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An authoritative global database for active submarine hydrothermal vent fields

Stace E. Beaulieu

Woods Hole Oceanographic Institution, 266 Woods Hole Road, Mail Stop 7, Woods Hole Oceanographic Institution, Woods Hole, MA 02543 USA (stace@whoi.edu)

Edward T. Baker

NOAA PMEL, Seattle, Washington, USA

Now at the Joint Institute for the Study of the Atmosphere and Ocean—PMEL, University of Washington, Seattle, Washington, USA

Christopher R. German and Andrew Maffei

Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, USA

[1] The InterRidge Vents Database is available online as the authoritative reference for locations of active submarine hydrothermal vent fields. Here we describe the revision of the database to an open source content management system and conduct a meta-analysis of the global distribution of known active vent fields. The number of known active vent fields has almost doubled in the past decade (521 as of year 2009), with about half visually confirmed and others inferred active from physical and chemical clues. Although previously known mainly from mid-ocean ridges (MORs), active vent fields at MORs now comprise only half of the total known, with about a quarter each now known at volcanic arcs and back-arc spreading centers. Discoveries in arc and back-arc settings resulted in an increase in known vent fields within exclusive economic zones, consequently reducing the proportion known in high seas to one third. The increase in known vent fields reflects a number of factors, including increased national and commercial interests in seafloor hydrothermal deposits as mineral resources. The purpose of the database now extends beyond academic research and education and into marine policy and management, with at least 18% of known vent fields in areas granted or pending applications for mineral prospecting and 8% in marine protected areas.

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1. Introduction

[2] The InterRidge Global Database of Active Submarine Hydrothermal Vent Fields, hereafter referred to as the InterRidge Vents Database, is available online as the authoritative source for locations of hydrothermal vent fields worldwide (linked to InterRidge homepage: <http://www.interridge.org>). The InterRidge Vents Database was developed to provide a comprehensive list of active submarine hydrothermal vent fields for use in academic research and education. A previous version of the database was used to review the global distribution of hydrothermal vent fields as of year ~2001 [Baker and German, 2004]. We thoroughly revised and restructured the database and here report a meta-analysis of the current known distribution of vent fields, highlighting important developments over this past decade. More recently, the database has become important in marine policy decisions on protected areas and the granting of mining tenements.

2. Data

2.1. Data Compilation

[3] The InterRidge Vents Database was commissioned by the InterRidge Working Group on Global Distribution of Hydrothermal Activity to be an international, interactive database for all known sites of submarine hydrothermal activity (InterRidge News 9.1, April 2000). The previous version, here considered Version 1, was updated intermittently through ~2006. During the decade 2000–2009, Hannington [Hannington *et al.*, 2004], E. Baker, and S. Petersen independently compiled three other global lists of vent fields. Version 2.0 of the InterRidge Vents Database was compiled from the merger of Version 1 (212 listings) with the three other global lists (an additional 250 listings), and the addition of vent fields from other global and regional publications [e.g., Gebruk, 2002; Tarasov *et al.*, 2005; Desbruyères *et al.*, 2006; Fujikura *et al.*, 2008; Bachraty *et al.*, 2009; Dando, 2010], primary literature, and cruise reports (an additional 92 listings). Version 2.0 was released online in 2010 and available for public comment for 1 year. The updated Version 2.1 (additional 34 listings), released 8 November 2011 and used in the meta-analysis below, provides a comprehensive listing of active hydrothermal vent fields through the end of 2009, as well as those discovered in 2010 and 2011 with published loca-

tions. Version 2.1 had 532 active and 56 inactive vent fields (please note: the database is not comprehensive for inactive vent fields). The full compilation of data for active vent fields is listed in Data set S1 in the supporting information.¹

2.2. Structure and Contents of the Database

[4] Version 2 of the InterRidge Vents Database is available online in an open source Drupal 6 Content Management System. Major improvements in the upgrade to Version 2 include unique vent field name identification, the use of taxonomy terms with controlled vocabulary, and export of the full list of vent fields as a comma-separated-value file. These upgrades were intended to improve access to categorized information and as a first step toward enabling interoperability with other oceanographic databases. In terms of interaction with the database, one advantage of using Drupal is that content can be added or edited online in a web browser. The site administrator (InterRidge Office) sets permissions for different user roles. Currently, permissions for anonymous users of the Drupal site are restricted to viewing only. Registered users may create or edit content, with authentication assured by administrative approval.

[5] Vetted details for each vent field include a unique name identification (ID), name aliases, names of individual vent sites contained within the field, hydrothermal activity, maximum temperature, location, water depth, ocean, national jurisdiction, region, tectonic setting, full spreading rate if applicable, year and means by which discovered, and literature references. The name ID is associated with a controlled vocabulary for Feature_ID VentField in the Marine Geoscience Data System (MGDS, within the U.S. Integrated Earth Data Applications facility). We distinguish a vent field as a cluster or assemblage of vent sites in relatively close proximity (i.e., on the order of 0.1–1 km). An ultimate goal is to list each vent field as “a cluster of vent openings presumed to have an interconnected water supply” [Hessler *et al.*, 1988]. As noted by Baker and German [2004], precise enumeration of vent fields is subjective. In order to distinguish vent fields in proximity to each other, when possible, we relied on peer-reviewed publications that specified distinct vent fields based on geophysical characterization [e.g.,

¹Additional supporting information may be found in the online version of this article.

Haymon *et al.*, 1991]. Otherwise, the determination is based on distance (e.g., all vent sites within a distance on the order of 1 km and separated from other vents by greater than this distance), depth, and local geological setting. Vent site names are associated with controlled vocabularies for Feature_ID Vent in MGDS.

[6] Hydrothermal activity is categorized as “confirmed” when authenticated by visual observations at the seafloor (i.e., ground-truthing) that may or may not also include temperature measurements, as “inferred” when water column measurements have detected a hydrothermal plume, or as “inactive.” In Version 2.1, over three quarters of the inferred sites (79%) are based on water column indicators (e.g., hydrothermal plumes detected by turbidity and/or chemical anomalies). The remaining 21% either had only seafloor sampling that did not include visual observations of venting fluids, or did not report the method by which hydrothermal activity was inferred. Thus, for most of the inferred active vent fields, some kind of activity is unquestionably confirmed, but not yet visually. We retain the distinction between “confirmed” and “inferred” active for two main reasons. First, observation of the active vents and sampling at the seafloor are important for geoscientists and biologists in site characterization (e.g., for biogeography of vent fauna). Second, the location for inferred active fields is less accurate; surveying hydrothermal plumes can locate vents to varying scales of precision [e.g., German *et al.*, 2008b]. We are inclusive of all submarine vent fields with vents at temperatures greater than ambient, from high-temperature black smoker vents to lower-temperature diffuse vents. Maximum temperature (°C) is provided when reported for confirmed active vent fields; otherwise assigned as “High” if chimneys and/or black smokers were observed or “Low” if only diffuse venting was observed. No temperature category is provided for inferred active fields.

[7] Locations (latitude, longitude) are provided in decimal degrees up to four decimal places (~10 m precision). Depth (m below sea level) is provided as either a range (deepest to shallowest) or single reported depth. Taxonomy, or classification, terms with controlled vocabularies are used for ocean, national jurisdiction, region, and tectonic setting. Ocean categories conform to the InterRidge Cruise Database, with the Arctic north of Iceland [as in Pedersen *et al.*, 2010b] and the Southern Ocean defined as south of latitude 60°S following the standards of the International Hydrographic Orga-

nization. We explicitly categorize vent fields into national jurisdiction or the high seas, based on querying the VLIZ Maritime Boundaries Geodatabase [VLIZ, 2009], using the location for each vent field. Region indicates the regional setting of the vent field along the world plate boundaries, with the exception of vent fields at intraplate volcanoes and coastal faults. In general, region corresponds to the MGDS Feature_ID catalog services hierarchy. We classified vent fields by region into five categories for tectonic settings: mid-ocean ridge (MOR), back-arc spreading center (BASC), arc volcano, intraplate volcano, or other; for more refined classification to tectonic and volcanic settings, please refer to Hannington [2009]. The MOR category also includes nascent oceanic rifts (e.g., Red Sea) and some short spreading segments on otherwise transform boundaries. BASC includes intraoceanic (e.g., North Fiji Basin) and intracontinental (e.g., Okinawa Trough) rifts associated with subduction zones. “Arc volcano” includes intraoceanic volcanic arcs (e.g., Kermadec arc), those with ocean crust on either side, and island arcs (e.g., Aeolian arc), with a basement of continental crust. The “other” category includes coastal faults and offshore extensions of subaerial geothermal systems. For each vent field categorized as MOR or BASC, the full spreading rate velocity (mm/yr) was determined from Bird [2003]. For the year and means by which discovered, visual confirmation at the seafloor is listed first, unless otherwise noted. Literature references for each vent field are available in the online database. Other entries in the online database that are not comprehensive for all vent fields include host rock, deposit type, site description, and biology notes.

3. Summary Statistics

[8] Hydrothermal vents have been discovered at most of Earth’s submarine plate boundaries and at several intraplate hotspots (Figure 1). We present statistics here for discoveries through the end of 2009, for which the Version 2.1 database is comprehensive for known active vent fields, both confirmed (245) and inferred (276). Statistics for the number of known active vent fields per tectonic setting and per region are summarized in Table 1. Vent fields at mid-ocean ridges (MORs) comprise half (52%) of the total known active, with about a quarter each at volcanic arcs (25%) and back-arc spreading centers (BASCs, 21%), and the remaining 2% at intraplate and other tectonic settings (Table 1 and Figure 2a). At spreading ridges

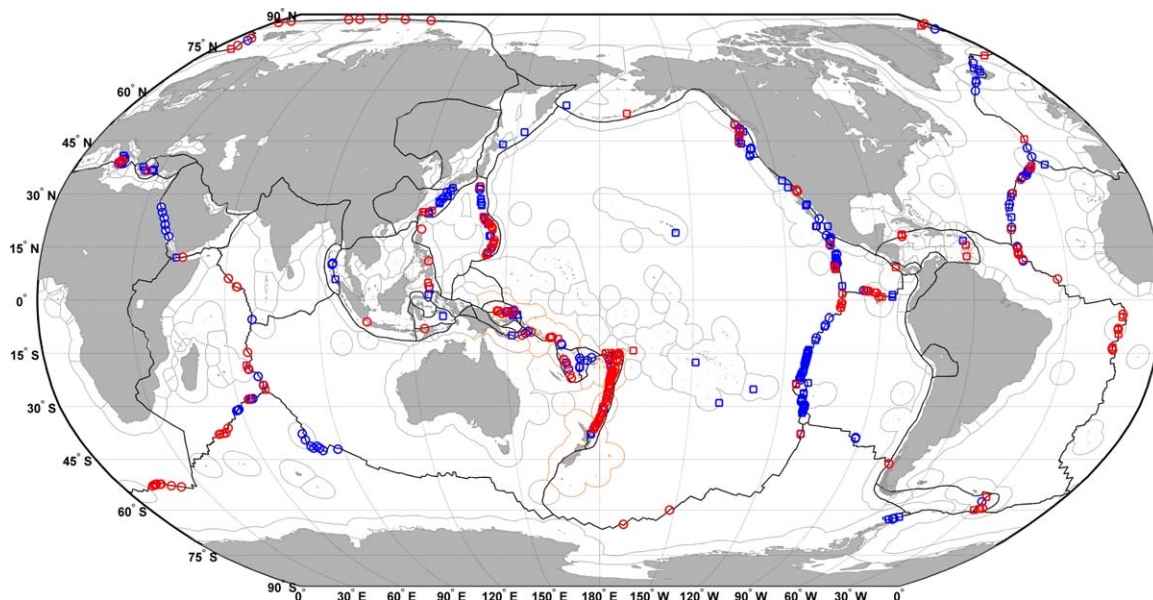


Figure 1. Locations of all known active vent fields, distinguishing confirmed (square) and inferred (circle) and whether discovered and/or confirmed prior to (blue) or after (red) year 2000 (Data set S1). Other plotted data sets include plate boundaries (thin black line) [Bird, 2003] and EEZs (thin gray line) [VLIZ, 2009]. Note the six EEZs with estimates for number of vent fields in mining tenements (granted and applications) are distinguished by orange outline.

(MORs and BASCs), there are 379 known active vent fields, representing 36% of the previously published global estimate (1060) [Baker and German, 2004]. A large proportion of those known at MORs are at slow and superfast spreading rates, while most of those known at BASCs are at intermediate spreading rates (Figure 3). Revised calculations for the total estimated population of vent fields at MORs and BASCs per spreading rate are in preparation (Beaulieu et al., manuscript in preparation, 2013). Statistics for the number of known active vent fields per national jurisdiction are summarized in Table 2. Although we expect more vents in international waters [e.g., Van Dover, 2011], the current proportion of known vent fields in high seas is only one third (34%; Table 2). The nations with the most known active vent fields within exclusive economic zones (EEZs) are Tonga (12%), USA (combined EEZ 7%), and Japan and New Zealand each at about 5% (Figure 2b).

[9] The depth distribution of known vent fields is strongly bimodal, with a peak in shallow waters (0–200 m depth bin) mainly because of vents at volcanic arcs and a peak at bathyal depths (2400–2600 m depth bin) mainly attributable to vents at fast spreading MORs (Figure 4). Vents at arc volcanoes dominate the upper ~1500 m, back-arc

vents are prominent at ~1500–2500 m, and MOR vents dominate at depths greater than ~2200 m (Figure 4). 90% of known active vent fields are at depths >200 m. The distinction between shallow and deep-sea vents at the 200 m isobath is important when considering the distribution of vent-obligate fauna (i.e., animals that live only at hydrothermal vents) [Dando, 2010]. The depth distribution is consistent with that previously published for high-temperature vents and related seafloor massive sulfide deposits [Hannington et al., 2005; Hannington, 2009]. Depths of known high-temperature, black smoker vents now range from 345 m (East Diamante) [Embley et al., 2007] to 4960 m (Piccard/Beebe) [Connelly et al., 2012; Kinsey and German, 2013].

[10] In general, shallower vents are lower temperature, bounded by the relationship of the two-phase (boiling) curve to pressure. Thus measured maximum temperatures at arc volcano vents tend to be less than temperatures at back-arc and MOR vents (Figure 5). In addition, some of the shallow arc vents may have a meteoric water source in combination with seawater (e.g., submarine flank of sub-aerial stratovolcano on island arc). At the same depths, vents in arc, back-arc, and intraplate settings tend to be at lower temperatures than MOR vents, perhaps relating to higher water: rock ratio

Table 1. Number of Known Active Vent Fields Per Region, Organized by Tectonic Setting

Regions	Confirmed Active	Inferred Active	SUM Active	% of Total Vent Fields ^a	% of Total Vent Fields Discovered 2000–2009 ^b
<i>Mid-Ocean Ridge</i>					
Aden Ridge	1	1	2	0.4	0.4
Carlsberg Ridge	0	3	3	0.6	1.3
Chile Rise ^c	0	2	2	0.4	0.0
Central Indian Ridge (CIR) ^c	4	4	8	1.5	1.8
Explorer Ridge	1	1	2	0.4	0.4
Gakkel Ridge	1	8	9	1.7	4.0
Galapagos Spreading Center (inclusive of Galapagos microplate, westward from Galapagos Triple Junction)	5	7	12	2.3	4.0
Gorda Ridge	2	4	6	1.2	0.0
Gulf of California	1	2	3	0.6	0.9
Juan de Fuca (JdF) Ridge	20	4	24	4.6	1.8
Knipovich Ridge	0	3	3	0.6	0.9
Kolbeinsey Ridge	3	1	4	0.8	0.0
Lena Trough	0	1	1	0.2	0.0
Mid-Cayman Rise ^c	0	3	3	0.6	1.3
Mohns Ridge	3	0	3	0.6	1.3
N East Pacific Rise (EPR) ^c	21	14	35	6.7	1.8
S EPR (inclusive of Easter and Juan Fernandez microplates)	27	35	62	11.9	2.2
Reykjanes Ridge	1	2	3	0.6	0.0
N Mid-Atlantic Ridge (MAR) ^c	15	24	39	7.5	5.7
S MAR ^c	4	4	8	1.5	3.5
Pacific-Antarctic Ridge	2	2	4	0.8	1.3
Red Sea	0	7	7	1.3	0.0
Southeast Indian Ridge (SEIR)	0	8	8	1.5	0.0
Southwest Indian Ridge (SWIR) ^c	1	19	20	3.8	6.2
Terceira Rift	1	0	1	0.2	0.0
SUM MORS	113	159	272	52.2	38.8
<i>Back-Arc Spreading Center</i>					
Andaman Basin	0	2	2	0.4	0.0
Bransfield Strait	2	2	4	0.8	0.0
East Scotia Ridge	2	1	3	0.6	0.9
Izu-Bonin back-arc	0	2	2	0.4	0.4
Lau Basin ^c	16	34	50	9.6	18.5
Manus Basin	8	3	11	2.1	2.6
Mariana Trough	6	1	7	1.3	1.8
New Hebrides back-arc	2	1	3	0.6	0.4
North Fiji Basin	3	4	7	1.3	0.0
Okinawa Trough	10	2	12	2.3	1.3
Taupo Volcanic Zone (and Havre Trough)	2	0	2	0.4	0.0
Tyrrhenian Back-Arc Basin, Tyrrhenian Sea	1	0	1	0.2	0.4
Woodlark Basin	1	2	3	0.6	0.4
SUM BASCS	53	54	107	20.5	26.9
SUM MORS and BASCS	166	213	379	72.7	65.6
<i>Arc Volcano</i>					
Aeolian Arc, Tyrrhenian Sea ^c	3	5	8	1.5	0.9
Aleutian Arc, western ^d	2	0	2	0.4	0.4
Banda/Sunda Arc ^c	2	2	4	0.8	0.9
Bismarck Arc ^c	1	0	1	0.2	0.0
Costa Rica fore arc ^c	1	0	1	0.2	0.4
Hellenic Arc, Aegean Sea ^c	6	1	7	1.3	0.4
Izu-Bonin Arc ^d	6	2	8	1.5	0.0
Kermadec Arc ^d	9	14	23	4.4	8.4
Kuril Arc ^d	2	0	2	0.4	0.0
Lesser Antilles Arc ^d	3	0	3	0.6	0.9
Luzon/Bicol Arc ^c	0	2	2	0.4	0.9
Mariana Arc ^d	15	8	23	4.4	7.0
New Hebrides Arc ^d	1	7	8	1.5	2.2
Ryukyu Arc ^c	5	0	5	1.0	0.0
Sangihe Arc ^c	3	1	4	0.8	0.9
Solomons Arc ^c	1	4	5	1.0	1.8
South Sandwich Arc ^{c,d}	0	2	2	0.4	0.9

Table 1. (continued)

Regions	Confirmed Active	Inferred Active	SUM Active	% of Total Vent Fields ^a	% of Total Vent Fields Discovered 2000–2009 ^b
Tabar-Feni Arc ^c	2	2	4	0.8	0.4
Tonga Arc ^{c,d}	5	13	18	3.5	7.5
SUM Arcs	67	63	130	25.0	33.9
Intra-plate volcano	5	0	5	1.0	0.4
Other	7	0	7	1.3	0.0
SUM Intra-Plate and Other	12	0	12	2.3	0.4
SUM ALL	245	276	521		

^a521 total known globally as of year 2009.

^b227 total discovered and/or confirmed globally in the decade 2000–2009.

^cRegions in which vents were discovered and/or confirmed in year 2010 or 2011.

^dIntraoceanic or possible intraoceanic arc.

^eIsland arc.

in more permeable host rock prior to discharge. Although only 131 of the confirmed active vent fields were $\geq 100^\circ\text{C}$ or categorized as high temperature in the database, most of the inferred active vent fields are likely to be high temperature based on their discovery by turbidity in the water column (i.e., particulates in hydrothermal plumes) and/or sulfide deposits from seafloor sampling. *German et al.* [2010] detail three “end-member

vent types” that are detected via plumes, with the most common reported from mafic-hosted, high-temperature systems under either neovolcanic or tectonic control. Plume detection via chemical sensors, more sensitive to lower-temperature diffuse venting and to high-temperature venting associated with serpentinization of ultramafic (i.e., of mantle rather than crustal origin) rocks, is becoming more common [e.g., *Baker et al.*, 2010]; thus, the assumption that “inferred” equates to high-temperature venting will not be accurate in the future. However, for now, one may argue that the global inventory of known active high-temperature fields may be as high as ~ 400 (a

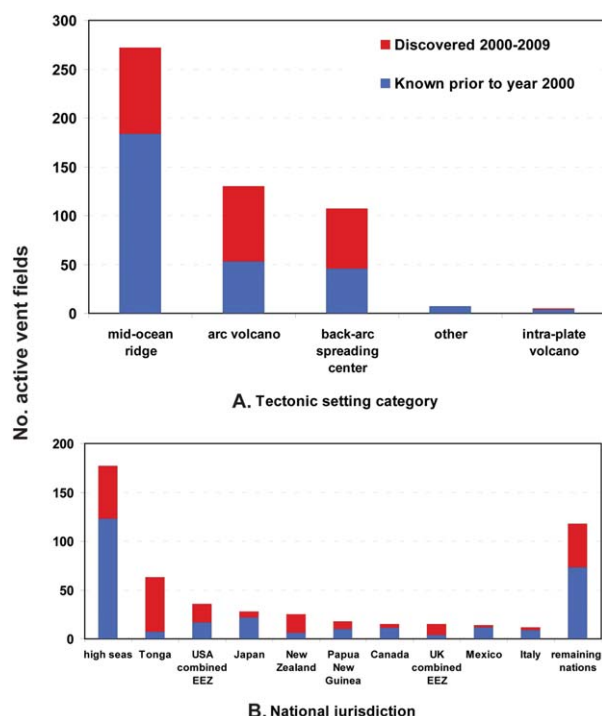


Figure 2. Number of active (confirmed and inferred) vent fields, distinguishing those discovered in the past decade. (a) Per tectonic setting category. (b) Per national jurisdiction. Nations with fewer than 10 known active vent fields are combined.

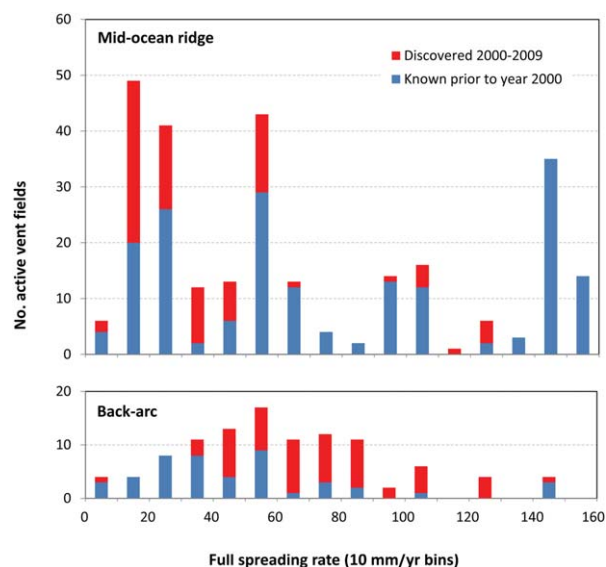


Figure 3. Stacked bar histogram of known number of active vent fields as functions of spreading rate for MORs and BASCs in 10 mm/y bins, distinguishing those discovered in the past decade.

Table 2. Number of Known Active Vent Fields Per National Jurisdiction

National Jurisdiction	Confirmed Active	Inferred Active	SUM Active	% of Total Vent Fields ^a	% of Total Vent Fields Discovered 2000–2009 ^b
High seas ^c	75	102	177	34.0	23.8
EEZs					
Antarctica	2	2	4	0.8	0.0
Canada	10	5	15	2.9	1.8
Chile ^c —Easter Island	2	6	8	1.5	0.0
Costa Rica	1	0	1	0.2	0.4
Denmark—Greenland	1	3	4	0.8	1.3
Djibouti	1	0	1	0.2	0.0
Dominica	1	0	1	0.2	0.4
Ecuador—Galapagos	3	6	9	1.7	4.0
Egypt	0	2	2	0.4	0.0
Fiji	3	6	9	1.7	0.4
France—Amsterdam Island and Saint Paul Island	0	3	3	0.6	0.0
France—French Polynesia	2	0	2	0.4	0.0
France—New Caledonia	0	1	1	0.2	0.4
France—Wallis and Futuna ^c	0	1	1	0.2	0.4
Greece	6	1	7	1.3	0.4
Grenada	1	0	1	0.2	0.4
Iceland	4	2	6	1.2	0.0
India—Andaman and Nicobar Islands	0	2	2	0.4	0.0
Indonesia	5	3	8	1.5	1.8
Italy	7	5	12	2.3	1.3
Japan	21	7	28	5.4	2.6
Japan—Korea Joint	0	1	1	0.2	0.0
Mauritius	2	1	3	0.6	0.9
Mexico ^c	6	8	14	2.7	0.9
New Zealand	11	14	25	4.8	8.4
Norway	1	3	4	0.8	1.3
Norway—Jan Mayen	2	0	2	0.4	0.9
Papua New Guinea	12	6	18	3.5	3.5
Philippines	0	2	2	0.4	0.9
Portugal—Azores ^c	6	3	9	1.7	0.9
Russia	3	0	3	0.6	0.0
Saudi Arabia	0	2	2	0.4	0.0
Solomon Islands	2	6	8	1.5	2.2
Sudan	0	3	3	0.6	0.0
Taiwan	2	0	2	0.4	0.4
Tonga ^c	20	43	63	12.1	24.7
UK—Ascension	2	2	4	0.8	1.8
UK—British Indian Ocean Territory	0	1	1	0.2	0.0
UK—Cayman Islands ^c	0	3	3	0.6	1.3
UK—Montserrat	1	0	1	0.2	0.0
UK—Pitcairn	1	0	1	0.2	0.0
UK—South Georgia ^c	2	3	5	1.0	1.8
USA	4	4	8	1.5	0.4
USA—American Samoa	1	0	1	0.2	0.4
USA—Hawaii	1	0	1	0.2	0.0
USA—Northern Mariana Islands and Guam	19	7	26	5.0	7.5
Vanuatu	2	6	8	1.5	1.8
Yemen	0	1	1	0.2	0.4
SUM EEZs	170	174	344	66.0	76.2
SUM ALL	245	276	521		

^a521 total known globally as of year 2009.

^b227 total discovered and/or confirmed globally in the decade 2000–2009.

^cNational jurisdictions in which vents were discovered and/or confirmed in year 2010 or 2011.

recent publication conservatively used >300) [Hannington *et al.*, 2011]. The highest stable temperature measured so far at a black smoker was 407°C at Turtle Pits vent, S MAR, at the critical point at ~3000 m depth [Koschinsky *et al.*, 2008].

[11] For visually confirmed vent fields, we categorized the “means by which discovered” to autonomous underwater vehicle (AUV), human-occupied vehicle (HOV), remotely operated vehicle (ROV), SCUBA, and towed camera (including TV grabs)

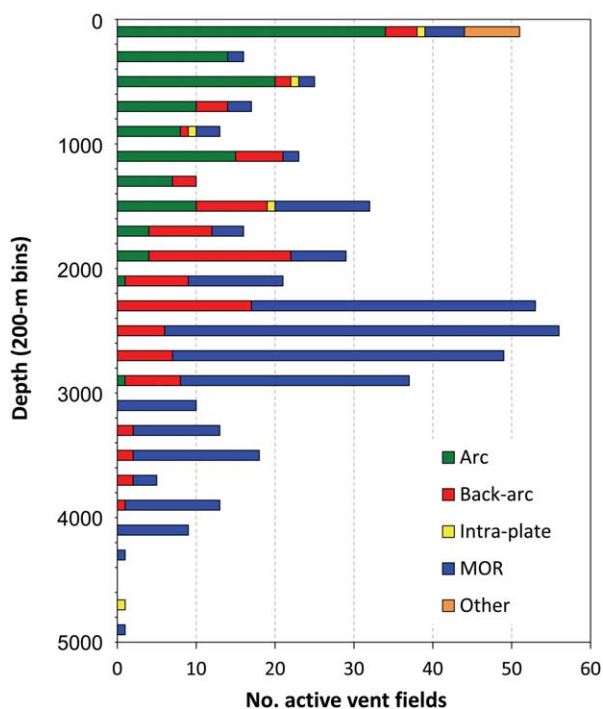


Figure 4. Depth distribution of active submarine hydrothermal vent fields in different tectonic settings. Two vent fields had no reported depth.

and plotted the cumulative number of discoveries by year (Figure 6). Confirmations in the first two decades of discoveries were mainly with HOV, towed camera, and SCUBA. The first confirmation with ROV was in 1993, and confirmations of vent fields during the past decade were dominated by ROV. Confirmations via towed camera systems and HOV (deep waters) continue at a reduced rate, while confirmations via SCUBA (shallow waters) are now rare. The first confirmations with AUV occurred in 2004 with several more in the ensuing years [German *et al.*, 2008b].

4. Revised Global Distribution of Active Submarine Hydrothermal Vent Fields

[12] Since the last global compilation one decade ago [Baker and German, 2004], the known number of active submarine hydrothermal vent fields has almost doubled from 277 to 521 at the end of 2009 (Data set S1). We note that the revised database identifies 294 vent fields known prior to year 2000, i.e., 17 more than in the previous review [Baker and German, 2004]. This slight increase mainly results from comprehensive inclusion of

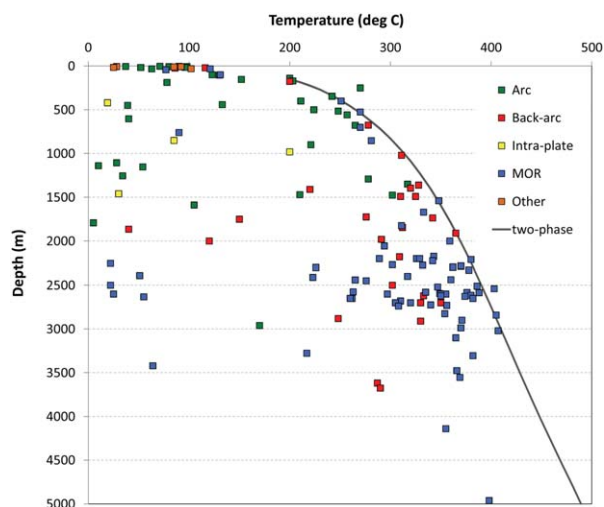


Figure 5. Temperature versus depth plot for confirmed vent fields per tectonic setting. Maximum reported temperature is plotted against single reported or average of maximum/minimum depth. Two-phase boundary (“seawater boiling curve”) from Bischoff and Rosenbauer [1988, their Table 3], with depth computed using p2z80 algorithm from Matlab Oceanography Toolbox.

shallow-water submarine hydrothermal vent fields in the revised compilation. Interestingly, the number of known vent fields in the southern hemisphere (263) now exceeds the northern hemisphere (258), with a higher proportion of discoveries in the southern hemisphere in the past decade 2000–2009 (Figure 1). Figure 1 also clearly demonstrates the great proportion of discoveries in the western Pacific over the past decade.

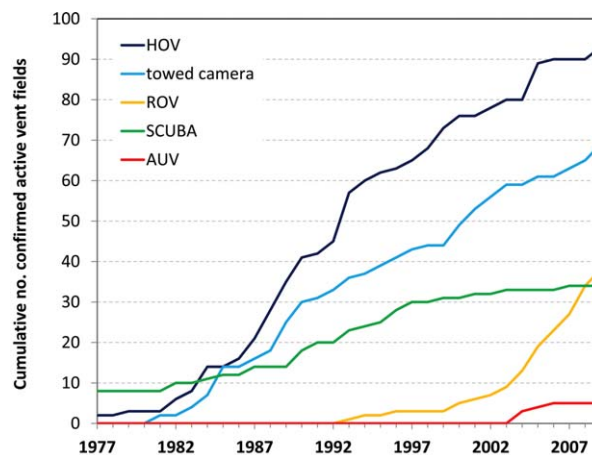


Figure 6. Means by which vent fields were visually confirmed. Cumulative number of vent fields per year to show slope in confirmations by human-occupied vehicles (HOV), towed camera systems including TV grabs, remotely-operated vehicles (ROV), SCUBA, and autonomous underwater vehicles (AUV).

4.1. Meta-Analysis With Respect to Tectonic Setting

[13] The revised database indicates a greater percentage of known active vent fields at convergent plate boundaries than previously reported. The majority of arc and back-arc vent fields (59 and 57%, respectively, per tectonic setting) were discovered in the past decade (Figure 2a). One back-arc region, the Lau Basin, stands out for accounting for ~19% of all discoveries in the past decade, and the associated Tonga (Tofua) arc combined with the Kermadec arc to the south account for ~16% more (Table 1). The rate of discoveries at MORs peaked in the 1990s (Supporting information Figure S1). The increased proportion along volcanic arcs and BASCs is a consequence of systematic surveys for hydrothermal activity [e.g., Baker *et al.*, 2008; de Ronde, 2011]. In particular for vents on volcanic arcs, as of 2009 we knew 89 active vent fields on intraoceanic arcs (Table 1), approaching the global estimates of 91–107 [Baker *et al.*, 2008] and 125 [de Ronde, 2011]. Island arcs are expected to host a smaller number of hydrothermally active submarine volcanic centers [de Ronde *et al.*, 2003], and as of 2009 we knew 41 submarine vent fields at island arcs (Table 1). We note that the percentage of total known active vent fields on volcanic arcs (25%) is much greater than reported for known massive sulfide deposits (i.e., 12%) [Hannington *et al.*, 2011], but this is not surprising given the lower temperatures at shallower arc vents (Figure 5). One consequence of the discoveries in arc and back-arc settings is the increased diversity of geological settings, effluent fluids, and chemosynthetic ecosystems known at submarine hydrothermal vents [e.g., de Ronde *et al.*, 2001; Embley *et al.*, 2007], including the first observations during this past decade of a submarine volcanic eruption (NW Rota-1) [Embley *et al.*, 2006], liquid CO₂ (NW Eifuku) [Lupton *et al.*, 2004], molten sulfur (Nikko and Daikoku) [Embley *et al.*, 2007], and a blue smoker (Hatoma Knoll) [Fuyuno, 2007].

[15] For vent fields on spreading ridges, a majority of the vents discovered at MORs in the past decade occurred at segments with slower spreading rates than the discoveries at BASCs (Figure 3). If we group discoveries at spreading ridges in 2000–2009 into the three categories used by Baker and German [2004] (fast (>55 mm/y, inclusive of intermediate spreading rates), slow (20–55 mm/y), and ultraslow (0–20 mm/y)), 66% of the discov-

eries at fast spreading ridges were at BASCs and 77% of the discoveries at slow and ultraslow were at MORs. Although the past decade included the first observations of black smokers on ultraslow ridges, SWIR Area A [Tao *et al.*, 2012] and Loki's Castle [Pedersen *et al.*, 2010a], most of the new discoveries at ultraslow ridges were inferred (27 versus 5 confirmed), reflecting the difficulty of finding vents in these kinds of ridges and in bringing ROV/HOVs to remote locations. Discoveries of vent fields on the ultraslow Arctic MOR over the past decade were recently reviewed by Pedersen *et al.* [2010b].

4.2. Meta-Analysis With Respect to National Jurisdiction

[16] Here for the first time, we explicitly categorize vent fields into national jurisdictions, finding a greater percentage in exclusive economic zones (EEZs; 66%) than in high seas (34%). More than 3/4 of the vent fields discovered in the past decade were in EEZs, another consequence of an increased frequency of discoveries in arc and back-arc settings. A quarter (25%) of discoveries of vent fields over the past decade occurred in Tonga, with two other EEZs contributing >5% of discoveries (New Zealand and USA—Northern Mariana Islands and Guam) (Figure 2b and Table 2). Other nations with an increase of >5 known active vent fields over the past decade are UK (combined EEZ), Ecuador, Papua New Guinea, and Japan, reflecting systematic hydrothermal surveys in some (e.g., Papua New Guinea) but not all cases (e.g., Japan). In particular the prominence of Tonga, New Zealand, and Papua New Guinea in discoveries over the past decade is associated with increased commercial and national interests in seafloor hydrothermal deposits as mineral resources, heightened by the 2003–2008 boom in commodity prices [e.g., Hoagland *et al.*, 2010]. High-temperature deposits of polymetallic sulfides can be rich in copper, zinc, and precious metals [e.g., Tivey, 2007]. In 2011 the first commercial mining lease for deep-sea sulfide deposits was granted by Papua New Guinea for Solwara 1 in Manus Basin, and extraction of the “world's first deep seafloor copper-gold mine” [Smith, 2011] is projected for this decade. The first commercial discoveries of deep-sea vent fields were in 2008, and as of the end of 2009, 11 new vent fields had been reported by commercial entities, with six in Tonga and five in Papua New Guinea (Data set S1).

4.3. Meta-Analysis With Respect to Mining Tenements and Marine Protected Areas

[17] Maps available to the public over the internet allowed us to identify the active vent fields within one commercial mining company's tenements (granted and applications) in six EEZs (Fiji, New Zealand, Papua New Guinea, Solomon Islands, Tonga, and Vanuatu) as well as within two sets of blocks granted by the International Seabed Authority (ISA) on the bed of the high seas (also known as "the Area") (Data set S1). Regulations on prospecting and exploration for polymetallic sulfides in "The Area" were adopted by the ISA in 2010, and almost immediately the first two sets of blocks (each covering $\sim 10,000$ km²) were granted in 2011 to China at the Southwest Indian Ridge (SWIR) and the Russian Federation at the northern Mid-Atlantic Ridge (N MAR).

[18] Of the commercial entities engaged in prospecting and exploration for seafloor massive sulfide (SMS) deposits at the time of this writing, only Nautilus Minerals, Inc., provided public online access to maps of tenements and tenement applications. As of the end of 2011, Nautilus Minerals held $\sim 243,000$ km² of granted tenements and $\sim 279,000$ km² under application in the EEZs of Papua New Guinea, Tonga, Solomon Islands, Fiji, Vanuatu and New Zealand, for a total area of approximately 522,000 km² (<http://www.nautilus-minerals.com/s/Tenements.asp>, accessed 5 Sept. 2012). Maps for these granted and pending tenements in six EEZs were available for download in portable document format (PDF) [SRK Consulting, 2011]. However, without access to polygon coordinates or GIS shapefiles, we could not apply a point-in-polygon algorithm to locate vent fields within tenements; rather, we performed an overlay of vent field locations to each PDF map by matching coordinate axes and map projections. Thus, there is some uncertainty in determining whether vent fields near the edges of these mapped areas are contained within or just outside a tenement. Another commercial entity reporting SMS tenements at the time of this writing was Neptune Minerals, Inc., with 3,447 km² of licensed tenements in New Zealand and Japan, an additional 80,494 km² of licensed tenements (EEZs not posted online), and 84,000 km² of license applications (EEZs not posted online) (<http://www.neptuneminerals.com/>, accessed 5 Sept. 2012). News reports have suggested that "1 million km² of sea floor in the Asia-Pacific region is under exploration

license" (<http://www.guardian.co.uk/environment/2012/aug/06/papua-new-guinea-deep-sea-mining>, The Guardian, 6 Aug. 2012). For the two ISA grants reported here for the SWIR and N MAR, coordinates for the corners of each ~ 10 km by 10 km block are available online in the ISA 17th session documents (<http://www.isa.org.jm/en/documents>), and we determined with certainty those vent fields on the high seas located within these blocks. Two additional polymetallic sulfide applications to the ISA for blocks in "The Area" were approved in 2012 for the Republic of Korea and the Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER), but coordinates were not available at the time of this writing.

[19] Summing the six SW Pacific nations and high seas blocks, at least 96 active vent fields are located in areas granted or pending applications for mineral prospecting and exploration (18.5% of total known; Data set S1). This is an underestimate, because at the time of this writing we did not have access to maps from other commercial companies, the ISA blocks approved in 2012, or other national interests within their own EEZs. The 81 within these commercial tenements are 62% of the known active vent fields in these six EEZs and also represent 34% of the total known active at arc and back-arc settings at the end of 2009. The 15 active vent fields in ISA blocks are 8.6% of the total known on the high seas and 5.6% of the total known at MORs. Regionally, the active vent fields within ISA blocks represent 26% of those known at N MAR and 20% of those known at SWIR. It is noteworthy that the first black smoker discovered at an ultraslow spreading ridge (SWIR Area A) [Tao *et al.*, 2012] is now within an ISA SWIR block. The ISA N MAR blocks contain Semyenov, the largest known hydrothermally active sulfide deposit on the MAR [Cherkashov *et al.*, 2010].

[20] In parallel over the past decade, a growing number of deep-sea hydrothermal vent fields has been designated as marine protected areas (MPAs). There are 41 deep-sea vent fields already incorporated into MPAs (8% of total known; Data set S1); some hydrothermal vents in shallow waters are also in MPAs but not comprehensively reviewed here. The first MPA for deep-sea vents was declared by Canada in 2003 (Endeavour segment of the Juan de Fuca Ridge), followed by Portugal (within the more recently designated Azores Marine Park), Mexico (Guaymas Basin and EPR, 21 N), and in 2009 the U.S. (Marianas Trench Marine National Monument). Efforts are also

underway to protect some vents on the high seas [e.g., *Christiansen, 2007*], most recently involving a list of 142 vent fields submitted by InterRidge to the ISA in 2011 (Data set S1).

5. Discussion of Factors Influencing Discoveries Over the Past Decade

[21] Discoveries of active hydrothermal vent fields over the past decade have been facilitated by developments in and access to technology to “hunt” for hydrothermal plumes and their sources at the seafloor. Conventional CTD/bottle casts and “tow-yos” used in systematic hydrothermal surveys are increasingly augmented by in situ sensors, usually optical devices to detect suspended particulates from hydrothermal plumes and oxidation-reduction potential (sometimes called “Eh”) sensors for chemical anomalies [see *German et al., 2008b*]. Many of the systematic hydrothermal surveys in the past decade used Miniature Autonomous Plume Recorders (MAPRs), designed to be small, dependable, and easy-to-operate; these have been used by investigators in 10 countries as part of a global effort to explore for hydrothermal vents [*Baker and Walker, 2010*]. Increased access to sensors such as MAPRs led to discoveries during targeted hydrothermal surveys [e.g., Carlsberg Ridge, *Ray et al., 2012*; Central Indian Ridge, *Zhu et al., 2008*; equatorial East Pacific Rise, *Chen et al., 2006*] or while conducting seafloor work, such as dredging [e.g., Woodlark Basin, *Laurila et al., 2012*] and side-scan sonar [e.g., N MAR, *Searle et al., 2008*]. In situ sensors have also been deployed on AUVs; for example AUV “r2D4” equipped with an in situ Mn analyzer mapped hydrothermal plumes on the Central Indian Ridge in 2006 [*Kawagucci et al., 2008*], confirmed with HOV as Dodo and Solitaire in 2009 [*Nakamura et al., 2012*]. In terms of visually confirming vent fields, the dramatic increase in use of ROVs reflects increased access to these deep-submergence vehicles (Figure 6). A major technological advance in this past decade in locating and confirming hydrothermal vents at the seafloor was the employment of a three-phase survey strategy with AUVs [*Yoerger et al., 2007*; *German et al., 2008b*]. The first vent fields to be confirmed by AUV were in the Lau Basin in 2004 (ABE, Kilo Moana, and Tow Cam) and on the S MAR at 4 48°S in 2005 [*German et al., 2008a, 2008b*].

[22] Discoveries of active hydrothermal vent fields over the past decade were also spurred by

increased commercial and national interests in mineral resources. It is not a coincidence that a quarter of the discoveries over the past decade occurred in Tonga (Table 2), including discoveries by commercial entities, and that among the MOR regions, the SWIR and the N MAR had the greatest percentage of new discoveries in the past decade (Table 1), including discoveries in blocks granted by the ISA. Originally intended for academic research and education, the purpose of the InterRidge Vents Database now extends into marine policy and management. In contrast to concerns about scientific exploitation and eco-tourism a decade ago [*Mullineaux et al., 1998*; *Dando and Juniper, 2001*], present concerns about mining, bioprospecting, and consequent risks to biodiversity have been discussed at international workshops for the management and conservation of hydrothermal vent ecosystems [*Van Dover, 2011*; *Van Dover et al., 2011, 2012*]. During this past decade, voluntary codes of conduct were developed for scientific work at deep-sea vents [*Devey et al., 2007*; *Godet et al., 2011*] and for marine mining by the International Marine Minerals Society. The recent surge in interest in seafloor massive sulfide deposits in western Pacific EEZs sparked the Pacific Islands Applied Geoscience Commission to develop guidelines for sustainable resource management [*Tawake, 2009*]. A comprehensive environmental impact assessment (EIA) was prepared for Solwara 1 [*Smith, 2011*], and a draft template for EIAs for deep-sea mining was recently released by the ISA [2012].

6. Recommendations for Future Database Upgrades

[23] To further expand the use of the InterRidge Vents Database, we have several recommendations for future upgrades. For example, we recommend that the next version include categorized information on host rock for each vent field, so that an assessment of the proportion of basalt- versus ultramafic- versus felsic- versus sediment-hosted and other categories can be made in the next review of global distribution [e.g., *Fouquet and Scott, 2009*]. We also recommend the inclusion of separate entries for year and means confirmed and year and means inferred. Presently, the visual confirmation at the seafloor is listed first in the database, and although this is consistent with how the community tends to report discoveries, a small percentage (8%) of the 2000–2009

discoveries was confirmations of previously inferred active vent fields. Another improvement that would capitalize on Drupal's flexibility in two-way interactions with users would include allowing researchers to submit publication citations to the database by identifying the vent field(s) referred to (e.g., using a bibliography module). Additional inter-operability with other global databases may be achieved by upgrading to Drupal 7, which has Resource Description Framework (RDF) functionality in its core. Linked Data RDF mappings can be applied to the "vent field" content type and attributes within. An ultimate goal would include interoperability with databases for deep-sea vehicle dives (to access imagery), geochemical measurements (e.g., VentDB in the EarthChem Library), and other data types collected at respective vent fields.

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References

- Bachraty, C., P. Legendre, and D. Desbruyères (2009), Biogeographic relationships among deep-sea hydrothermal vent faunas at global scale, *Deep Sea Res., Part I*, *56*, 1371–1378, doi:10.1016/j.dsr.2009.01.009.
- Baker, E. T., and C. R. German (2004), On the global distribution of hydrothermal vent fields, in *Mid-Ocean Ridges: Hydrothermal Interactions Between the Lithosphere and Oceans*, *Geophys. Monogr. Ser.*, vol. 148, edited by C. R. German et al., pp. 245–266, AGU, Washington, D. C., doi:10.1029/148GM10.
- Baker, E. T., and S. L. Walker (2010), Global ocean exploration on a shoestring, Abstract IT21B-08 presented at AGU-ASLO-TOS Ocean Sciences Meeting, Portland, Oreg., 22–26 Feb.
- Baker, E. T., R. W. Embley, S. L. Walker, J. A. Resing, J. E. Lupton, K. Nakamura, C. E. J. de Ronde, and G. J. Massoth (2008), Hydrothermal activity and volcano distribution along the Mariana arc, *J. Geophys. Res.*, *113*, B08S09, doi:10.1029/2007JB005423.
- Baker, E. T., F. Martinez, J. A. Resing, S. L. Walker, N. J. Buck, and M. H. Edwards (2010), Hydrothermal cooling along the Eastern Lau Spreading Center: No evidence for discharge beyond the neovolcanic zone, *Geochem. Geophys. Geosyst.*, *11*, Q08004, doi:10.1029/2010GC003106.
- Bird, P. (2003), An updated digital model of plate boundaries, *Geochem. Geophys. Geosyst.*, *4*, 1027, doi:10.1029/2001GC000252.
- Bischoff, J. L., and R. J. Rosenbauer (1988), Liquid-vapor relations in the critical region of the system NaCl–H₂O from 380 to 415°C: A refined determination of the critical point and two-phase boundary of seawater, *Geochim. Cosmochim. Acta*, *52*, 2121–2126, doi:10.1016/0016-7037(88)90192-5.
- Chen, Y. J., J. Zhu, J. Lin, S. Guo, and E. T. Baker (2006), Hydrothermal plume anomalies along the East Pacific Rise near the equator, *Eos Trans. AGU*, *87*(52), Fall Meet. Suppl., Abstract OS31D-1670.
- Cherkashov, G., et al. (2010), Seafloor massive sulfides from the northern equatorial Mid-Atlantic Ridge: New discoveries and perspectives, *Mar. Georesour. Geotechnol.*, *28*, 222–239, doi:10.1080/1064119X.2010.483308.
- Christiansen, S. (2007), *Marine Protected Areas in Areas Beyond National Jurisdiction: Proposed High Seas MPAs in the North East Atlantic by WWF 1998–2006*, 38 pp., World-wide Fund for Nature, Hamburg, Germany.
- Connelly, D. P., et al. (2012), Hydrothermal vent fields and chemosynthetic biota on the world's deepest seafloor spreading centre, *Nat. Commun.*, *3*, 620, doi:10.1038/ncomms1636.
- Dando, P., and S. K. Juniper (2001), Management and conservation of hydrothermal vent ecosystems, InterRidge workshop report, 29 pp., Inst. of Ocean Sci., Sidney, B. C.
- Dando, P. R. (2010), Biological communities at marine shallow-water vent and seep sites, in *The Vent and Seep Biota, Topics in Geobiology*, vol. 33, edited by S. Kiel, pp. 333–378, Springer, New York, NY, doi:10.1007/978-90-481-9572-5_11.
- de Ronde, C. E. J. (2011), Seafloor hydrothermal systems of intraoceanic arcs, paper presented at the MTS/IEEE OCEANS'11, Waikoloa, Hawaii, 19–22 Sept.
- de Ronde, C. E. J., E. T. Baker, G. J. Massoth, J. E. Lupton, I. C. Wright, R. A. Feely, and R. R. Greene (2001), Intra-oceanic subduction-related hydrothermal venting, Kermadec volcanic arc, New Zealand, *Earth Planet. Sci. Lett.*, *193*, 359–369, doi:10.1016/S0012-821X(01)00534-9.
- de Ronde, C. E. J., G. J. Massoth, E. T. Baker, and J. E. Lupton (2003), Submarine hydrothermal venting related to volcanic arcs, in *Giggenbach Memorial Volume*, Special Publication 10, edited by S. F. Simmons, and I. G. Graham, pp. 91–110, Soc. of Econ. Geol., Boulder, CO.
- Desbruyères, D., M. Segonzac, and M. Bright (Eds.) (2006), *Handbook of Deep-Sea Hydrothermal Vent Fauna, Denisia*, vol. 18, 544 pp., Linz, Austria.
- Devey, C. W., C. R. Fisher, and S. Scott (2007), Responsible science at hydrothermal vents, *Oceanography*, *20*, 162–171, http://dx.doi.org/10.5670/oceanog.2007.90.
- Embley, R. W., W. W. Chadwick Jr., E. T. Baker, D. A. Butterfield, J. A. Resing, C. E. J. de Ronde, V. Tunnicliffe, J. E. Lupton, S. K. Juniper, and K. H. Rubin (2006), Long-term eruptive activity at a submarine arc volcano, *Nature*, *441*, 494–497.
- Embley, R. W., et al. (2007), Exploring the Submarine Ring of Fire: Mariana Arc—Western Pacific, *Oceanography*, *20*, 68–79, doi:10.5670/oceanog.2007.07.

- Fouquet, Y., and S. Scott (2009), The science of seafloor massive sulfides (SMS) in the modern ocean: A new global resource for base and precious metals, paper presented at Offshore Technology Conference, Houston, Tex, 4–7 May.
- Fujikura, K., T. Okutani, and T. Maruyama (Eds.) (2008), *Deep-Sea Life—Biological Observations Using Research Submersibles*, Tokai Univ. Press, Kanagawa.
- Fuyuno, I. (2007), Undersea vent blows blue, *Nature*, doi:10.1038/news070129-1.
- Gebbruk, A. (Ed.) (2002), *Biology of Hydrothermal Systems*, 543 pp., KMK Press, Moscow.
- German, C. R., et al. (2008a), Hydrothermal activity on the southern Mid-Atlantic Ridge: Tectonically- and volcanically-controlled venting at 4–5°S, *Earth Planet. Sci. Lett.*, 273, 332–344, doi:10.1016/j.epsl.2008.06.048.
- German, C. R., D. R. Yoerger, M. Jakuba, T. M. Shank, C. H. Langmuir, and K. Nakamura (2008b), Hydrothermal exploration with the autonomous benthic explorer, *Deep Sea Res., Part I*, 55, 203–219, doi:10.1016/j.dsr.2007.11.004.
- German, C. R., et al. (2010), Diverse styles of submarine venting on the ultraslow spreading Mid-Cayman Rise, *Proc. Natl. Acad. Sci. U. S. A.*, 107, 14,020–14,025, doi:10.1073/pnas.1009205107.
- Godet, L., K. A. Zelnio, and C. L. Van Dover (2011), Scientists as stakeholders in conservation of hydrothermal vents, *Conserv. Biol.*, 25, 214–222, doi:10.1111/j.1523-1739.2010.01642.x.
- Hannington, M. D. (2009), Modern submarine hydrothermal systems—A global perspective on distribution, size and tectonic settings, in *Submarine Volcanism and Mineralization: Modern Through Ancient*, vol. 19, edited by B. L. Cousens, and S. J. Piercey, pp. 91–146, Geol. Assoc. of Can., Miner. Deposits Div, St. Johns, Newfoundland, Canada.
- Hannington, M. D., S. Petersen, P. M. Herzig, and I. R. Jonasson (2004), A global database of seafloor hydrothermal systems, including a digital database of geochemical analyses of seafloor polymetallic sulfides, *Geol. Surv. of Can. Open File*, 4598, 12 pp.
- Hannington, M. D., S. Petersen, P. M. Herzig, and I. R. Jonasson (2005), Sea-floor tectonics and submarine hydrothermal systems, in *Economic Geology 100th Anniversary Volume*, edited by J. W. Hedenquist et al., pp. 111–141, Soc. of Econ. Geol., Littleton, Colo.
- Hannington, M., J. Jamieson, T. Monecke, S. Petersen, and S. Beaulieu (2011), The abundance of seafloor massive sulfide deposits, *Geology*, 39, 1155–1158, doi:10.1130/G32468.1.
- Haymon, R. M., D. J. Fornari, M. H. Edwards, S. Carbotte, D. J. Wright, and K. C. MacDonald (1991), Hydrothermal vent distribution along the East Pacific Rise crest (9° 09′–54°N) and its relationship to magmatic and tectonic processes on fast-spreading mid-ocean ridges, *Earth Planet. Sci. Lett.*, 104, 513–534, doi:10.1016/0012-821X(91)90226-8.
- Hessler, R. R., W. M. Smithey Jr., M. A. Boudrias, C. H. Keller, R. A. Lutz, and J. J. Childress (1988), Temporal change in megafauna at the Rose Garden hydrothermal vent (Galapagos Rift; eastern tropical Pacific), *Deep Sea Res., Part A*, 35, 1681–1709.
- Hoagland, P., S. Beaulieu, M. A. Tivey, R. G. Eggert, C. German, L. Glowka, and J. Lin (2010), Deep-sea mining of seafloor massive sulfides, *Mar. Policy*, 34, 728–732, doi:10.1016/j.marpol.2009.12.001.
- International Seabed Authority (2012), Environmental management needs for exploration and exploitation of deep sea minerals, Report of a workshop held by the International Seabed Authority in collaboration with the Government of Fiji and the SOPAC Division of the Secretariat of the Pacific Community, 29 November–2 December, 2011, Nadi, Fiji, *ISA Tech. Study* 10, 52 pp.
- Kawagucci, S., K. Okamura, K. Kiyota, U. Tsunogai, Y. Sano, K. Tamaki, and T. Gamo (2008), Methane, manganese, and helium-3 in newly discovered hydrothermal plumes over the Central Indian Ridge, 18°–20°S, *Geochem. Geophys. Geosyst.*, 9, Q10002, doi:10.1029/2008GC002082.
- Kelley, D. S., et al. (2012), Endeavour segment of the Juan de Fuca Ridge: One of the most remarkable places on earth, *Oceanography*, 25, 44–61, doi:10.5670/oceanog.2012.03.
- Kinsey, J. C., and C. R. German (2013), Sustained volcanically-hosted venting at ultraslow ridges: Piccard Hydrothermal Field, Mid-Cayman Rise, *Earth Planet. Sci. Lett.*, 380, 162–168, doi:10.1016/j.epsl.2013.08.001.
- Koschinsky, A., D. Garbe-Schönberg, S. Sander, K. Schmidt, H. Gennerich, and H. Strauss (2008), Hydrothermal venting at pressure-temperature conditions above the critical point of seawater, 5°S on the Mid-Atlantic Ridge, *Geology*, 36, 615–618, doi:10.1130/G24726A.1.
- Laurila, T. E., S. Petersen, C. W. Devey, E. T. Baker, N. Augustin, and M. D. Hannington (2012), Tectonic and magmatic controls on hydrothermal activity in the Woodlark Basin, *Geochem. Geophys. Geosyst.*, 13, Q09006, doi:10.1029/2012GC004247.
- Lupton, J., et al. (2004), Liquid carbon dioxide venting at the Champagne hydrothermal site, NW Eifuku Volcano, Mariana Arc, *Eos Trans. AGU*, 85(47), Fall Meet. Suppl., Abstract V43F-08.
- Mullineaux, L., S. K. Juniper, D. Desbruyeres, and M. Cannat (1998), Steps proposed to resolve potential research conflicts at deep-sea hydrothermal vents, *Eos Trans. AGU*, 79, 533, doi:10.1029/98EO00391.
- Nakamura, K., et al. (2012), Discovery of new hydrothermal activity and chemosynthetic fauna on the Central Indian Ridge at 18°–20°S, *PLoS ONE*, 7, e32965, doi:10.1371/journal.pone.0032965.
- Pedersen, R. B., H. T. Rapp, I. H. Thorseth, M. D. Lilley, F. J. A. S. Barriga, T. Baumberger, K. Flesland, R. Fonseca, G. L. Fruh-Green, and S. L. Jorgensen (2010a), Discovery of a black smoker vent field and vent fauna at the Arctic Mid-Ocean Ridge, *Nat. Commun.*, 1, 126, doi:10.1038/ncomms1124.
- Pedersen, R. B., I. H. Thorseth, T. E. Nygård, M. D. Lilley, and D. S. Kelley (2010b), Hydrothermal activity at the Arctic mid-ocean ridges, in *Diversity of Hydrothermal Systems on Slow Spreading Ocean Ridges*, *Geophys. Monogr. Ser.*, vol. 188, edited by P. A. Rona et al., pp. 67–89, AGU, Washington, D. C., doi:10.1029/2008GM000783.
- Ray, D., K. A. Kamesh Raju, E. T. Baker, A. Srinivas Rao, A. V. Mudholkar, J. E. Lupton, L. Surya Prakash, R. B. Gawas, and T. Vijaya Kumar (2012), Hydrothermal plumes over the Carlsberg Ridge, Indian Ocean, *Geochem. Geophys. Geosyst.*, 13, Q01009, doi:10.1029/2011GC003888.
- Searle, R., et al. (2008), Structure and development of the axial volcanic ridge: Cruise JC24 to the Mid-Atlantic Ridge, 45°N, *InterRidge News*, 17, 11–15.
- Smith, S. (2011), Deep ocean seafloor mineral extraction—Environmental and social responsibility for a new industry, paper presented at MTS/IEEE OCEANS’11, Waikoloa, Hawaii, 19–22 Sept.
- SRK Consulting (2011), Nautilus Minerals Incorporated, NI43-101 Tech. Rep. 2010, PNG, Tonga, Fiji, Solomon Islands, New Zealand, Vanuatu and the ISA, SRK Consulting (Australasia) Pty Ltd, West Perth, WA, Australia.

- Tao, C., et al. (2012), First active hydrothermal vents on an ultraslow-spreading center: Southwest Indian Ridge, *Geology*, *40*, 47–50, doi:10.1130/G32389.1.
- Tarasov, V., A. Gebruk, A. Mironov, and L. Moskalev (2005), Deep-sea and shallow-water hydrothermal vent communities: Two different phenomena?, *Chem. Geol.*, *224*, 5–39, doi:10.1016/j.chemgeo.2005.07.021.
- Tawake, A. (2009), Deep-sea minerals in the Pacific Islands region: A legal and fiscal framework for sustainable resource management, *InterRidge News*, *18*, 37–38.
- Tivey, M. K. (2007), Generation of seafloor hydrothermal vent fluids and associated mineral deposits, *Oceanography*, *20*, 50–65, doi:10.5670/oceanog.2007.80.
- Van Dover, C. L. (2011), Tighten regulations on deep-sea mining, *Nature*, *470*, 31–33, doi:10.1038/470031a.
- Van Dover, C.L., et al. (2011), Environmental management of deep-sea chemosynthetic ecosystems: Justification of and considerations for a spatially based approach, Report of a workshop, 31 May–4 June 2010, *ISA Tech. Study 8*, Dinard, France.
- Van Dover, C. L., C. R. Smith, J. Ardron, D. Dunn, K. Gjerde, L. Levin, Smith S., and Dinard Workshop Committee (2012), Designating networks of chemosynthetic ecosystem reserves in the deep sea, *Mar. Policy*, *36*, 378–381, doi:10.1016/j.marpol.2011.07.002.
- VLIZ (2009), Maritime Boundaries Geodatabase, version 5, released 2009-10-01. Vlaams Instituut voor de Zee, Oostende, Belgium. [Available at <http://www.vliz.be/vmcdcd/marbound>.]
- Yoerger, D. R., A. M. Bradley, M. Jakuba, M. A. Tivey, C. R. German, T. M. Shank, and R. W. Embley (2007), Mid-ocean ridge exploration with an autonomous underwater vehicle, *Oceanography*, *20*, 52–61, doi:10.5670/oceanog.2007.05.
- Zhu, J., J. Lin, S. Guo, and Y. Chen (2008), Hydrothermal plume anomalies along the Central Indian Ridge, *Chin. Sci. Bull.*, *53*, 2527–2535, doi:10.1007/s11434-008-0208-6.