THE OFFICIAL MAGAZINE OF THE OCEANOGRAPHY SOCIETY

Oceanography

CITATION

Tivey, M.K., E. Becker, R. Beinart, C.R. Fisher, P.R. Girguis, C.H. Langmuir, P.J. Michael, and A.-L. Reysenbach. 2012. Links from mantle to microbe at the Lau Integrated Study Site: Insights from a back-arc spreading center. *Oceanography* 25(1):62–77, http://dx.doi.org/10.5670/oceanog.2012.04.

DOI

http://dx.doi.org/10.5670/oceanog.2012.04

Links from Mantle to Microbe at the Lau Integrated Study Site

INSIGHTS FROM A BACK-ARC SPREADING CENTER

BY MARGARET K. TIVEY, ERIN BECKER, ROXANNE BEINART, CHARLES R. FISHER, PETER R. GIRGUIS, CHARLES H. LANGMUIR, PETER J. MICHAEL, AND ANNA-LOUISE REYSENBACH

Active hydrothermal vent deposits at the Tu'i Malila vent field on the Valu Fa Ridge within the Lau Integrated Study Site, Southwest Pacific. Lush animal communities take advantage of the locally elevated primary productivity close to the vents. The black snail *Ifremeria nautilei* and mussel *Bathymodiolus brevior* shown in this image are two of the chemoautotrophic symbiont-containing mollusk species that dominate biomass in this vent system.

ABSTRACT. The Lau Integrated Study Site (ISS) has provided unique opportunities for study of ridge processes because of its back-arc setting in the southwestern Pacific. Its location allows study of a biogeographical province distinct from those of eastern Pacific and mid-Atlantic ridges, and crustal compositions along the ridge lie outside the range of mid-ocean ridge crustal compositions. The Lau ISS is located above a subduction zone, at an oblique angle. The underlying mantle receives water and other elements derived from the downgoing lithospheric slab, with an increase in slab influence from north to south. Water lowers the mantle melting temperature and leads to greater melt production where the water flux is greater, and to distinctive regional-scale gradients along the ridge. There are deeper faulted axial valleys with basaltic volcanism in the north and inflated axial highs with andesites in the south. Differences in igneous rock composition and release of magmatic volatiles affect compositions of vent fluids and deposits. Differences in vent fluid compositions and small-scale diffuse-flow regimes correlate with regional-scale patterns in microbial and megafaunal distributions. The interdisciplinary research effort at the Lau ISS has successfully identified linkages between subsurface processes and deep-sea biological communities, from mantle to microbe to megafauna.

INTRODUCTION

A central aim of the Ridge 2000 Program is to understand the flow of energy and mass from Earth's deep mantle to the seafloor and ocean, and how this flow influences deep-sea biological communities. Among the three designated sites for intense studies, the Lau Integrated Study Site (ISS) provides unique opportunities that derive from the back-arc tectonic setting of this spreading center. The flux of water and other elements derived from the downgoing lithospheric slab (brittle portion of the descending crust and mantle) influence back-arc spreading ridges (Figure 1). The volcanic front lavas that occur ~ 110 km above the slab most prominently display these elements. In regions of extension, back-arc basin spreading centers open behind the volcanic front. Because back-arc ridges are often oblique to the arc, they sample the mantle at varying distances above the slab and receive an "arc geochemical signal" that decreases with distance from the volcanic front of the arc. This arc signal prominently includes water, which has a major effect on mantle melting and differentiation, and also other volatiles and elements such as CO_2 and S that play major roles in biological processes.

The tectonic and geographic setting of the Eastern Lau Spreading Center (ELSC) and Valu Fa Ridge (VFR) provide some valuable opportunities for studying ridge processes. In particular, the contrast in lava compositions relative to mid-ocean ridges (MORs) and the gradients in ridge characteristics that result from the oblique configuration of arc and spreading center provide a natural experiment on how differences in ridge characteristics influence life. In addition, the location of the ridge in the southwestern Pacific allows study of a biogeographical province that is different and distinct from those of eastern Pacific and mid-Atlantic ridges.

These opportunities have led to a rather different approach than those at the East Pacific Rise (EPR) at 9°50'N and the Endeavour Segment of the Juan de Fuca Ridge ISSs (see Fornari et al., 2012, and Kelley et al., 2012, both in this issue). At the Lau ISS, a regional perspective was taken to permit study of the range of vent fluid, chimney, and lava compositions, and associated biological communities, and how they respond to changing ridge characteristics. In comparison to the Endeavour and EPR ISSs, there was a relative lack of information about the ELSC because it did not have the decades of previous intensive work that characterized the other two ISSs. The challenge, which was successfully met by using a carefully coordinated series of staged voyages, was to explore and investigate a significant length of ridge, find hydrothermal sites,

Margaret K. Tivey *(mktivey@whoi.edu) is Senior Scientist, Marine Chemistry and Geochemistry Department, Woods Hole Oceanographic Institution, Woods Hole, MA, USA.* **Erin Becker** *is Postdoctoral Researcher, Biology Department, Pennsylvania State University, University Park, PA, USA.* **Roxanne Beinart** *is Doctoral Candidate, Department of Organismic and Evolutionary Biology, Harvard University, Cambridge, MA, USA.* **Charles R. Fisher** *is Professor, Biology Department, Pennsylvania State University, University Park, PA, USA.* **Peter R. Girguis** *is Loeb Associate Professor of Natural Sciences, Department of Organismic and Evolutionary Biology, Harvard University, Cambridge, MA, USA.* **Charles H. Langmuir** *is Professor of Geochemistry, Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA, USA.* **Peter J. Michael** *is Professor, Department of Geosciences, The University of Tulsa, Tulsa, OK, USA.* **Anna-Louise Reysenbach** *is Professor, Biology Department, Portland State University, Portland, OR, USA.*

and carry out meaningful integrated studies on the limited timeframe of the Ridge 2000 Program.

Initial work consisted of four cruises in 2004 and 2005. The first mapped the ELSC and VFR, obtained water column profiles to locate the regions with most intense hydrothermal activity (Baker et al., 2006; Martinez et al., 2006; Figure 2), and deployed floats to study the deep flow field in the Lau Basin (see Speer and Thurnherr, 2012, in this issue). The second cruise obtained rock samples along the length of the ridge, and used the *Autonomous Benthic Explorer* (*ABE*) and the TowCam digital deep-sea imaging system (Fornari and the WHOI TowCam Group, 2003) to discover three new hydrothermal sites along the ELSC (named Kilo Moana, TowCam, and ABE; German et al., 2008; Bezos et al., 2009; Escrig et al., 2009); participants in this cruise also collaborated in the discovery of the Mariner vent field on the VFR with Japanese scientists who were in the area at that time. The third cruise used the remotely operated vehicle (ROV) *Jason 2* to map the vent fields, photograph biological communities, and sample hydrothermal fluids and deposits, as well as discover an additional vent site (Tu'i Malila; Ferrini et al., 2008). The fourth cruise then carried out more detailed biological and coupled biological and chemical studies of the vent sites. Follow-on studies included a large seismic experiment in 2009 and 2010 to more thoroughly investigate mantle processes using passive and active seismic techniques, and additional detailed microbial, biological, and biogeochemical field work conducted in 2009 using the ROV *Jason 2*. The latter provided a temporal component to biological and vent geochemical studies. In addition, further plume mapping of a section of the ELSC (from 19°54'S to 21°S) and of the VFR (21°54'S to 22°24'S) was carried out in 2008 (Baker et al., 2010). Results of those surveys included successful mapping of plumes, all occurring within ~ 1.5 km of the ridge axis, with no detection of plumes farther off axis, and detection of oxidation-reduction potential anomalies on the VFR consistent with the presence of low-temperature hydrothermal sources on the axial flank. A full listing of all US cruises to the Lau ISS can be found at http://www.marine-geo.org/portals/ridge2000/ under Lau Back-arc Basin, Expeditions/Compilations.

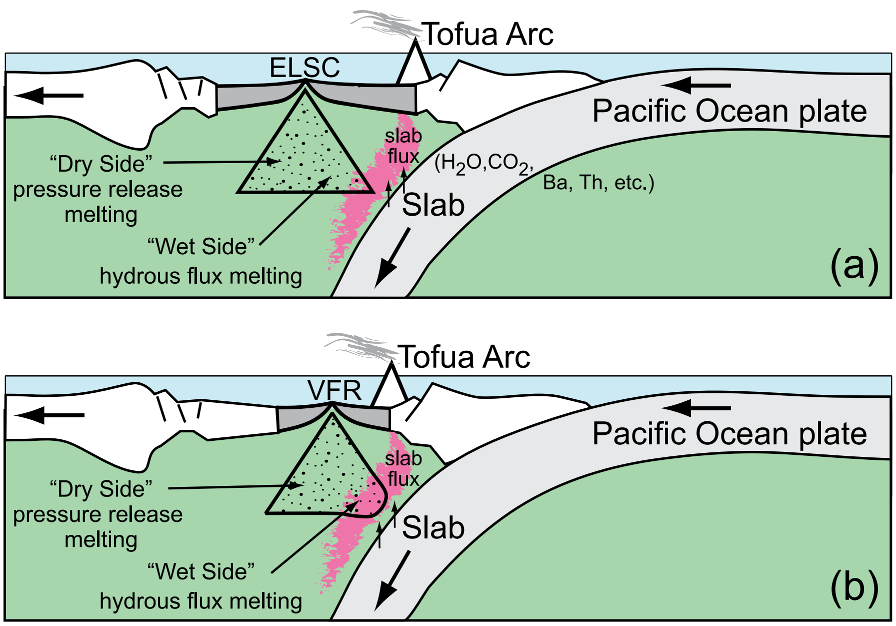

Figure 1. Schematic of the back-arc system of the southern Lau Basin showing the change in subduction influence from north to south, substantially modified from Martinez et al. (2007). (a) In the north, the Eastern Lau Spreading Center (ELSC) is about 100 km from the Tofua arc. The melting regime for the back-arc is just slightly influenced by the slab flux that dominates the geochemical signals at the volcanic front of the arc. (b) In the south, Valu Fa Ridge (VFR) is only 45 km from the arc, and the subduction component strongly influences the back-arc melting system. More water is added to the spreading center melting regime, causing higher extents of melting and greater crustal thickness at the same time as an increased flux of water and other elements from the slab. In general, back-arc magmas are a mixture of melts produced by decompression melting as at normal ridges in the half of the melting regime distal to the arc (the "dry side"), and melts produced by hydrous flux melting in the proximal side of the melting regime (the "wet side") (Langmuir et al., 2006).

CHARACTERISTICS OF THE ELSC/VFR

Ridge Morphology and Petrology

The Lau ISS is located between 19°20'S and 22°45'S along the ELSC and VFR (Figure 2). Along this distance of ~ 240 km, the spreading center and ridge exhibit systematic changes in a number of variables from north to south. The lateral and depth distances to arc magma sources vary substantially (i.e., slab; Figure 1), the spreading rate decreases from 95 mm yr^{-1} to 40 mm yr^{-1} (full rate), and axial depth decreases from 2,700 m to 1,740 m. From north to south, the spreading ridge morphology changes from a highly faulted axial valley to an inflated axial ridge, and the seismically detected "lens" of melt in the crust beneath the spreading axis varies from being absent or only present as isolated melt sills to continuously present (Martinez et al., 2006; Jacobs et al., 2007). Crustal thickness along axis increases from about 5 to 9 km (Turner et al., 1999; Crawford et al., 2003), and lava chemistry changes from compositions that include tholeiitic basalts depleted in elements like Ba, Rb, La, Th, and U (similar to mid-ocean ridge basalts) to more andesitic compositions with a strong arc geochemical signature (i.e., enriched in the above elements; Peate et al., 2001; Pearce et al., 2005; Bezos et al., 2009; Escrig et al., 2009).

These characteristics have some surprising contrasts with MORs. For most MORs, as spreading rate declines, ridge morphology changes from an axial high to an axial rift, and the intensity of faulting increases. In contrast, shallow axial highs and minimal faulting characterize the slower-spreading southern portions of the ELSC/VFR, while the fastest-spreading portions exhibit deeper rift valleys with flatter axes and a greater faulting intensity (Martinez et al., 2006; Figure 2). There is a rather abrupt transition between the two types of ridge morphology near 20°35'S, over a distance of about 20 km along a short segment in the middle of the study region.

Although there is insufficient sampling to fully explore the time dimension (across axis), in general terms of change in subduction component, the north-south morphological changes observed along the ELSC/VFR are also observed across the axis. Back-arc

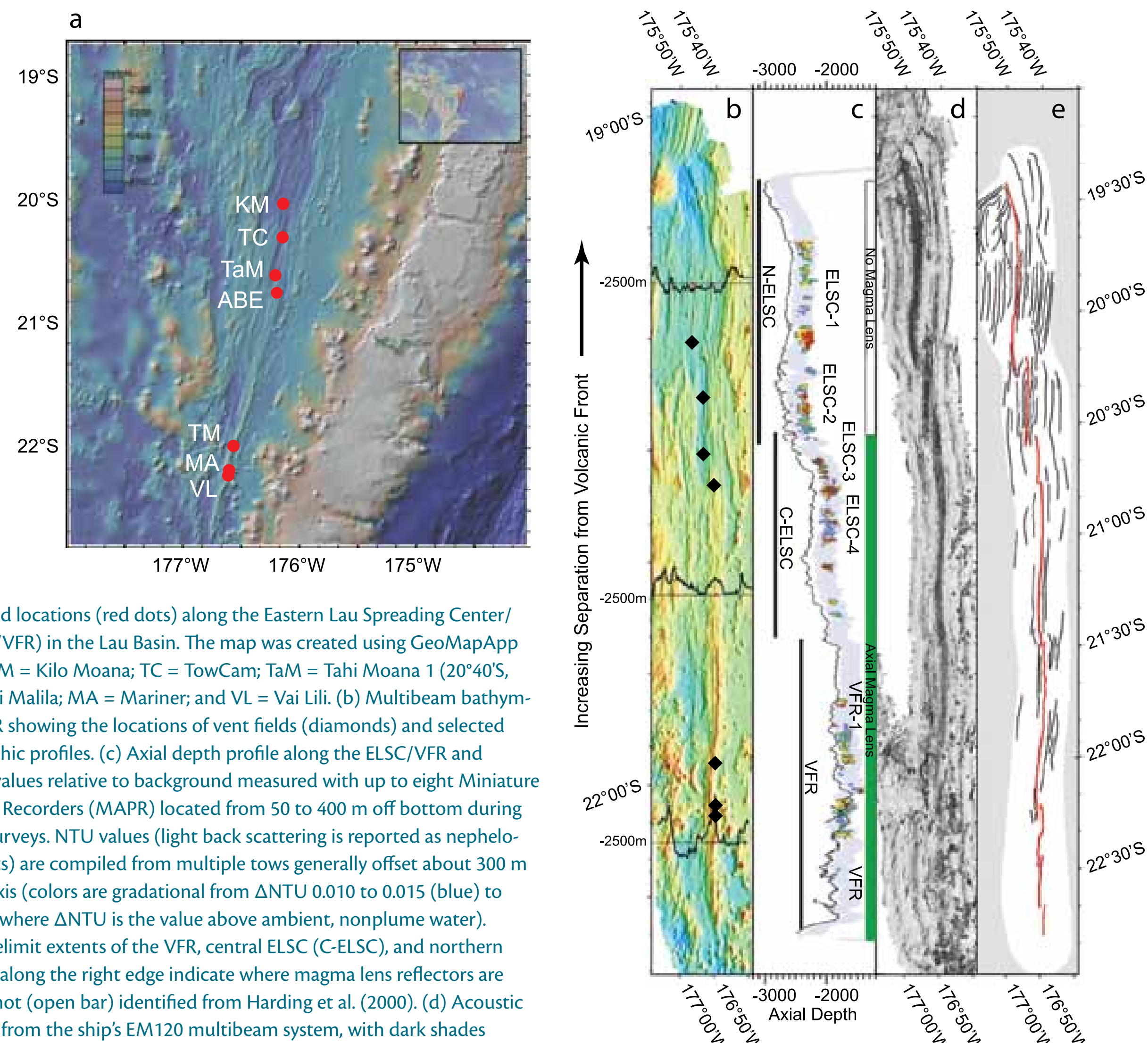

Figure 2. (a) Vent field locations (red dots) along the Eastern Lau Spreading Center/Valu Fa Ridge (ELSC/VFR) in the Lau Basin. The map was created using GeoMapApp (Ryan et al., 2009). KM = Kilo Moana; TC = TowCam; TaM = Tahi Moana 1 (20°40'S, 176°11'W); TM = Tu'i Malila; MA = Mariner; and VL = Vai Lili. (b) Multibeam bathymetry of the ELSC/VFR showing the locations of vent fields (diamonds) and selected across-axis topographic profiles. (c) Axial depth profile along the ELSC/VFR and optical backscatter values relative to background measured with up to eight Miniature Autonomous Plume Recorders (MAPR) located from 50 to 400 m off bottom during deep-towed sonar surveys. NTU values (light back scattering is reported as nephelometric turbidity units) are compiled from multiple tows generally offset about 300 m to each side of the axis (colors are gradational from ΔNTU 0.010 to 0.015 (blue) to 0.070 to 0.080 (red), where ΔNTU is the value above ambient, nonplume water). Black vertical bars delimit extents of the VFR, central ELSC (C-ELSC), and northern ELSC (N-ELSC). Bars along the right edge indicate where magma lens reflectors are (green bar) and are not (open bar) identified from Harding et al. (2000). (d) Acoustic backscatter imagery from the ship's EM120 multibeam system, with dark shades indicating high backscatter (less sediment cover and presumably younger seafloor). (e) Distribution of near-axis large faults identified both in side-scan imagery and bathymetry. White area shows approximate limits of coverage considered in the fault identification. The red line is the ELSC axis location. *After Martinez et al. (2006)*

spreading centers are much less stable than MORs. Ridges are born, propagate, and die over periods of a few million years or less, changing the spatial relationship of the ridge to the arc and slab. In the Lau Basin, the ridge has steadily propagated southward. As it propagated, the location of the ridge with respect to the arc became increasingly distal, with increasing distance behind the propagating tip. Thus, with age, seafloor spreading separates the ridge from the Tofua arc, isolating it from the water flux from the slab that enhances mantle melting and leads to more voluminous and compositionally distinct magmas (Figure 1). New geophysical data show that one million years ago, the northern part of the ELSC looked physically more like the ridge to the south, with more rugged bathymetry and thicker, lower density (probably andesitic) crust (Dunn and Martinez, 2011). Preliminary geochemical data for rocks collected off axis show this scenario is likely (based on data of author Michael). The change is rapid, as it is along the axis, suggesting to Dunn and Martinez that there is a threshold effect related to the distance to the arc.

As noted, observed morphological differences in the Lau Basin correlate with compositional differences. Along the ELSC/VFR axis, changes in ridge morphology correspond with large changes in the temperatures, compositions, and amounts of crystallization of the erupted lavas (Figure 3). As magmas ascend into cold crust, their temperatures decrease and they crystallize, causing their MgO contents to decrease. For normal MORs, MgO decreases with very little increase in SiO_2. At convergent margins, however, decreasing MgO is associated with a marked increase in SiO_2, leading to the succession of lava types: basalt-andesite-dacite-rhyolite. This difference is reflected in the change in differentiation path along the ELSC and VFR. In the north, high-temperature basaltic lavas with ~ 8 wt % MgO make up most of the recovered samples, and SiO_2 does not change much as MgO decreases. Over the restricted region where there is an abrupt change in axial morphology (near 20°35'S), the lavas become andesitic as the MgO content drops (Figure 3a). Lavas in this region generally have less than 5.5% MgO, and higher SiO_2. Further south, along the VFR, dacites (lavas with > 59% SiO_2 and with only 2–3 wt % MgO) are a significant component of the recovered rocks. Thus, the path of differentiation changes from one similar to ocean ridges located far from the subduction setting to one more similar to arc lavas.

Along with these changes in rock type and inferred eruptive temperature, there are large changes in the concentrations of trace elements that reflect the flux of material (e.g., H_2O, Ba, Th, and, to a lesser extent, La) from the downgoing slab (Figure 1), with concentrations increasing markedly southward. The various elements are tracers of downgoing slab materials and the processes that transport them. For example, Th is an element with high concentrations in sediment that is insoluble in hydrous fluids, while Ba is both high in sediments and easily transported by

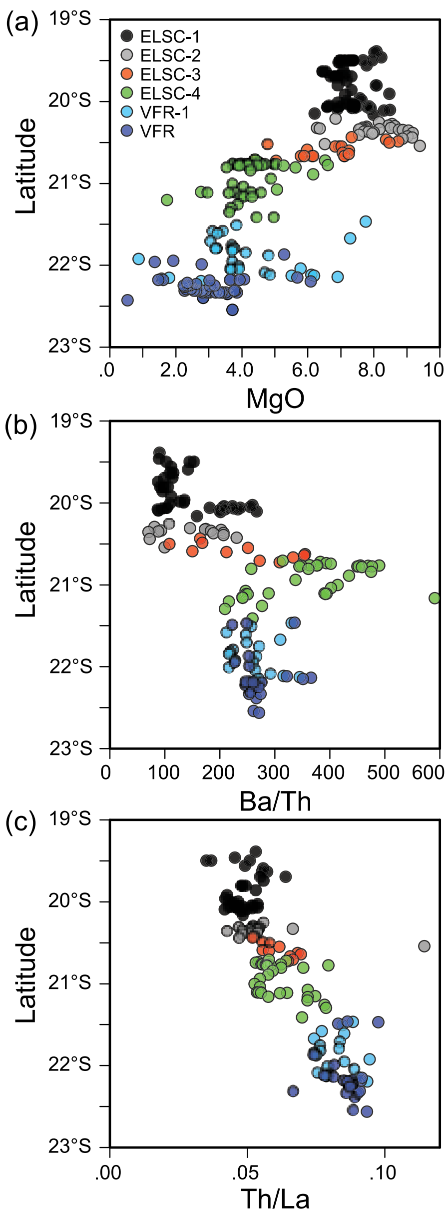

Figure 3. Changes in compositions of erupted lavas with location along axis. Figure 2 shows segment locations. The Kilo Moana vent field is at the southern end of Eastern Lau Spreading Center-1 (ELSC-1), the TowCam vent field is within ELSC-2, the Tahi Moana 1 vent field is within the short ELSC-3 segment, the ABE vent field is at the northern end of ELSC-4, Tu'i Malila is within VFR-1, and Mariner and Vai Lili vent fields are at the northern end of the VFR segment. Color changes with each segment. (a) MgO (wt %), which corresponds closely with magma temperature; (b) Ba/Th; (c) Th/La. Ba, Th, and La are trace elements that are associated with fluxes from the downgoing slab; Th is an element with high concentrations in sediment that is insoluble in hydrous fluids, while Ba is both high in sediments and easily transported by fluids. Changes in the various ratios of these tracers thus give an indication of materials and processes at depth. Note from the different characteristics of the Ba/Th and Th/La profiles that there is not a simple two-component behavior. Multiple slab components that vary along the arc are necessary. Data are from Bezos et al. (2009), and Escrig et al., (2009), and recent work of author Langmuir and colleagues.

fluids. Changes in the various ratios of these tracers thus give an indication of materials and processes at depth. Generically these tracers are called "subduction components."

If there were simply a homogeneous subduction component increasing in strength as the ridge approaches the arc, then there would be smooth increases in ratios and concentrations moving southward along the ridge. While there is an overall increase from north to south, the changes are not a smooth gradient and show that there is not a single subduction component (see Figure 3). There are two geochemical transitions: one at ~ 20°35'S characterized by a jump in Ba/Th, Th/La, and La/Sm, and another between ~ 21°4.2'S and 21°12.6'S that is more gradual, with a decrease in Ba/Th and increases in Th/La, La/Sm, and $^{206}Pb/^{204}Pb$, but not in Ba/Nb (Escrig et al., 2009). There is clearly some process at depth that leads to a preferential enrichment of Ba relative to Th midway along the ridge (Figure 3b). The more northern transition correlates with the change in ridge morphology from an axial rift valley to an axial high, and the decrease in MgO and increase in SiO_2 that marks the change from basaltic to andesitic crust noted above (Escrig et al., 2009).

One of the notable results of the closely spaced rock sampling carried out in 2004 is the correspondence between geochemical signals along the back-arc spreading center and the position of volcanoes along the volcanic arc. Pb isotope ratios undulate along the back-arc in conformity with the positions of arc front volcanoes, and the complex mixing trajectories leading to the irregular along-axis patterns of trace element ratios result from mixing toward distinct compositions of volcanoes from the arc (Escrig et al., 2009). The change in chemical compositions then relates in part to the distance of the back-arc spreading center from the arc, and in part to whether the back-arc is directly behind an arc volcano or not. This result is particularly intriguing in light of seismic evidence that suggests substantial horizontal mantle flow parallel to the volcanic front (Smith et al., 2001; Conder and Wiens, 2007). A possible solution is that the flow of slab-derived hydrous fluid and wedge-derived melt is rapid relative to solid mantle flow so that the mantle flow does not offset the position of the fluid flux.

The hydrous fluid flux from the slab to the mantle is critical to the overall behavior of the back-arc spreading center. Water lowers the mantle's melting temperature, increasing the extent of partial melting and melt production, and therefore increasing crustal thickness. Water contents of basalts are lowest on the northern ELSC and increase toward the VFR in the south, as the distance to the arc decreases. Crustal thickness increases from ~ 5 km beneath Kilo Moana vent field in the north to ~ 9 km beneath Mariner vent field in the south (Turner et al., 1999; Crawford et al., 2003). The higher water content also causes basaltic magmas to evolve to more silica-rich andesites and dacites as they cool. This process may be particularly important at Mariner vent field, which has dacitic lavas and basalts in close proximity. These changes in magma supply and composition conceptually could lead to the changes in the depth and shape of the ELSC/VFR noted above that are opposite to what is observed at normal MORs (Martinez et al., 2006; Figure 2). The deeper, rifted, fast-spreading northern part of the ELSC would have the normal characteristics of an intermediate MOR owing to low water content. The slower-spreading VFR in the south would have the characteristics normally associated with a fast-spreading MOR because of the increased flux caused by increased water content.

Because water also affects the path of differentiation and the viscosity and temperature of erupted lavas, these changes also influence the crust's physical characteristics, which in turn can affect hydrothermal systems. Crustal seismic velocities in the north are similar to those of MORs (5–6 km s^{-1} at 1 km depth), but those on the VFR in the south are slower (~ 4 km s^{-1} at 1 km depth; Jacobs et al., 2007). The slow velocities could be due to greater porosity of the crust, owing to higher vesicle content from the lavas' higher water contents (Carlson and Herrick, 1990). Another factor could be the higher SiO_2. Either way, the slow velocities are outside the behavior of normal MORs, and they are a direct response to a changing volatile content associated with the arc influence.

Qualitative and quantitative models can further test these hypotheses of possible relationships between hydrous fluid flux from the slab to the mantle and ridge morphology. Dunn and Martinez (2011) propose a qualitative model with a narrow ridge melting regime where the melting regime becomes abruptly disconnected from the arc flux, leading to the rapid change in the physical and chemical characteristics of the ELSC near 20°35'S. This model, however, has difficulty accounting for the clear existence of a continuing arc signature to the north of this boundary. Harmon and Blackman (2010) have constructed quantitative two-dimensional models for the various spreading centers of the back-arc basin. Their models produce a wide melting regime and do not reproduce the abrupt change close to the arc proposed by Dunn and Martinez (2011). They are able to produce a substantial change in crustal thickness between the VFR and the ELSC, but the overall thicknesses exceed the observations. Because the variations in arc flux are clearly three dimensional (Escrig et al., 2009), results from three-dimensional modeling studies will be an important step forward.

In terms of mantle impact on hydrothermal and biological systems, an important difference between the northern and southern parts of the ELSC/VFR is the contribution from the magmas to hydrothermal fluids, both through release of volatile species during magmatic degassing, and through reaction between seawater and the solidified igneous rock (Mottl et al., 2011). As magmas ascend, they decompress and become oversaturated with vapor. They produce additional vapor as they crystallize in the axial magma chamber. Beneath the northern vent fields (TowCam, Kilo Moana), degassing of MOR basalt (MORB)-like magmas release mostly CO_2 (Moore et al., 1977). Degassing beneath the southern hydrothermal vent fields is very different though. Basalt glasses there have H_2O contents that are oversaturated for their depth of eruption, and very low sulfur contents (data of author Michael), indicating that H_2O is the major exsolving gas and it likely carries sulfur gases with it. These gases (e.g., SO_2) can affect the composition of hydrothermal fluids and are available for biological activity at the seafloor. The magmatic gases present in some back-arc environments, particularly SO_2, can influence the pH and other chemical parameters of the fluids and result in differences in vent deposit composition, as discussed in more detail below.

Other elements that are far in excess of their concentrations in MORB, notably Ba and Pb, accompany water from the subducting slab into the mantle wedge, and from there to the magmas and crust. Reaction of evolving hydrothermal fluids with these enriched igneous rocks results in vent fluids enriched in some elements (e.g., Ba, Pb) relative to vent fluids present at MORs, and the compositions of hydrothermal mineral deposits at the Lau vent fields reflect these chemical differences (Tivey et al., 2005; Lau Workshop Report, 2006). Barium, in particular, plays an important role, with the mineral barite ($BaSO_4$) being stable under seafloor conditions and resulting in vent deposits with greater structural integrity than many found at vent fields along MORs.

The ratio of volatiles (e.g., H_2O, CO_2, SO_2, H_2S) to other elements may be a critical aspect of the influence of magma compositions on the hydrothermal systems, both through addition of volatiles and from seawater/rock reaction. While it is possible to measure primary water contents for the lavas from the northern part of the study area, the lavas from the south are sufficiently water-rich and the ridge sufficiently shallow that primary water compositions cannot be obtained from the lavas themselves. In the north, however, Bezos et al. (2009) were able to obtain the compositions of the hydrous fluids that were contributing to the (low-amplitude) arc signature that is nonetheless present there. One of the striking results is that the ratio of H_2O to trace elements in basaltic glasses along the ELSC is much higher than it is for a similar calculation carried out for the Mariana Trough back-arc spreading center (Stolper and Newman, 1994). This result can be understood from the effect of temperature on characteristics of fluids coming off the slab (Kessel et al., 2005). At low temperatures, trace elements have low solubility in hydrous fluids. As the temperature increases, the solubility increases by orders of magnitude. One of the features of the ELSC is the very fast convergence rate of the downgoing Pacific Plate. This fast convergence carries a low-temperature slab to greater depth faster, leading to a slab environment beneath the arc and back-arc that is cool relative to other arcs. Other back-arcs have slower convergence rates, and slab temperatures may be higher, leading to a different relative flux of volatiles to other elements. These results suggest that different back-arc basins may have distinct system-wide responses to the arc influence.

Newly Discovered Vent Fields

A major goal of Lau ISS studies was discovery of additional vent fields, particularly along the ELSC. Vent fields had been identified prior to 2000 along the VFR (e.g., Fouquet et al., 1991), but not along the ELSC. Nine previously undiscovered vent fields have been located along the ELSC/VFR since 2004, six as part of Ridge 2000 Program studies and three as part of commercial ventures, making it possible to investigate links between crustal and hydrothermal vent fluid compositions. Towed CTD (conductivity, temperature, depth) plume data (Baker et al., 2006, 2010) were used to identify areas along the spreading axis where venting was occurring. Discoveries of the ABE, Kilo Moana, and TowCam sites (Figure 2) were then facilitated by use of a nested discovery process using the *ABE* vehicle and a towed digital deep-sea camera (German et al., 2008). The Tahi Moana 1, Tu'i Malila, and Mariner vent fields were discovered by more traditional techniques such as tow-yos, camera tows, and follow-up ROV or human-occupied submersible dives (Ishibashi et al., 2006; German et al., 2008; Ferrini et al., 2008; Zhou et al., 2008; SRK Consulting Report for Nautilus Minerals, 2008; Figure 2). Three additional sites, TELVE, Si'I Si'I, and Misiteli, were discovered using plume data from Baker et al. (2006, 2010) as part of surveys conducted by Nautilus Minerals for commercial interests; they have not been a subject of Ridge 2000 studies (SRK Consulting Report for Nautilus Minerals, 2008).

Ultrahigh-resolution (submeter) near-bottom multibeam bathymetric mapping of six of the known vent fields (Kilo Moana, TowCam, ABE, Tu'i Malila, Mariner, Vai Lili) documented dimensions and spatial relationships among tectonic, volcanic, and hydrothermal features. The two northernmost vent fields, Kilo Moana and TowCam (Figure 2), are located at similar depths (~ 2,620 m and ~ 2,700 m, respectively) and exhibit similar hydrothermal activity, which is and has in the past been associated with faults and fissures that crosscut broad, low-relief volcanic domes and pillow and lobate flows (Ferrini et al., 2008). The igneous hosts for these fields are the high MgO, incompatible-element-depleted samples documented above (Bezos et al., 2009; Escrig et al., 2009). The Tahi Moana 1 vent field is located at a depth of ~ 2,230 m, ~ 41 km south of the TowCam vent field, and ~ 9 km north of the ABE vent field on a separate ridge segment (Figure 2), but detailed mapping has not yet been carried out. Of interest is that this vent field is located very close (20°40'S) to the petrologic transition observed at ~ 20°35'S (Escrig et al., 2009; Figure 3).

The terrain of the ABE and Tu'i Malila vent fields (Figure 2) exhibits more variable and complex volcanic morphology than that within the Kilo Moana and TowCam vent fields, and they differ considerably from MOR terrain. There are high-aspect-ratio volcanic domes within and proximal to the vent fields along with pillow flows, aa-type lavas, and distinct fingerlike flows, likely reflecting the effects of higher lava viscosity on flow transport and deposition (Ferrini et al., 2008). Although these vent fields are located at significantly different depths (ABE at ~ 2,140 m and Tu'i Malila at ~ 1,720 m) on two different spreading center segments, both are hosted in substrate ranging from basaltic andesite to andesite. At the Mariner vent field (and the Vai Lili vent field 4 km to the south; Figure 2), located on the VFR very near the overlapping spreading center at 22°10'S, small (tens of meters diameter) domes and lava flows dominate the volcanic morphology, and crosscutting faults or fissures are absent (except for a single identified fault within the Vai Lili vent field); volcanic relief is greater than that within vent fields to the north, and aa-type lava flows dominate, consistent with more viscous lavas (Ferrini et al., 2008). Silica contents of lavas recovered in 1989 from near the latitude of these vent fields indicate rocks of basaltic andesite and andesite composition, with some basalts and dacites also recovered (Fouquet et al., 1993).

Sampling and analysis of vent fluids from each of these vent fields has identified some correlations between igneous rock composition and vent fluid chemistry (Figure 4). Concentrations of mobile trace elements in the vent fluids (e.g., B, K, Rb, Cs, Ba, Pb) increase from Kilo Moana southward to Tu'i Malila (and, for B, Ba, and Pb, southward to the Mariner vent field), consistent with a higher abundance of these elements

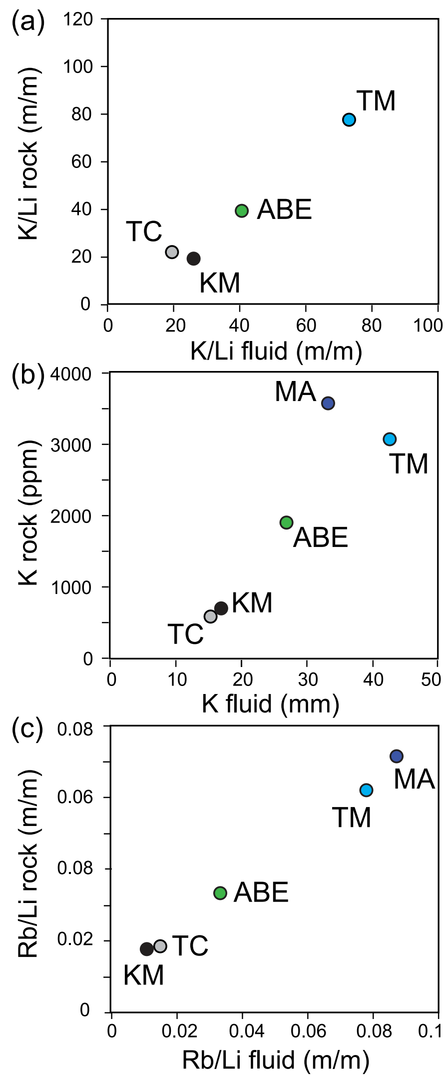

Figure 4. Correlations between igneous rock composition and vent fluid chemistry. Note that ratios with Li are far better correlations than elements alone, which would be expected because ratios are independent of fluid mass and water/rock ratio. Rock data are from Bezos et al. (2009), Escrig et al. (2009), and recent work of author Langmuir and colleagues. Fluid data are end-member compositions from Mottl et al. (2011), averaged for each vent area. m/m = millimoles kg^{-1}. ppm = parts per million.

in more slab-influenced felsic rocks. Differences observed for other elements (e.g., Fe, Mn, H_2S) are attributed to their being solubility-controlled species that are largely determined by temperature; concentrations of these species decrease from Kilo Moana to Tu'i Malila (as maximum temperatures of venting decrease from 333°C to 312°C), and then are significantly greater in Mariner vent fluids, which exhibit higher (up to 363°C) venting temperatures (Mottl et al., 2011; Figure 5). Relative to all vent fluids from vent fields to the north, Mariner vent fluids sampled in 2004 and 2005 (Takai et al., 2008; Mottl et al., 2011) and Vai Lili vent fluids sampled in 1989 (Fouquet et al., 1991) exhibit substantially higher concentrations of CO_2, F (in excess of seawater), H_2S, and transition metals and are much more acidic (pH < 2.8 at 25°C at Mariner in 2005; pH ~ 2 at 25°C at Vai Lili in 1989; Figure 5). These more dramatic differences are consistent with magmatic volatile input and addition of acidity generated by disproportionation of magma-derived SO_2 (Mottl et al., 2011).

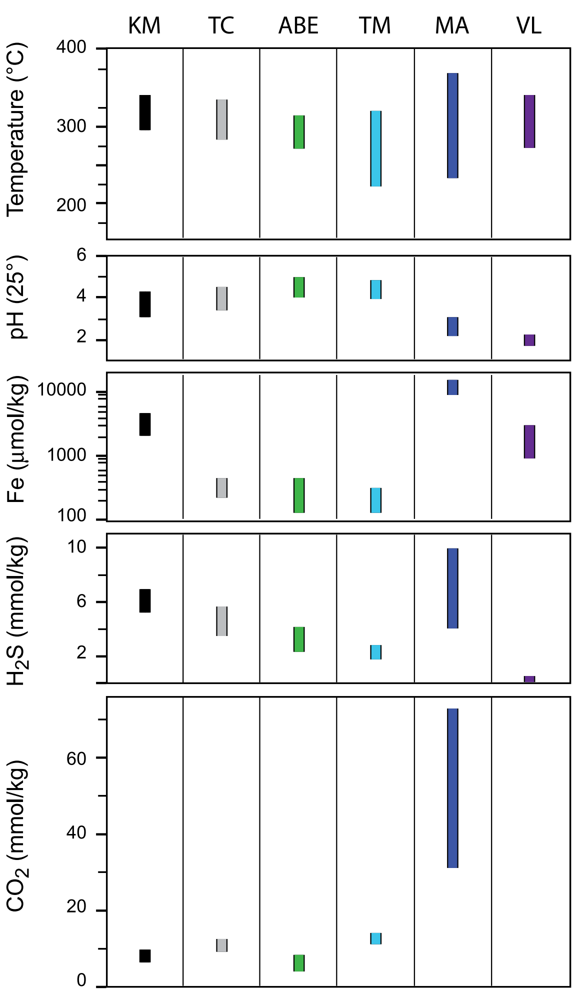

Figure 5. Ranges of temperature, pH measured at 25°C, and zero-Mg end-member Fe, H_2S, and CO_2 for low Mg (< 10 mmol kg^{-1}) vent fluid samples collected in 2005 for Kilo Moana (KM), TowCam (TC), ABE, Tu'i Malila (TM) and Mariner (MA) vent fields, and in 1989 for Vai Lili (VL). *After Mottl et al. (2011); Vai Lili data from Fouquet et al. (1993)*

Vent deposit composition and morphology also differ from north to south, correlating with changes in rock and vent fluid chemistry (Tivey et al., 2005; Lau Workshop Report, 2006; Ferrini et al., 2008; Takai et al., 2008). At the Kilo Moana and TowCam vent fields, high-temperature fluids exit from both open conduit "black smokers" and from "diffusers," or "white smoker" spires that lack any large open conduits, and dominant minerals present (identified by X-ray diffraction and reflected and transmitted light petrography) include cubic cubanite ($CuFe_2S_3$; at Kilo Moana), chalcopyrite ($CuFeS_2$), and wurtzite ((Zn,Fe)S), with pyrite and marcasite (FeS_2) more prevalent in deposit exteriors, similar to chimneys found on MORs. At the Tahi Moana 1, ABE, and Tu'i Malila vent fields, high-temperature fluids exit both open conduit "black smokers" and "diffusers," and slightly cooler fluids pool beneath flanges that protrude from either fault scarps or sulfide-rich edifices; dominant minerals include chalcopyrite and wurtzite, minor pyrite and barite ($BaSO_4$), and trace galena (PbS). The presence of barite and galena reflects enrichments of Ba and Pb in the vent fluids from water-rock interaction with enriched igneous rocks. These minerals, and flanges, are also found in MOR deposits hosted in enriched MORBs (e.g., at Lucky Strike [Mid-Atlantic Ridge] and Endeavour Segment [Juan de Fuca Ridge] vent fields; Tivey and Delaney, 1986; Langmuir et al., 1997; Tivey et al., 1999; Kristall et al., 2006). The presence of flanges at vent sites has been attributed to the presence of minerals that increase the structural integrity of deposits, such as barite, amorphous silica, and calcite, with the presence of amorphous silica attributed to high pH (relative to most MOR vent fluids; Tivey et al., 1999). Abundant flanges were also observed at Kilo Moana vent field in 2009 (data of authors Tivey and Reysenbach). At the Mariner vent field, high-temperature fluids vent from the base and sides of tall (< 10 to 27 m high), narrow (~ 3 to 4 m diameter) pinnacles, and lower-temperature fluids emanate from tabular, squat edifices. High-temperature Mariner chimneys are lined with chalcopyrite, and bornite and trace amounts of tennantite ($Cu_{12}As_4S_{13}$) are observed in mid- and exterior layers, with barite and minor sphalerite and pyrite, and trace galena, prevalent in the lower temperature squat edifices. The As-rich mineral tennantite has also been observed in deposits from Vai Lili and other arc and back-arc vent fields, reflecting enrichments of As in vent fluid produced from interactions in a more felsic (relative to MOR) magmatic-hydrothermal system (Fouquet et al., 1991; Hannington et al., 2005). No high-temperature venting (> 121°C) was observed at the Vai Lili vent field in 2005, although thick layers (centimeters) of warm (~ 60°C) iron-manganese oxide mats reminiscent of those at Loihi Seamount (Glazer and Rouxel, 2009) were prevalent in the area. Trends observed in the bulk geochemical compositions of vent deposits from each vent field (Lau Workshop Report, 2006; data of author Tivey) correlate with trends observed in vent fluid chemistry, with concentrations of Pb, Ba, As, and Sb lowest in deposits from the Kilo Moana vent field and higher in deposits to the south, likely reflecting the influence of the host substrate on vent fluid compositions.

COMMUNITY ECOLOGY AT THE LAU ISS

Like most hydrothermal systems, lush animal communities populate hydrothermal vents along the ELSC/VFR, a stark contrast to the otherwise barren surrounding seafloor (Fisher et al., 2007; Podowski et al., 2010). At depths well below the penetration of sunlight, reduced chemicals in vent fluids are the energy source that drives primary production through microbial chemosynthesis. As seen at other vents, the visually prominent individuals in animal communities at ELSC/VFR vents are typically dominated by animal-microbial symbioses, namely, invertebrates that form symbiotic associations with chemosynthetic bacteria (Cavanaugh et al., 2006; Dubilier et al., 2008). At ELSC/VFR vents, the most abundant symbioses involve mollusks, mainly two genera of provannid snails and a bathymodiolid mussel (Desbruyères et al., 1994; Podowski et al., 2010). The spreading centers are also home to numerous nonsymbiotic invertebrates such as crabs, anemones, sea cucumbers, shrimp, and barnacles (Desbruyères et al., 1994; Podowski et al., 2010). The ELSC/VFR vent fauna are generally representative of the animal communities found at vent systems in its biogeographic province, such as the other southwestern Pacific back-arc basins (e.g., Manus and North Fiji) and the Mariana Trough (Ramirez-Llodra et al., 2007; Bachraty et al., 2009).

At vents, where microbial primary productivity is associated with vent fluid flow, organisms must often be exposed to diffuse vent fluids to support symbiont chemosynthesis or to access food such as free-living microbes. A need for reduced chemicals or food, balanced by physiological or behavioral adaptations to the stress accompanying exposure to venting fluid, drives, to varying degrees, habitat preference. Biological interactions, such as competition for the limited space surrounding vent orifices, also play a role in structuring vent communities.

Previous research on other vent systems has found that species are typically associated with particular physicochemical habitats, indicating that both abiotic and biotic factors affect animal distribution (Fisher et al., 1988a,b; Shank et al., 1998; Luther et al., 2001; Le Bris et al., 2006; Moore et al., 2009). These studies have shed much light on those factors that govern the distribution of animals within a single site. As described above, the ELSC/VFR differs from other systems as it exhibits a diversity of chemical, thermal, and geological attributes at both the local (vent field) and regional (along-axis) scale. Thus, the ELSC/VFR offers a unique opportunity to examine how both local and regional gradients in the physical and chemical milieu affect faunal distribution.

How Geological Features Influence Megafaunal Distributions in the Lau Basin

Image-based analyses of diffuse-flow megafauna communities reveal regional-scale patterns of animal distribution along the spreading center that implicate geology as a primary factor influencing the presence of animals at each site (Podowski et al., 2009, 2010). The tendency for point-source-type emissions with limited horizontal dispersion from pillow basalts in the northern vent field diffuse-flow communities at Kilo Moana and TowCam contrasts with high spatial autocorrelation (inverse relationship between distance and similarity) of physicochemical parameters for more dispersed, horizontally extensive emissions from substrate (more crumbly andesites) in southern vent communities at ABE and Tu'i Malila (Podowski et al., 2010). Podowski et al. (2010) hypothesize that these physical differences produce the different small-scale flow regimes in the upper centimeters of the seafloor and strongly influence vent animal distributions among the four vent fields. For example, anemones can be quite dense on the northern basalts (Figure 6a), where the anemones may benefit from higher prey densities associated with enhanced chemosynthetic primary productivity in their immediate vicinity without exposure to toxic, high-temperature vent fluids.

The Influence of Vent Fluid Composition on the Distribution of Animal-Microbial Symbioses

Within the framework of a geographic information system, high-resolution photomosaics and discrete in situ electrochemical measurements of sulfide and oxygen concentrations were coupled with temperature measurements to examine animal distribution in relation to physicochemical data. The dominant symbioses in the ELSC/VFR, the white hairy snail *Alviniconcha* spp., the black snail *Ifremeria nautilei*, and the mussel *Bathymodiolus brevior*, are mobile and can readily move as adults to seek out optimum local habitat. In both diffuse flow and chimneys across the region, these symbioses consistently distribute around vent orifices according to their differential tolerances to vent fluid exposure. Occasionally, this pattern qualitatively resembles a "bull's-eye," in which *Alviniconcha* spp. occupy areas closest to the venting source (highest temperature and sulfide, lowest oxygen) and are, in turn, surrounded by *I. nautilei* and mussels, corresponding to decreasing exposure to vent fluid (Figure 6b; Waite et al., 2008; Podowski et al., 2009, 2010). This local pattern of distribution around venting fluid is consistent, despite the decreasing amount of hydrogen sulfide in the end-member as well as diffuse vent fluids along the spreading axis from Kilo Moana to Tu'i Malila (see Figure 5; Gartman et al., 2011; Mottl et al., 2011; Luther et al., 2012, in this issue). The mollusks occupy similar thermal regimes throughout the region, but are found in areas of decreasing hydrogen sulfide concentration from north to south. These data, along with shipboard experiments demonstrating tolerance to hydrogen sulfide concentrations well beyond those measured in situ (Henry et al., 2008), suggest that in the Lau Basin the maximum exposure of the symbiont-containing mollusks to vent fluid is constrained by temperature tolerance, not sulfide toxicity. Biological interactions such as competition or facilitation are also implicated in determining the realized distribution of these animals where their physiological tolerances and requirements overlap (Podowski et al., 2010).

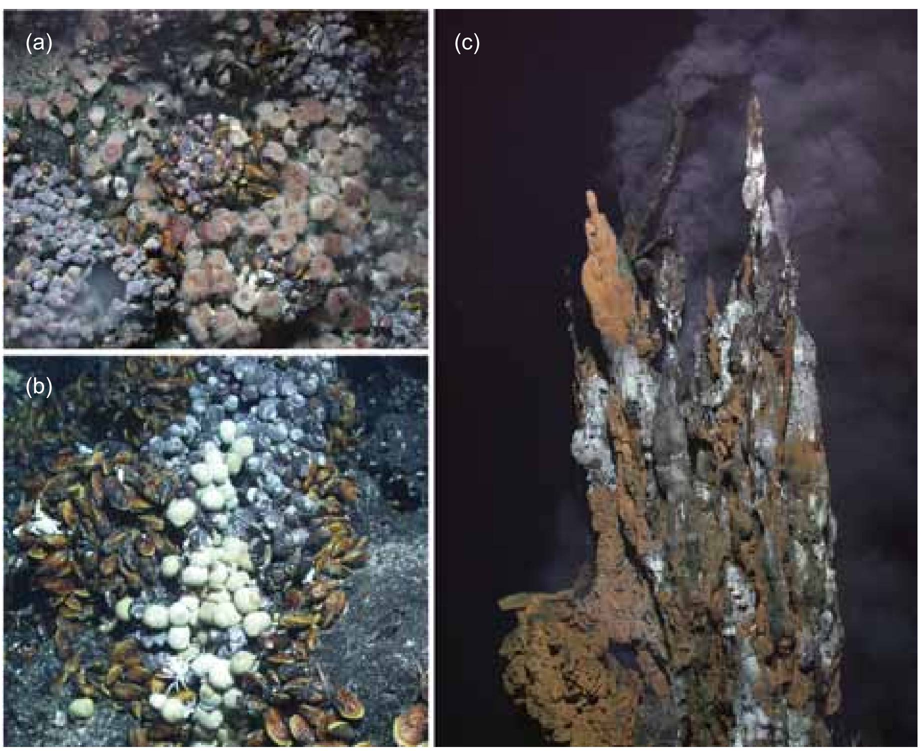

Figure 6. (a) Anemones are common and often quite dense on the pillow basalts of the northernmost vent fields along the Eastern Lau Spreading Center. The anemones reside in close proximity to vent flows where they can access higher prey densities supported by enhanced local primary production. (b) A canonical "bull's-eye" assemblage of *Alviniconcha* spp. snails shown in the middle, surrounded by *Ifremeria nautilei* snails and *Bathymodiolus brevior* mussels. *Alviniconcha* spp. occupy the region of greatest exposure to vent fluid. (c) Mariner field vents exhibit ample fluid flow but do not host any of the chemoautotrophic symbioses commonly found within the Eastern Lau Spreading Center/Valu Fa Ridge, likely due to substantial differences in vent fluid geochemistry (see http://media.marine-geo.org/video/hydrothermal-vent-mariner-vent-field-2009). Widths of images are (a) ~ 1.3 m, (b) ~ 60 cm, and (c) ~ 1 m.

In the Lau Basin, the differing chemical composition of vent fluid (end-member and diffuse) may drive the distribution of closely related vent symbioses along the spreading axis. Preliminary data from a study of *Alviniconcha* snail symbioses suggest that four different *Alviniconcha* spp. host types are found in the Lau Basin, and they form specific associations with three phylotypes of proteobacterial endosymbionts. These distinct holobionts (symbiont + host) were found to distribute differentially along the spreading axis, varying in abundance from north to south (data of author Beinart). Though these preliminary data suggest that north-south geochemical differences may influence the distribution and abundance of these symbioses, ongoing studies are aimed at better understanding precisely which factors govern the observed distributions.

Vent fluid geochemistry also likely plays a primary role in the distinctive composition of the animal community at the Mariner vent field. Numerous reddish-brown black smoker chimneys populate this site, and it lacks the symbiotic mollusks that dominate the other sites (Figure 6c). Nevertheless, many of the nonsymbiotic vent fauna (shrimp, crabs, polynoids, and limpets) are found here, indicating local microbial primary productivity. The absence of the symbioses may be attributable to higher concentrations of heavy metals such as manganese and iron in the vent fluids (Hsu-Kim et al., 2008; Mottl et al., 2011; Yücel et al., 2011; see Figure 5), which bind to sulfide and might make it biologically inaccessible to the bacterial endosymbionts. To date, however, no studies have directly addressed why animal-microbial symbioses are absent from Mariner.

Characterizing Microbial Diversity Along the ELSC

Understanding the nature and extent of microbial diversity at hydrothermal vents has been a long-standing objective of microbiologists. Oceanic ridge systems, which are discontinuous seafloor features residing in a more contiguous ocean, provide an opportunity to examine how hydrological, geological, geochemical, and biological factors influence microbial ecology across spatial and temporal scales. The aforementioned gradients in geology and vent fluid composition along the ELSC/VFR provide a natural setting for microbial diversity and ecology studies.

Using high-throughput DNA sequencing approaches that provide both the depth and breadth needed to explore patterns of microbial diversity, some interesting insights are emerging concerning the microbial diversity of deposits along the ELSC/VFR. Most notably, the communities at Mariner are very different from others further north (Figure 7; Gilbert Flores, Portland State University, *pers. comm.*, July 14, 2011). Additionally, from studies in 2009, communities from Kilo Moana deposits appear to be more different from those at TowCam, Tahi Moana 1, ABE, and Tu'i Malila, with communities at ABE and Tahi Moana 1 being most similar to each other (Figure 7; Flores, *pers. comm.*). These trends were apparent by taxa level associations (e.g., among the *Epsilonproteobacteria*) and sequence-level discrimination (operational taxonomic units) for both Archaea and Bacteria. Of interest is that these trends mirror the extent to which fluid compositions differ among the vent sites, with Mariner exhibiting the greatest differences in vent fluid pH, and Fe, CO_2, and H_2S concentrations, followed by Kilo Moana, with ABE and Tu'i Malila exhibiting greatest similarity (Figure 5; Mottl et al., 2011; Yücel et al., 2011). However, because of a relatively small set of vent deposits analyzed from Kilo Moana

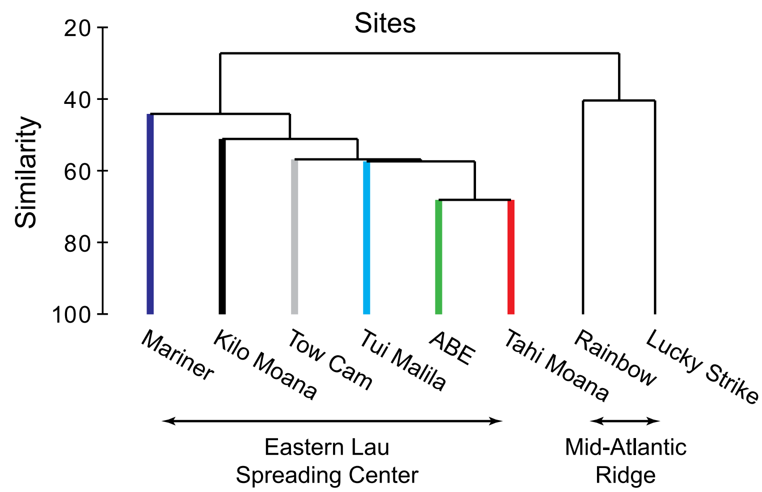

Figure 7. Relationships of the bacterial communities associated with vent deposits sampled in 2009 from the different vent sites along the Eastern Lau Spreading Center/Valu Fa Ridge (ELSC/VFR) and from Mid-Atlantic Ridge sites (branches nearer to each other are more closely related). The 16S rRNA gene pyrotagged sequence diversity of multiple samples collected from each vent field was combined to reflect the overall diversity of each vent field. Cluster analysis was done using the Bray Curtis similarity index using Primer-6 software package. Note that Mariner bacterial communities are more different in composition from all other sites, while communities from ABE and Tahi Moana 1 cluster together. Furthermore, ELSC/VFR sites are more similar to each other than to Mid-Atlantic Ridge sites (Lucky Strike and Rainbow), providing evidence for an emerging biogeography of bacterial communities associated with hydrothermal deposits. These similarities among ELSC/VFR communities mirror relative similarities in pH, Fe, H_2S, and CO_2 for fluids sampled in 2005 (Figure 5; Mottl et al., 2011). Compositions of vent fluids sampled in 2009 are similar to those sampled in 2005 with some exceptions at the Kilo Moana and Mariner vent fields. In 2009, H_2S concentrations at some vents at Mariner exceeded measured values in 2005 samples, and Fe and H_2S concentrations at Kilo Moana were significantly lower than measured values in 2005, with H_2S concentrations similar to those at TowCam vent field (in both 2005 and 2009), but with Fe concentrations still slightly higher at Kilo Moana than at TowCam vent field (Jeffrey Seewald, Woods Hole Oceanographic Institution and Geoffrey Wheat, University of Alaska Fairbanks, *pers. comm.*, January 5, 2012).

(four samples) and Tu'i Malila (three samples), these observations should be considered as preliminary, while those from Mariner, ABE, and Tahi Moana 1 are statistically robust.

Like at other vents sites worldwide, the *Epsilonproteobacteria* dominate the microbial communities associated with vent deposits along the ELSC/VFR. In sampled deposits, *Camnibacter* spp. were more prevalent at Mid-Atlantic Ridge vents (Flores et al., 2011), with the diversity of *Epsilonproteobacteria* very different along the ELSC/VFR. Members of the *Lebidomonas* (moderate acidophiles) were more prevalent at all ELSC/VFR vent fields, with a shift at Mariner (Flores, *pers. comm.*) to the anaerobic Nautiliales (represented by *Nautilia*) that also drives the notable differences between Mariner and the other vent sites along the ELSC/VFR (Figure 7).

In addition to the composition of the *Epsilonproteobacteria*, the archaeal composition differed between deposits from Mariner and the other ELSC/VFR sites (Flores, *pers. comm.*). All sites, except Mariner, exhibit a rich diversity of Crenarchaeaota, with the prevalence of members of the hyperthermophilic Desulfurococcaceae (*Aeropyrum*-related) and Thermofilaceae. It is notable that *Thermofilum*-type archaea have rarely been isolated and are only sometimes viewed in enrichments (personal observation of author Reysenbach). In contrast, Thermococcales dominate the archaeal communities of many of the deposits at Mariner (Takai et al., 2008; Flores, *pers. comm.*). This observation is interesting because cultivated Thermococcales are generally hyperthermophilic heterotrophs that use a wide range of complex organic compounds. The Mariner Thermococcales may be carboxydotrophs by capitalizing on the high CO_2 (and CO) by CO-oxidation (see Figure 5), as has been reported for a close relative isolated from the PACMANUS vent field in the western Pacific (Lee et al., 2008). Furthermore, numerous sequences never previously obtained from deep-sea vents have been found in Mariner vent deposit samples. These sequences are all affiliated with extremely acidophilic microbes associated with terrestrial solfataras (Reysenbach et al., 2006).

The ELSC/VFR vent fields have also been a hotbed for novel cultivated thermophiles. Isolates from Mariner provided the first glimpse of the physiology of the deep-sea vent endemic taxonomic clade "DHVE2" (Reysenbach et al., 2006), now named *Aciduliprofundum boonei*. This organism was the first thermoacidophile detected from deep-sea vents, and its genome has been sequenced (Reysenbach and Flores, 2008) and completed (NCBI # NC_013926). Additional members of the "Aciduloprofundales" have been isolated from vents along the East Pacific Rise and Mid-Atlantic Ridge (Flores et al., in press). Furthermore, other new thermoacidophiles isolated from the ELSC/VFR vents are members of the *Deltaproteobacteria*, the first members of *Hippea* from deep-sea vents (Flores et al., 2011) and the first thermoacidophilic *Hippea* species. Among the other novel genera isolated from ELSC/VFR vent deposits are *Thermosulfurimonas dismutans*, a thermophilic sulfur-disproportionating bacterium from Mariner, and *Deferrisoma camini*, a moderately thermophilic dissimilatory Fe(III)-reducer from ABE (Slobodkin et al., 2011; Slobodkina et al., 2011).

SUMMARY AND CONCLUDING REMARKS

Water enables Earth's surface to support life and enhances the convective vigor of Earth's interior, supporting and perhaps enabling plate tectonics. The study of the ELSC/VFR also shows the importance of water to the operation of the ridge system, from mantle to microbe to megafauna. Because of the location of the spreading center above a subduction zone, the underlying mantle receives an increased flux of water and other elements transported from the subducting slab (Figure 1). In turn, water lowers the mantle melting temperature and leads to greater melt production where the water flux is greater. Higher water content in the mantle source region is coupled with increased concentrations of other elements such as K, Ba, and Pb, influencing the chemical composition of hydrothermal fluids and the mineralogy of hydrothermal deposits.

Because the influence of the subducting slab increases from north to south, there are corresponding increases in water and other slab-derived elements in the mantle source region that are reflected by physical changes in the crustal properties along the spreading axis. Additionally, the dynamic effect of the slab in the mantle may also be important in enhancing magma production, as numerical geodynamic models suggest that there may be greater upwelling leading to decompression melting with faster subduction (Harmon and Blackman, 2010). The enhanced magmatism at the southern end of the ELSC/VFR leads to thicker crust and a domed ridge axis, in contrast with the rifted ridge of the northern ELSC. Higher water in the magma leads to crystallization trends that make the crust richer in silica. The water also exsolves and creates bubbles in the magma as it ascends through the crust. Vapor bubbles may promote greater porosity and influence fluid flow in the crust, and also influence the crustal density and physical properties. It is hypothesized that these physical changes may influence the extent of very shallow dispersed versus focused fluid flow, creating different habitats for biological communities.

The north-south differences in mantle-source water and elemental content also manifest in a regional-scale gradient in vent fluid geochemistry, which is relevant to the biological communities found along the spreading axis. Concentrations of mobile trace elements in the vent fluids (e.g., Ba, Pb) increase from Kilo Moana southward to the Mariner vent field, consistent with a higher abundance of these elements in more slab-influenced felsic rocks. Where water is highest and the effects on differentiation most extreme, the exsolved magmatic H_2O, CO_2, and SO_2 may, as in the Mariner vent field, rise and join with circulating hydrothermal fluids and profoundly change the chemistry of vent fluids in ways that never happen on mid-ocean ridges. The resulting more acid fluids can react with the underlying rocks and dissolve more transition metals. These chemical differences can result in striking geochemical differences for fauna, as observed at the Mariner vent field (Takai et al., 2008).

In total, the Lau ISS's distinctive regional-scale gradients in physical and chemical properties have revealed exciting linkages between subsurface processes and deep-sea biological processes, and they underscore the degree to which subsurface physical and chemical phenomena can drive biological processes. Indeed, the influence of the subducting slab is transmitted from the mantle to the seafloor, profoundly affecting the hydrothermal vent ecosystems in this region. Gradients in the composition of the hydrothermal fluids, mineral components, and structure of vent deposits result in different habitats for biological organisms at a regional scale. At the Lau ISS, Ridge 2000 studies have documented that mantle-derived processes clearly shape both microbial and animal biological communities. The totality of studies carried out at the Lau ISS, which traverse ocean sciences disciplines, further demonstrates the causal links that operate at spreading ridges, and that extend from the mantle to microbes at the seafloor.

ACKNOWLEDGEMENTS

We gratefully acknowledge the collaborations of our sea-going and laboratory-based colleagues, ship's officers and crewmembers, and deep submergence vehicles' crewmembers that were critical to the success of Ridge 2000 studies at the Lau ISS. We also thank the Kingdom of Tonga for allowing us to carry out studies within its Exclusive Economic Zone. The final manuscript benefited greatly from the exceptionally quick turnaround reviews and constructive comments of Dan Fornari, Jim Holden, George Luther, Lauren Mullineaux, Ken Rubin, Maya Tolstoy, and an anonymous reviewer. Additional input was kindly provided by Stace Beaulieu and Ed Baker. Margaret Sulanowska is thanked for help with drafting figures. Support was provided by National Science Foundation grants OCE-1038135 to MKT, OCE-0732369 and OCE-0240985 to CRF, OCE-0732369 and OCE-0838107 to PRG, OCE-0242618 to CHL, OCE-0242902 and OCE-0752256 to PJM, OCE-0728391 and OCE-0937404 to A-LR, and a GRFP to RB.

REFERENCES

Bachraty, C., P. Legendre, and D. Desbruyères. 2009. Biogeographic relationships among deep-sea hydrothermal vent faunas at global scale. *Deep Sea Research Part I* 56:1,371–1,378, http://dx.doi.org/10.1016/j.dsr.2009.01.009.

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. *Geochemistry Geophysics Geosystems* 11, Q08004, http://dx.doi.org/10.1029/2010GC003106.

Baker, E.T., J.A. Resing, S.L. Walker, F. Martinez, B. Taylor, and K. Nakamura. 2006. Abundant hydrothermal venting along melt-rich and melt-free ridge segments in the Lau back-arc basin. *Geophysical Research Letters* 33, L07308, http://dx.doi.org/10.1029/2005GL025283.

Bezos, A., S. Escrig, C.H. Langmuir, P.J. Michael, and P.D. Asimow. 2009. Origins of chemical diversity of back-arc basin basalts: A segment-scale study of the Eastern Lau Spreading Center. *Journal of Geophysical Research* 114, B06212, http://dx.doi.org/10.1029/2008JB005924.

Carlson, R.L., and C.N. Herrick. 1990. Densities and porosities in the oceanic crust and their variations with depth and age. *Journal of Geophysical Research* 95:9,153–9,170, http://dx.doi.org/10.1029/JB095iB06p09153.

Cavanaugh, C., Z. McKiness, I.L.G. Newton, and F.J. Stewart. 2006. Marine chemosynthetic symbioses. *The Prokaryotes* 1:475–507, http://dx.doi.org/10.1007/0-387-30741-9_18.

Conder, J.A., and D.A. Wiens. 2007. Rapid mantle flow beneath the Tonga volcanic arc. *Earth and Planetary Science Letters* 264:299–307, http://dx.doi.org/10.1016/j.epsl.2007.10.014.

Crawford, W.C., J.A. Hildebrand, L.M. Dorman, S.C. Webb, and D.A. Wiens. 2003. Tonga Ridge and Lau Basin crustal structure from seismic refraction data. *Journal of Geophysical Research* 108(B4), 2195, http://dx.doi.org/10.1029/2001JB001435.

Desbruyères, D., A.M. Alayse-Danet, S. Ohta, and the Scientific Parties of biolauand starmer Cruises. 1994. Deep-sea hydrothermal communities in southwestern Pacific back-arc basins (the North Fiji and Lau Basins): Composition, microdistribution and food web. *Marine Geology* 116:227–242, http://dx.doi.org/10.1016/0025-3227(94)90178-3.

Dubilier, N., C. Bergin, and C. Lott. 2008. Symbiotic diversity in marine animals: The art of harnessing chemosynthesis. *Nature Reviews Microbiology* 6(10):725–740, http://dx.doi.org/10.1038/nrmicro1992.

Dunn, R.A., and F. Martinez. 2011. Contrasting crustal production and rapid mantle transitions beneath back-arc ridges. *Nature* 469:198–202, http://dx.doi.org/10.1038/nature09690.

Escrig, S., A. Bezos, S.L. Goldstein, C.H. Langmuir, and P.J. Michael. 2009. Mantle source variations beneath the Eastern Lau Spreading Center and the nature of subduction components in the Lau Basin–Tonga arc system. *Geochemistry Geophysics Geosystems* 10, Q04014, http://dx.doi.org/10.1029/2008GC002281.

Ferrini, V.L., M.K. Tivey, S.M. Carbotte, F. Martinez, and C. Roman. 2008. Variable morphologic expression of volcanic, tectonic, and hydrothermal processes at six hydrothermal vent fields in the Lau back-arc basin. *Geochemistry Geophysics Geosystems* 9, Q07022, http://dx.doi.org/10.1029/2008GC002047.

Fisher, C.R., J.J. Childress, A.J. Arp, J.M. Brooks, D.L. Distel, J.A. Dugan, H. Felbeck, L.W. Fritz, R.R. Hessler, K.S. Johnson, and others. 1988b. Variation in the hydrothermal vent clam *Calyptogen magnifica* at the Rose Garden vent on the Galapagos spreading center. *Deep Sea Research Part I* 35:1,811–1,831, http://dx.doi.org/10.1016/0198-0149(88)90051-9.

Fisher, C.R., J.J. Childress, A.J. Arp, J.M. Brooks, D. Distel, J.A. Favuzzi, H. Felbeck, R. Hessler, K.S. Johnson, M.C. Kennicutt II, and others. 1988a. Microhabitat variation in the hydrothermal vent mussel *Bathymodiolus thermophilus* at the Rose Garden vent on the Galapagos Rift. *Deep Sea Research Part I* 35:1,769–1,791, http://dx.doi.org/10.1016/0198-0149(88)90049-0.

Fisher, C.R., K. Takai, and N. Le Bris. 2007. Hydrothermal vent ecosystems. *Oceanography* 20(1):14–23, http://dx.doi.org/10.5670/oceanog.2007.75.

Flores, G.E., R.C. Hunter, Y. Liu, A. Mets., S. Schouten, and A.-L. Reysenbach. 2011. *Hippea jasoniae* sp. nov. and *Hippea alviniae* sp. nov., thermoacidophilic *Deltaproteobacteria* isolated from deep-sea hydrothermal vent deposits. *International Journal of Systematic and Evolutionary Microbiology,* http://dx.doi.org/10.1099/ijs.0.033001-0.

Flores, G.E., I.D. Wagner, Y. Liu, and A.-L. Reysenbach. In Press. Distribution, abundance, and diversity patterns of the thermoacidophilic "Deep-sea Hydrothermal Vent Euryarchaeota 2" (DHVE2). *Frontiers in Extreme Microbiology*.

Fornari, D.J., K.L. Von Damm, J.G. Bryce, J.P. Cowen, V. Ferrini, A. Fundis, M.D. Lilley, G.W. Luther III, L.S. Mullineaux, M.R. Perfit, and others. 2012. The East Pacific Rise between 9°N and 10°N: Twenty-five years of integrated, multidisciplinary oceanic spreading center studies. *Oceanography* 25(1):18–43, http://dx.doi.org/10.5670/oceanog.2012.02.

Fornari, D.J., and the WHOI TowCam Group. 2003. A new deep-sea towed digital camera and multi-rock coring system. *Eos, Transactions American Geophysical Union* 84(8):69, http://dx.doi.org/10.1029/2003EO080001.

Fouquet, Y., U. Von Stackelberg, J.L. Charlou, J.P. Donval, J. Erzinger, J.P. Foucher, P. Herzig, R. Mühe, S. Soakai, M. Wiedicke, and H. Whitechurch. 1991. Hydrothermal activity and metallogenesis in the Lau back-arc basin. *Nature* 349:778–781, http://dx.doi.org/10.1038/349778a0.

Fouquet, Y., U. von Stackelberg, J.L. Charlou, J. Erzinger, P.M. Herzig, R. Muhe, and M. Wiedicke. 1993. Metallogenesis in back-arc environments: The Lau Basin example. *Economic Geology* 88:2,154–2,181, http://dx.doi.org/10.2113/gsecongeo.88.8.2154.

Gartman, A., M. Yücel, A.S. Madison, D.W. Chu, S. Ma, C.P. Janzen, E.L. Becker, R.A. Beinart, P.R. Girguis, and G.W. Luther III. 2011. Sulfide oxidation across diffuse flow zones of hydrothermal vents. *Aquatic Geochemistry* 17:583–601, http://dx.doi.org/10.1007/s10498-011-9136-1.

German, C.R., D.R. Yoerger, M. Jakuba, T.M. Shank, C.H. Langmuir, and K. Nakamura. 2008. Hydrothermal exploration with the *Autonomous Benthic Explorer*. *Deep-Sea Research Part I* 55:203–219, http://dx.doi.org/10.1016/j.dsr.2007.11.004.

Glazer, B.T., and O.J. Rouxel. 2009. Redox speciation and distribution within diverse iron-dominated microbial habitats at Loihi Seamount. *Journal of Geomicrobiology* 26:606–622, http://dx.doi.org/10.1080/01490450903263392.

Hannington, M.D., C.E.J. de Ronde, and S. Petersen. 2005. Sea-floor tectonics and submarine hydrothermal systems. Pp. 111–141 in *100th Anniversary Volume of Economic Geology*. J. Hedenquist, J.F.H. Thompson, R.J. Goldfarb, and J.P. Richards, eds, Society of Economic Geologists, Littleton, CO.

Harding, A.J., G.M. Kent, and J.A. Collins. 2000. Initial results from a multichannel seismic survey of the Lau back-arc basin. *Eos, Transactions, American Geophysical Union* 81:Fall meeting supplement Abstract T61C-16.

Harmon, N., and D.K. Blackman. 2010. Effects of plate boundary geometry and kinematics on mantle melting beneath the back-arc spreading centers along the Lau Basin. *Earth and Planetary Science Letters* 298:334–346, http://dx.doi.org/10.1016/j.epsl.2010.08.004.

Henry, M.S., J.J. Childress, and D. Figueroa. 2008. Metabolic rates and thermal tolerances of chemoautotrophic symbioses from Lau Basin hydrothermal vents and their implications for species distributions. *Deep-Sea Research Part A* 55:679–695, http://dx.doi.org/10.1016/j.dsr.2008.02.001.

Hsu-Kim, H., K.M. Mullaugh, J.J. Tsang, M. Yücel, and G.W. Luther III. 2008. Formation of Zn- and e-sulfides near hydrothermal vents at the Eastern Lau Spreading Center: Implications for sulfide bioavailability to chemoautotrophs. *Geochemical Transactions* 9:6, http://dx.doi.org/10.1186/1467-4866-9-6.

Ishibashi, J., J.E. Lupton, T. Yamaguchi, J. Querellou, T. Nunoura, and K. Takai. 2006. Expedition reveals changes in Lau Basin hydrothermal system. *Eos, Transactions, American Geophysical Union* 87(2):13, http://dx.doi.org/10.1029/2006EO020001.

Jacobs, A.M., A.J. Harding, and G.M. Kent. 2007. Axial crustal structure of the Lau back-arc basin from velocity modeling of multichannel seismic data. *Earth and Planetary Science Letters* 259:239–255, http://dx.doi.org/10.1016/j.epsl.2007.04.021.

Kelley, D.S., S.M. Carbotte, D.W. Caress, D.A. Clague, J.R. Delaney, J.B. Gill, H. Hadaway, J.F. Holden, E.E.E. Hooft, J.P. Kellogg, and others. 2012. Endeavour Segment of the Juan de Fuca Ridge: One of the most remarkable places on Earth. *Oceanography* 25(1):44–61, http://dx.doi.org/10.5670/oceanog.2012.03.

Kessel, R., M.W. Schmidt, P. Ulmer, and T. Pettke. 2005. Trace element signature of subduction-zone fluids, melts and supercritical liquids at 120–180 km depth. *Nature* 437:724–727, http://dx.doi.org/10.1038/nature03971.

Kristall, B., D.S. Kelley, M.D. Hannington, and J.R. Delaney. 2006. Growth history of a diffusely venting sulfide structure from the Juan de Fuca Ridge: A petrological and geochemical study. *Geochemistry Geophysics Geosystems* 7, Q07001, http://dx.doi.org/10.1029/2005GC001166.

Langmuir, C.H., A. Bezos, S. Escrig, and S.W. Parman. 2006. Chemical systematics and hydrous melting of the mantle in back-arc basins. Pp. 87–146 in *Back-Arc Spreading Systems: Geological, Biological, Chemical, and Physical Interactions*. D.M. Christie, C.R. Fisher, S.-M. Lee, and S. Givens, eds, Geophysical Monograph Series, vol. 166, American Geophysical Union, Washington, DC.

Langmuir, C., S. Humphris, D. Fornari, C. Van Dover, K. Von Damm, M.K. Tivey, D. Colodner, J.-L. Charlou, D. Desonie, C. Wilson, and others. 1997. Hydrothermal vents near a mantle hot spot: The Lucky Strike vent field at 37°N on the Mid-Atlantic Ridge. *Earth and Planetary Science Letters* 148:69–91, http://dx.doi.org/10.1016/S0012-821X(97)00027-7.

Lau Workshop Report. 2006. *Ridge 2000 Workshop Report: Lau Integrated Studies Site Focus Workshop*. Available online at: http://www.ridge2000.org/science/meetings/index.php (accessed January 12, 2012).

Le Bris, N., B. Govenar, C. Le Gall, and C.R. Fisher. 2006. Variability of physico-chemical conditions in 9°50'N EPR diffuse flow vent habitats. *Marine Chemistry* 98:167–182, http://dx.doi.org/10.1016/j.marchem.2005.08.008.

Lee, H.S., S.G. Kang, S.S. Bae, J.K. Lim, Y. Cho, Y.J. Kim, J.H. Jeon, S.S. Cha, K.K. Kwon, H.T. Kim, and others. 2008. The complete genome sequence of *Thermococcus onnurineus* NA1 reveals a mixed heterotrophic and carboxydotrophic metabolism. *Journal of Bacteriology* 190:7,491–7,499, http://dx.doi.org/10.1128/JB.00746-08.

Luther, G.W. III, A. Gartman, M. Yücel, A.S. Madison, T.S. Moore, H.A. Nees, D.B. Nuzzio, A. Sen, R.A. Lutz, T.M. Shank, and C.R. Fisher. 2012. Chemistry, temperature, and faunal distributions at diffuse-flow hydrothermal vents: Comparison of two geologically distinct ridge systems. *Oceanography* 25(1):234–245, http://dx.doi.org/10.5670/oceanog.2012.22.

Luther, G.W. III, T.F. Rozan, M. Taillefert, D.B. Nuzzio, C. Di Meo, T.M. Shank, R.A. Lutz, and S.C. Cary. 2001. Chemical speciation drives hydrothermal vent ecology. *Nature* 410:813, http://dx.doi.org/10.1038/35071069.

Martinez, F., K. Okino, Y. Ohara, A.-L. Reysenbach, and S.K. Goffredi. 2007. Back-arc basins. *Oceanography* 20(1):116–127, http://dx.doi.org/10.5670/oceanog.2007.85.

Martinez, F., B. Taylor, E.T. Baker, J.A. Resing, and S.L. Walker. 2006. Opposing trends in crustal thickness and spreading rate along the back-arc Eastern Lau Spreading Center: Implications for controls on ridge morphology, faulting, and hydrothermal activity. *Earth and Planetary Science Letters* 245:655–672, http://dx.doi.org/10.1016/j.epsl.2006.03.049.

Moore, J.G., J.N. Batchelder, and C.G. Cunningham. 1977. CO_2-filled vesicles in mid-ocean basalt. *Journal of Volcanology and Geothermal Research* 2:309–327, http://dx.doi.org/10.1016/0377-0273(77)90018-X.

Moore, T.S., T.M. Shank, D.B. Nuzzio, and G.W. Luther III. 2009. Time-series chemical and temperature habitat characterization of diffuse flow hydrothermal sites at 9°50'N East Pacific Rise. *Deep Sea Research Part II* 56:1,616–1,621, http://dx.doi.org/10.1016/j.dsr2.2009.05.008.

Mottl, M.J., J.S. Seewald, C.G. Wheat, M.K. Tivey, P.J. Michael, G. Proskurowski, T.M. McCollom, E. Reeves, J. Sharkey, C.F. You, and others. 2011. Chemistry of hot springs along the Eastern Lau Spreading Center. *Geochimica et Cosmochimica Acta* 75:1,013–1,038, http://dx.doi.org/10.1016/j.gca.2010.12.008.

Pearce, J.A., R.J. Stern, S.H. Bloomer, and P. Fryer. 2005. Geochemical mapping of the Mariana arc-basin system: Implications for the nature and distribution of subduction components. *Geochemistry Geophysics Geosystems* 6, Q07006, http://dx.doi.org/10.1029/2004GC000895.

Peate, D.W., T.F. Kokfelt, C.J. Hawkesworth, P.W. VanCalsteren, J.M. Hergt, and J.A. Pearce. 2001. U-series isotope data on Lau Basin glasses: The role of subduction-related fluids during melt generation in back-arc basins. *Journal of Petrology* 42:1,449–1,470, http://dx.doi.org/10.1093/petrology/42.8.1449.

Podowski, E.L., S. Ma, G.W. Luther III, D. Wardrop, and C.R. Fisher. 2010. Biotic and abiotic factors affecting distributions of megafauna in diffuse flow on andesite and basalt along the Eastern Lau Spreading Center, Tonga. *Marine Ecology Progress Series* 418:25–45, http://dx.doi.org/10.3354/meps08797.

Podowski, E.L., T.S. Moore, K.A. Zelnio, G.W. Luther III, and C.R. Fisher. 2009. Distribution of diffuse flow megafauna in two sites on the Eastern Lau Spreading Center, Tonga. *Deep-Sea Research Part I* 56:2,041–2,056, http://dx.doi.org/10.1016/j.dsr.2009.07.002.

Ramirez-Llodra, E., T.M. Shank, and C.R. German. 2007. Biodiversity and biogeography of hydrothermal vent species: Thirty years of discovery and investigations. *Oceanography* 20(1):30–41, http://dx.doi.org/10.5670/oceanog.2007.78.

Reysenbach, A.-L., and G.E. Flores. 2008. Electron microscopy encounters with unusual thermophiles helps direct genomic analysis of *Aciduliprofundum boonei*. *Geobiology* 6:331–336, http://dx.doi.org/10.1111/j.1472-4669.2008.00152.x.

Reysenbach, A.-L., Y. Liu, A.B. Banta, T.J. Beveridge, J.D. Kirshtein, S. Schouten, M.K. Tivey, K.L. Von Damm, and M.A. Voytek. 2006. A ubiquitous thermoacidophilic archaeon from deep-sea hydrothermal vents. *Nature* 442:444–447, http://dx.doi.org/10.1038/nature04921.

Ryan, W.B.F., S.M. Carbotte, J.O. Coplan, S. O'Hara, A. Melkonian, R. Arko, R.A. Weissel, V. Ferrini, A. Goodwillie, F. Nitsche, and others. 2009. Global multi-resolution topography synthesis. *Geochemistry Geophysics Geosystems* 10, Q03014, http://dx.doi.org/10.1029/2008GC002332.

Shank, T.M., D.J. Fornari, K.L. Von Damm, M.D. Lilley, R.M. Haymon, and R.A. Lutz. 1998. Temporal and spatial patterns of biological community development at nascent deep-sea hydrothermal vents (9°50'N, East Pacific Rise). *Deep Sea Research Part II* 45:465–515, http://dx.doi.org/10.1016/S0967-0645(97)00089-1.

Slobodkin, A.I., A.-L. Reysenbach, G.A. Slobodkina, R.V. Baslerov, N. Kostrikina, I. Wagner, E. Bonch-Osmolovskaya. 2011. *Thermosulfurimonas dismutans* gen. nov., sp. nov. a novel extremely thermophilic sulfur-disproportionating bacterium from a deep-sea hydrothermal vent. *International Journal of Systematic and Evolutionary Microbiology,* http://dx.doi.org/10.1099/ijs.0.034397-0.

Slobodkina, G.B., A.-L. Reysenbach, A. Panteleeva, N. Kostrikina, I. Wagner, E. Bonch-Osmolovskaya, and A.I. Slobodkin. 2011. *Deferrisoma camini* gen. nov., sp. nov. a novel moderately thermophilic dissimilatory Fe(III)-reducing bacterium from a deep-sea hydrothermal vent that forms a distinct phylogenetic branch in *Deltaproteobacteria*. *International Journal of Systematic and Evolutionary Microbiology,* http://dx.doi.org/10.1099/ijs.0.038372-0.

Smith, G.P., D.A. Wiens, K.M. Foscher, L.M. Dorman, S.C. Webb, and J.A. Hildebrand. 2001. A complex pattern of mantle flow in the Lau backarc. *Science* 292:713–716. http://dx.doi.org/10.1126/science.1058763.

Speer, K., and A.M. Thurnherr. 2012. The Lau Basin Float Experiment (LAUB-FLEX). *Oceanography* 25(1):284–285, http://dx.doi.org/10.5670/oceanog.2012.27.

SRK Consulting Report for Nautilus Minerals. 2008. *2008 Exploration Program Papua New Guinea, Tonga, Fiji, Solomons Islands and New Zealand, Nautilus Minerals Inc.* Available online at: http://www.nautilusminerals.com/i/pdf/2008NautilusExplorationNI43-101Report.pdf (accessed January 12, 2012).

Stolper, E., and S. Newman. 1994. The role of water in the petrogenesis of Mariana Trough magmas. *Earth and Planetary Science Letters* 121:293–325, http://dx.doi.org/10.1016/0012-821X(94)90074-4.

Takai, K., T. Nunoura, J.-I. Ishibashi, J. Lupton, R. Suzuki, H. Hamasaki, Y. Ueno, S. Kawagucci, T. Gamo, Y. Suzuki, and others. 2008. Variability in the microbial communities and hydrothermal fluid chemistry at the newly discovered Mariner hydrothermal field, southern Lau Basin. *Journal of Geophysical Research* 113, G02031, http://dx.doi.org/10.1029/2007JG000636.

Tivey, M.K., P. Craddock, J. Seewald, V. Ferrini, S. Kim, M. Mottl, A. Sterling, A.-L. Reysenbach, C.G. Wheat, and the Scientific Party of TUIM05MV. 2005. Characterization of six vent fields within the Lau Basin. *Eos, Transactions, American Geophysical Union* 86(52):Fall Meeting Supplement Abstract T31A-0477.

Tivey, M.K., and J.R. Delaney. 1986. Growth of large sulfide structures on the Endeavour Segment of the Juan de Fuca Ridge. *Earth and Planetary Science Letters* 77:303–317, http://dx.doi.org/10.1016/0012-821X(86)90142-1.

Tivey, M.K., D.S. Stakes, T.L. Cook, M.D. Hannington, and S. Petersen. 1999. A model for growth of steep-sided vent structures on the Endeavour Segment of the Juan de Fuca Ridge: Results of a petrologic and geochemical study. *Journal of Geophysical Research* 104:22,859–22,883, http://dx.doi.org/10.1029/1999JB900107.

Turner, I.M., C. Peirce, and M.C. Sinha. 1999. Seismic imaging of the axial region of the Valu Fa Ridge, Lau Basin: The accretionary processes of an intermediate back-arc spreading ridge. *Geophysical Journal International* 138:495–519, http://dx.doi.org/10.1046/j.1365-246X.1999.00883.x.

Waite, T.J., T.S. Moore, J.J. Childress, H. Hsu-Kim, K.M. Mullaugh, D.B. Nuzzio, A.N. Paschal, J. Tsang, C.R. Fishers, and G.W. Luther III. 2008. Variation in sulfur speciation with shellfish presence at a Lau Basin diffuse flow vent site. *Journal of Shellfish Research* 27:163–168, http://dx.doi.org/10.2983/0730-8000(2008)27[163:VISSWS]2.0.CO;2.

Yücel, M., A. Gartman, C.S. Chan, and G.W. Luther III. 2011. Hydrothermal vents as a kinetically stable source of iron-sulphide-bearing nanoparticles to the ocean. *Nature Geoscience* 4:367–371, http://dx.doi.org/10.1038/NGEO1148.

Zhou, H., J. Li, and Q. Yang. 2008. Microbiological oxidation of sulfide chimney promoted by warm diffusing flow in CDE hydrothermal field in Eastern Lau Spreading Center. *Eos, Transactions, American Geophysical Union* 89(48):Fall Meeting Supplement Abstract B51D-0405.