

Chapter 45. Hydrothermal Vents and Cold Seeps

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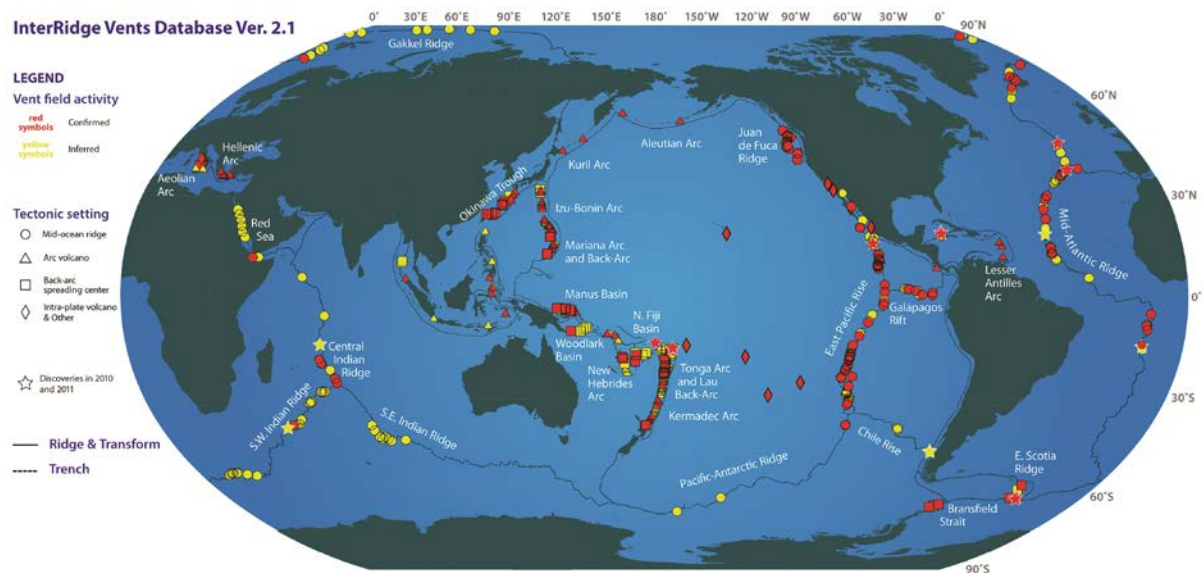
1. Inventory

Hydrothermal vents and cold seeps constitute energy hotspots on the seafloor that sustain some of the most unusual ecosystems on Earth. Occurring in diverse geological settings, these environments share high concentrations of reduced chemicals (e.g., methane, sulphide, hydrogen, iron II) that drive primary production by chemosynthetic microbes (Orcutt et al. 2011). Their biota are characterized by a high level of endemism with common specific lineages at the family, genus and even species level, as well as the prevalence of symbioses between invertebrates and bacteria (Dubilier et al., 2008; Kiel, 2009).

Hydrothermal vents are located at mid-ocean ridges, volcanic arcs and back-arc spreading centres or on volcanic hotspots (e.g., Hawaiian archipelago), where magmatic heat sources drive the hydrothermal circulation. Venting systems can also be located well away from spreading centres, where they are driven by exothermic, mineral-fluid reactions (Kelley, 2005) or remanent lithospheric heat (Wheat et al., 2004). Of the 521 vent fields known (as of 2009), 245 are visually confirmed, the other being inferred active by other cues such as tracer anomalies (e.g. temperature, particles, dissolved manganese or methane) in the water column (Beaulieu et al., 2013) (Figure 1).

Sediment-hosted seeps occur at both passive continental margins and subduction zones, where they are often supported by subsurface hydrocarbon reservoirs. The migration of hydrocarbon-rich seep fluids is driven by a variety of geophysical processes, such as plate subduction, salt diapirism, gravity compression or the dissociation of methane hydrates. The systematic survey of continental margins has revealed an increasing number of cold seeps worldwide (Foucher et al., 2009; Talukder, 2012). However, no recent global inventory of cold seeps is available.

Both vent and seep ecosystems are made up of a mosaic of habitats covering wide ranges of potential physico-chemical constraints for organisms (e.g., in temperature, salinity, pH, and oxygen, CO₂, hydrogen sulphide, ammonia and other inorganic volatiles, hydrocarbon and metal contents) (Fisher et al., 2007; Levin and Sibuet, 2012; Takai and Nakamura, 2010). Some regions (e.g., Mariana Arc or Costa Rica margin) host both types of ecosystems, forming a continuum of habitats that supports species with affinities for vents or seeps (Watanabe et al., 2010; Levin et al., 2012). Habitats indirectly related to hydrothermal venting include inactive sulphide deposits and hydrothermal sediments (German and Von Damm, 2004). Similarly, cold-water corals growing on the carbonate precipitated from the microbial oxidation of methane are among the seep-related habitats, although they typically occur long after seepage activity has ceased (Cordes et al., 2008; Wheeler and Stadnitskaya, 2011).



The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by the United Nations.

Figure 1. Global map from InterRidge database (<http://vents-data.interridge.org/maps>) displaying visually confirmed and inferred hydrothermal vents fields. Credits: Beaulieu, S., Joyce, K., Cook, J. and Soule, S.A. Woods Hole Oceanographic Institution (2015); funding from Woods Hole Oceanographic Institution, U.S. National Science Foundation #1202977, and InterRidge. Data sources: InterRidge Vents Database, Version 2.1, release date 8 November 2011; University of Texas PLATES Project plate boundary shapefiles.

2. Features of trends in extent or quality

Chemosynthetic ecosystems in the deep sea were first discovered 40 years ago using towed camera systems and manned submersibles; hydrothermal vents in 1977 for diffuse vents on the Galapagos Spreading Center (Corliss et al. 1979), and in 1979 for black smokers on the East Pacific Rise (Spiess et al., 1980), and cold seeps at the base

of the Florida escarpment in the Gulf of Mexico in 1984 (Paull et al., 1984). Compared to other deep-sea settings, the exploration of vent and seep habitats is thus recent (Ramirez-Llodra et al., 2011). In the last decade, high-resolution seafloor mapping technologies using remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs) have yet enhanced the capacity to explore the deep seabed.

Since the last global compilation (Baker and German, 2004), the known number of active hydrothermal vent fields has almost doubled, with an increasing proportion of new discoveries being in arc and back-arc settings, as a result of increasing exploration efforts (Beaulieu et al., 2013). These exploration efforts have emphasized the highly heterogeneous and patchy distribution of habitats associated with diffuse and focused-flow vents, hosting diverse microbial and faunal communities.

A large spatial and temporal variability of vent fluid temperature and chemical properties over mid-ocean ridges and arc and back-arc settings has been described, in relation to different geological substrate, hydrothermal activity, volcanic or tectonic instability (e.g. eruptions) (German and Von Damm, 2004; Charlou et al., 2010). This variability generates strong environmental constraints on chemosynthetic primary producers (Amend et al., 2011; Le Bris and Duperron, 2010; Takai and Nakamura, 2010) and dominant fauna including vent-endemic species of tubeworms, mussels, gastropods, clams, shrimp or crabs (Desbruyères et al., 2001; Fisher et al., 2007; Watanabe et al., 2010).

Common features are shared among vent and seep ecosystems. At seeps, microbial consortia oxidizing methane and their end-product (e.g., sulphide) sustain abundant microbial populations exhibiting diverse metabolic pathways. These microbes produce large amounts of organic matter, fuelling high invertebrate biomass. Many forms of symbiosis between chemosynthetic bacteria and host-invertebrates have adapted specifically to the energy-rich environmental conditions of vent and seep environments (Dubilier et al., 2008).

Within methane seeps and other types of seeps, different seepage intensities create distinct habitats dominated by chemosynthetic bacterial mats, and endemic and non-endemic species of tubeworms, mussels, gastropods, clams, shrimp or crabs, and supporting numerous associated invertebrate species. Faunal biodiversity is generally low within each seep habitat (Levin, 2005) but the vast array of geomorphic and biogenic habitats, each with highly adapted species, contributes significantly to beta diversity in the deep-sea (Cordes et al., 2010). Extensive trophic niche partitioning of microbes by heterotrophs also contributes to biodiversity at seeps (Levin et al., 2013). Methane seep sediments share many species with surrounding margin sediments (Levin et al., 2010), and numerous families and genera with hydrothermal vents and organic falls (Bernardino et al., 2012)¹.

¹ Text originally prepared for Chapter 36F (Open Ocean Deep Sea)

Despite recent global efforts, biological inventories are still largely incomplete. At the end of the Census of Marine Life programme (CoML, Crist et al., 2010), the ChEssBase dedicated to chemosynthetic ecosystems reported 700 hydrothermal vent species and 600 species from cold seeps (Ramirez-Llodra and Blanco, 2005; German et al., 2011). Around 200 new species were reported between 2002-2010 (i.e., 25 species/year), most of them belonging to mega and macrofauna. Much remains to be described, particularly in the meiofauna. Currently, vent fauna constitute between 7 and 11 biogeographic provinces, including new discoveries in the Arctic and Southern Oceans (Bachraty et al., 2009; Moalic et al., 2012; Rogers et al., 2012). Each newly identified vent or seep contains a diversity of unidentified species and these biogeographic patterns should be considered as preliminary (German et al., 2011). Furthermore, new types of chemosynthetic ecosystems are still being discovered, such as serpentinite-hosted ecosystems found on continental margins, ridges and trenches (Ohara et al., 2012; Kelley, 2005).

Few vent and seep areas have repeated observations over more than ten years from which temporal trends can be described (Glover et al., 2010). Recolonization of habitats impacted by volcanic eruptions was repeatedly documented on the 9°50'N vent field of the fast-spreading East Pacific Rise (Shank et al., 1998) and over different locations of the intermediate-spreading Juan de Fuca Ridge (Tunnicliffe et al., 1997). The resilience capacity of vent communities, however, cannot be generalized from the re-establishment of microbial communities and few dominant fauna species adapted to these highly unstable systems. Even on those areas, persistent effects on larvae patterns have been documented over years after an eruption suggesting long-lasting impacts on community recovery (Mills et al., 2013). Volcanic activity is furthermore much less frequent at slow or ultra-slow spreading ridges (e.g. Mid-Atlantic Ridge), resulting in a much lower frequency of natural perturbations, and in the absence of knowledge about the potential response of their specific communities to major disturbance. Succession at cold seeps, including later stages of deep-water coral colonization, may proceed over centuries to millennia with slow-growing and long-lived species that should be considered particularly vulnerable to disturbance (Cordes et al., 2009).

Life histories of key species and their links with resource and habitat variability have just started to be described (Ramirez-Llodra et al., 2010). Important biodiversity components supporting ecosystem functions also remain under-studied. In particular, a much lower number of studies dealt with meiofaunal organisms (< 1mm) from vent and seep sites than with macrofauna (Vanreusel et al., 2010). Following the massive molecular inventories allowed by New Generation Sequencing, we are just now getting glimpses into the diversity of microbes in both vent and seep environments. That diversity appears higher by orders of magnitude than those hitherto revealed with classical sequencing and cloning tools. Insufficient knowledge of the drivers of ecosystem and community dynamics at vent and seeps makes anticipating any trends in their ecological status problematic or even elusive in a context of multiple pressures.

3. Major pressures linked to the trends

The deep sea is being seen as a new frontier for hydrocarbon and mineral resource extraction, as a response to increasing demand for raw materials for emerging high-technology industries and worldwide urbanization. As a consequence, vent and seep ecosystems, so far preserved from direct impacts of human activities, are confronted with increasing pressures (Ramirez-Llodra et al., 2011; Santos et al., 2012).

Offshore oil extraction increasingly occurs in waters as deep as 3000 m and exploration for oil and gas now predominantly occurs in deep water (> 450m) or ultra-deep water (> 1500m depth), where typical seep ecosystems are found. Seafloor installations can directly affect cold seep communities in their impact area, if visual surveys and Environmental Impact Assessments (EIAs) are not completed prior to drilling. In addition, an increasing threat exists of large-scale impacts from accidental spills, such as the 2010 *Deepwater Horizon* blowout in the Gulf of Mexico, which was the largest accidental release of oil into the ocean in human history (McNutt et al., 2012) with a significant impact on surrounding deep-seabed habitats (Montagna et al., 2013; Fisher et al., 2014).

Further pressures on cold seep communities may arise from the combined effects of increasing demand for energy and technological progress in the exploitation of new types of energy resources. This type of development is shown by the world's first marine methane hydrate production test in the Nankai Trough in 2013. Sequestration of CO₂ in deep-sea sedimentary disposal sites and igneous rocks (Goldberg et al., 2008) should also be considered a potential threat specific to these communities (IPCC, 2005).

The increased demand for metals is promoting deep-sea mineral resource exploration both within Exclusive Economic Zones (EEZs) and in the Area (as defined in the United Nations Convention on the Law of the Sea), raising the issue of potential impacts on vent ecosystems (Van Dover, 2012). In 2011, the granting of a mining lease to exploit sulphide minerals for gold, copper and zinc in the EEZ of Papua New Guinea will shortly turn the deep-sea mining industry into a reality. Additionally, in the last five years, the International Seabed Authority has granted two new exploration permits for polymetallic sulphide deposits and two others are about to be signed for sites on the Atlantic and Indian mid-ocean ridges (<http://www.isa.org.jm/en/scientific/exploration/contractors>).

Significant threats are anticipated on the largely unknown communities associated with active hydrothermal deposits and the typical vent communities that can occur in close proximity to these areas (ISA, 2011). Inactive areas, which no longer had any detectable fluid venting with temperature anomaly as defined in the InterRidge Vents Database, have been mostly described so far in the vicinity of active areas with typical vent communities. These active areas where venting fluid is warmer than ambient, are inclusive of low-temperature diffuse flow and will require systematic exploration surveys and dedicated impact studies. Communities from inactive areas furthermore still need to be described. It is, for example, unclear whether they encompass species assemblages closely related to deep seabed areas out of any hydrothermal influence, or whether they host specific fauna adapted to the local

metal-rich substrate or to the proximity of highly productive chemosynthetic ecosystem at local to regional scale. Furthermore, despite the absence of high temperature associated with black smokers, some of these inferred 'inactive' areas may display diffuse flow vents, that are much more difficult to detect from water column surveys.

Indirect pressures on vent and seep ecosystems resulting from global anthropogenic forcing, including pollution and climate change, are not well constrained. These systems are less sensitive to changes in photosynthetic primary production than other deep-sea ecosystems, but potential threats also exist. Changes in water-mass circulation could affect larval dispersal, potentially reducing the capacity for species' populations to maintain themselves across fragmented habitats (Adams et al., 2011). The extension of hypoxia or anoxia on continental margins and in semi-enclosed seas could also profoundly alter the functioning of these ecosystems because of the high oxygen demand of chemosynthetic activity (Childress and Girguis, 2011). Warming is already affecting the deep ocean waters, especially at high latitudes (e.g., Arctic) and in enclosed seas (e.g., Mediterranean) hosting vent and seep ecosystems (Glover et al., 2010). Cold seep ecosystems could be affected, through direct impacts on the activity of fauna and the microbial consortia or major disturbances, such as landslides and gas extrusion caused by hydrate destabilization.

These ecosystems occupy fairly small areas of the seabed (typically km-scale) and may be more vulnerable to common deep-sea pressures such as deep-sea fishing or waste dumping. Deep-sea fishing on seamounts flanks and margins down to at least 1500m depth are part of the existing pressure on cold seep, even though rarely documented so far (Ramirez-Llodra et al., 2011). This pressure is potentially exerted on vent communities occurring at those depths on mid-ocean ridge flanks or volcanic arc and back-arc seamount chains. Even activities such as scientific research or bioprospecting can pose a threat to the integrity of these unique communities and their endemic species (Baker et al., 2010). Impacts of ecotourism on vent environments should also be accounted, since this is a growing activity.

4. Implications for services to ecosystems and humanity

Chemosynthetic communities are functionally distinct from other marine communities, with capacity to form very high biomasses relative to other deep-sea ecosystems, though many questions remain open about their distribution, diversity, functioning and environmental features that limit the ability to estimate associated ecosystem services (Armstrong et al., 2012).

Nevertheless, deep-sea vents and seeps represent one of the most physically and chemically diverse biomes on Earth and have a strong potential for discovery of new species of eukaryotes and prokaryotes (Takai and Nakamura, 2011). Their specialized phyla are adapted to a range of environmental constraints. Archaea that live at extremes in pressure, temperature and pH are particularly attractive to industrial sectors (UNU-IAS, 2005). The hydrothermal vent and cold seep animals have evolved traits that allow them to not only tolerate extreme environmental conditions, but in

some cases to accumulate and transport chemicals toxic to most other marine species (Childress and Fisher, 1992; Le Bris and Gaill, 2007).

This makes these ecosystems a vast genomic repository of unique value to screen for highly specific metabolic pathways and processes. The vent and seep biota thus constitute a unique pool of potential for the provision of new biomaterials, medicines and genetic resources that has already led to a number of patents (Gjerde, 2006; Arrieta et al., 2010; Thornburg et al., 2010). This great potential value to humankind is accounted for in the public awareness of potential threats and acceptability of deep-sea conservation programmes (Jobstvogt et al., 2014).

Chemosynthetic ecosystems are linked with adjacent deep-sea ecosystems through dispersing larvae and juveniles, and through the export of local productivity to mobile fauna and surrounding deep-sea corals and other filter-feeding communities, but the quantitative importance of their chemosynthetic production at the regional scale still remains to be appraised. At the global scale, a significant role of seep ecosystems is recognized in the regulation of methane fluxes, oxygen consumption and carbon storage from anaerobic methane oxidation by microbial consortia in sediments (Boetius and Wenzhöfer, 2013). Recent evidence shows that hydrothermal vent plumes sustain microbial communities with potential connections to zooplankton communities and biogeochemical fluxes in the deep ocean (Dick et al., 2013). The biological stabilization of metal (e.g., iron, copper) from hydrothermal vents under dissolved or colloidal organic complexes for long-range export in the water column has been documented recently (Wu et al., 2011; Hawkes et al., 2013). Recent assessments of these iron sources indicate their significance for deep-water budgets at oceanic scales and underscore the possibility for fertilizing surface waters through vertical mixing in particular regional settings (Tagliabue et al., 2010) and supporting long-range organic carbon transport to abyssal oceanic areas (German et al., 2015).

Because of their unique biodiversity and ecological functions in the Earth's biosphere, their geophysically-driven primary production sustained by chemosynthesis, their significance in global element cycles (i.e., iron), and their potential for natural products, vent and seep areas hold important (yet largely unknown) implications for services to ecosystems and humanity. As such, they will benefit from protection from adverse impacts caused by human activities. Furthermore, beyond the requirement to maintain biodiversity for future generations, cultural ecosystem services such as generation of scientific knowledge and inspiration for citizens to learn about the natural world and for new generations to enter scientific careers, and tourism, should also be recognized in an assessment of their economic value (Jobstvogt et al., 2014).

5. Conservation responses

Action to protect vents and seeps has taken place at national and international levels through the development of informal or voluntary protection plans or codes of conduct and formal protection measures under State or international law. An

example of informal measures is the adoption by the scientific community of the InterRidge Statement of Commitment to Responsible Research Practices (Devey et al., 2007). The marine mining industry has also produced the International Marine Minerals Society Code for Environmental Management of Marine Mining (IMMS, 2011), which outlines principles and best practice for use by industry, regulatory agencies, scientists and other interested parties (Boschen et al., 2013). The OSPAR Commission recommended strengthening the protection of hydrothermal vents/fields occurring on oceanic ridges as a threatened and/or declining habitat in order to recover the habitat, to improve its status and ensure its effective conservation in Region V of the OSPAR maritime area (OSPAR, 2014).

Formal protection measures for hydrothermal vent ecosystems have been undertaken mainly within the EEZs of States (Table 1). The Rainbow hydrothermal vent field was proposed to be included in the Azores Marine Park by the Portuguese Government at an OSPAR meeting considering these questions, even though it lies outside the EEZ (Ribeiro, 2010; Calado et al., 2011). Portugal proceeded with this area as a Marine Protected Area on the understanding that the area is located on its extended continental shelf. It is also notable that some areas protected from bottom fishing also contain chemosynthetic ecosystems (e.g., on several southern hemisphere ridges), although this protection does not apply to other activities, such as mining.

The Strategic Plan for conservation of Biodiversity 2011-2020 adopted by the Conference of the Parties at the Convention on Biological Diversity (CBD) established a target stating that 10 per cent of marine areas are conserved through systems of protected areas and other effective area-based conservation measures (Aichi Biodiversity Target 11²). In decision IX/20, the Conference of the Parties adopted the scientific criteria for identifying Ecologically or Biologically Significant Marine Areas (EBSAs) in need of protection in areas beyond national jurisdiction, and the scientific guidance for designing representative networks of marine protected areas. Because of their unique biodiversity, ecological properties and potential services, vent and seep areas meet the scientific and technical criteria defined for EBSA (Clark et al., 2014; Dunn et al., 2014; CBD scientific criteria for ecologically or biologically significant areas annex I, decision IX/20). As emphasized by decision X/29 of the Conference of the Parties, the identification of EBSAs and the selection of conservation and management measures is a matter for States and competent intergovernmental organizations, in accordance with international law, including the United Nations Convention on the Law of the Sea (CBD COP decision X/29, para. 26, 2010).

Scientists have called for the development of a cohesive network of such protected areas in which management of marine mining activities would be extremely risk averse, and often mining would be prohibited (Boschen et al., 2013; Van Dover et al.,

² Aichi Biodiversity Target 11 states “By 2020, at least 17 per cent of terrestrial and inland water, and 10 per cent of coastal and marine areas, especially areas of particular importance for biodiversity and ecosystem services, are conserved through effectively and equitably managed, ecologically representative and well connected systems of protected areas and other effective area-based conservation measures, and integrated into the wider landscapes and seascapes”.

2012). It is important to note that, in the context of vents and seeps, natural variability is acknowledged to underlie many of the changes that are happening. Knowledge gaps concerning the ecological dynamics and responses to combined pressures, therefore, currently make it difficult to devise effective conservation measures. In any case, implementation of such measures would require actions at the national, regional and (in some cases) global level to be coordinated with each other.

At present, in the absence of any formal framework for general coordination, voluntary cooperation among the International Seabed Authority (ISA) and RFMOs is taking place. Without further efforts to promote cooperation between the relevant sectoral regulatory authorities and to close gaps in knowledge, both the effectiveness of on-going conservation measures and the development of more wide-ranging protection for vents and seeps are likely to be put at risk.

Table 1. Summary of vent and seep ecosystems protected to date under national or international law (Santos et al., 2012; Calado et al., 2011; ISA, 2011; USFWS, 2012; NTL 2009-G40 ; New Zealand ENMS circular 2007; Gouvernement de Nouvelle Calédonie)

Ocean region	Name of site	Type of chemosynthetic ecosystem	Depth & location	Legal framework
North East Pacific	Endeavour hydrothermal vents MPA	Five vent fields including black smokers	2250m depth, 250km SW of Vancouver Island in Canadian EEZ.	Protected under the Canadian Government's Ocean Act.
North East Pacific	Guaymas Basin Hydrothermal Vents Sanctuary	Hydrothermal vents located in a sedimented seabed.	Gulf of California, depth of ~2500m, Within Mexican EEZ.	Protected under Mexican State Law.
North East Pacific	Eastern Pacific Rise Hydrothermal Vents Sanctuary	Hydrothermal vents located on the East Pacific Rise	East Pacific Rise, depth of ~2800m, in Mexican EEZ.	Protected under Mexican State Law.
North West Pacific	Mariana Trench National Monument	Hydrothermal vents, CO ₂ vents, sulphur lake.	Located around three northernmost Mariana Islands & Mariana Trench 10m - 1650m depth.	Protected under US Law following Presidential Proclamation.
South West Pacific	Several deep-sea benthic protection areas	Hydrothermal vents	Northern to mid-Kermadec arc	New Zealand
West Pacific	Parc naturel de la mer de Corail (nature park of the Coral Sea)	Hydrothermal vent and cool seeps (suspected)	Up to 7919 m, encompassing the whole French EEZ around New Caledonia	Protected under New Caledonia Government
Gulf of Mexico	Numerous individual sites hosting 'high-densities benthic communities'	Hydrocarbon seeps and associated deep-sea corals	400 - 3300 m, in US EEZ	US Legal Framework: Bureau of Ocean Energy Management Notice to Lessees
North Atlantic	The Azores Hydrothermal Vent MPA	Seven hydrothermal vent fields including Lucky Strike, Menez Gwen, Rainbow and Banco Dom João de Castro. Except for Rainbow they are all Natura 2000 SAC (special areas of	Amongst or to the south west of Azores Islands, N. Atlantic. 40m - 2300m depth.	Protected under Portuguese national & EU Habitats Directive, Rainbow is the first protected vent site located outside of an EEZ. It is included in the Azores Marine Park.

		conservation under the EU habitats directive)		
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