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An atlas of protected hydrothermal vents

Elisabetta Menini[a,*], Cindy Lee Van Dover[b]

[a] Division of Marine Science and Conservation, Nicholas School of the Environment, Duke University, Beaufort, NC, 28516, USA

[b] Erasmus Mundus Master Course on Maritime Spatial Planning (Universities of Seville, the Azores and Iuav di Venezia), Campo della Lana 601, 30135, Venice, Italy

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ABSTRACT

Active hydrothermal vents are valued worldwide because of the importance of their biodiversity and their influence on scientific discovery and insight about life on Earth and elsewhere in the Universe. There exist at least 20 areas and area networks with conservation measures for deep-sea hydrothermal vents, established by 12 countries and three Regional Fisheries Management Organisations, in six oceanic regions. Area-based management tools (ABMT) implemented by these countries illustrate multiple categories and means of protection and management of these rare and vulnerable habitats. Some ABMTs only regulate bottom and deep-trawling fisheries activities, others manage additional activities such as mining, scientific research, and bioprospecting, while still others protect active hydrothermal vents through broad conservation interventions. This atlas summarizes the "who", "what", "when", "where" of protected hydrothermal vents worldwide and underscores recognition of the importance of hydrothermal-vent ecosystems by coastal States.

1. Introduction

Active hydrothermal vents in the deep sea are chemosynthetic ecosystems that host endemic and extraordinary organisms adapted to life in one of the most chemically and physically extreme environments on our planet [1]. Vent ecosystems are rare, occupying globally an area about the size of the island of Manhattan [2]. Like other "small marine systems" [3,4], they deliver ecosystem functions and services that far outstrip their dimensions [5]. In terms of scientific (cultural) services alone, study of vent ecosystems has contributed to theories of the origin of life and the origin of photosynthesis on Earth and the potential for life on other planets, as well as to the appreciation of novel physiological and biological adaptation to extreme environments and the functional diversity of microorganisms, among other research themes [2,6,7].

Hydrothermal vents are also put forward as examples of Vulnerable Marine Ecosystem (VME) by the FAO and Regional Fisheries Management Organisations [8]. Furthermore, in Europe, vents are included within the OSPAR List of Threatened and/or Declining Species and Habitats [9] and within the category "reef" as one of the habitats to preserve through the Natura 2000 Network [10].

Because vents are highly valued, there are well-known efforts to protect them, including but not limited to the establishment of the Endeavour Hydrothermal Vents Marine Protected Area (MPA) in 2003 [11] within the Canadian Exclusive Economic Zone (EEZ) and the Marine Park of the Azores (2016) in the Portuguese EEZ and in the extended continental shelf claim [12,13].

This Atlas reviews key information about the Area based Management Tools (ABMTs) that protect deep-sea hydrothermal vents established by 12 coastal States and three RFMOs from 1921 to July 2018 (Table 1). The objective is to identify who established the protections and when, where the protection is located, and what is protected. The Atlas includes references and links to original documents and institutional websites associated with the ABMTs, here considered as "regulations of human activity in a specified area to achieve conservation or sustainable resource management objectives" and they can include marine protected areas (MPAs), marine spatial planning (MSP) and sectoral tools [14,15]. The ABMTs, hereafter called also spatial regulation, are presented chronologically according to the year a protection intervention was established, permitting scientists, policy makers, and other stakeholders to track the pace and scope of protection efforts to date at hydrothermal vents.

2. Methods

This study is based on a geospatial analysis using ArcGIS software V 10. Geospatial data for active hydrothermal vents was obtained from the InterRidge Database [16,17] and for the spatial regulations from the World Database of Protected Areas (WDPA) [18] that include in its available data MPAs as well as other sectorial spatial tools such as

* Corresponding author.
E-mail addresses: elisabetta.menini@duke.edu (E. Menini), clv3@duke.edu (C.L. Van Dover).

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Table 1
Summary of the Area Based Management Tools with hydrothermal vents in chronological order. ABMT: Area Based Management Tool; n.a.: not applicable or not available; ABNJ: area beyond national jurisdiction.

	ABMTs	Country of Jurisdiction	Current Designation	Management Authority	Year of First Establishment	Year of inclusion of Vents	Number and Status of Vent (s)	Most Recent Management Plan	Reported Area (km^2)	Means of Inclusion of Vents[a]
1	Palau Anak Krakatau	Indonesia	Nature Reserve	Nature Resource Conservation, Lampung, Sumatra	1921	n.a.	1 Inferred	2003	352	Geographic
2	Kirishima- Kinkowan	Japan	National Park	Ministry of the Environment - Japan	1934	n.a.	1 Active	n.a.	370	Geographic
3	National Marine Sanctuary of American Samoa	United States	National Marine Sanctuary	NOAA & the American Samoa Department of Commerce (AS DOC)	1986	2009	1 Active	2012	35,175	Specific
4	Kermadec	New Zealand	Marine Reserve, Benthic Protection Area	Ministry for Primary Industries	1990	2007	15 Active	n. a.	620,000	Specific
5	Galapagos Marine Reserve	Ecuador	Marine Reserve/National Park/Biosphere Reserve/ World Heritage Site	Co-management: Participative Management Board with Inter-institutional Management Authority	1998	n.a.	5 Active, 1 Inactive	2014	133,000	Geographic
6	Seamounts 6B2a – 6B2b	New Zealand	Seamounts Closure	Ministry for Primary Industries	2001	2001	2 Active	n.a.	13,690	Specific
	Tectonic Reach	New Zealand	Benthic Protection Area	Ministry for Primary Industries	2007	2001	5 Active	n.a.	13,690	Specific
7	Endeavour Hydrothermal Vents Marine Protected Area	Canada	MPA	Government of Canada, Fisheries and Oceans Canada	2003	2003	6 Active	2009	98.5	Specific
8	Deep Water Restriction	ABNJ	Fisheries Restricted Area	General Fisheries Commission of the Mediterranean	2005	2005	2 Active	n.a.	$1,7 \times 10^6$	Geographic
9	Lucky Strike MPA Menez Gwen MPA D. João de Castro Seamount Rainbow MPA	Portugal - Autonomous Region of Azores	Marine Park of the Azores	Marine Park of the Azores; Regional Directorate for Sea Affairs; Regional Secretariat for the Sea, Science and Technology	2006	2006	2 Active 2 Active 1 Active 1 Active	n. a.	192.2 92.5 353.7 22.15	Specific
	Southwest hydrothermal field				2016	2016	5 Active		11,029	
10	Mariana Arc of Fire	United States	National Wildlife Refuge	The Director of United States Fish and Wildlife Service	2009	2009	20 Active	In process - last update 2014	153,235	Specific
11	Hydrothermal Vents of Guaymas Basin and of East Pacific Rise	Mexico	Sanctuary	Secretaría de Medio Ambiente y Recursos Naturales	2009	2009	2 Active	2014	14,455	Specific
	Deep Mexican Pacific	Mexico	Biosphere Reserve	Comisión Nacional de Áreas Naturales Protegidas	2016	2016	5 Active 1 Inactive	2016	436,146.9	Specific
12	British Indian Ocean Territory Marine Protected Area - Chagos	United Kingdom	Marine Protected Area	BIOTA British Indian Overseas Territory Administration	2010	2010	1 Active	2014	640,000	Geographic
13	Unnamed seamount number 15 Closure	ABNJ	VME Closures	South East Atlantic Fishery Organisation	2011	2011	1 Active	n.a.	41,950[c]	Specific
	Kreps seamounts Closure						4 Active		100,680[c]	
	Unnamed number 17 Closure						2 Active		50,784[c]	
14	South Georgia and South Sandwich Islands Marine Protected Area	United Kingdom	Marine Protected Area	Government of South Georgia and South Sandwich Islands	2012	2012	4 Active	2013	$1,07 \times 10^6$	Specific
15	Agoa Sanctuary	France	Specially Protected Area	French Marine Protected Area Agency	2012	n.a.	1 Inferred	2012	143,256	Geographic
16	Coral Sea Natural Park	France	Marine Protected Area	New Caledonian Government	2014	2014	1 Active	In process – internal document from 2016	$1,3 \times 10^6$	Specific
17	Pitcairn Islands Marine Reserve	United Kingdom	Marine Protected Area	Government of Pitcairn Islands	2016	2014	1 Active	2016	834,334	Geographic
18	Mid Indian Ridge	ABNJ	Benthic Protected Area	Southern Indian Ocean Deep Fishery Association	2016	2016	2 Active	n.a.	135,688	Specific
19	Offshore Pacific Seamounts and Vent Closure	Canada	Marine Refuge	Government of Canada, Fisheries and Oceans Canada	2017	2017	12 Active	n.a.	82,689	Specific

(*continued on next page*)

Table 1 (*continued*)

	ABMTs	Country of Jurisdiction	Current Designation	Management Authority	Year of First Establishment	Year of inclusion of Vents	Number and Status of Vent (s)	Most Recent Management Plan	Reported Area (km^2)	Means of Inclusion of Vents[a]
20	Thalassia Periochi Koloumvo	Greece	Site of Community Importance (European Union Habitat Directive)	Cyclades Prefecture Protected Areas Management Authority	2017	2017	1 Active	n.a.	50.1	Specific[b]

[a] "Specific" inclusion: specific hydrothermal vents recognised; "geographic" inclusion: protected area not explicitly designed to protect hydrothermal vents.
[b] Koloumvo is the name of the seamount and hydrothermal vent that are the focus of the area of protection. Besides the name, there is no other reference to this vent.
[c] Values retrieved from original shapefiles.

fishing closures. All protected active vents were identified using an overlap analysis between these two data sets. Scientific studies, management plans, official governmental documents such as decisions, recommendations, resolutions and laws, grey literature and web-sources were consulted during the bibliographic research to answer the "who", "what", "when", "where" questions.

3. Results and discussion

3.1. Global perspective

Within EEZs, 16 spatial regulations include some measure of protection of hydrothermal vents by coastal States and a 17th ABMT is located on the extended continental shelf claim of Portugal. Three other sectoral tools established by RFMOs are located beyond national jurisdiction in the Area (Fig. 1, Table 1). These 20 spatial regulations occur in 6 oceanic regions:

- *Mediterranean Sea:* Thalassia Periochi Koloumvo Site of Community Importance (SCI), General Fishery Commission for the Mediterranean (GFCM) Fisheries Regulated Area (FRA).
- *Atlantic Basin:* Azores Marine Park with 5 MPAs; South East Atlantic Fisheries Organisation (SEAFO) Vulnerable Marine Ecosystem (VME) Closures.
- *Caribbean:* Agoa Sanctuary.
- *Indian Ocean:* British Indian Ocean Territory (BIOT)–Chagos MPA, Palau Anak Krakatau Nature Reserve, Southern Indian Ocean Deep Fishery Agreements (SIODFA) Benthic Protection Area (BPA).
- *Southern Ocean:* South Georgia and South Sandwich Island (SGSSI) MPA.
- *Pacific Ocean*: Kirishima Kinkowan National Park, Mariana Arc of Fire Wildlife Refuge, Coral Sea Natural Park, National Marine Sanctuary of American Samoa, Kermadec BPA, Tectonic Reach BPA and Seamount Closures 6B2a and 6B2b, Pitcairn Island Marine Reserve, Offshore Pacific Seamounts and Vents Closure and Endeavour Hydrothermal Vents MPA, Hydrothermal Vents of Guaymas Basin and the East Pacific Rise Sanctuary, the Deep Pacific Mexican Biosphere Reserve, Galapagos Marine Reserve.

The firsts ABMTs to protect hydrothermal vents were established in the 1920's and 1930s, well before the discovery of deep-sea vent ecosystems in 1977 [19]. The most recent intervention was delineated in 2018 (Table 1). Some spatial regulations that protected vents have evolved into protected area networks, such as in Portugal and Mexico. New Zealand was the first country to intervene with area-based fisheries management measures to protect seamounts with hydrothermal vents in 2001, followed by the 2003 Canadian intervention with Endeavour Hydrothermal Vents MPA, which was the first Marine Protected Area established specifically for the conservation of hydrothermal fields.

3.2. ABMTs with active hydrothermal vents

3.2.1. Palau Anak Krakatau Nature Reserve

The Palau Anak Krakatau Nature Reserve was the first protected area established in Java (Indonesia), in 1921. In 1992, the Reserve was integrated within the Ujung Kulon National Park established by the Ministry of Forestry Decree 284/Kpts-II/1992. Ujung Kulon National Park encompasses five Nature Reserves and an extended Marine Reserve [20]. The Palau Anak Krakatau Nature Reserve is of geological interest for the volcanic activity of Krakatau Volcano on Anak Krakatau Island. Four submarine hydrothermal vents (250 m) were discovered in 2004 through plume signals and dredge samples [21] and were described in 2012 [22]. To our knowledge, the coordinates of the submarine vents are not available; they are marked on Fig. 1 at Krakatau Volcano. The Management Plan of the Ujung Kulon National Park

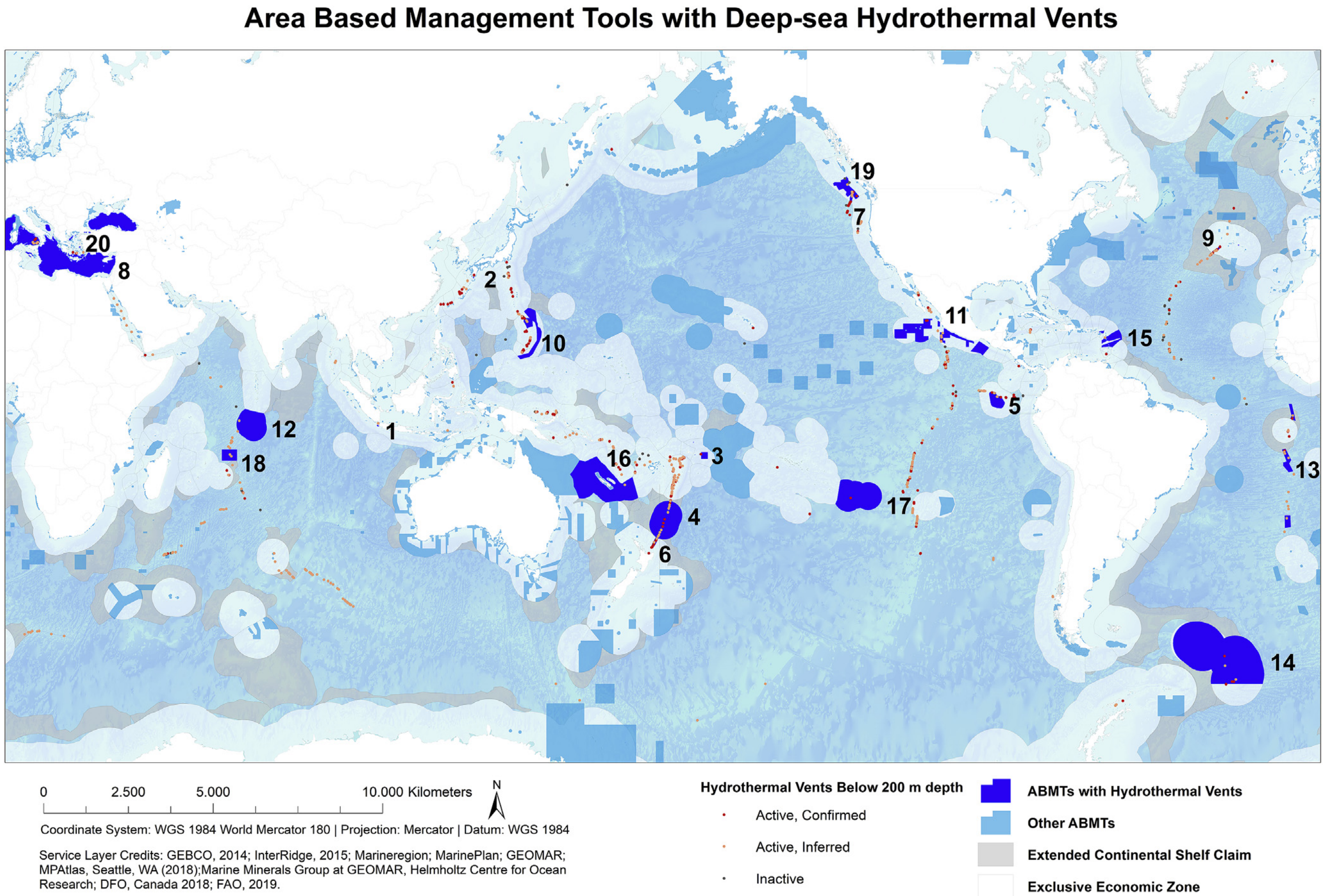

Fig. 1. Area Based Management Tools with deep-sea hydrothermal vents. **1.** Palau Anak Krakatau Nature Reserve; **2.** Kirishima Kinkowan National Park; **3.** National Marine Sanctuary of American Samoa**;** **4.** Kermadec MPA; **5.** Galapagos Marine Reserve; **6.** Tectonic Reach Benthic Protection Areas, 6B2a and 6B2b Seamount Closures; **7.** Endeavour Hydrothermal Vents MPA; **8.** GFCM Deepwater Fishery Restriction; **9.** Lucky Strike, Menez Gwen, Rainbow, D. João de Castro Seamount Hydrothermal Vent MPAs (part of the Marine Park of the Azores); 10. Mariana Arc of Fire National Wildlife Refuge; **11.** Hydrothermal Vents of Guaymas Basin and of the East Pacific Rise Sanctuary and the Deep Pacific Mexican Biosphere Reserve; **12.** BIOT-Chagos MPA; **13.** SEAFO VME Closures (Kreps seamount closure, Unnamed seamount number 15 Closure, Unnamed number 17 Closure); **14.** South Georgia and South Sandwich Islands MPA; **15.** Agoa Sanctuary; **16.** Coral Sea Natural Park; **17.** Pitcairn Island Marine Reserve; **18.** SIODFA Benthic Protected Area (Mid Indian Ridge); **19.** Offshore Pacific Seamounts and Vent Closure; **20.** Thalassia Periochi Koloumvo Site of Community Importance. *[ABMTs 1, 2, and 9 are visible in the figure at original size (A0 format); ABMTs 20 is the smallest and it is not visible in the figure at original size (A0 format)]*.

(2001–2020) does not mention hydrothermal vents explicitly, but it does protect 443 km^2 of marine area and its biodiversity. An objective of the management plan is the elaboration of a bestiary of the area and the development of the sustainable use of marine genetic resources, species, and ecosystems [23].

3.2.2. Kirishima- Kinkowan National Park

The Kirishima-Kinkowan National Park in Japan was established in 1934 [24] to protect terrestrial calderas, volcanoes, and hot-springs, but the Park also encompasses the marine environment of the Kagoshima Bay, where a shallow (200 m) hydrothermal vent field was discovered in 1993 [25–27]. Park regulations do not specify management measures regarding the submarine hydrothermal field, but the marine environment of the Park is protected under the Natural Park Act and mining the seabed and subsoil is forbidden in and within one km of a Marine Park [28].

3.2.3. National Marine Sanctuary of American Samoa

The National Marine Sanctuary of American Samoa, established in 2009 by President George W. Bush, is the only Marine Sanctuary in US territory in the southern hemisphere. The 2009 proclamation joined the Rose Atoll Marine National Park to the Fagatele Bay National Marine Sanctuary, forming the National Marine Sanctuary of American Samoa and increasing the size from 0.65 km^2 to 35,142.2 km^2 [29]. The Management Plan and the Environmental Impact Statement delineate 6 management units within the Sanctuary. About 97% of the Sanctuary comprises the marine areas of the Rose Atoll Marine National Monument within the Muliāva Unit (13,508 square miles), in federal waters, the only unit with a hydrothermal vent, on Vailulu's Seamount. Vailulu's Seamount was added as a square appendix on the northwestern boundary of the Unit. This additional area includes 155 km^2 of the Exclusive Economic Zone (EEZ) surrounding Vailulu's Seamount [29]. The hydrothermal vent field (700–1000 m) was discovered in 2000 through the identification of the plume in the water column. In 2005, the vent was finally visited with a submersible during an expedition of the US National Oceanic and Oceanographic Administration (NOAA) Office of Exploration and Research [17]. Since its discovery, the vent has been the subject of numerous scientific studies about microbial diversity, geochemistry, and geological origins of the seabed features in the area [30–32]. Measures that favour protection of the hydrothermal-vent ecosystems include prohibition of bottom trawling, mining, and pollution [33].

3.2.4. Kermadec and Tectonic Reach Benthic Protection Areas and Seamount Closures 6B2a,b

New Zealand protects 30% of the area of its marine environment through multiple types of ABMTs, including Benthic Protection Areas (BPAs) and Seamount Closures [34]. The Kermadec BPA is rooted in the Marine Reserve established in 1990 that applied only to the territorial sea. The Kermadec BPA now encompasses the benthic environment within the limit of the EEZ and was proposed as an Ocean Sanctuary in 2015, but to date a decision remains pending [34,35]. Bottom trawling and dredging are prohibited in all BPAs (occupying 1.1 × 106 km^2, nearly one third of New Zealand's seabed) and midwater trawling is strictly regulated through vertical zoning that prohibits fishing activities within 100 m of the seabed [34]. Two BPAs—Kermadec and Tectonic Reach—include 19 named hydrothermal vent fields (Table S1). The Tectonic Reach BPA also includes two Seamount Closures (where all trawling is prohibited) with hydrothermal vents at Brothers Volcano (Seamount Closure 6B2-a) and at Rumble III Volcano (Seamount Closure 6B2-b) [36]. Further regulations for the protection of the living and non-living resources, including prohibitions on fisheries and mineral or oil prospecting will be implemented if the proposed Kermadec Ocean Sanctuary is successful [37].

3.2.5. Galapagos Marine Reserve

Although the first discovered deep hydrothermal vent was located just outside the Galapagos EEZ [19], hydrothermal vents within the Galapagos Marine Reserve (Table S2) were only recently discovered [17]. To our knowledge, the only official document that describes any deep feature in the Marine Reserve is the "Management Plan the Protected Areas of Galapagos for the Good Living" [38]. Within the Reserve, no industrial fishery is allowed; only local artisanal and small-scale fleets are able to fish within the waters encompassed by the protected area. There is no clear prohibition of bottom-trawling fisheries, but there is a list of fishing techniques allowed that include trawl line with baits, hand line, fishing poles, rod with reel, with lure drag line [38].

3.2.6. The Endeavour Hydrothermal Vents MPA

The Endeavour Hydrothermal Vents MPA (EHV-MPA) was the first MPA established under the Canadian Oceans Act which provides a framework for ocean management activities. The EHV-MPA is the first MPA in the world specifically established for the conservation of deep-sea hydrothermal fields. EHV-MPA Regulation SOR/2003-87 constrains individuals from carrying out activities in the MPA that directly or indirectly "disturb, damage or destroy, or remove from the Area, any part of the seabed, including a venting structure, or any part of the subsoil, or any living organism or any part of its habitat" [11]. The only exception are activities related to scientific research for the conservation, protection and understanding of the EHV MPA that comply with the MPA Regulations and other national legal instruments related to the marine environment [11,39]. The EHV-MPA has had a management plan in force since 2010 based on four management principles: precautionary approach, ecosystem-based approach, adaptive management, and collaboration [11].

The Endeavour vent fields continue to be a focus for study of geological, geochemical, and ecological dynamics of hydrothermal vent ecosystems through the Ocean Networks Canada Endeavour Observatory [40,41]. They are also the focus of studies on the magnitude of natural and human disturbance, threats, recovery potential, and connectivity among and between vents and the EHV-MPA is a case study for the development of indicators for effective monitoring of hydrothermal vents in MPAs [42].

The EHV-MPA is currently subdivided into 4 management areas (*Salty Dawg, High Rise, Main Endeavour, Mothra*) that contain numerous hydrothermal vents (Table S3) and where different activities can or cannot be pursued. The *Mothra* and *Main Endeavour* vent fields are the most intensively studied fields within the MPA; research activities ranging from observations to moderately intensive sampling are allowed, if consistent with conservation objectives. The *Salty Dawg* and *High Rise* vent fields have the highest level of precaution, where only observation-based or minimally intrusive activities are allowed. *Sasquatch* and other minor vents fields in EHV-MPA are not yet included in the management plan [11].

3.2.7. GFCM Deepwater fishery restriction

A trawling ban below 1000 m depth in the whole Mediterranean Sea and in the Black Sea was established by the General Fisheries Commission for the Mediterranean Sea (GFCM) in 2005. This spatial regulation prohibits the use of bottom trawling and dredges below 1000 m for the conservation of the demersal and deep-water fisheries stocks. Therefore, Palinuro and Sisifo hydrothermal vents, located on the Italian extended continental shelf at 1000 and at 1200 m depth respectively, are included in this spatial regulation [43,44].

3.2.8. The Marine Park of the Azores

Azores ABMTs for hydrothermal vents were initiated in 2006, when three MPAs with active hydrothermal vent fields (Lucky Strike, Menez Gwen, Rainbow) were nominated by Portugal as part of the OSPAR MPA network [45]. In 2007, the Azores Autonomous Region introduced a new Regional Protected Areas Network composed of two units, one of which is the Azores Marine Park with interventions from 12 to 200 nm [46]. The Azores Marine Park now integrates all ABMTs in the region into a single management instrument to streamline the administration [12,47].

The Azores Marine Park is composed of areas that encompass different types of marine environments, including seamounts, banks, submerged islands, and hydrothermal vents. Within the Park, 2 deep (> 500 m) hydrothermal vent fields within the EEZ (*Lucky Strike, Menez Gwen*; Table S4) are protected as Marine Natural Reserves [IUCN Category 1 [48]] [12], wherein all deep-water fishing activities and resource exploitation, among other things, are prohibited [47]. The *Rainbow* hydrothermal field lies on the ECSC and is also protected as a Marine Natural Reserve, with the same activity prohibitions as *Lucky Strike* and *Menez Gwen* [13]. In addition to deep hydrothermal fields, the Banco Dom João de Castro includes a small Marine Natural Reserve that encompasses shallow (20 m) hydrothermal vents, which in turn are encompassed by a larger Marine Protected Area for Resource Management (IUCN Category VI). *Lucky Strike, Menez Gwen, Rainbow* and *D. João de Castro* hydrothermal fields are also listed as MPAs of the OSPAR regional sea. Further protection of the deep sea throughout the Azores region was added in 2014 by creation of an extensive fishery management area where bottom-trawling is banned, and all incidental capture of corals and sponges is required to be georeferenced and reported to authorities [49].

3.2.9. Mariana Arc of Fire National Wildlife Refuge

The Mariana Arc of Fire National Wildlife Refuge is the "Volcanic Unit" of the Marianas Trench Marine National Monument, which was established by President George W. Bush [50]. Geological and biological characteristics of deep-sea hydrothermal ecosystems were key drivers for establishment of the Mariana Trench Marine National Monument, along with the rich biological diversity of the marine environment of the Mariana Archipelago in general. The Volcanic Unit hosts 21 submarine volcanic and hydrothermal features (Table S5), each protected within a one nmi2 (3.43 km^2) area [50]. Three hydrothermal vent fields—Ahyi, Maug, Zealandia, and part of the Est Diamante vent field—are shallower than 200 m (Table S5) and are natural laboratories for study of interactions between chemosynthetic ecosystems and coral reefs [51]. Management objectives of the Volcanic Unit are the protection, preservation, maintenance, and restoration of the geological features and all living organisms associated with them, and to provide opportunities for national and international scientific exploration to promote capacity building and knowledge sharing [52]. The Mariana Trench National Monument does not have a completed management plan, but a multi-year/multi-agency process to develop an exhaustive management plan is ongoing.

3.2.10. Hydrothermal vent sanctuary of Guaymas Basin and the East Pacific Rise

This Sanctuary was established specifically for the conservation of two deep-sea hydrothermal fields, one in Guaymas Basin, the other on the East Pacific Rise (Table S6). The two protected areas are classified by the National Commission on the Knowledge and Use of Biodiversity (CONABIO) as priority marine regions in the North Pacific [53].

The management program of the Sanctuary areas was implemented in 2014 [54] and includes vertical zoning, where the first 500 m from the sea surface is a multiuse area. The Sanctuary is composed of two volumes comprising cubical core zones that start at 500 m water depth and extend to the seabed. One core volume is centred on *Guaymas* vents in the Gulf of California, the other on East Pacific Rise vents at *21°N*, where black smokers were first discovered in 1979 [55]. Each core area has 2-km-wide perimeters (also extending from 500 m to the seabed) that serve as buffer zones. Conservation tools in these areas include protection measures that prohibit bottom trawling, pollution, and seabed mining, plus a strict regulation on scientific research and collection of living resources [54]. The *21°N* hydrothermal field is also within a Core Zone of the newly established Mexican Deep Pacific Biosphere Reserve (see Section 3.2.16) but is managed separately under the Sanctuary program.

3.2.11. British Indian Ocean Territory (BIOT)-Chagos marine protected area

The BIOT-Chagos MPA is one of the largest MPAs in the world. It encompasses the entire EEZ of the Chagos Archipelago in Indian Ocean, resulting in 640,000 km^2 of "no-take" zone, except within three nautical miles of Diego Garcia Island. The coastal waters are especially renowned for the richness of the coral reefs and atolls that form and surround the archipelago [56,57].

The latest documentation regarding the management of BIOT-Chagos MPA was published in 2014, within which there is an explicit vision towards conservation. There is no reference to bioprospecting or seabed mining in the management framework. The deep-sea environment within the BIOT-Chagos MPA is not well-represented in the scientific literature. Nevertheless, the Interim Conservation Management Framework emphasizes the pristine nature of the deep-sea ecosystem, including seamounts, a deep knoll, and an abyssal trench that represent an important opportunity for deep-sea conservation and scientific research. The one known vent field associated with the *Vityaz megamullion* (3500 m depth)—within the MPA is very poorly studied [17,58].

3.2.12. SEAFO VME closures

The South East Atlantic Fisheries Organisation is currently managing 13 VME closures in the areas beyond national jurisdiction. All fishing activity in these areas have been prohibited since January 2011. Three of these VME Closures, encompass a total of seven deep hydrothermal vents distributed along the ridge at north and south of the Ascension Islands (Fig. 1, Table S9). Two of the VME closures (Unnamed number 17 Closure and Kreps seamounts) are located across the United Kingdom extended continental shelf claim and the Area, while the other VME closures are completely in the area beyond national jurisdiction (Fig. 1) [59–61].

3.2.13. South Georgia and South Sandwich Islands marine protected area (SGSSI-MPA)

South Georgia and the South Sandwich Islands are hot spots of marine biodiversity in the Southern Ocean, between Antarctica and the South American continents. The waters of the archipelago now constitute a large MPA (1.07 million km^2) through a South Georgia and South Sandwich Islands MPA Order, which came into force in February 2012. Within the MPA, all destructive practices for the benthic environment are prohibited, i.e., bottom trawling, dredging and mining activities are not allowed [62].

The SGSSI-MPA is nearly all in deep water between 2000 and 6000 m. Benthic closure areas were established to protect juvenile toothfish, gorgonians, and other types of potentially sensitive fauna (largely unknown) present on seamounts and at hydrothermal vents. The hydrothermal vent *Kemp Caldera* is within one of the benthic closures, and the banning of bottom trawling throughout the MPA [62] provides protection to the other four hydrothermal vents within the EEZ of the archipelago (Table S7).

3.2.14. Agoa Sanctuary

The Agoa Sanctuary, established in October 2012 under the Cartagena Convention, encompasses the French Antilles in the French territorial collectivities of Guadeloupe, Martinique, Saint-Martin and Saint-Barthélemy in the Caribbean Sea. Agoa is a Specially Protected Area for Wildlife (SPAW) and is recognised internationally for protection of large migratory species of marine mammals that populate its waters. Within its geographical scope, one active hydrothermal vent associated with the Montserrat-Marie Galante fault (1000 m) is located between the islands of Montserrat and Guadalupe [63]. Hydrothermal vent field are not acknowledged within the management plan of the Sanctuary [64], but one of the priorities is to prevent and reduce the "pollution resulting, directly or indirectly, from activities relating to the exploration and exploitation of the seabed and its subsoil" implying a strict regulation for activities in the deep [64].

3.2.15. Coral Sea Natural Park

The Coral Sea Natural Park is an extremely large marine protection tool located in a tropical-subtropical region of the southern hemisphere. It occupies the entire EEZ of French New Caledonia (1.3 million km^2), including part of the Coral Sea, the maritime area between Australia, Papua New Guinea, the Solomon Islands, Vanuatu, and New Caledonia. This area is heavily influenced by the atmospheric phenomena of El Niño and La Niña, and the bathymetry and the oceanography present in this area provide high primary production that results in a high biological activity [65].

The only hydrothermal vent in the Park is *Eva,* located on a submarine volcano (Evita) in the eastern part of the Natural Park, at 1600 m depth. It is known from plume detection in 2008 and remains poorly studied [17]. The management authority of the Natural Park recognizes the value of the deep-sea environment in terms of scientific knowledge and exploration and sustainable exploitation of marine genetic resources, minerals, and rare Earth elements [65]. Within the list of management actions, adopted in March 2018, there is the intent to protect hydrothermal vents and other key deep-sea biodiversity hot spots [65].

3.2.16. Deep Pacific Mexican Biosphere Reserve

The Deep Pacific Mexican Biosphere Reserve was established to preserve representative natural environments below 800 m, including hydrothermal vents, abyssal plains, canyons, and the mid oceanic ridge, ensuring the balance and continuity of the evolutionary and ecological processes in these areas [66]. Implementation of the Deep Mexican Pacific Biosphere Reserve was preceded by a scientific study that identified the most important deep-sea ecosystems in the Mexican EEZ [67]. Within the Reserve there are six known hydrothermal vents, three within core zones and three in buffer zones (Table S8). All of the vents are protected by prohibitions on pollution, sea-bed mining, introduction of invasive species, and collection of living resources [66].

3.2.17. Pitcairn Islands marine protected area

The Pitcairn Islands MPA was established by Governor Jonathan Sinclair in Wellington in 2016 [68]. The area of the MPA comprises the EEZ and territorial seas of Pitcairn, Henderson, Ducie and Oeno Islands and encompasses multiple seamounts and submarine volcanos, one of which hosts the Bounty hydrothermal vent at 420 m [69,70]. The vent is fully protected from bottom-fisheries activities, mining, disturbance or the removal of non-living natural material, dumping of waste or other materials (including from vessels or structures), and sound that is likely to have an adverse effect on marine life [68].

3.2.18. The Offshore Pacific Seamounts and Vent Closure

The Offshore Pacific Seamounts and Vents Closure (OPSVC) is the latest (2017) spatial regulation specifically established for the protection of hydrothermal vents in Canada. The OPSVC includes 100% of known hydrothermal vents in Canadian waters and encompasses the Endeavour Hydrothermal Vents MPA, established in 2003. The OPSVC is a spatial fishery management tool within the Canadian EEZ off the coast of British Columbia and is managed under the Canadian Fisheries Act. All commercial and recreational bottom-contact fisheries are excluded in order to preserve the deep-sea environment. The OPSVC was established after the identification of the Ecologically or Biologically Significant Marine Areas (EBSAs) in the Offshore Pacific Bioregion in 2016 [71]. The OPSVC encompasses 35 hydrothermal fields, including 14 within the previously established Endeavour Hydrothermal Vent MPA (Section 3.2.6) plus 21 additional fields (Table S10).

The OPSVC is the first step toward the establishment of a large (139,700 km^2) MPA specifically dedicated to protection and conservation of unique seafloor features and their ecosystems in the Offshore Pacific Bioregion Area of Interest (AOI). This MPA is planned to be implemented under the Ocean Act, the Canadian national law for the management of the marine environment and resources, by 2020 [72].

3.2.19. Thalassia Periochi Koloumvo Site of Community Importance

The Thalassia Periochi Koloumvo in the Eastern Mediterranean Sea is a Sites of Community Importance (SCI) [73,74]. Among other things, SCIs may contribute to biological diversity within the biogeographic region concerned (European Commission Habitats Directive 92/43/EEC). Sites of Community Importance, once adopted in the formal list, are subject to general protection measures that must be followed by the European member states, including avoidance of deterioration of habitats and species, and are to be designated within six years as Special Areas of Conservation (SAC) [75]. The submarine volcano Kolumbo and its hydrothermal vent lie within the SCI and are thus protected at the national and European Union level. No management plan is yet established for this SCI.

3.2.20. Mid-Indian Ridge Benthic protected area

This area is the northern of the 13 BPAs proposed in 2016 and now implemented by the Southern Indian Ocean Deep Fishery Agreement (SIODFA) in the Indian Ocean Basin. This BPA encompass two active hydrothermal vents located in the area beyond national jurisdiction (as stated in the Interridge Database: Central Indian Ridge, 8–17°S: Segment 6, 14.3°S at 3500 m and 8–17°S: Segment 6, 14.75°S at 3400 m). The Mid-Indian Ridge BPA is an area of seamounts rising to 650 m at the 'Triple Junction' of the Australian, African and Indian tectonic plates. This is a tropical region in pristine biological condition [76]. The Mid-Indian Ridge BPA is a deep-sea fishery management tool for the preservation of biodiversity beyond national jurisdiction (BBNJ) from deep-sea trawling and mid-water trawling. However, unlike RFMO closures, the SIODFA BPAs apply only to member companies and cannot control or exclude other activities such as seabed mining explorations [77].

3.2.21. Other interventions

While this Atlas is meant to be a comprehensive list of ABMTs with hydrothermal vents, other conservation actions that protect hydrothermal vents are likely to exist, including, for example, the establishment of the "Mid-Atlantic Ridge North of the Azores High Seas MPA" by collective action of the contracting parties to OSPAR [45]. This MPA, currently protecting only the water column, may extend to the seabed when Portugal assumes responsibility for the MPA when its extended continental shelf claim will be approved [78]. Given that the Mid-Atlantic Ridge hosts active hydrothermal vents at intervals along its entire extent, the "Mid-Atlantic Ridge North of the Azores High Seas MPA" is likely to include vent fields.

The Convention for the Conservation of Antarctic Resources (CCAMLR) bans commercial bottom trawling altogether in the CCAMLR region [59] and the Madrid Protocol on Environmental Protection to the Antarctic Treaty [79] prohibits all activities related to mining until 2048. These protections hold for known and yet-to-be-discovered hydrothermal vents of the mid-ocean ridges and back arc basins within the Treaty region [80].

Other protections remain somewhat obscure or may be aspirational. For example, Iceland is reported to have an inshore MPA to protect hydrothermal vents [81] of Eyjafjörður [p. 16 [82]], but such an MPA is not listed in the WDPA, nor in the protected area listings of the Environment Agency of Iceland [83].

Still other ABMT interventions are aspirational. The Convention on Biological Diversity, through its process of designating Ecologically or Biologically Significant Areas (EBSAs; [84]) that provide competent authorities and States parties with information that enables conservation efforts [85]. The current list of designated EBSAs that mention hydrothermal vents in high-level descriptions includes the Hydrothermal Vent Fields, Guaymas Basin Hydrothermal Vents Sanctuary (with management actions in place as noted in Sections 3.2.10, 3.2.16), Eastern Caribbean, and Juan de Fuca Ridge Hydrothermal Vents EBSAs [86]. UNESCO, in contemplating World Heritage sites in the High Seas, put forward the Lost City hydrothermal field on the Mid-Atlantic Ridge as an example of a hydrothermal vent field of outstanding universal value and worthy of area-based management [87].

Finally, pending ABMT interventions by the International Seabed Authority (ISA), which has regulatory competency for protection of the seabed in the area beyond national jurisdiction, will provide protections for active hydrothermal vent and other seabed habitats from impacts of mining activities. These protections will emerge through ISA Regional Environmental Management Plans [88] and establishment of precautionary networks of no-mine areas on mid-ocean ridges [89].

4. Conclusion

This Atlas reviews the variety of ABMTs used to protect hydrothermal vents. To date, these protections have been applied to vents in EEZs of some coastal States, as well as three regional seas conventions that have implemented bottom-fishing bans (VME closures) and Benthic Protection Areas. There is one example of MPA located on an extended continental shelf claim. There remain other active hydrothermal vents in EEZs and in areas beyond national jurisdiction that are without protection. While vents may be threatened by bottom-trawling activities in some areas, they may now be in the crosshairs of an emergent deep-sea mining community [90]. For a number of reasons, many of which are described in Van Dover et al. (2018) [2] and in supporting documents cited above that implement ABMTs explicitly intended to protect active hydrothermal vents, discussion of their protection from mining activities is underway among the stakeholders and contracting parties of the International Seabed Authority (Van Dover, pers. obs.). The ABMTs described in this Atlas represent a collection of practices that may be applied to ecosystem-based management by MPAs managers, policy makers, governments and international organisations for hydrothermal vents and other deep-sea environments.

Declaration of interest

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Appendix A. Supplementary data

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