Manifestations of hydrothermal discharge from young abyssal hills on the fast-spreading East Pacific Rise flank

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ABSTRACT

Spectacular black smokers along the mid-ocean-ridge crest represent a small fraction of total hydrothermal heat loss from ocean lithosphere. Previous models of measured heat flow suggest that 40%–50% of oceanic hydrothermal heat and fluid flux is from young seafloor (0.1–5 Ma) on mid-ocean-ridge flanks. Despite evidence that ridge-flank hydrothermal flux affects crustal properties, ocean chemistry, and the deep-sea biosphere, few ridge-flank vent sites have been discovered. We describe the first known seafloor expressions of hydrothermal discharge from tectonically formed abyssal hills flanking a fast-spreading ridge. Seafloor manifestations of fluid venting from two young East Pacific Rise abyssal hills (0.1 Ma at 10°20′N, 103°33.2′W; 0.5 Ma at 9°27′N, 104°32.3′W) include fault-scarp hydrothermal mineralization and macrofauna; fault-scarp flocculations containing hyperthermophilic microbes; and hilltop sediment mounds and craters possibly created by fluid expulsion. These visible features can be exploited for hydrothermal exploration of the vast abyssal hill terrain flanking the mid-ocean ridge and for access to the subseafloor biosphere. Petrologic evidence suggests that abyssal hills undergo repeated episodes of transitory fluid discharge, possibly linked to seismic events, and that fluid exit temperatures can be briefly high enough to transport copper (≥250 °C).

Keywords: hydrothermal vents, mid-ocean ridge, East Pacific Rise, abyssal hills, ridge flanks, hyperthermophiles, subsurface biosphere.

INTRODUCTION

Ocean lithosphere is cooled as it spreads away from the mid-ocean ridge by heat conduction and hydrothermal heat advection (Wolery and Sleep, 1976). It is estimated that ~50% of the hydrothermal heat loss (~5.5×10^{12} W) (Stein et al., 1995) and fluid flux (~2.3×10^{12} m^3/yr) (Johnson and Pruis, 2003) is from seafloor that is 5 Ma or younger. Extensive mineral precipitation from fluids circulating through 0.1–5 Ma crust explains rapid observed increase in layer 2a seismic velocity and reduction in upper-crust porosity and permeability with age (Fisher and Becker, 2000), as well as basalt alteration and vein formation in ca. 6.9 Ma drill core at Hole 504B (Alt, 1995). Despite evidence for large-magnitude ridge-flank flux, direct observations of seafloor hydrothermal vents in this immense region are sparse, owing to lack of exploration and insufficient knowledge of how signatures of ridge-flank hydrothermal discharge are manifested on the seafloor. Hundreds of active vents have been found along the mid-ocean-ridge crest, where exploration has been concentrated and where refined search methods exploit well-known characteristics of venting. By contrast, few active seafloor hydrothermal sites have been located off-axis on ridge flanks (Alt et al., 1987; Hekinian and Fouquet, 1985; Kelley et al., 2001; Lonsdale, 1977; Mottl et al., 1998; Wheat and McDuff, 1995), and only two are clearly unrelated to magmatic seamount formation: Galapagos Mounds, on 0.6 Ma seafloor south of the Galapagos Rift (Lonsdale, 1977), and Lost City, on 1 Ma seafloor west of the Mid-Atlantic Ridge (Kelley et al., 2001).

Abyssal hills cover a large geomorphic terrain and are the most common landforms on Earth (Macdonald et al., 1996), but little is known about hydrothermal venting from these ubiquitous features. We describe here two recently active seafloor hydrothermal vent sites on young (0.1–0.5 Ma) abyssal hills flanking the East Pacific Rise. These are the first abyssal hill hydrothermal sites found near a fast-spreading mid-ocean ridge, and they are on younger lithosphere than previously known nonseamount ridge-flank hydrothermal sites. Observations at these sites offer clues to the nature of young ridge-flank hydrothermal systems and means for visually locating ridge-flank vents.

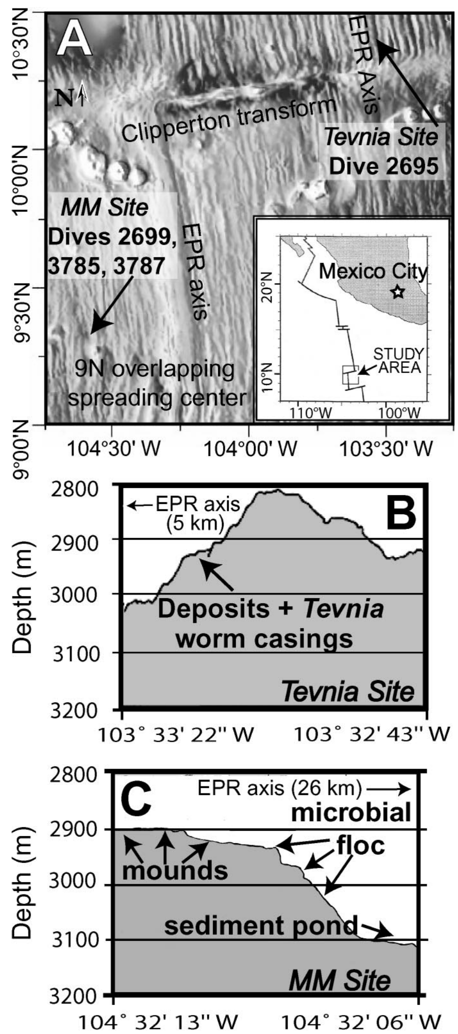

Figure 1. A: Locations of East Pacific Rise (EPR) abyssal hill hydrothermal sites. B: *Alvin* depth profile across abyssal hill at Tevnia site; labeled areas show location of vent fauna and mineral deposits (Fig. 2). C: *Alvin* depth profile across axis-facing fault scarp of abyssal hill at MM site; labeled areas show where microbial floc (Fig. 3) and sediments (Fig. 4) were collected.

SITE DESCRIPTIONS

Tevnia Site

The Tevnia site is north of the Clipperton Fracture Zone, ~5 km east of the East Pacific Rise axis at lat 10°20′N, long 103°33.2′W (Figs. 1A, 1B), on ca. 0.1 Ma seafloor (Carbotte and Macdonald, 1992). The site was photographed and sampled in 1994 during *Alvin* dive 2695. At the Tevnia site, hydrothermal deposits (Fig. 2) are present on a 200-m-high axis-facing fault scarp bounding the west side of an abyssal hill. The deposits are on a bench in volcanic sheet flows exposed above talus covering the lower scarp face. The site is named for clumps of dead *Tevnia* tubeworm casings clinging precariously to the fault scarp. *Tevnia* worms are early colonizers of hydrothermal vents on the nearby East Pacific

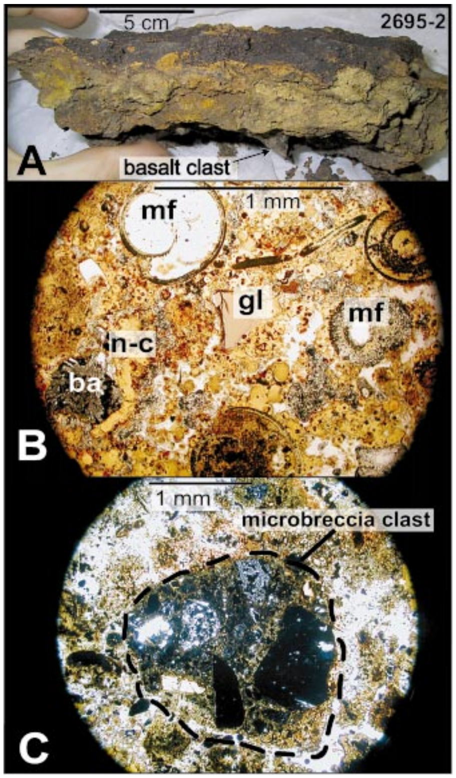

Figure 2. Mineralized breccia at Tevnia site, modified from Benjamin (2004). A: Hand sample with Fe (green), Si (orange), and Mn (black) mineral zonation (see text), and macroscopic basalt clast. B: Photomicrograph (in plane-polarized light) of breccia components (mf = microfossils; n-c = hydrothermal nontronite-celadonite; gl = glass shard; ba = basalt clast; unlabeled hydrothermal iron oxide and silica are finely dispersed). C: Photomicrograph (in cross-polarized light) of microbreccia clast internally cemented by early hydrothermal precipitates and surrounded by matrix of later hydrothermal precipitates.

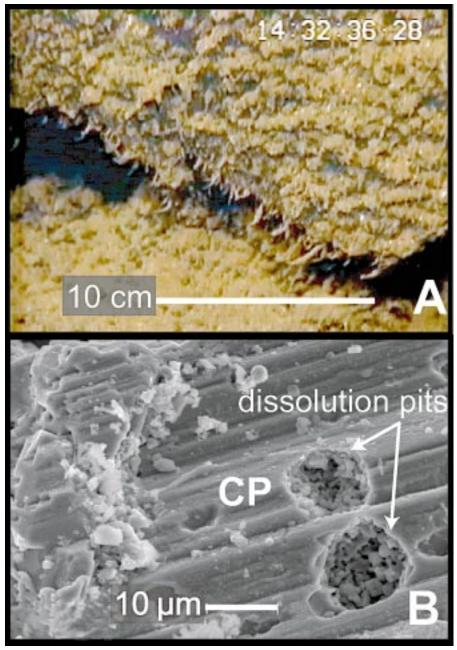

Figure 3. A: *Alvin* digital photograph of orange-brown flocculations clinging to basalt substrate on fault scarp at MM site; slurp samples of this fault scum contain unusual Archaea assemblage with hyperthermophilic affinities (Ehrhardt et al., 2003). B: Electron photomicrograph of corroded chalcopyrite (CP) particle associated with Archaea in fault scum (chalcopyrite identified by X-ray energy dispersive and X-ray diffractometry analyses).

Rise axis at 9°50′–51′N (Shank et al., 1998), but previously have not been found off axis. The presence of mechanically fragile, biodegradable worm casings on an active fault scarp indicates that (1) transitory fluxes of hydrothermal fluids here carried sufficient H_2S to nourish the worms, and (2) waning of hydrothermal activity was too recent for destruction of the worm casings by in situ degradation or downslope mass wasting. No temperature (*T*) anomalies were detected at the Tevnia site (the *Alvin* low-*T* sensor was not working on dive 2695); however, divers' observations of live ''dandelion'' colonial siphonophores and galatheiid crabs suggest that hydrothermal fluid discharge either was ongoing and invisibly diffuse, or had ceased very recently (within months). Patches of mossy, orange-brown flocculations visible on the fault scarp at the Tevnia site were not sampled.

MM Site

The Mounds and Microbes (MM) site is on an East Pacific Rise abyssal hill located at lat 9°27′N, long 104°32.3′W. This exceptionally large hill is on ca. 0.5 Ma seafloor ~26 km west of the East Pacific Rise axis (Figs. 1A, 1C). The hill was traversed in 1994 on *Alvin* dive 2699. The axis-facing scarp and adjacent 2900-m-deep hilltop (Fig. 1C) were explored and sampled in 2002 on dives 3785 and 3787. In 2002, divers sampled patches of mossy, orange-brown flocculations attached to rocky surfaces in the exposed fault scarp (Fig. 3A). The hilltop above is draped by sediment estimated to be ≤15 m thick, based on lithosphere age and a regional sedimentation rate of 2.3 cm/yr (Lonsdale and Spiess, 1980). On the hilltop, more than 100 sediment mounds, <1 m high and 0.5–1 m in diameter, were observed in an area ~0.1 km^2 (Fig. 4A). The mounds are light in color and stand out in contrast to darker surrounding sediments. Mounds sometimes occur at the margins of shallow (<1 m) crater-like depressions (Fig. 4A). Some have smooth surfaces and are populated by sessile epifauna, while others are covered by irregular chunks (to 10 cm in size) of light colored sediment. The *Alvin* low-*T* probe was inserted into crevices on the fault scarp where mossy floc was sampled, and into hilltop sediments within and adjacent to mounds. On the scarp, 0.15–0.2 °C anomalies were measured, confirming that diffuse hydrothermal fluid was oozing from the scarp. In the sediments, where depth of thermocouple penetration could be measured, a thermal gradient of ~0.4 °C/m was determined.

SAMPLE DESCRIPTIONS AND IMPLICATIONS

Tevnia Site Hydrothermal Deposits

Description. Two samples of the Tevnia site fault scarp deposits were collected on *Alvin* dive 2695 (Fig. 2). The deposits are breccias that contain volcanic, hydrothermal, and sediment components, and record multiple events of fragmentation, alteration, and hydrothermal cementation (Benjamin, 2004). Brecciation occurs at macroscopic (Fig. 2A) and microscopic (Fig. 2C) scales. Microbreccia clasts cemented by hydrothermal precipitation were fragmented and recemented during later events (Fig. 2C). Radiolarian and foraminifera microfossils in hydrothermal cements (Fig. 2B) show that hydrothermal precipitation took place on the exposed fault scarp. Hydrothermal minerals in altered clasts and matrix cement include mixed-layer nontronite-celadonite, iron oxide, silica, birnessite, and todorokite. These minerals form distinct colored zones that impart layering to some samples (green nontronite-celadonite → orange silica + iron oxide → brown-black manganese oxide; Fig. 2A). This Fe-Si-Mn mineral zoning most likely formed along an oxygen gradient between hydrothermal fluid and seawater at the scarp face (Benjamin, 2004).

Implications. Formation of Mg-poor, K-rich nontronite-celadonite suggests that the vent fluids lost Mg and gained K during reaction at depth with basalt at relatively high *T* (Edmond et al., 1979). The absence of Cu and Zn minerals in the samples indicates that prior to discharge the fluids cooled below temperatures needed to transport Cu and Zn. The fluids likely vented at $T < 140$ °C (Benjamin, 2004), and possibly were similar in composition to East Pacific Rise axial fluids modified by subseafloor conductive cooling and metal sulfide precipitation (Von Damm, 1995). The nontronite-celadonite, silica, and iron oxide in the deposits resemble the earliest alteration and vein-filling assemblage found in borehole samples from fast-spreading seafloor (Alt and Teagle, 2003), and suggest that near-ridge off-axis fault scarps are tapping fluids responsible for the earliest phase of ocean crust alteration.

As the abyssal hill at the Tevnia site was uplifted, dusted with sediment, and spread to its present location, the fault scarp deposits appear to have formed from episodic brecciation followed by periods of hydrothermal mineralization. Biological observations indicate waning in 1994 of a relatively recent hydrothermal event. To create the 200-m-high scarp at the Tevnia site in 100 k.y., an average uplift rate of 2 mm/yr is required. This is a minimum rate, since damming of lava flows from the ridge axis can reduce scarp height and apparent throw on off-axis faults (Macdonald et al., 1996). The magnitudes of off-axis earthquakes located on abyssal hill fault scarps typically are <M5; hence, most slip events likely have small vertical displacement (a few centimeters). Therefore fault slippage must repeat on a decadal time scale to match the observed rate of hill uplift, possibly breaking open pathways and rejuvenating hydrothermal flow on a very frequent basis. In addition, Clipperton transform fault slip may subject the Tevnia site to frequent, large (M5–M6) seismic events with strong ground shaking and hydraulic pressure pulses capable of breaking open subseafloor pathways clogged with fragile minerals. Thus, we hypothesize that the multiple brecciation and cementation events recorded in the Tevnia site samples, and biological indicators for recent venting at the site, are evidence that hydrothermal plumbing systems may be maintained semi-continuously over 10^5 yr by extremely frequent tectonic shaking and reactivation as abyssal hills are uplifted on ridge flanks.

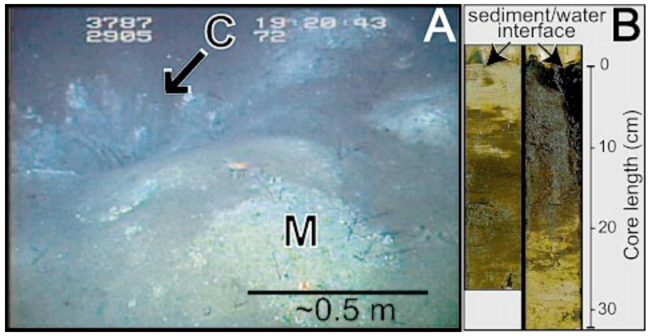

Figure 4. A: *Alvin* photograph on hilltop at MM site of sediment mound (labeled M) adjacent to crater (C; indicated by arrow). B: On right: core collected from undisturbed surrounding sediment in which dark brown ferromanganiferous layer is underlain by light colored calcareous ooze. On left: core from mound showing inverted stratigraphy relative to surrounding sediment.

MM Site Sediment Cores

Description. We collected 10 push cores in the field of mounds on top of the abyssal hill at the MM site (Fig. 4A). Core lengths ranged from 13 to 30 cm. Five cores were collected in mounds, four were collected 1–10 m away in undisturbed surrounding sediments, and one was collected in a crater (Fig. 4A). In undisturbed areas 1–10 m away from mounds the top 4–22 cm of the cores is a dark chocolate-brown layer composed dominantly of pelagic carbonate ooze and ferromanganese oxide (Fig. 4B, on right). This metal-enriched top layer overlies light colored carbonate ooze. By contrast, cores collected within mounds exhibit inverted stratigraphy (Fig. 4B, on left) with light colored carbonate ooze overlying a dark brown ferromanganese oxide–enriched layer. The single core collected in a crater contains a bottom layer of light colored carbonate ooze terminated at the top by a scoured surface, and overlain by dark brown sediment-seawater slurry. Push cores were subsampled immediately aboard ship for CH_4 analyses ashore by gas chromatography (following methods in Popp et al., 1995). No CH_4 enrichments were found. The C isotope compositions of benthic foraminifera tests (*Uvigerina juncea*) extracted from one of the mound cores show normal values ($\delta^{13}C$ = −1.119‰ to −0.905‰) and record no evidence for incorporation of isotopically light, methane-derived carbon.

Implications. The observed mounds are too large to be created by any known burrowing organisms. The inverted stratigraphy of the mounds compared to surrounding sediment suggests that the mounds are composed of sediment ejected from the subsurface. Bottom current action and ongoing sediment burial should smooth the tops of mounds with time. Normal diffusive diagenesis will remobilize buried Fe and Mn and gradually precipitate these metals at the oxidative sediment-seawater interface to form a top layer of dark brown, metal-enriched sediment. Observed variations in the smoothness, color, and habitation of mounds therefore indicate that the mounds are not all the same age. We speculate that the large number of mounds observed have accumulated from many episodes of sediment ejection from the hilltop.

What mechanism can explain formation over time of many meter-scale mounds and craters such as those described here? Huge blow-out features are produced on shallow continental shelves by CH_4 gas venting from thick accumulations of organic carbon–rich sediments. However, hydrostatic pressure at ~3 km water depth, thin sediment, and absence of measurable CH_4 in the cores from the MM site render CH_4 release an unlikely mechanism for creating the MM site mounds. It is more probable that the mounds are small mud volcanoes formed by episodic expulsion of fluid through viscous hilltop sediments. Occasionally, sediment may overturn to form mounds adjacent to craters (as in Fig. 4A). Episodic fluid release may be triggered by slip on the local faults bounding the abyssal hill, and/or by larger, more distant earthquakes. Abrupt changes in mid-ocean-ridge-crest hydrothermal flow rates and fluid properties have been observed following small local earthquakes and larger earthquakes located >200 km away (Johnson et al., 2001; Sohn et al., 1998). Hydraulic pulses of fluid expelled from abyssal hills following seismic events may explain formation of the sediment structures seen at the MM site.

MM Site Microbial Floc

Description. Orange-brown floc attached to bare basalt outcrops exposed in the axis-facing fault scarp at the MM site (fault scum in Fig. 3A) were sampled on dive 3787 by using two slurp guns mounted on the *Alvin* sample basket. The nozzles of the slurp guns were inserted into crevices and under small ledges on the fault scarp where attached strings of fault scum were seen moving with currents. The slurp guns were cleaned for microbial sampling prior to the dive. After the dive, filtrates of slurp samples were analyzed for DNA sequences and mineral content. Results of 16S rDNA sequence analyses show that the microbial Archaea assemblage includes hyperthermophilic taxa within Crenarchaeota and Euryarchaeaota, as well as members of Korarchaeota and marine groups I and II (Ehrhardt et al., 2003). Most sequences belong to the orders Thermoproteales and Desulfurococcales within Crenarchaeota (Ehrhardt et al., 2003). Dominance of hyperthermophilic Crenarchaeaota sequences in the clone library for the fault-scarp Archaea assemblage is unusual. Hyperthermophilic Euryarchaeota typically are the dominant high-T organisms identified in molecular surveys of ridge-crest hydrothermal vents (Reysenbach et al., 2000; Nercessian et al., 2003). Particles associated with hyperthermophilic microbes in the slurp samples include corroded chalcopyrite grains (Fig. 3B). Cu is transported in submarine hydrothermal fluids by chloride complexes that are unstable below ~250 °C, and chalcopyrite precipitates in chimneys on the East Pacific Rise crest at temperatures ≥250 °C (Haymon, 1983). Corroded chalcopyrite particles in the slurp samples at the MM site indicate precipitation from high-T, Cu- and H_2S-enriched fluids, and subsequent oxidation and dissolution by seawater after cessation of high-T fluid discharge.

Implications. Chalcopyrite occurrence indicates that hydrothermal fluids ≥250 °C vented along the scarp face, possibly pooling beneath rocky ledges in the same way that hot, buoyant fluids pool beneath the flanges of active hydrothermal chimneys (Delaney et al., 1992). Venting of high-T fluid is consistent with the hyperthermophilic affinities of the fault floc Archaea assemblage. Note that (1) the DNA of hyperthermophilic taxa is not entirely degraded, (2) microscopic chalcopyrite grains are not completely oxidized, and (3) 0.15–0.2 °C anomalies were detected where the slurp sample was collected. These observations suggest that venting of high-*T* fluid from the scarp was recent and that waning has been quick. We speculate that the overlying hilltop mound field formed from frequent episodes of fluid release triggered by seismic events, and that the fault scarp also releases frequent, transitory bursts of high-*T* fluid that rapidly becomes diffuse and wanes on a decadal time scale. Hyperthermophiles in the subsurface may flush out and bloom on the fault scarp during these events and then remain dormant until the next event. Monitoring of abyssal hill fault scarps is needed to test these ideas.

SUMMARY

We present evidence from two East Pacific Rise abyssal hill sites for often repeated events of hydrothermal discharge along bounding fault scarps. Maximum *T* of fluids venting at these young sites apparently can be ≥250 °C, though such high-*T* venting is probably short-lived. Frequent pulses of ridge-flank hydrothermal discharge are plausible, in view of the recurrence rate for seismic events capable of rejuvenating fluid flow, and may have important biogeographic implications. Hydrothermally active fault scarps may give us access to microbes inhabiting the upper crust. Many of the hilltop sediment mounds that we describe appear to be meter-scale mud volcanoes of variable ages. These features may be independent indicators of episodic bursts of fluid flow from young abyssal hills. We have not proved that the mounds are hydrothermal in origin, but their appearance is similar to meter-scale sediment features described at the volcanic Marianas Mounds site (Lonsdale and Hawkins, 1985), where detailed heat-flow observations and pore-water studies provide solid evidence of hydrothermal advection through sediments (Wheat and McDuff, 1995). We concur with Johnson et al. (2001) that relationships between hydrothermal fluid flow, biology, and seismicity on ridge flanks must now be investigated vigorously.

ACKNOWLEDGMENTS

This research was supported by National Science Foundation grants OCE98-16021 (to Macdonald) and OCE-0002816 (to Haymon). We thank P.J. Fox for 1994 dive observations, D. Valentine, B. Popp, and E. Olson for help with CH_4 analyses, T. Hill for C isotope analysis, J. Blasius for aid with core sampling, N. Ward and J. Heidelberg of The Institute for Genomic Research for help with microbial sample collection at sea, and P. Holden, M. Lamontagne, and J. Saleta for aid with microbiological analyses at University of California, Santa Barbara. We also thank H.P. Johnson, S. Sievert, and an anonymous reviewer for thoughtful reviews of the manuscript.

REFERENCES CITED

Alt, J.C., 1995, Subseafloor processes in mid-ocean ridge hydrothermal systems, *in* Humphris, S.E., et al., eds., Seafloor hydrothermal systems: Physical, chemical, biological and geological interactions: American Geophysical Union Geophysical Monograph 91, p. 85–114.

Alt, J.C., and Teagle, D.A.H., 2003, Hydrothermal alteration of upper oceanic crust formed at a fast-spreading ridge: Mineral, chemical, and isotopic evidence from ODP Site 801: Chemical Geology, v. 201, p. 191–211.

Alt, J.C., Lonsdale, P., Haymon, R., and Muehlenbachs, K., 1987, Hydrothermal sulfide and oxide deposits on seamounts near 21°N, East Pacific Rise: Geological Society of America Bulletin, v. 98, p. 157–168.

Benjamin, S.B., 2004, Hydrothermal activity on the flanks of a fast-spreading ridge: Mineral deposits and sedimentary features recently discovered on East Pacific Rise abyssal hills [M.S. thesis]: Santa Barbara, University of California, 95 p.

Carbotte, S., and Macdonald, K.C., 1992, East Pacific Rise 8°–10°30′N: Evolution of ridge segments and discontinuities from SeaMARC II and three-dimensional magnetic studies: Journal of Geophysical Research, v. 97, p. 6959–6982.

Delaney, J.R., Robigou, V., McDuff, R.E., and Tivey, M.K., 1992, Geology of a vigorous hydrothermal system on the Endeavour segment, Juan de Fuca Ridge: Journal of Geophysical Research, v. 97, p. 19,663–19,682.

Edmond, J.M., Measures, C., McDuff, R., Chan, L.H., Collier, R., Grant, B., Gordon, L.I., and Corliss, J.B., 1979, Ridge crest hydrothermal activity and the balances of the major and minor elements in the ocean: The Galapagos data: Earth and Planetary Science Letters, v. 46, p. 1–18.

Ehrhardt, C., Haymon, R., Lamontagne, M., and Holden, P., 2003, Geomicrobiology of Archaeal communities isolated from an off-axis abyssal hill scarp on the East Pacific Rise at 9°27′N: Eos (Transactions, American Geophysical Union), v. 84, abs. B12A-0732.

Fisher, A.T., and Becker, K., 2000, Channelized fluid flow in oceanic crust reconciles heat flow and permeability data: Nature, v. 403, p. 71–74.

Haymon, R.M., 1983, Growth of black smoker hydrothermal chimneys: Nature, v. 301, p. 695–698.

Hekinian, R., and Fouquet, Y., 1985, Volcanism and metallogenesis of axial and off-axial structures on the East Pacific Rise near 13°N: Economic Geology, v. 80, p. 221–249.

Johnson, H.P., and Pruis, M.J., 2003, Fluxes of fluid and heat from the oceanic crustal reservoir: Earth and Planetary Science Letters, v. 216, p. 565–574.

Johnson, H.P., Dziak, R.P., Fisher, C.R., Fox, C.G., and Pruis, M.J., 2001, Earthquakes' impact on hydrothermal systems may be far-reaching: Eos (Transactions, American Geophysical Union), v. 82, p. 233–236.

Kelley, D.S., Karson, J.A., Blackman, D.K., Fruh-Green, G.L., Butterfield, D.A., Lilley, M.D., Olson, E.J., Schrenk, M.O., Roe, K.K., Lebon, G.T., Rivizziggno, P., and Party, A.-S., 2001, An off-axis hydrothermal field near the Mid-Atlantic Ridge at 30°N: Nature, v. 412, p. 145–149.

Lonsdale, P., 1977, Deep tow observations at the Mounds abyssal hydrothermal field: Earth and Planetary Science Letters, v. 36, p. 92–110.

Lonsdale, P., and Hawkins, J., 1985, Silicic volcanism at an off-axis geothermal field in the Mariana Trough back-arc basin: Geological Society of America Bulletin, v. 96, p. 940–951.

Lonsdale, P., and Spiess, F.N., 1980, Deep-tow observations at the East Pacific Rise, 8°45′N, and some interpretations, *in* Rosendahl, B.R., and Hekinian, R., Initial reports of the Deep Sea Drilling Project, Volume 54: Washington, D.C., U.S. Government Printing Office, p. 43–62.

Macdonald, K.C., Fox, P.J., Alexander, R.T., Pockalny, R., and Gente, P., 1996, Volcanic growth faults and the origin of Pacific abyssal hills: Nature, v. 380, p. 125–129.

Mottl, M.J., Wheat, C.G., Baker, E., Becker, K., Davis, E.E., Feely, R., Grehan, A., Kadko, D., Lilley, M.D., Massoth, G.J., Moyer, C.L., and Sansone, F.J., 1998, Warm springs discovered on 3.5 Ma oceanic crust, eastern flank of the Juan de Fuca Ridge: Geology, v. 26, p. 51–54.

Nercessian, O., Reysenbach, A.-L., Prieue, D., and Jeanthon, C., 2003, Archaeal diversity associated with in situ samplers deployed on hydrothermal vents on the East Pacific Rise (13°N): Environmental Microbiology, v. 5, p. 492–502.

Popp, B.N., Sansone, F.J., Rust, T.M., and Merritt, D.A., 1995, Determination of concentration and carbon isotopic composition of dissolved methane in sediments and nearshore waters: Analytical Chemistry, v. 67, p. 405–411.

Reysenbach, A.-L., Longnecker, K., and Kirshtein, J., 2000, Novel bacterial and archaeal lineages from an in situ growth chamber deployed at the Mid-Atlantic Ridge hydrothermal vent: Applied and Environmental Microbiology, v. 66, p. 3798–3806.

Shank, T.M., Fornari, D.J., Damm, K.L.V., Lilley, M.D., Haymon, R.M., and Lutz, R.A., 1998, Temporal and spatial patterns of biological community development at nascent deep-sea hydrothermal vents (9°50′N, East Pacific Rise): Deep-Sea Research II, v. 45, p. 465–515.

Sohn, R.A., Fornari, D.J., Damm, K.L.V., Hildebrand, J.A., and Webb, S.C., 1998, Seismic and hydrothermal evidence for a cracking event on the East Pacific Rise crest at 9°50′N: Nature, v. 396, p. 159–161.

Stein, C.A., Stein, S., and Pelayo, A., 1995, Heat flow and hydrothermal circulation, *in* Humphris, S.E., et al., eds., Seafloor hydrothermal systems: Physical, chemical, biological and geological interactions: American Geophysical Union Geophysical Monograph 91, p. 425–445.

Von Damm, K.L., 1995, Controls on the chemistry and temporal variability of seafloor hydrothermal fluids, *in* Humphris, S.E., et al., eds., Seafloor hydrothermal systems: Physical, chemical, biological and geological interactions: American Geophysical Union Geophysical Monograph 91, p. 222–247.

Wheat, C.G., and McDuff, R.E., 1995, Mapping the fluid flow of the Mariana mounds ridge flank hydrothermal system: Pore water chemical tracers: Journal of Geophysical Research, v. 100, p. 8115–8131.

Wolery, T.J., and Sleep, N.H., 1976, Hydrothermal circulation and geothermal flux at mid-ocean ridges: Journal of Geophysical Research, v. 84, p. 249–275.

Manuscript received 16 August 2004
Revised manuscript received 22 October 2004
Manuscript accepted 22 October 2004

Printed in USA