butterfield, M.D. Lilley, E.J. Olson, M.O. Schrenk, K.K. Roe, G.T. Lebon, P. Rivizzignothe A.-60 S. Party, An off-axis hydrothermal vent field near the Mid-Atlantic Ridge at 30° N, Nature 412 (2001) 145–149, http://dx.doi.org/10.1038/35084000.

[31] F. Micheli, C.H. Peterson, L.S. Mullineaux, C.R. Fisher, S.W. Mills, G. Sancho, G.a. Johnson, H.S. Lenihan, Predation structures communities at deep-sea hydrothermal vents, Ecol. Monogr. 72 (2002) 365–382, http://dx.doi.org/10.1890/0012-9615(2002)072[0365:PSCADS]2.0.CO;2.
[32] M. Tsurumi, V. Tunnicliffe, Tubeworm-associated communities at hydrothermal vents on the Juan de Fuca Ridge, northeast Pacific, Deep. Res. Part I 50 (2003) 611–629.
[33] A.D. Thaler, W. Saleu, J. Carlsson, T.F. Schultz, C.L. VanDover, Population structure of Bathymodiolus manusensis, a deep-sea hydrothermal vent-dependent mussel from Manus Basin, Papua New Guinea, PeerJ 5 (2017) e3655, http://dx.doi.org/10.7717/peerj.3655.
[34] R. Nakajima, T. Yamakita, H. Watanabe, K. Fujikura, K. Tanaka, H. Yamamoto, Y. Shirayama, Species richness and community structure of benthic macrofauna and megafauna in the deep-sea chemosynthetic ecosystems around the Japanese archipelago: an attempt to identify priority areas for conservation, Divers. Distrib. 20 (2014) 1160–1172, http://dx.doi.org/10.1111/ddi.12204.
[35] J.S. Cabral, P. Weigelt, W.D. Kissling, H. Kreft, Biogeographic, climatic and spatial drivers differentially affect α-, β- and γ-diversities on oceanic archipelagos, Proc. Biol. Sci. 281 (2014) 20133246, http://dx.doi.org/10.1098/rspb.2013.3246.
[36] D. Desbruyeres, A. Biscoito, T. Comtet, A. Khripounoff, N. LeBris, P. Sarradin, M. Segonzac, A review of the distribution of hydrothermal vent communities along the northern Mid-Atlantic Ridge: dispersal vs. environmental controls, Hydrobiologia 440 (2000) 201–216.
[37] P.J. Turner, L.M. Campbell, C.L. VanDover, Stakeholder perspectives on the importance of rare-species research for deep-sea environmental management, Deep Sea Res. Part I Oceanogr. Res. Pap. 125 (2017) 129–134.
[38] E. Bayraktarov, M.I. Saunders, S. Abdullah, M. Mills, J. Beher, H.P. Possingham, P.J. Mumby, C.E. Lovelock, The cost and feasibility of marine coastal restoration, Ecol. Appl. 26 (2015) 15–1077.1, http://dx.doi.org/10.1890/15-1077.1.
[39] D. Moreno-Mateos, E.B. Barbier, P.C. Jones, H.P. Jones, J. Aronson, J.A. López-López, M.L. McCrackin, P. Meli, D. Montoya, J.M. Rey Benayas, Anthropogenic ecosystem disturbance and the recovery debt, Nat. Commun. 8 (2017) 14163, http://dx.doi.org/10.1038/ncomms14163.
[40] C.L. VanDover, J. Aronson, L. Pendleton, S. Smith, S. Arnaud-Haond, D. Moreno-Mateos, E. Barbier, D. Billett, K. Bowers, R. Danovaro, A. Edwards, S. Kellert, T. Morato, E. Pollard, A. Rogers, R. Warner, Ecological restoration in the deep sea: Desiderata, Mar. Policy 44 (2014) 98–106, http://dx.doi.org/10.1016/j.marpol.2013.07.006.
[41] M. Hannington, J. Jamieson, T. Monecke, S. Petersen, S. Beaulieu, The abundance of seafloor massive sulfide deposits, Geology 39 (2011) 1155–1158, http://dx.doi.org/10.1130/G32468.1.
[42] US Geological Survey, Mineral Commodity Summaries, (2017), http://dx.doi.org/10.3133/701801 (Accessed 10 September 2017), 〈https://minerals.usgs.gov/minerals/pubs/mcs/2017/mcs2017.pdf〉.
[43] J.R. Hein, K. Mizell, A. Koschinsky, T.a. Conrad, Deep-ocean mineral deposits as a source of critical metals for high- and green-technology applications: comparison with land-based resources, Ore Geol. Rev. 51 (2013) 1–14, http://dx.doi.org/10.1016/j.oregeorev.2012.12.001.
[44] T. Monecke, S. Petersen, M.D. Hannington, H. Grant, I. Samson, The minor element endowment of modern sea-floor massive sulfide deposits and comparison with deposits hosted in ancient volcanic successions, Rev. Econ. Geol. 18 (2016) 245–306.
[45] E.T. Baker, J.A. Resing, R.M. Haymon, V. Tunnicliffe, J.W. Lavelle, F. Martinez, V. Ferrini, S.L. Walker, K. Nakamura, How many vent fields? New estimates of vent field populations on ocean ridges from precise mapping of hydrothermal discharge locations, Earth Planet. Sci. Lett. 449 (2016) 186–196, http://dx.doi.org/10.1016/j.epsl.2016.05.031.
[46] C.R. German, S. Petersen, M.D. Hannington, Hydrothermal exploration of mid-ocean ridges: where might the largest sulfide deposits be forming? Chem. Geol. 420 (2016) 114–126, http://dx.doi.org/10.1016/j.chemgeo.2015.11.006.
[47] S. Petersen, M. Hannington, A. Krätschell, Technology developments in the exploration and evaluation of deep-sea mineral resources, Ann. Des. Mines – Responsab. Environ. 85 (2017) 14–18.
[48] A. Jaeckel, J.A. Ardron, K.M. Gjerde, Sharing benefits of the common heritage of mankind – is the deep seabed mining regime ready? Mar. Policy 70 (2016) 198–204, http://dx.doi.org/10.1016/j.marpol.2016.03.009.
[49] M. Lodge, The Common Heritage of Mankind, Int. J. Mar. Coast. Law 27 (2012) 733–742, http://dx.doi.org/10.1163/15718085-12341248.
[50] H. Yao, M. Dao, T. Imholt, J. Huang, K. Wheeler, A. Bonilla, S. Suresh, C. Ortiz, Protection mechanisms of the iron-plated armor of a deep-sea hydrothermal vent gastropod, Proc. Natl. Acad. Sci. USA 107 (2010) 987–992, http://dx.doi.org/10.1073/pnas.0912988107.
[51] J. Simoni, New approaches in commercial development of artificial oxygen carriers, Artif. Organs 38 (2014) 621–624, http://dx.doi.org/10.1111/aor.12371.
[52] D. Leary, M. Vierros, G. Hamon, S. Arico, C. Monagle, Marine genetic resources: a review of scientific and commercial interest, Mar. Policy 33 (2009) 183–194, http://dx.doi.org/10.1016/j.marpol.2008.05.010.
[53] ECORYS, Study to Investigate the State of Knowledge of Deep-Sea Mining, (2014) (Accessed 10 September 2017), 〈https://webgate.ec.europa.eu/maritimeforum/sites/maritimeforum/files/FGP96656_final_rep._formatted._november_2014.pdf〉.
[54] K. Coley, Uncharted depths: exploring the Marianas with SuBastian, Mar. Technol. Rep. (2017) 44–51.
[55] A. Fundis, M. Cook, K. Sutton, S. Munro, D. Larsh, K. Moran, A. Alexandra, S. Wishnak, S. Poulto, Nautilus education & outreach programs: igniting interest and promoting literacy in ocean exploration and STEM careers, Oceanography (30 Suppl.) (2017) S18–S23.
[56] C.L. VanDover, The Octopus's Garden, Addison-Wesley, Reading, MA, 1996.
[57] E. Gowell, Fountains of Life, Franklin Watts, London, 1998.
[58] V.Tunnicliffe, Kira's Undersea Garden, Trafford, 2004.
[59] C. Nouvian, The Deep, University of Chicago Press, 2007.
[60] M. Baker, B. Ebbe, J. Hoyer, L. Menot, B. Narayanaswarmy, E. Ramirez-Llodra, M. Steffensen, Deeper than Light, Bergen Museum Press, Bergen, 2007.
[61] B. Hague, Alien Deep, National Geographic Society, Washington, DC, 2012.
[62] F. Nimmo, R.T. Pappalardo, Ocean worlds in the outer solar system, J. Geophys. Res. Planets 121 (2016) 1378–1399, http://dx.doi.org/10.1002/2016JE005081.
[63] N. LeBris, S. Arnaud-Haond, S. Beaulieu, E. Cordes, A. Hilario, A. Rogers, S. VanDeGaever, H. Watanabe, Chapter 45. Hydrothermal Vents and Cold Seeps, World Ocean Assess, (2016), pp. 1–18 〈http://www.un.org/Depts/los/global_reporting/WOA_RegProcess.htm〉.
[64] Fisheries and Oceans Canada, Government of Canada identifies large ocean area off the coast of British Columbia for protection (News Release), 2017. 〈https://www.canada.ca/en/fisheries-oceans/news/2017/05/government_of_canadaidentifieslargeoceanareaoffthecoastofbritish.html〉, (Accessed 10 September).
[65] Council of the European Union, COUNCIL REGULATION (EC) No 734/2008 of 15 July 2008 on the protection of vulnerable marine ecosystems in the high seas from the adverse impacts of bottom fishing gears, Off. J. Eur. Union (2008) 8–13.
[66] CBD, COP 9, Decision IX/20, UNEP/CBD/COP/DEC/IX/20, annex I, 2008.
[67] N.J. Bax, J. Cleary, B. Donnelly, D.C. Dunn, P.K. Dunstan, M. Fuller, P.N. Halpin, Results of efforts by the convention on biological diversity to describe ecologically or biologically significant marine areas, Conserv. Biol. 30 (2016) 571–581, http://dx.doi.org/10.1111/cobi.12649.
[68] FAO, International guidelines for the management of deep-sea fisheries in the high seas, Rome, Italy, 2009.
[69] M. Gianni, S.D. Fuller, D.E.J. Currie, K. Schleit, L. Goldsworthy, B. Pike, B. Weeber, S. Owen, A. Friedman, M. Gianni, S.D. Fuller, D.E.J. Currie, K. Schleit, L. Goldsworthy, B. Pike, B. Weeber, S. Owen, A. Friedman, How much longer will it take? A ten-year review of the implementation of United Nations General Assembly resolutions 61/105, 64/72, 2016. 〈http//www.savethehighseas.org/resources/publications/much-Longer-Will-Take-Ten-Year-Review-Implementation-United-Nations-General-Assembly-Resolutions-61105-6472-6668-Management-Bottom-Fisheries-Areas-beyond-Nat/〉, (Accessed 3 January 2018).
[70] OSPAR, Agreement 2008–07. Description of habitats on the OSPAR list of threatened and/or declining species and habitats, 2008. 〈https://www.ospar.org/convention/agreements/〉, (Accessed 10 September 2017).
[71] OSPAR, OSPAR Recommendation 2014/11 on furthering the protection and conservation of hydrothermal vents/fiels occuring on oceanic ridge in Region V of the OSPAR maritime area, annex 16, 2014. 〈https://www.ospar.org/convention/agreements/〉, 〈https://www.ospar.org/meetings/archive?Q = &a = &y = 1993&s = 〉, (Accessed 10 September 2017).
[72] C. Devey, C. Fisher, S. Scott, Responsible science at hydrothermal vents, Oceanography 20 (2007) 162–171.
[73] OSPAR, OSPAR 2008-1. Code of Conduct for Responsible Marine Research in the Deep Seas and High Seas of the OSPAR Maritime Area, 2008. 〈https://www.ospar.org/convention/agreements/〉 (Accessed 10 September 2017).
[74] D. Freestone, D. Laffoley, F. Douvere, T. Badman, World Heritage in the Deep Sea: An Idea Whose Time has Come, UNESCO, Paris, 2017〈http://whc.unesco.org/en/news/1535/〉.
[75] J.B. Corliss, J. Dymond, L.I. Gordon, J.M. Edmond, R.P. Von, R.D. Ballard, K. Green, D. Williams, A. Bainbridge, K. Crane, Submarine thermal springs on the Galapagos Rift, Science 203 (1979) 1073–1083 (80-.).
[76] F. Spiess, K. Macdonald, T. Atwater, B. Ballard, A. Carranza, D. Cordoba, C. Cox, M. Diaz Garcia, J. Francheteau, J. Guerrera, J. Hawkins, R. Haymon, R. Hessler, M. Juteau, M. Kastner, R. Larson, B. Luyendyk, J. Macdougall, S. Miller, W. Normak, J. Orcutt, C. Rangin, East Pacific rise: hot spring and geophysical experiments, Science 207 (1980) 1421–1433 (80-.), 〈http://www.researchgate.net/publication/6060140_East_pacific_rise_hot_springs_and_geophysical_experiments/file/5046351f9a358b9a1c.pdf〉.
[77] International Seabed Authority, ISBA/16a/12/rev1 Decision of the Assembly of the International Seabed Authority relating to the regulations on prospecting and exploration for polymetallic sulphides in the Area, 2010. 〈https://www.isa.org.jm/sites/default/files/files/documents/isba-16a-12rev1_0〉. 〈http://dx.doi.org/10.1163/157180811X576929〉.
[78] Seabed Disputes Chamber, Responsibilities and Obligations of States Sponsoring Persons and Entities with Respect to Activities in the Area, Advisory Opinion, ITLOS Reports, 10, 2011.
[79] A. Trouwborst, The precautionary principle in general international law: combating the Babylonian confusion, Rev. Eur. Commun. Int. Environ. Law 16 (2007) 185–195, http://dx.doi.org/10.1111/j.1467-9388.2007.00553.x.
[80] International Seabed Authority, Working Draft Regulations and Standard Contract Terms on Exploitation for Mineral Resources in the Area, 2016. 〈https://www.isa.org.jm/sites/default/files/files/documents/isba-16a-12rev1_0.pdf〉.
[81] International Seabed Authority, A discussion paper on the development and drafting of Regulation on Exploitation for Mineral Resources in the Area (Environmental Matters), 2017. 〈https://www.isa.org.jm/files/documents/EN/Regs/DraftExpl/DP-EnvRegsDraft25117.pdf〉, (Accessed 10 September 2017).
[82] R. Goodland, Responsible mining: the key to profitable resource development, Sustainability 4 (2012) 2099–2126, http://dx.doi.org/10.3390/su4092099.
[83] IWC, International Convention for the Regulation of Whaling, Schedule 2016 – as amended by the Commission at the 66th Meeting, October 2016, paragraph 10(e), 2016. 〈https//archive.iwc.int/pages/view.php?Ref = 3606&k = 〉, (Accessed 25 December 2017).

[84] Antarctic Treaty, Protocol on Environmental Protection to the Antarctic Treaty; Adopted 4 October 1991, entered into force on 14 January 1998, 1991. ⟨https://2001-2009.state.gov/g/oes/ocns/9570.htm#protocol⟩, (Accessed 10 September 2017).
[85] A. Jaeckel, The International Seabed Authority and the Precautionary Principle, Brill, Leiden, The Netherlands, 2017.
[86] M. Lodge, D. Johnson, G. LeGurun, M. Wengler, P. Weaver, V. Gunn, Seabed mining: International Seabed Authority environmental management plan for the Clarion–Clipperton Zone. A partnership approach, Mar. Policy 49 (2014) 66–72, http://dx.doi.org/10.1016/j.marpol.2014.04.006.
[87] M. Yamamoto, M. Nakamura, R. Kasaya, T. Kumagai, H. Suzuki, K. Takai, Spontaneous and widespread electricity generation in natural deep-dea hydrothermal fields, Angew. Chem. Int. Ed. 61 (2017) 5819–5822.