Geochemistry
Geophysics
Geosystems
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Article
Volume 14, Number 10
16 October 2013
doi: 10.1002/ggge.20243
ISSN: 1525-2027

Published by AGU and the Geochemical Society

Moytirra: Discovery of the first known deep-sea hydrothermal vent field on the slow-spreading Mid-Atlantic Ridge north of the Azores

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[1] Geological, biological, morphological, and hydrochemical data are presented for the newly discovered Moytirra vent field at 45°N. This is the only high temperature hydrothermal vent known between the Azores and Iceland, in the North Atlantic and is located on a slow to ultraslow-spreading mid-ocean ridge uniquely situated on the 300 m high fault scarp of the eastern axial wall, 3.5 km from the axial volcanic ridge crest. Furthermore, the Moytirra vent field is, unusually for tectonically controlled hydrothermal vents systems, basalt hosted and perched midway up on the median valley wall and presumably heated by an off-axis magma chamber. The Moytirra vent field consists of an alignment of four sites of venting, three actively emitting "black smoke," producing a complex of chimneys and beehive diffusers. The largest chimney is 18 m tall and vigorously venting. The vent fauna described here are the only ones documented for the North Atlantic (Azores to Reykjanes Ridge) and significantly expands our knowledge of North Atlantic biodiversity. The surfaces of the vent chimneys are occupied by aggregations of gastropods (*Peltospira* sp.) and populations of alvinocaridid shrimp (*Mirocaris* sp. with *Rimicaris* sp. also present). Other fauna present include bythograeid crabs (*Segonzacia* sp.) and zoarcid fish (*Pachycara* sp.), but bathymodiolin mussels and actinostolid anemones were not observed in the vent field. The discovery of the Moytirra vent field therefore expands the known latitudinal distributions of several vent-endemic genera in the north Atlantic, and reveals faunal affinities with vents south of the Azores rather than north of Iceland.

Components: 8,953 words, 11 figures, 2 tables.

Keywords: Mid-Atlantic Ridge; hydrothermal vent; massive sulfides; vent biota; median valley fault.

Index Terms: 3017 Hydrothermal systems: Marine Geology and Geophysics; 3045 Seafloor morphology, geology, and geophysics: Marine Geology and Geophysics; 3035 Midocean ridge processes: Marine Geology and Geophysics; 1034 Hydrothermal systems: Geochemistry; 3616 Hydrothermal systems: Mineralogy and Petrology; 4832 Hydrothermal systems: Oceanography: Biological and Chemical; 8135 Hydrothermal systems: Tectonophysics; 8424 Hydrothermal systems: Volcanology; 0930 Oceanic structures: Exploration Geophysics; 0460 Marine systems: Biogeosciences; 0450 Hydrothermal systems: Biogeosciences; 4800 Oceanography: Biological and Chemical: Biogeosciences.

Received 4 April 2013; **Revised** 29 July 2013; **Accepted** 5 August 2013; **Published** 16 October 2013.

Wheeler, A. J., et al. (2013), Moytirra: Discovery of the first known deep-sea hydrothermal vent field on the slow-spreading Mid-Atlantic Ridge north of the Azores, *Geochem. Geophys. Geosyst.*, *14*, 4170–4184, doi:10.1002/ggge.20243.

1. Introduction

[2] Hydrothermal vent fields are sites where high-temperature, mineral-rich fluids discharge from the seafloor following the circulation, heating, and geochemical reactions of seawater in oceanic crust [*Corliss et al*., 1979]. Dissolved constituents of the venting fluids play an important role in the geochemical mass balance of the oceans [*Edmond et al*., 1979], and precipitates from the fluids create seafloor massive sulfide deposits [*Francheteau et al*., 1979] that are now being considered as targets for deep-ocean mining [*Hoagland et al*., 2010; *Van Dover*, 2011]. Hydrothermal vent fields also typically sustain abundant populations of faunal species in the deep sea by the autochthonous primary production of chemosynthetic microbes [*Grassle*, 1985], which use reduced compounds in vent fluids to fix inorganic carbon [*Karl et al*., 1980]. More than 400 new faunal species have been described from deep-sea hydrothermal vents [*Desbruyères et al*., 2006], enhancing our knowledge of marine biodiversity and the dispersal and evolution of species in our planet's largest biome [*Van Dover et al*., 2002].

[3] To date, two distinct types of geological settings have been identified for mid-oceanic ridge high-temperature hydrothermal vent sites: magmatically hosted and tectonically controlled [*Baker* and *German*, 2004]. For fast- and intermediate-spreading rate ridges (i.e., those spreading in excess of 40 mm a^{-1} full rate),

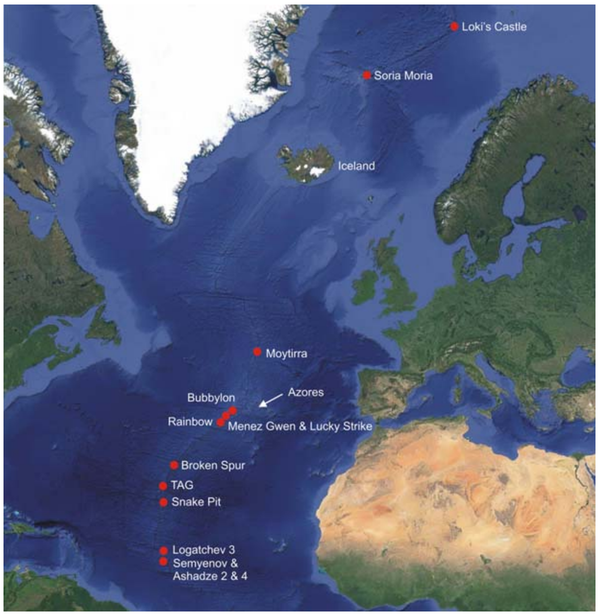

Figure 1. Location map showing all verified active high temperature hydrothermal vent sites in the North Atlantic. All data from the InterRidge Vents Database (http://www.interridge.org/irvents/). See also Table 1.

hydrothermal activity is magmatically controlled being closely associated with young volcanic systems [*German et al*., 1995] and correlated with the presence and depth of axial magma chambers [*Haymon et al*., 1991]. Here extensive melt lenses underlie much of the fast-spreading axes, at a depth of 1.5 to 3 km, and provide the necessary heat source to drive high-temperature hydrothermal circulation. At intermediate-spreading rate ridges, axial magma chambers are not as prevalent, but their occurrence along with young volcanic flows still correlates with hydrothermal vent sites [*Baker*, 1996]. Slow to ultraslow-spreading ridges (i.e., spreading at less than 40 mm a^{-1}) have a diversity of hydrothermal venting which includes both volcanic-hosted and tectonically controlled systems in equal proportions [*Rona et al*., 2010]. The latter are associated with deep detachment faulting, the formation of oceanic core complexes, and the tectonic uplift of lower crustal and upper-mantle ultramafic lithologies. Here fault zones provide deep pathways for hydrothermal circulation [*McCaig et al*., 2007]. Surprisingly, although most slow-spreading ridge segments also have a deep axial valley, bounded by major normal fault scarps of up to 1000 m throw and planes that penetrate deep into young and hot oceanic crust they have not been associated with hydrothermal activity, until now.

[4] Furthermore, 11 high temperature vent fields have been visually confirmed in the axial valley of the Mid-Atlantic Ridge (MAR) between the equator and the Azores Triple Junction at ~39°N (InterRidge Vents Database, http://www.interridge.org/irvents/) (Figure 1), no hydrothermal vent fields have been observed between the Azores Triple Junction and the Charlie Gibbs Fracture Zone at 52.50°N, which divides the MAR from the Reykjanes Ridge. Further north in the Atlantic, only a single vent field has been observed directly on the Reykjanes Ridge at latitude 63.10°N and depth 350 m—the Steinàholl vent field [*German et al*., 1994]. This site but does not appear to host fauna endemic to chemosynthetic environments [*Tarasov et al*., 2005] and is a non-sulfide-precipitating, low temperature, geothermal structure (InterRidge Vents Database: http://www.interridge.org/irvents/). Table 1 shows the site characteristics of North Atlantic verified hydrothermal vents confirming Moytirra's unique geological settling and isolated location.

[5] Our knowledge of the benthic biodiversity of the deep North Atlantic at latitudes greater than 39°N is derived from studies of abyssal plains [e.g., Billett *et al*., 2001], seamounts [e.g., *Moore et al*., 2003], non-hydrothermal areas of mid-ocean ridge [e.g., *Copley et al*., 1996; *Gebruk et al*., 2010; *Priede et al*., 2013], and continental slopes [e.g., *Tyler* and *Zibrowius*, 1992] including slope-specific habitats such as coral mounds [e.g., *Wheeler et al*., 2011a], submarine canyons [e.g., *Cunha et al*., 2011], and cold seeps (e.g., *Vanreusel et al*., 2009]. Based on a relationship between magmatic budget and the incidence of vent fields, hydrothermal vent fields may be expected to occur with a frequency of ~1 per 100 km along the MAR north of the Azores [*Baker* and *German*, 2004], but none have previously been observed directly on the seafloor, and the contribution of their fauna to the biodiversity of the region is therefore unknown.

[6] Here, we report the discovery of a deep-sea high-temperature hydrothermal vent field between the Azores and Iceland. Named the Moytirra vent field, this multiple discharge hydrothermal system is located one third of the way up a 300 m high, near-vertical fault scarp forming the eastern median valley wall of the MAR at 45°N. As such, it is the only hydrothermal vent known to be perched high-up on the steep scarps forming the median valley wall, with a tectonic setting and basaltic host lithology. This unusual location adds to the diversity of geological settings for active hydrothermal fields at slow-spreading ridges and emphasizes the interplay between faulting and magmatic

Table 1. Characteristics of All Verified Active High Temperature Hydrothermal Vents[a]

Hydrothermal	Location	Latitude °N	Control		Hosted		Located On
Vent site			Tectonic	Magmatic	Basalt	Peridotite	Medial valley wall
Loki's Castle	North of Iceland	73.55		x	x		
Soria Moria	North of Iceland	71.25		x	x		
Moytirra	**Between Azores and Iceland**	**45.48**	**x**		**x**		**x**
Menez Gwen	South of the Azores	37.84		x	x		
Bubbylon	South of the Azores	37.8		x	x		
Lucky Strike	South of the Azores	37.29		x	x		
Rainbow	South of the Azores	36.23	x		x	x	
Broken Spur	South of the Azores	29.17		x	x		
TAG	South of the Azores	26.14		x	x		
Snake Pit	South of the Azores	23.37		x	x		
Logatchev 3	South of the Azores	14.70	x			x	
Semyenov	South of the Azores	13.51	x			x	
Ashadze 2	South of the Azores	12.99	x			x	
Ashadze 4	South of the Azores	12.97	x			x	

[a]Lower Temperature Icelandic nonsulfide forming geothermal vents are omitted. See Figure 1 for hydrothermal vent locations. All data from the InterRidge Vent Database (http://www.interridge.org/irvents/) where further references are available.

heat sources. Furthermore, this discovery also enhances our knowledge of the biodiversity of deep Atlantic waters north of the Azores to include the fauna of deep-sea vent environments for the first time in this region.

2. Geological Setting

[7] At 45°N, the MAR contains a 40 km long, second order ridge segment that is bound to its north by a dextral nontransform discontinuity with an offset of less than 5 km [*Searle et al*., 2010]. High resolution bathymetry data reveal a deep, 8 to 12 km wide median valley that is bound to the east and west by steep-sided walls forming near vertical cliffs up to 500 m high. Rising from the generally flat median valley floor is an axial volcanic ridge (AVR) that occupies the center of the ridge segment. The AVR forms a prominent morphological feature that extends up to 25 km long, is ~400 m high and 2 to 6 km wide (Figure 2a). Its most elevated portions are characterized by a hummocky morphology with bright sonar-backscatter and a high crustal magnetic intensity [*Searle et al*., 2010], indicative of young volcanic terrain. The hummocks comprise more than 3000 small volcanic centers (average volume ~0.001 km^3), often overlapping, with basaltic pillow lavas as the dominant extrusive lithology [*Yeo et al*., 2012]. Deep-towed magnetic crustal intensity mapping reveals the AVR as the most strongly magnetized part of the ridge segment and hence the loci of the most recent volcanic activity [*Searle et al*, 2010].

[8] AVRs are common features of slow-spreading ridges and are considered to represent the loci of crustal accretion. They are also, therefore, the most volcanically active parts of the spreading center. Surrounding the AVR at 45°N, the median valley floor forms a low-lying and generally smoother seafloor (Figure 2a) partially covered by sheet-flows. In places, these appear on TOBI side-scan sonar images to emanate from the flat-topped volcanoes where they often cover areas of several square kilometers [*Searle et al*., 2010]. Based on magnetic intensity data, the AVR is estimated to be less than 12 ka old [*Searle et al*., 2010] and the median valley floor greater than 12 ka old. Off axis, beyond the inner valley walls, the seafloor is covered in pelagic sediments up to 1 m thick, indicating an age of 200 ka. Hence, relatively recent volcanic activity is largely restricted to the median valley floor and AVR while off axis, outside and beyond the median valley, recent volcanic activity is sparse.

[9] The 45°N median valley is bound to the east and west by steep fault scarps forming inner valley walls. These are up to 500 m high and comprise near vertical faces of exposed basalt and dolerite (Figure 2). At the center of the segment, where the AVR is widest, the eastern inner valley wall fault extends to within 1.5 km of the foot of the AVR. Elsewhere, the inner valley wall fault lies several kilometers beyond the edge of the area of young volcanism, as defined by the highest intensity sonar backscatter [*Searle et al*., 2010].

3. Methods

[10] Background data for the 45°N MAR segment, including preliminary indications of hydrothermal plumes, were acquired during research cruise

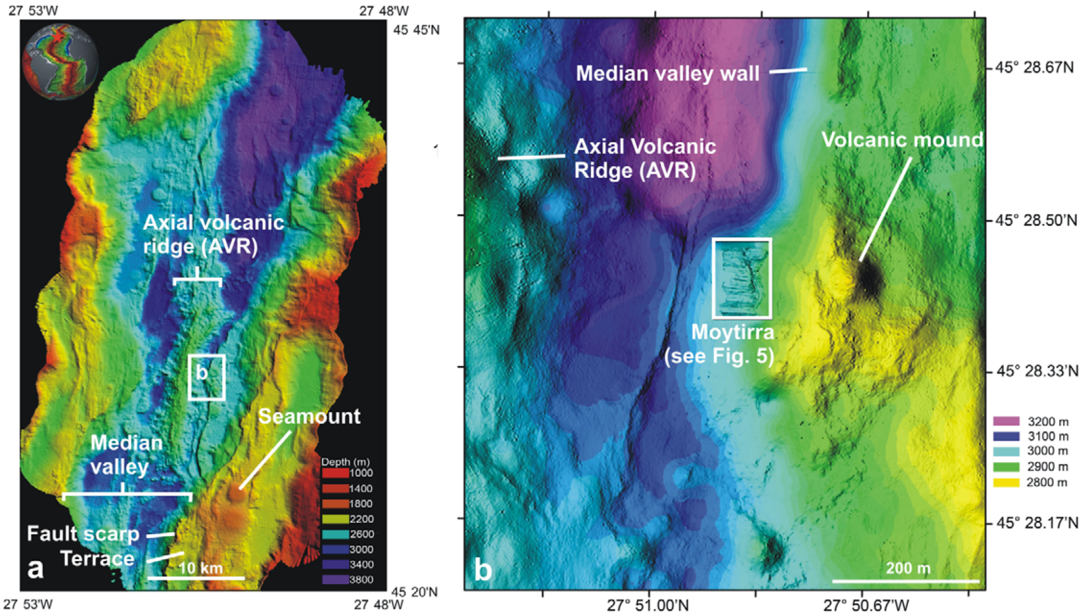

Figure 2. (a) Bathymetric map of the median valley of the Mid-Atlantic Ridge at 45°N color coded by water depth. The axial volcanic ridge (AVR) is the prominent linear rise (coded green) in the center of the median valley. The median valley is bounded by step fault controlled cliffs defining a series of terraces. Small circular topographic highs are seamounts [*Searle et al.*, 2010]. (b) Close up of the Moytirra vent field (in white box—see also Figure 5) setting showing its location on a median valley wall underneath a small inactive volcanic mound.

JC24 of the RRS James Cook in 2008 and reported in *Searle et al*. [2010]. For the VENTuRE cruise (reported here), investigations and sampling of the Moytirra vent field were carried out on board the research ship RV Celtic Explorer and using the Holland I remotely operated vehicle (ROV) between 11 July and 4 August 2011 (A. J. Wheeler and Science Party, unpublished report, University College Cork, 2011). The Holland I is a 3000 m rated SMD Quasar workclass ROV equipped with two manipulator arms, an aspirator, CTD, Eh meter and multibeam echosounder. The vehicle has a high-definition video camera with parallel laser scale (0.1 m spacing), forward pan-and-tilt standard definition video camera and downward-looking standard definition video camera, as well as a pan-and-tilt digital stills camera.

[11] Hydrothermal plume mapping was initially performed using a Sea Bird Electronics SBE 911+ CTD and included a dissolved oxygen sensor, fluorometer, and a custom made Eh sensor (courtesy of Prof. Koichi Nakamura). The CTD was "tow-yoed" at ~0.25 ms^{-1} (continuous repeated vertical profiling through the water column whilst occupying a survey line) covering a depth interval of 2000–3000 m. Navigation was provided by an ultrashort baseline (USBL) system, using a remote beacon attached to the ROV and a tracking head attached to the drop keel on the RV Celtic Explorer to provide three-dimensional location fixes to within ±10 m.

[12] Tow-yo CTD surveys occupied mutually perpendicular lines, each centered on the maximum plume intensity identified from the previous line. By this method, the source of the hydrothermal effluent was rapidly (within 32 h) identified by narrowing down the size of the area occupied by the peak plume intensity. In addition to optical backscatter (nephels), Eh anomalies (sensitive to reduced ionic species) further reduced the size of the search area. Hydrogen sulfide and Fe^{2+} are readily oxidized in the water column and generate a strongly negative Eh anomaly, which is taken as an indicator for proximal emissions of reduced (hydrothermal) fluids. Similarly, positive temperature anomalies that extend all the way to the seafloor are further indications of the location of high-temperature fluid discharge at the seafloor.

[13] Once the source of the hydrothermal effluent was located to within an area of ~500 m × 500 m, the ROV was launched to locate and map the source of hydrothermal venting. The ROV carried a multibeam swath sonar (RESON Seabat 7125) that was mounted to scan vertically downward. The sonar acquired data from 512 equidistant beams forming a swath angle of 120°, and using a pulse length of 20

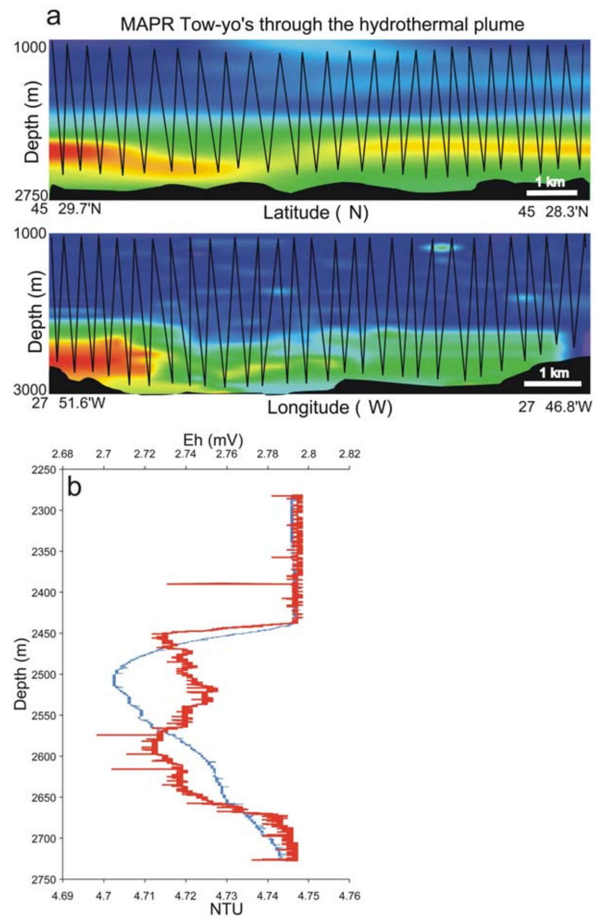

Figure 3. (a) Gridded tow-yo profiles through the plume vented from the Moytirra vent field as imaged in 2008 [see *Searle et al*., 2008] showing δNTU (nephal turbidity units) or the difference in turbidity above background level. A high turbidity anomaly finding neutral buoyancy is shown in deeper profiles. Dark Blue = 0.00V δNTU, Red = 0.04V δNTU. Sea surface δNTU was 0.01V and (b) CTD cast in the immediate vicinity of the Moytirra vent field showing anomalies in Eh (blue) and turbidity (red).

ms and a ping rate of about 30 Hz. Sensor attitude data were derived from an Ixsea Octans optical gyro and USBL navigation supplemented by a 60 kHz Doppler velocity log. A sound velocity profile was calculated from the CTD casts. Acoustic navigation was derived from a "Compat 5" Sonardyne USBL beacon positioned on the vehicle with the relevant offsets and lever arms calculated and implemented in the swath sonar mapping acquisition software PDS2000. Final data cleaning and mosaicing were done in NOCS using in-house software.

[14] Geological (rock), geochemical (fluid), and faunal sampling were performed using the ROV manipulator arms, titanium vent fluid syringes, and an aspirator, respectively. Fauna were also collected using a baited trap. Faunal specimens were identified to genus level aboard ship using morphological characters where possible.

[15] Digital stills photography and high and standard definition (HD and SD) video footage were recorded to document the occurrence of vent fauna, and to produce composite images of two vent structures. These composite images were constructed by extracting frames from high definition digital video using Final Cut Pro software, and compiling frames into composite images using Adobe Photoshop, with morphological features of structures providing points of reference for manual mosaicing of frames.

4. Results

4.1. Hydrothermal Plume Indications at 45°N

[16] Initial indications of a hydrothermal plume over the 45°N segment of the MAR were documented by R. C. Searle et al. (unpublished cruise report, National Oceanography Centre, 2008). Using Miniature Autonomous Plume Recorders (MAPRs; courtesy of Ed Baker, PMEL, NOAA) in a tow-yo mode, R. C. Searle et al. (unpublished cruise report, 2008) identified a number of neutrally buoyant nephel plumes between depths of

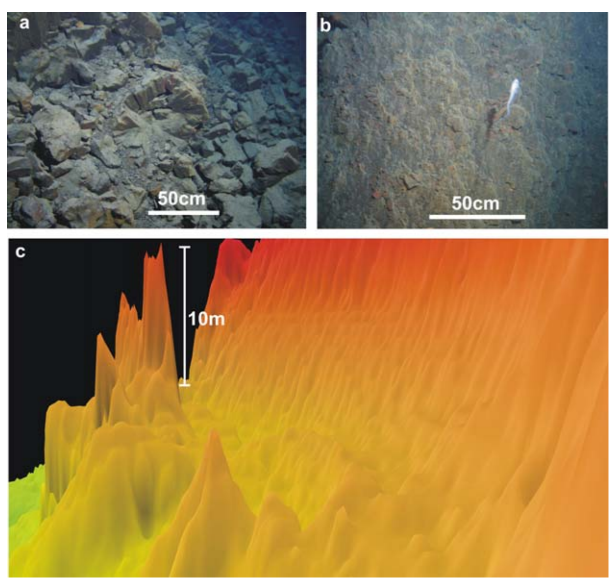

Figure 4. (a) ROV image of pillow lavas exposed in the scarp wall. (b) An area of diffuse venting forming a thick crust of massive sulfides on the scarp wall, visibly distinct from the ubiquitous rocky scarp wall else (see Figure 4a), covered in bacterial mats. (c) Digital terrain model of scarp wall showing the close proximity of vent chimneys.

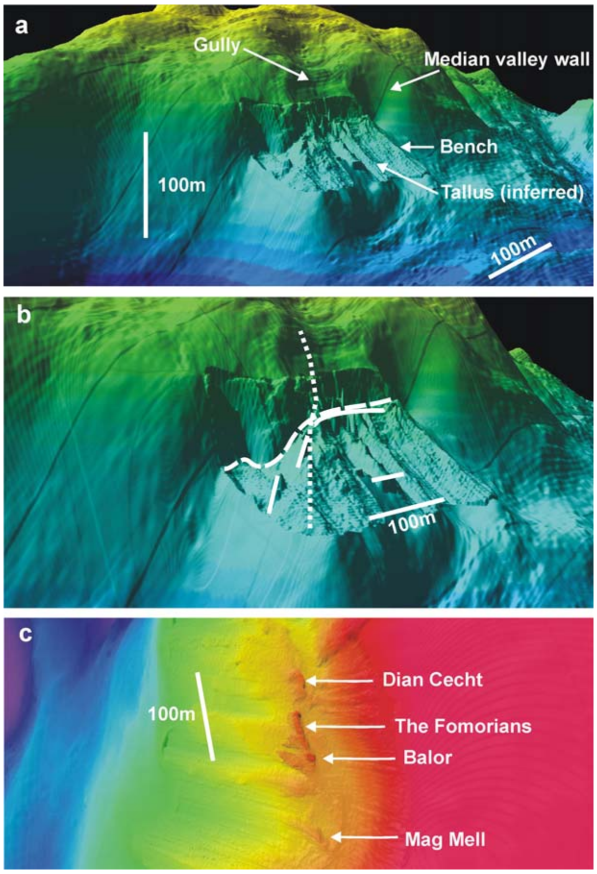

Figure 5. (a) Multibeam echosounder bathymetry of the Moytirra vent field setting. Moytirra is imaged in higher resolution and sits on a bench at the base of a steep median valley wall fault scarp with ridges of assumed tallus extending downslope. (b) Close up of the vent field showing major lineations. Chimneys are aligned (solid line) parallel to the boundary fault (dashed line). They occur at the intersection of an other fault marking a gully in the headwall (dotted line) (c) Plan view showing the named chimney clusters in close alignment.

2500 m and 3200 m (Figure 3a). Here the peaks in particulate optical density are likely to be signatures from a number of neutrally buoyant, distal plumes originating from individual vent sources of either different heat flux and/or source depth. The most prominent and thickest plume was found several hundred meters above the eastern flank of the central part of the AVR, with an upper depth of between 2500 and 2780 m. Based on a typical rise height in the north Atlantic for hydrothermal plumes of 250–300 m, and from the geometry of the upper surface of the plume (where a possible momentum overshoot was identified), a hydrothermal source was tentatively located on the eastern flank of the AVR at a depth of between 2750 and 3080 m (i.e., near a position of 45° 29.3′N/27° 51.0′W). Despite a clear indication of hydrothermal venting, the source was not confirmed during the 2008 cruise. Hence, in 2011, we reoccupied the area with CTD tow-yos and ROV surveys.

[17] During a 32 h period of CTD operations, we relocated the plume and narrowed down the search area to one containing a strong Eh, nephel, and temperature signal on the seafloor (Figure 3b). The plume was centered within a radius of 100 m around a position of 45° 28.4′N/27° 50.7′W, located on the scarp of the eastern inner valley wall, 3.5 km from the crest of the AVR. The water depth here is between 2845 m and 3060 m, and nephel, Eh and temperature anomalies were found to increase in strength all the way to the seafloor, indicating a buoyant hydrothermal plume and proximal source of venting.

4.2. The Moytirra Vent Field

[18] Following the CTD survey, visual investigations by the ROV Holland I found that the buoyant plume was centered on an extinct volcanic mound (Figure 2b) at the top of the eastern axial valley wall. However, the seafloor here is covered in sediment covered pillow lavas and hydrothermal emissions from the seafloor are absent. Less than 50 meters to the west of the mound, where the axial valley wall forms a slightly curved, west-facing, north-south trending fault scarp several hundred meters high, the ROV visually detected small quantities of black sulfate particles in the water indicative of rising hydrothermal effluent.

[19] The scarp exposes brecciaed pillow lavas (Figure 4a) and, nearer the base, broken dolerite dykes. Here the rocks are bathed in warm, black, iron particulate, and sulfide-rich water and are encrusted in a massive sulfide crust that is a few centimeters thick (Figure 4b). At a depth of 2095 m, four tall, active, and extinct hydrothermal composite structures are aligned for ~50 m along a ledge in the scarp face. Together, these structures and vents form the Moytirra vent field (named after the Irish mythological "plain of the pillars") (Figure 4c).

[20] High resolution ROV-based multibeam data, integrated with ship-acquired swath bathymetry soundings, reveal in greater detail the geological context and extent of the vent field (Figure 5a). Unusually, the Moytirra vent site is located on the side of a steep fault-scarp forming the inner bounding fault of the eastern side of the median valley. At about one third of the way up from the median valley floor, the hydrothermal chimneys

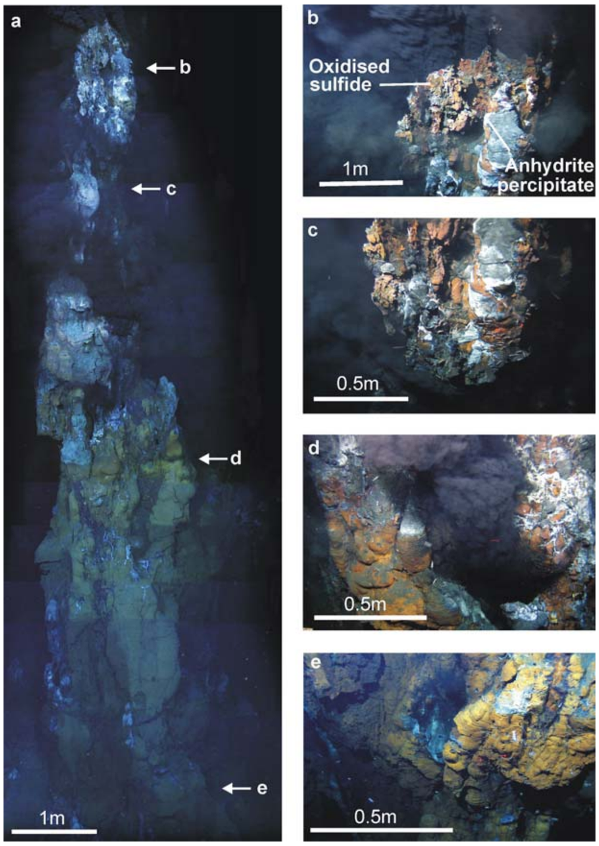

Figure 6. (a) Video mosaic of the 18 m Balor chimney with close ups of (b) the top showing profuse venting, oxidized sulfides and with anhydrite precipitates, (c) upper section as above with some side venting, and (d and e) the lower and basal, again with small amount of venting.

are aligned along a curved, 10–30 m wide ledge that extends along strike for over a 100 meters. The ledge is cut into a steep, ~300 m high, convex, and slightly domed scarp that is the footwall of the eastern median valley wall. The active vents are clustered at the intersection of a second obliquely oriented fault trace forming a gully and indentation in the axial wall. A series of additional perpendicular rills and gullies that are of either erosional or tectonic origin, also dissect the scarp (Figure 5b). Thus, the vent field is localized by the intersection of oblique minor faults with a major median valley bounding fault, located ~1.5 km from the edge of the neovolcanic AVR and 3.5 km from the AVR crest. With over 300 m of throw, the median valley wall fault plunges steeply beneath the adjacent neovolcanic zone on the median valley floor. Here, the basement lithologies are dominated by brecciated pillow lavas and more massive dolerite dykes. On inspection, the basalt and dykes are found to be altered to lower greenschist facies. The association of intercalated basalts with dykes is typical of the "transition zone" found in ophiolites toward the base of the extrusive layer. Its exposure here indicates a significant amount of throw on the inner median valley wall fault, possibly accommodating the full 300 m height of the scarp in a single fault plane.

[21] The arrangement of the different hydrothermal structures within the vent field is shown on the high-resolution bathymetry map (Figure 5c). The largest of the active hydrothermal chimneys is an 18 m tall, >1 m thick sulfide column, named "Balor" (after an Irish mythological fiery giant), comprising branching chimneys topped by beehive diffusers (Figure 6). These are coated in anhydrite and vigorously erupt black-colored, iron and sulfide-rich hydrothermal effluent.

[22] Adjacent to "Balor" is an alignment of slightly shorter and more slender sulfide chimneys called "The Fomorians" (named after Balor's mythical army). These also actively vent black hydrothermal fluids (Figure 7). Thirty meters to the north, where the ledge meets the axial valley fault scarp, is a complex of smaller chimneys and sulfide crusts (we called "Dian Cecht"—an Irish mythical river-boiling healer) that emit a vigorous flux of vent fluid (Figures 8a, 8d, and 8e). To the south of "Balor" is an older and extinct sulfide chimney complex characterized by a large number of densely packed slender pipe-like structures. These are more oxidized and lithified than the active sulfide chimneys and diffuse mainly clear fluids from their base (Figure 8b and 8c). We named this complex "Mag Mell" (after an Irish mythological place of dead warriors).

[23] Using the vigor of fluid venting and the degree of oxidation and weathering of the sulfide structures as a proxy for their age, the locus of hydrothermal activity appears to have migrated from south to north along the strike of the axial valley wall. The detailed ROV acquired multibeam bathymetry shows a number of oblique structures intersecting the main axial valley scarp. These are interpreted as minor faults and fissures, probably associated with the larger oblique fault that cuts the axial wall. It is possible that northward migration of the loci of displacement on these oblique faults has affected the permeability of the basement such that the focus of hydrothermal fluid flux has also migrated north.

[24] Unlike many other slow-spreading hydrothermal sites, the Moytirra vent field does not include a mound of sulfide rubble. Instead, where imaged,

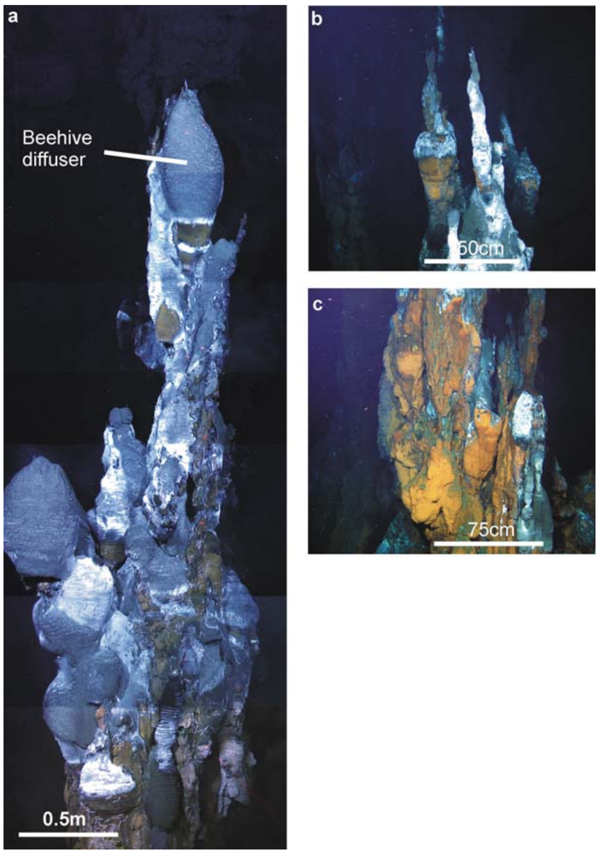

Figure 7. (a) Video mosaic of one of the Fomorian chimneys showing slender organ pipes topped with beehive diffusers, (b) the upper part of an adjacent Fomorian again showing slender organ pipes on top of a stockier base, and (c) close up of the base of a Fomorian.

the chimneys are built upon a basement of basaltic breccia. As such, this may mean that hydrothermal activity is relatively recent at this location. Alternatively, it is not clear whether there is sulfide rubble at the foot of the axial wall slope, as we were unable to reach depths greater than 3050 m with the ROV. If there is a sulfide rubble mound, then the Moytirra vent field is more similar to other vent sites on the MAR, with the exception of it being located on a steep fault scarp.

4.3. Vent Biota

[25] The macrofauna on the actively venting sulfide structures of the Moytirra vent field ("Balor," "The Fomorians," and "Dian Cecht") were visually dominated by peltospirid gastropods (*Peltospira* sp.; Figure 9a) and alvinocaridid shrimp (*Mirocaris* sp.; Figure 9b). The peltospirid limpets were patchily distributed in aggregations of up to $\sim$50,000 indiv m^{-2} (Figure 8e), estimated from HD video footage using parallel laser scale. The dominant morphospecies of alvinocaridid shrimp occurred in aggregations around crevices and sources of diffuse vent fluids, but were otherwise more sparsely distributed on sulfide surfaces (Figure 9c).

[26] A second species of larger alvinocaridid shrimp (*Chorocaris* sp.) was also present at lower densities on actively venting structures, along with occasional bythograeid crabs (*Segonazacia* sp.; Figure 10a). At the diffuser structures of "Dian Cecht," we also observed a third species of alvinocaridid shrimp (*Rimicaris* sp.), which was rarer in occurrence than the other alvinocaridid shrimp. Faunal samples collected by the ROV's aspirator sampler at the actively venting structures also included skeneid (*Protolira* sp.; Figure 10b) and turrid (*Phymorhyncus* sp.) gastropods, spionid and terebellomorph polychaetes, and a gammarid amphipod (*Harpinia* sp.).

[27] The extinct sulfide chimneys of "Mag Mell" were visually devoid of primary consumer fauna, with only occasional motile predators or scavengers such as zoarcid fish observed (*Pachycara* sp.; Figure 10c). Zoarcid fish and bythograeid crabs also occurred at the base of all the sulfide structures observed during ROV dives (Figure 8d), and specimens of both taxa were collected by baited trap. The axial valley wall forming a scarp above the vent field was coated with widespread bacterial mats (Figure 4b), among which free-living polynoid polychaetes were observed. No bathymodiolin mussels or actinostolid anemones were observed at any structures or areas of the vent field examined during the ROV dives.

5. Discussion

[28] Slow-spreading ridges host a greater diversity of geological settings for hydrothermal activity than their fast-spreading counterparts [*Baker and German*, 2004]. While fast-spreading ridges are invariably associated with young volcanic centers and axial magma chambers [*Haymon et al.*, 1991], along the MAR about 50% of vent sites are hosted on volcanic centers and 50% on tectonically uplifted ultramafic blocks [*Rona et al.*, 2010]. The volcanic hosted vent sites are centered on the crest or flanks of AVRs, and sometimes associated with an axial summit graben [*Murton et al.*, 1994]. Tectonic controlled vent sites are hosted in ultramafic lithologies exposed on the foot-walls of oceanic core complexes [*McCaig et al.*, 2007] at nontransform discontinuities [e.g., the Rainbow vent field – Douville *et al.*, 2002].

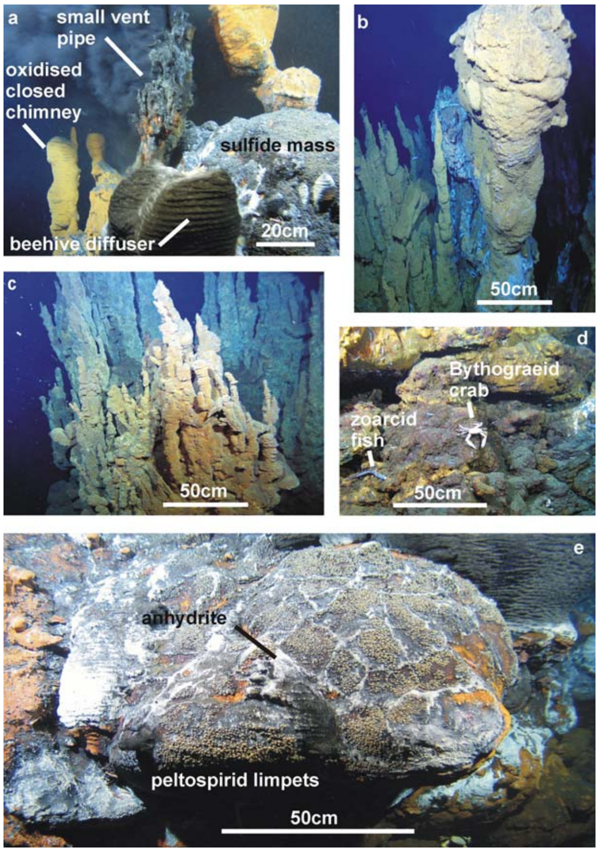

Figure 8. (a) Close up of Dian Cecht showing venting from small pipes, beehive diffusers and older oxidized closed chimneys surround a sulfide mass, (b and c) oxidized older organ pipes at Mag Mell, (d) detail of the base of Dian Cecht with bythograeid crab (*Segonzacia* sp.) and zoarcid fish (*Pachycara* sp.), and (e) close up of the Dian Cecht showing a mass of sulfide which is cracked allowing heat to dissipate and anhydrite to precipitate. The cooler surface between the cracks is covered by peltospirid limpets (*Peltospira* sp.).

[29] In contrast, at 45°N, the venting is located on the hanging wall of an eastern ridge axis median valley wall fault scarp. Its location, at several kilometers distant from the AVR, and association with a major axial wall fault that is itself dissected by transverse/oblique faults, suggest it belongs to the tectonic class of vent fields. Although clearly tectonically controlled, it is hosted on mafic lithologies (brecciated pillow lavas and dykes) rather than plutonic or ultramafic rocks and in this way is unusual. It is also doubly unusual for being sited one third of the way up the steep axial valley wall. A comparison with all high temperature hydrothermal vent sites in the North Atlantic is presented in Table 1. This table demonstrates Moytirra as the only pure basalt-hosted tectonically controlled vent site and one that is uniquely situated on the median valley wall.

[30] Several tens of meters to the west of the vent field the axial wall fault plane plunges below the neovolcanic zone and the median valley floor. Any high-temperature fluids, driven by a heat source located beneath the AVR, would require a flow path that was gently inclined beneath the median valley floor and across the axial valley wall fault plane. The large, normal fault forming the axial wall provides a highly permeable channel for any crustal fluid flow. As such, it could act as a conduit for hot buoyant vent fluids to rise and exit the seafloor either at the fault trace or through the hanging wall some distance to the east of the heat source. A schematic illustration of the Moytirra Vent geological site context is shown in Figure 11.

[31] Assuming a heat source and a depth of reaction of 2 to 3 km below the AVR crest, then the vent fluid would have to flow 2 to 3 km laterally

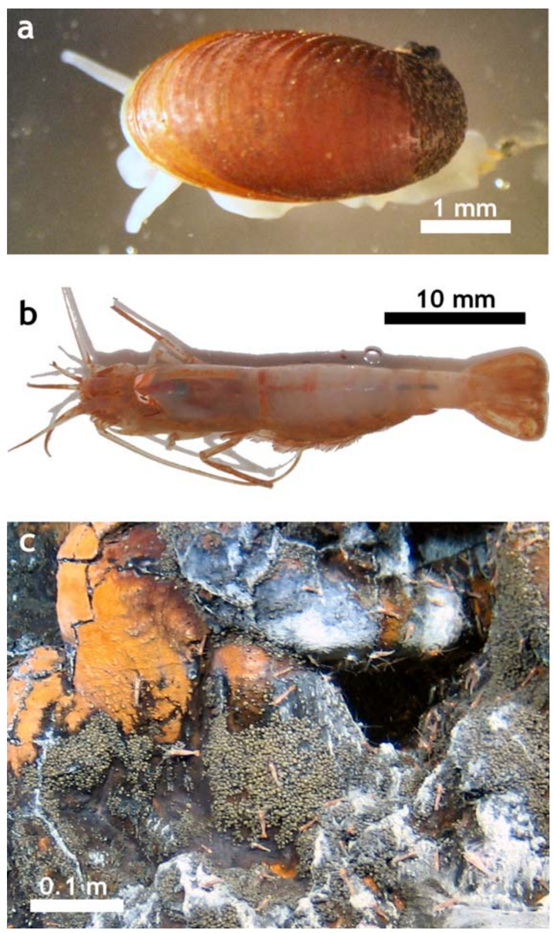

Figure 9. Visually dominant macrofaunal on actively venting structures of the Moytirra vent field: (a) *Peltospira* sp. limpet, (b) *Mirocaris* sp. shrimp, and (c) typical distribution of Peltospira limpets and Mirocaris shrimp on sulfide surfaces.

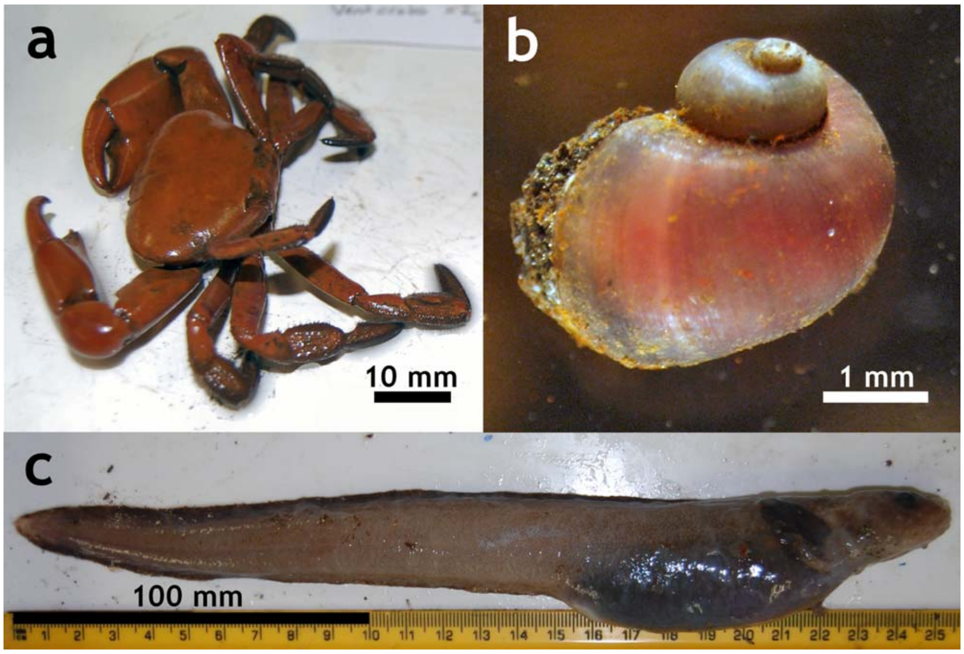

Figure 10. (a) Bythograeid crab (*Segonzacia* sp.) collected by baited trap, (b) Skeneid gastropod (*Protolira* sp.) collected by aspirator sampler, and (c) Zoarcid fish (*Pachycara* sp.) collected by baited trap.

toward a colder region of crust, crossing open fissures and permeable fault zones along its route, to emerge at the site of the Moytirra vent field. A more likely alternative to this involves a heat source located directly below the vent field. The seafloor at the top of the axial valley wall is sediment covered, as is an adjacent volcanic mound. Hence, there is no evidence for recent or active volcanism in the immediate vicinity. However, the median valley floor is covered in young, massive, sheet flows, and hosts some large (1–2 km diameter) volcanoes. Magnetic crustal intensity also shows that the flows on the median valley floor are younger than would be expected from the plate spreading rate alone [*Searle et al.*, 2010]. Together, these recent flows and volcanoes indicate a magma supply that is not directly associated with the AVR but is located under the median valley floor.

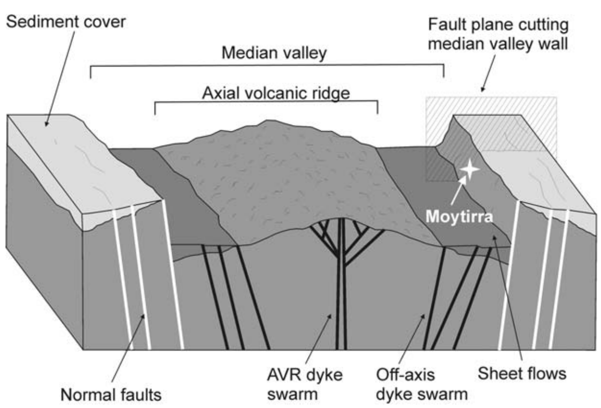

Figure 11. Schematic diagram showing the geological context of the Moytirra vent site. Moytirra is situated some distance from the axial volcanic ridge on the median valley wall fault scarp where it intersects a perpendicular fault. The heat source is though to be from an off-axis magma chamber.

[32] We suggest that an off-axis magma body, located beneath the eastern axial valley wall, provides the heat for the Moytirra vent field. Furthermore, the interaction between the axial valley wall fault and the crosscutting transverse faults seen on the high-resolution bathymetry for the vent field provide an enhanced permeability channel for the rising hydrothermal fluids to exploit. Together, this geological setting generates an optimal mechanism for focusing upwelling hydrothermal circulation and discharge at the seafloor that is a hybrid between tectonic mining of heat via tectonic uplift of faulted blocks and magmatic heat supplied from off axis melt accumulations. Located on the axial valley wall fault scarps above the median valley floor, mineral deposits formed in this way are likely to accumulate significant volumes of material without being buried by later lava flows erupted on the median valley floor or, at some distance away, on the AVR. It also satisfies the quandary of why axial faults that cut deep into the hot and young crust

Table 2. Variation in Relative Abundances of Key Faunal Genera Present as "Abundant" in At Least One Vent Field in the North Atlantic or Arctic[a]

	Northern Mid-Atlantic Ridge (MAR) South of the Azores								MAR Azores to Iceland	Mid-Ocean Ridges North of Iceland	
Vent Field	Ashadze[b]	Logatchev[c]	Snake Pit[d]	TAG[e]	Broken Spur[f]	Rainbow[g]	Lucky Strike[g]	Menez Gwen[g]	Moytirra	Jan Mayen FZ area[i]	Loki's Castle[j]
Latitude (°N)	12.97	14.75	23.37	26.14	29.17	36.23	37.29	37.84	**45.48**	71.25–30	73.55
Depth (m)	4200	3050	3500	3670	3100	2320	1740	850	**2095**	500–750	2400
Cnidaria - Anthozoa											
Maractis	++++	–	+++	+++	++	–	+	–	**–**	–	–
Annelida - Polychaeta											
Nicomache	–	–	–	–	–	–	–	–	**–**	*	+++
Sclerolinum	–	–	–	–	–	–	–	–	**–**	–	++++
Mollusca - Bivalvia											
Bathymodiolus	–	+++	+	+	+	++	+++	+++	**–**	–	–
Mollusca - Gastropoda											
Peltospira	++	++	+	–	–	–	++	++	**+++**	–	–
Pseudosetia	–	–	–	–	–	–	–	–	**–**	+++	+++
Skenea	–	–	–	–	–	–	–	–	**–**	*	+++
Arthropoda -Crustacea											
Exitomelita	–	–	–	–	–	–	–	–	**–**	–	+++
Mirocaris	+++	+	+	+	+	+++	+++	++	**+++**	–	–
Rimicaris	+	+++	++++	++++	++	++	+	–	**++**	–	–

[a]Key to relative abundances of genera: – absent; * present but no relative abundance data reported; + rare; ++ common; +++ abundant; ++++ dominant.
[b]*Fabri et al*. [2011].
[c]*Gebruk et al*. [2000].
[d]*Segonzac et al*. [1992].
[e]*Copley et al*. [2007].
[f]*Copley et al*. [1997], *O'Mullan et al*. [2001].
[g]*Desbruyères et al*. [2001].
[h]*Cuvelier et al*. [2009].
[i]*Schander et al*. [2010], *Sweetman et al*. [2013].
[j]*Pedersen et al*. [2010], *Tandberg et al*. [2012].

of the median valley floor are not observed to localize hydrothermal activity. We predict that other examples of this type of hydrothermal vent setting will be found where off-axis magmatism coincides with intersecting normal faults on the median walls of slow-spreading ridges. The setting of the Moytirra vent field also provides evidence that median valley wall faults are able to provide significant pathways for hydrothermal fluid emissions elsewhere, contributing to both the net chemical and heat flux from the oceanic crust, and providing hitherto unknown sites for vent fauna to colonize.

[33] The elucidation of vent biota at Moytirra extends the recorded ranges of several genera, previously only known at vent fields south of the Azores. Although identification of taxa to species level requires future molecular analyses to exclude the occurrence of possible cryptic species [*Vrijenhoek*, 2009], the fauna of the Moytirra vent field exhibit taxonomic affinities, at least at generic level, to vent fields south of the Azores (Table 2).

[34] *Mirocaris* shrimp occur at Moytirra with a similar distribution and abundance to *Mirocaris fortunata* at the Lucky Strike vent field (latitude 37°18'N, depth ~1740 m; *Cuvelier et al*. [2009]). Similarly, the aggregations of *Peltospira* gastropods at Moytirra are similar in population density to those at Lucky Strike [*Bouchet* and *Warén*, 2001], although coverage of chimneys by aggregations may be less extensive at Lucky Strike.

[35] Other taxa observed at Moytirra that are only previously recorded from vent fields south of the Azores include the alvinocaridid shrimp genera *Chorocaris* and *Rimicaris*, with the latter present as a panmictic population of *R. exoculata* [*Teixeira et al*., 2012]. *Rimicaris* exhibits considerable variation in relative abundance among vent fields on the Mid-Atlantic Ridge (Table 2), with low abundances at some sites attributed to topography of vent edifices [*Copley et al*., 1997] or limited availability of suitable habitat for nutrition on chimney surfaces [*Schmidt et al*., 2008; *Fabri et al*., 2011].

[36] The bythograeid crab genus *Segonzacia* is widely distributed among Mid-Atlantic vent fields south of the Azores [*Desbruyères et al*., 2006], and the skeneid gastropod genus *Protolira* is

known from vent and whalefall environments in the North Atlantic, with *Protolira valvatoides* occurring at Menez Gwen and Lucky Strike [*Warén* and *Bouchet*, 1993]. Among the seven species of the zoarcid fish genus *Pachycara* recorded in the Atlantic, two species (*Pachycara thermophilum* and *Pachycara saldanhai*) have previously been described from hydrothermal vent environments [*Geistdoerfer*, 1994; *Biscoito* and *Almeida*, 2004], but subsequently synonymized on the basis of molecular evidence (*Stefanni et al*., 2007]

[37] Aggregations of bathymodiolin mussels dominate active vent chimneys in the Lucky Strike vent field [*Cuvelier et al*., 2009], but no mussels were observed in comparable chimney habitats at Moytirra. Bathymodiolin mussels are present at higher latitudes in the north Atlantic, however, at cold seeps [*Vanreusel et al*., 2009]. The genus *Bathymodiolus* exhibits variation in relative abundance at vent fields south of the Azores (Table 2), with its absence also noted at the Ashadze-1 vent field [*Fabri et al*., 2011]. High concentrations of suspended mineral particles in vent fluids have been proposed to interfere with suspension feeding of bathymodiolin mussels, potentially limiting their occurrence at some sites [*Desbruyères et al*., 2001].

[38] It remains to be established whether such factors exclude bathymodiolin mussels from Moytirra, or whether the taxon occurs in areas not surveyed by ROV dives. The absence of bathymodiolin mussels on chimneys, however, may allow expansion of aggregations of peltospirid limpets compared with vent fields such as Lucky Strike. Actinostolid anemones were also not observed during ROV dives at Moytirra; the genus *Maractis* occurs in varying relative abundance at vent sites south of the Azores, but is also not recorded at some southern sites (Table 2).

[39] Future molecular analyses should determine whether species at Moytirra are identical or cryptic to those present at vents south of the Azores, and if shared species are present, the discovery of Moytirra may extend the scope for investigations of population connectivity at Mid-Atlantic hydrothermal vents. In contrast with the faunal similarities between Moytirra and vent fields south of the Azores, the visually dominant genera at Moytirra are not shared with those reported at vent fields north of Iceland (Table 2), indicating that a biogeographic boundary may occur further north between northern Atlantic and Arctic vent fauna.

Acknowledgments

[40] The VENTuRE survey was principally funded by the Marine Institute under the 2011 Ship-Time Programme of the National Development Plan and by the National Geographic Society with additional support from National Geographic Television, National Oceanography Centre, UK, University of Southampton, UK, Geological Survey of Ireland (INFOMAR programme), University College Cork and National University of Ireland, Galway. J. Carlsson was supported by the Beaufort Marine Research Award in Fish Population Genetics funded by the Irish Government under the Sea Change Programme. Dan Toal, University of Limerick is thanked for supplying the multibeam echosounder system and Reson for technical support during mobilization. Multibeam processing was supported by NOCS (Tim Le Bas) and GSI INFOMAR programme (Maria Judge). A special thanks goes to the RV Celtic Explorer officers and crew, ROV technical team and onshore support team in the Marine Institute and P&O Maritime.

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