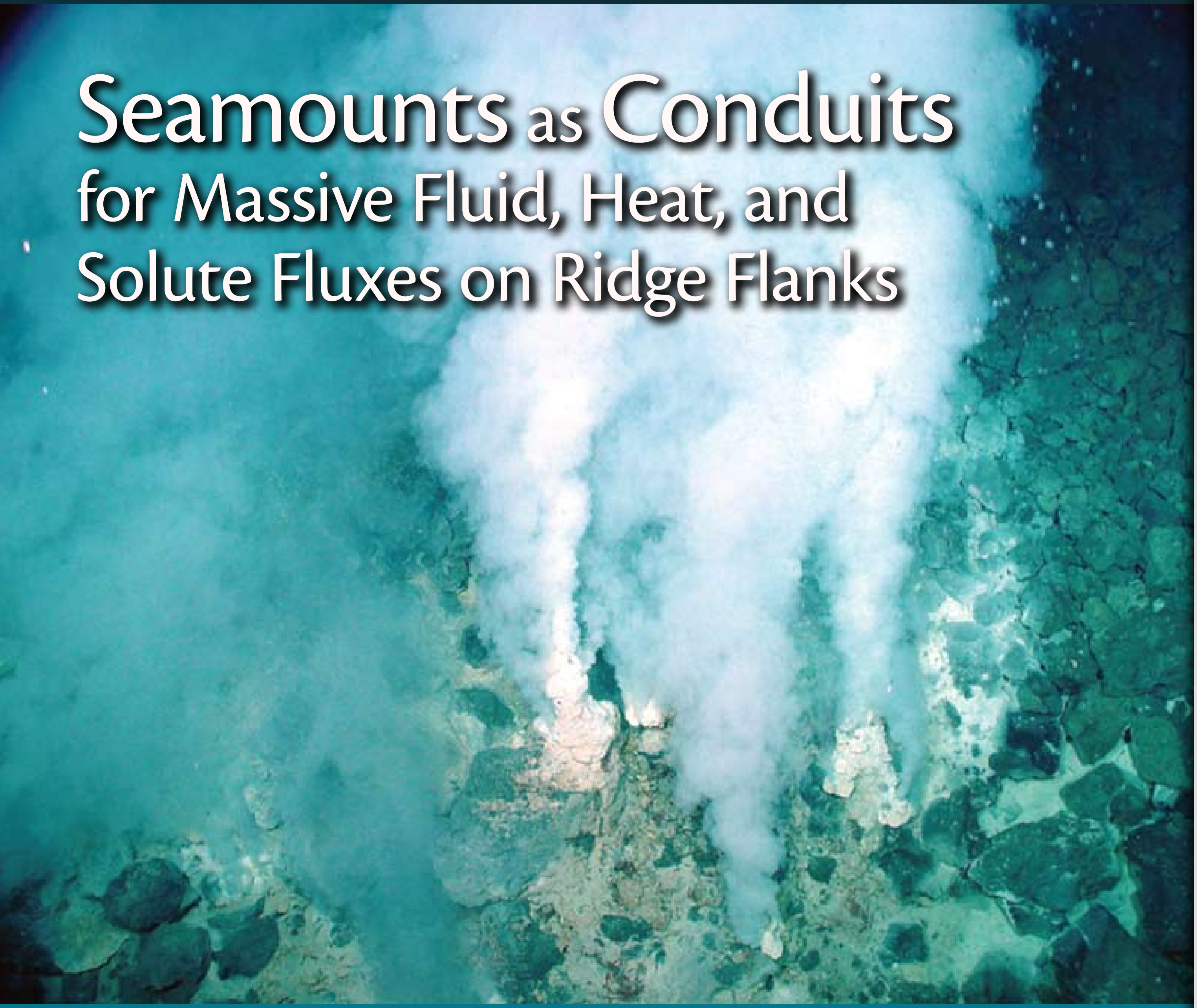
BY ANDREW T. FISHER AND C. GEOFFREY WHEAT

Seamounts as Conduits for Massive Fluid, Heat, and Solute Fluxes on Ridge Flanks



NW Eifuku Volcano, Champagne vent. The white-smoker chimneys are ~ 20-cm across and ~ 50-cm high, and venting fluids measure 103°C. White flocculent mats and elemental sulfur coatings surround the chimneys, and liquid CO_2 droplets rise from the seafloor. *From Embley et al., 2007*

ABSTRACT. Seamounts play a fundamental role in facilitating the exchange of fluids, heat, and solutes between the oceanic lithosphere and the overlying ocean. Global heat flow compilations indicate that much of the seafloor loses a significant fraction of lithospheric heat because of fluid flow from the crust, and most of this advective heat loss occurs on ridge flanks, areas far from the thermal influence of magmatic emplacement at seafloor spreading centers. The driving forces available to move fluid between the crust and ocean are modest, and most of the seafloor is blanketed by low-permeability sediment that prevents vertical fluid flow at thermally significant rates. Thus, most of the thermally important fluid exchange between the crust and ocean must occur where volcanic rocks are exposed at the seafloor; little fluid exchange on ridge flanks occurs through seafloor sediments overlying volcanic crustal rocks. Seamounts and other basement outcrops focus ridge-flank hydrothermal exchange between the crust and the ocean. We describe the driving forces responsible for hydrothermal flows on ridge flanks, and the impacts that these systems have on crustal heat loss, fluid composition, and subseafloor microbiology. We show data collected from two ridge-flank areas that illustrate how the extent of fluid exchange, lithospheric heat loss, and chemical reaction and transport depend on the rate of fluid flow, fluid residence time, and temperature in crustal hydrologic systems. Seamounts are ideal places to sample crustal fluids as they exit the crust and enter the ocean, to determine their chemical and microbial characteristics, and to assess the importance of this global hydrogeologic system on the evolution of Earth's lithosphere, ocean, and biosphere.

INTRODUCTION

Oceanic heat flow is generally highest close to mid-ocean ridge spreading centers and decreases as the lithosphere ages. This broad pattern is a natural consequence of lithospheric cooling, as predicted by conductive models based on plate thickness, basal temperature, thermal conductivity, and heat capacity (e.g., Davis and Lister, 1974; Parsons and Sclater, 1977). Seafloor heat flow is also highly variable near spreading centers, where sediment cover is thin or patchy and volcanic rocks are exposed at the seafloor across large areas. Conductive seafloor heat flow through ridge flanks, areas far from the thermal influence of magmatic emplacement at seafloor spreading centers, tends to be less variable, particularly where sediment cover is more continuous.

Measurements of conductive heat flow typically fall below predictions of lithospheric cooling models until an average lithospheric age of ~ 65 Ma. This deviation from model predictions, and the variability of seafloor heat flow commonly observed on ridge flanks, is generally attributed to hydrothermal circulation. This circulation also contributes to geochemical reactions that facilitate the exchange of solutes between the crust and ocean, redistribute elements within the crust, and alter the physical state of plates as they age (e.g., Staudigel et al., 1981; Wilkens et al., 1991; Alt, 2004).

Earth's geothermal heat output is about 44 TW, with most heat loss occurring through ocean basins (e.g., Sclater et al., 1980; Pollack et al., 1993). Seafloor hydrothermal heat output is on the order of 10 TW, ~ 25% of Earth's total geothermal heat output, and ~ 30% of the oceanic lithospheric heat output (Figure 1A). Only a small fraction of this advective heat output occurs at high temperatures at mid-ocean ridges; the vast majority occurs at lower temperatures (generally 5–20°C) on ridge flanks, suggesting an associated fluid discharge of ~ 10^{16} kg yr^{-1} (Figure 1B) (C. Stein et al., 1995; Mottl, 2003; Wheat et al., 2003). This low-temperature flow rivals the discharge of all rivers to the ocean (4 x 10^{16} kg yr^{-1}), and is about three orders of magnitude greater than the sum of high-temperature hydrothermal discharges at mid-ocean ridges (~ 10^{13} kg yr^{-1}). Resulting ridge-flank chemical fluxes impact biogeochemical cycles for numerous solutes (e.g., Wheat et al., 2003), and may help to sustain vast subseafloor microbial ecosystems (Edwards et al., 2005; Huber et al., 2006). Unfortunately, there are few direct measurements of fluid fluxes and chemical compositions from typical ridge-flank hydrothermal systems. Instead, local and regional fluid and heat flows on ridge flanks have been calculated from seafloor heat flow deficits, and fluid composition has been inferred from pore fluid samples squeezed from sediments collected just above the basalt contact (e.g., Elderfield et al., 1999; Wheat and Mottl, 2004).

One reason for the lack of direct measurements and samples from typical ridge-flank hydrothermal systems is the difficulty in locating sites of low-temperature discharge. Vent fields on mid-ocean ridges are often located by detecting small thermal, chemical, and particle anomalies tens of meters above the seafloor (e.g., E. Baker and Massoth,

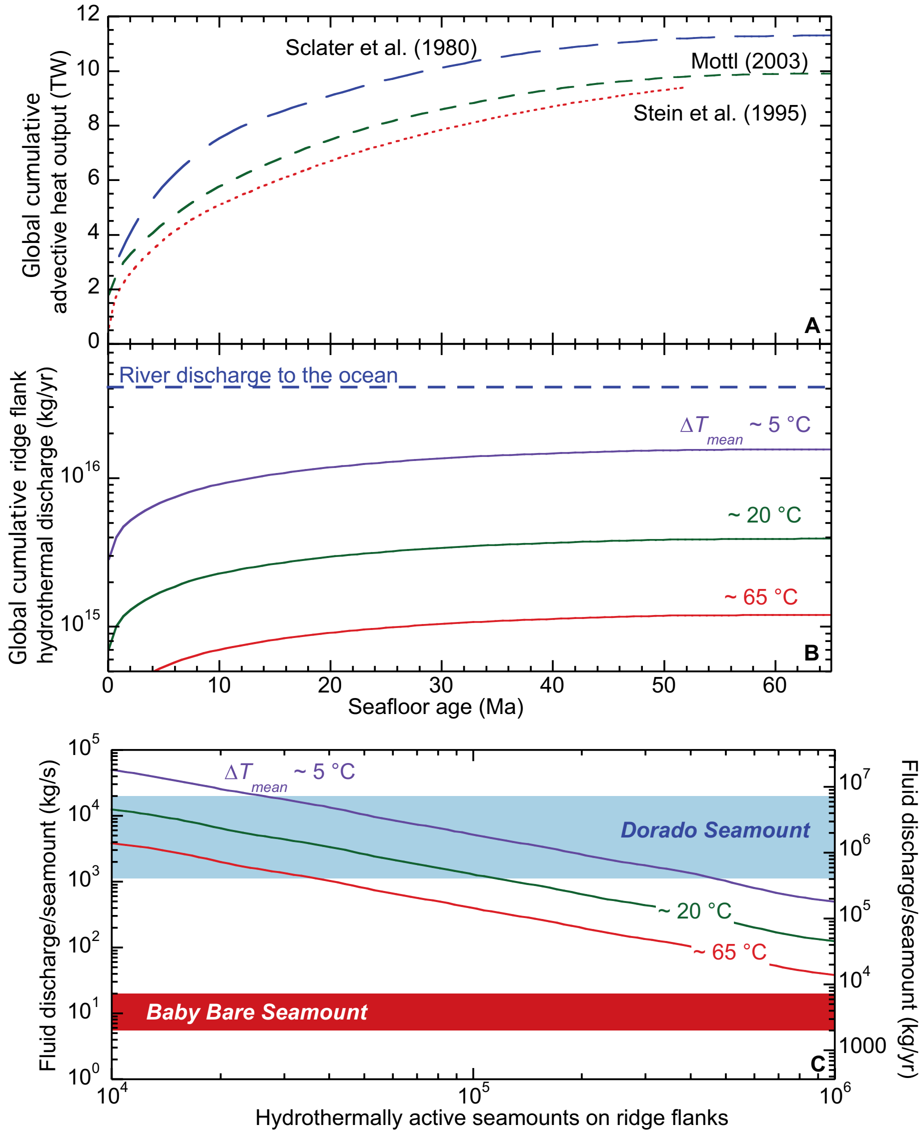


Figure 1. Calculated ridge-flank hydrothermal advective heat output, fluid discharge, and discharge per seamount. (A) Global cumulative advective heat output as a function of seafloor age (data from Mottl, 2003, and references therein). Red dotted line = C. Stein et al. (1995). Blue dashed line = Sclater et al. (1980). Green short dashed line = Mottl (2003). Most of this advective heat loss occurs on ridge flanks, areas far from the thermal influence of magmatic emplacement at seafloor spreading centers. (B) Global cumulative fluid discharge necessary to advect the amount of heat estimated by Mottl (2003), plotted as function of age. Curves are shown for assumed temperature differences between bottom water and hydrothermal fluid of 5°C, 20°C, and 65°C. Lower thermal values are most typical of ridge-flank hydrothermal circulation that mines lithospheric heat. The higher thermal value is characteristic of weak ridge-flank circulation that results in significant local fluid and rock alteration, but has little regional thermal influence. (C) Calculated fluid discharge per seamount, assuming that all of the fluid flow estimated earlier passes through seamounts. The number of hydrothermally active seamounts is estimated to be somewhere between 10^4 and 10^6, based on mapping and seamount population estimates by Wessel (2001) and Hillier and Watts (2007), and the observation that, of the seamounts and outcrops that have been surveyed, a significant fraction appear to be hydrothermally active (Fisher et al., 2003a, 2003b; Hutnak et al., 2008; Villinger et al., 2002). Also shown are estimates of the fluid flux through Baby Bare and Dorado seamounts, as discussed in the text.

1987). Low-temperature discharge on ridge flanks is unlikely to create easily identifiable plumes because differences in physical and chemical properties between crustal fluids and ocean bottom water can be so small (Wheat et al., 1997). Seamounts and other basement outcrops provide readily identifiable windows into ridge-flank conditions and processes that are important, but otherwise would be difficult to quantify.

In this paper, we describe the critical role that seamounts play in global-scale, ridge-flank hydrothermal processes. Seamounts were initially defined as submarine volcanic constructions rising at least 1000 m above the surrounding seafloor (Menard and Ladd, 1963). Some of the basaltic edifices discussed in this paper do not meet this strict definition, either because they never were 1000 m high or because they are now mostly buried by marine sediments. To be consistent with other studies in this special issue of *Oceanography*, we adopt a more recent definition (Schmidt and Schmincke, 2000; Staudigel and Clague, 2010) and refer to all volcanic edifices on the seafloor that were originally ≥ 100 m tall as "seamounts."

In the next section, we describe the driving force of ridge-flank hydrothermal circulation flowing through seamounts, and discuss the potential for

Andrew T. Fisher *(afisher@ucsc.edu) is Professor, Earth and Planetary Sciences Department and Institute for Geophysics and Planetary Physics, University of California, Santa Cruz, Santa Cruz, CA, USA.* **C. Geoffrey Wheat** *is Research Professor, Global Undersea Research Unit, University of Alaska Fairbanks, based at Moss Landing, CA, USA.*

these flows to influence the chemical composition of the crust and ocean. In order to elucidate these physical and chemical concepts, we discuss results of field, laboratory, and computer modeling studies of two field sites that represent end members along a continuum of ridge-flank conditions, fluid residence time, chemical alteration, and global impact.

SEAMOUNTS AS CONDUITS FOR RIDGE-FLANK HYDROTHERMAL CIRCULATION

The Importance of Seamounts in Extracting Lithospheric Heat

Most of the seafloor is blanketed by fine-grained marine sediment (Figure 2A). Sediment cover is generally absent on and near seafloor spreading centers where the crust is young, and below subtropical gyres, but becomes increasingly continuous as seafloor spreads and ages. Typical marine sediment has a permeability much lower than that of the upper volcanic crust (Spinelli et al., 2004; Fisher et al., 2008; Figure 2B). Hydrothermal flow through the sediment and volcanic crust is regulated by pressure gradients on ridge flanks. Simple physical considerations (discussed in the next section) indicate that the driving forces for ridge-flank hydrothermal circulation tend to be no more than a few hundreds of kilopascals, and are often much less. Pressure differences this small cannot sustain fluid flow through marine sediment at rates sufficient to extract a significant fraction of lithospheric heat once sediment thickness exceeds 10–20 m. Thus, the vast majority of fluid flow that is responsible for advective heat loss from oceanic lithosphere must bypass sediment rather than flow directly through sediment.

Seamounts help to connect the oceanic crustal hydrogeologic system to the overlying ocean, along with fracture zones, large igneous provinces, and other basement outcrops. The qualitative importance of seamounts to ridge-flank hydrogeology has been appreciated for decades, but researchers generally avoided collecting heat flow data in proximity to these features (or discounted such data when they were collected), because many seafloor thermal studies were intended to test lithospheric cooling models. In this context, the confounding influence of advective heat extraction around seamounts was to be avoided, not quantified. In addition, the lack of continuous multibeam bathymetric maps and precise navigation upon which seismic and heat flow surveys could be collocated often limited quantitative interpretation of heat flow data collected close to seamounts. Improvements in the availability and quality of bathymetric, seismic, and closely spaced transects of heat flow data, and renewed interest in understanding the dynamics and impacts of ridge-flank hydrothermal circulation, have focused attention in recent years on the physical and chemical composition of fluid flow through seamounts on ridge flanks (e.g., Wheat and Mottl, 2004).

Physics of Ridge-Flank Hydrothermal Circulation: The Hydrothermal Siphon

The primary driving force moving fluids in and out of the seafloor on ridge flanks is the difference between pressures at the base of recharging and discharging columns of fluid within the crust, with the flowing system functioning like a "hydrothermal siphon" (Figure 3). Ridge-flank hydrothermal fluids have a density that depends on temperature, with thermal expansivity of $\alpha \approx 1$ to 5×10^{-4} K^{-1} within a temperature range of 0–50°C. Seawater is also slightly compressible, but the influence of compressibility on ridge-flank fluid circulation is small.

In areas of ridge-flank hydrothermal recharge, fluid pressure is greatest at the base of a cold column of crustal fluid, where the downward flow is sufficiently rapid so as to minimize heating during descent (Figure 3A). In contrast, fluid pressure in the crust is lower at the base of an upward-flowing column of (warmer) discharging hydrothermal fluid (Figure 3B). The difference between these two pressures comprises the primary driving force for ridge-flank hydrothermal circulation (Figure 3C). Given this pressure differential, the rate at which seawater recharges, flows laterally within the crust, and ascends to discharge depends mainly on the permeability (ease of flow) within the crustal aquifer.

The siphon concept explains why marine sediment is such a powerful impediment to recharging and discharging hydrothermal fluids (Figure 2C). When fluid passes through a layered hydrologic system, the effective permeability is the harmonic mean of layer properties. Adding just 10 or 20 m of sediment above the volcanic crust slows the rates of fluid ascent and descent, essentially "consuming" some or all of the pressure differential that drives flow. If flow slows, the temperature difference between recharging and discharging fluids is reduced, slowing the flow even more. This negative feedback

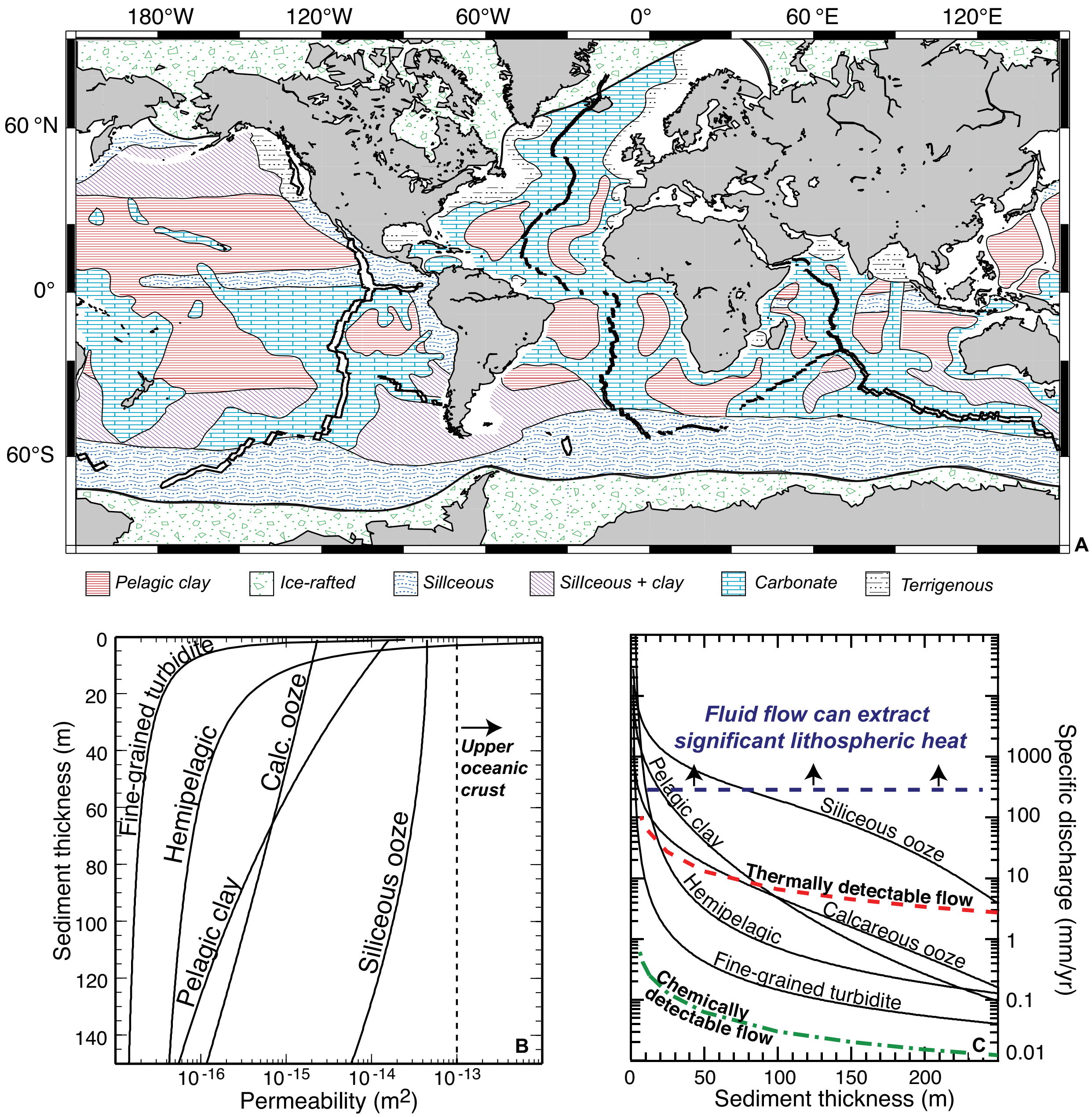


Figure 2. Sediment type, permeability, and limits on fluid flow through seafloor sediments on ridge flanks (figures modified from Spinelli et al., 2004). (A) Distribution of seafloor sediment types. Sediment tends to be thinner near mid-ocean ridges (defined by 1 m.y. isochrons, black lines) and thicker on older seafloor, close to large continental areas affected by terrigenous inputs, where upwelling supports high biogenic productivity, and at high latitudes affected by ice-rafted debris. In contrast, thin sediment exists below subtropical gyres, particularly in the North Atlantic and South Pacific oceans. (B) Typical permeability of seafloor sediments as a function of sediment thickness. The dashed vertical line shows the typical lower limit on permeability of upper oceanic basement rocks (see recent compilation of basement observations in Fisher et al., 2008). (C) Typical fluid seepage speeds through marine sediments of various kinds (solid curves, as labeled), based on typical excess fluid pressures of 20 kPa, and minimum seepage speeds necessary to detect fluid seepage via pore water solute (green curve) or thermal data (red curve). Also shown is the typical flow rate needed to remove a significant fraction of lithospheric heat on a regional basis (blue curve). For the vast majority of seafloor areas covered with sediments, fluid flow is not capable of extracting a significant fraction of lithospheric heat, except by bypassing the sediment layer entirely through seamounts or other basement outcrops.

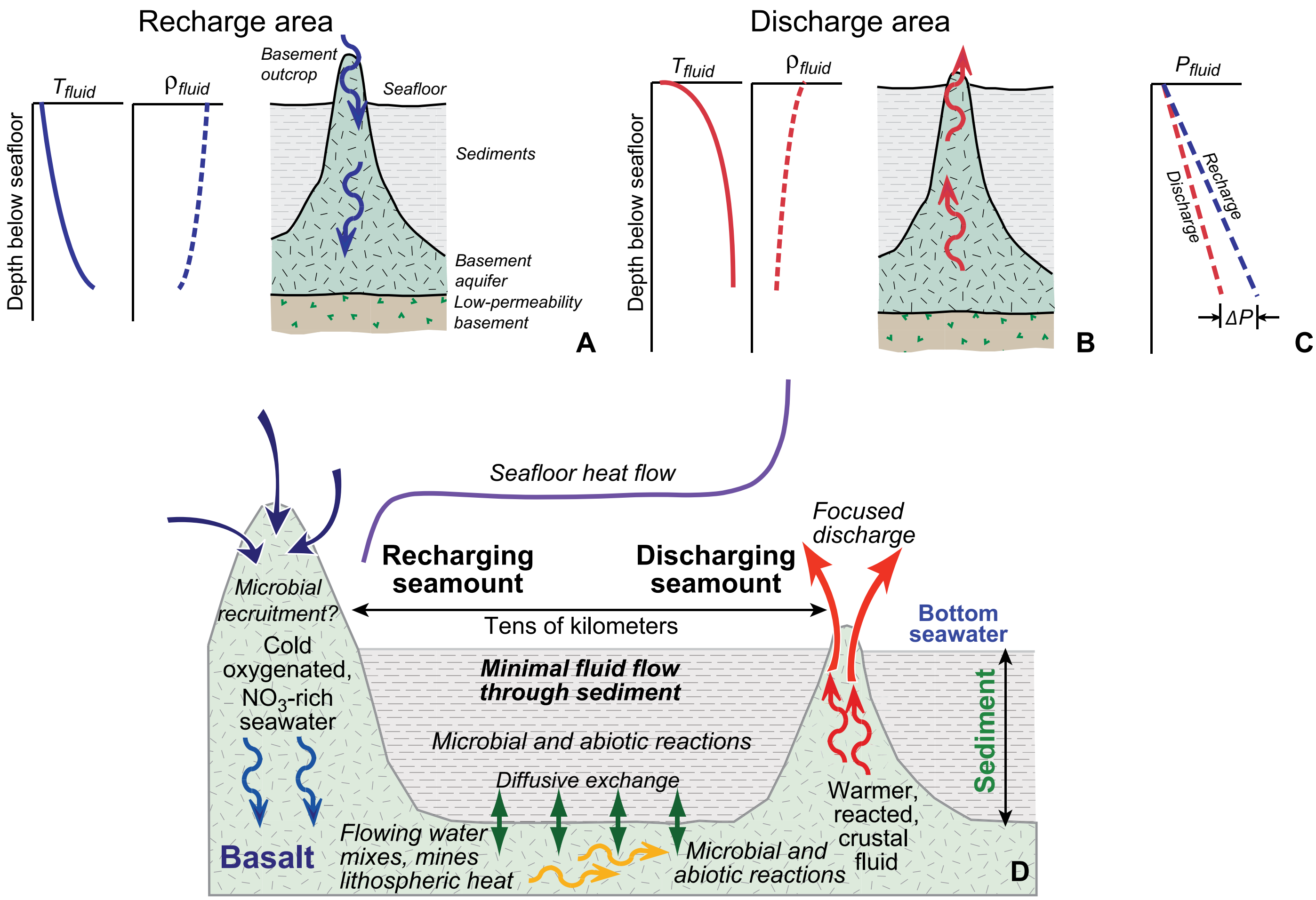


Figure 3. Schematic illustrations of the causes and impacts of ridge-flank hydrothermal circulation guided by seamounts. Within recharging and discharging seamounts (A and B, respectively), fluid temperatures (T_{fluid}) and densities (ρ_{fluid}) remain relatively constant so long as vertical transport (descent and ascent) is sufficiently rapid. The difference between fluid pressures (P_{fluid}) at the base of recharging and discharging columns of fluid (C) is the primary driving force for ridge-flank hydrothermal circulation. This pressure difference is available to move fluid laterally within the reactive basement aquifer (D), mining heat, reacting with the crust, and providing nutrients and/or energy to microbial communities living in pore spaces (Wheat and Fisher, 2008). Seafloor heat flow is generally higher adjacent to discharging seamounts, and lower adjacent to recharging seamounts. Between seamounts, heat flow may be equal to or less than conductive plate cooling values, depending on the regional efficiency of lithospheric heat extraction.

can shut down a hydrothermal siphon. The hydrothermal siphon concept applies to ridge-flank hydrothermal circulation in general, not only through seamounts, but also in the crust, where fluid temperature and pressure differences tend to be small when large areas of basement are exposed because the extent of circulation keeps the crust cool on a regional basis.

There are additional hydrothermal circulation systems associated with individual seamounts on ridge flanks (Harris et al., 2004). Lateral thermal gradients associated with bathymetric relief can drive low-temperature fluid circulation through these features, without seamount-to-seamount flow. These flows may impact local thermal conditions, and the global fluid flux associated with these systems could be large. But because of low fluid temperatures and short residence times, these flows are likely to have a smaller influence on crustal fluid composition than systems discussed in this study.

Seamounts and the Geochemistry of Ridge-Flank Hydrothermal Fluids

Rock sampling has documented the integrated history of crustal evolution and water-rock interaction on ridge flanks, and pore and crustal formation fluid samples provide a synoptic view of present-day conditions. High- and low-temperature ridge-flank hydrothermal circulation collectively transfer some elements to the ocean (e.g., Mn, Fe, Si, and Ca), but simultaneously remove others (e.g., C, P, Mg, and K). Crustal alteration is often most intense within cracks, faults, and breccia layers, demonstrating the importance of heterogeneous fluid pathways to crustal evolution (e.g., Alt, 2004). In addition, closely spaced boreholes have yielded rocks indicating very different alteration histories, often as a function of basement relief. For example, crustal samples recovered from Deep Sea Drilling Project (DSDP) Hole 417A, which penetrated basement that is topographically elevated relative to the surrounding area, are highly altered, consistent with an extensive history of warm ridge-flank hydrothermal flow (Donnelly et al., 1980; Staudigel et al., 1981, 1996). Perhaps the presence of a local basement high that penetrated surrounding sediments helped to focus the discharge of altered crustal fluids. In contrast, samples from DSDP Hole 418A, located just ~ 4 km away where the top of basement is lower, were much less altered and contained less common secondary mineralization (Donnelly et al., 1980; Staudigel et al., 1981).

Additional insight is provided by studies of crustal fluids. Pore water data from sediment samples collected above basement rocks can resolve the presence, patterns, and rate of fluid circulation though underlying volcanic rocks. In many cases, there are chemical deviations from bottom seawater composition in sedimentary pore fluids. But, within basal sediments close to the sediment-basalt interface, there is often a return to bottom seawater-like compositions (e.g., P. Baker et al., 1991). This pattern requires the rapid flow of seawater into and through the upper basaltic crust. In some cases, relatively high nutrient concentrations in hydrothermal fluids require that there be minimal interaction with sediment, meaning that recharge occurs nearby and/or that fluids have a relatively short residence time in the crust. In general, transects of sites are the most helpful for resolving patterns of transport, rates of reaction, and locations of recharge from pore fluid data (Wheat et al., 2000).

The extent of crustal fluid alteration depends on the amount of time that fluid spends in the crust, the extent of diffusional exchange with overlying sedimentary pore waters, and the rates of inorganic and microbially mediated reactions. Based on experimental and observational data, the most important parameter seems to be the temperature during water-rock interaction (Seyfried and Bishoff, 1979; Mottl and Wheat, 1994; Figure 4). At low temperatures (2–10°C), seawater-basalt reactions occur particularly slowly, and the fluid composition results from a balance

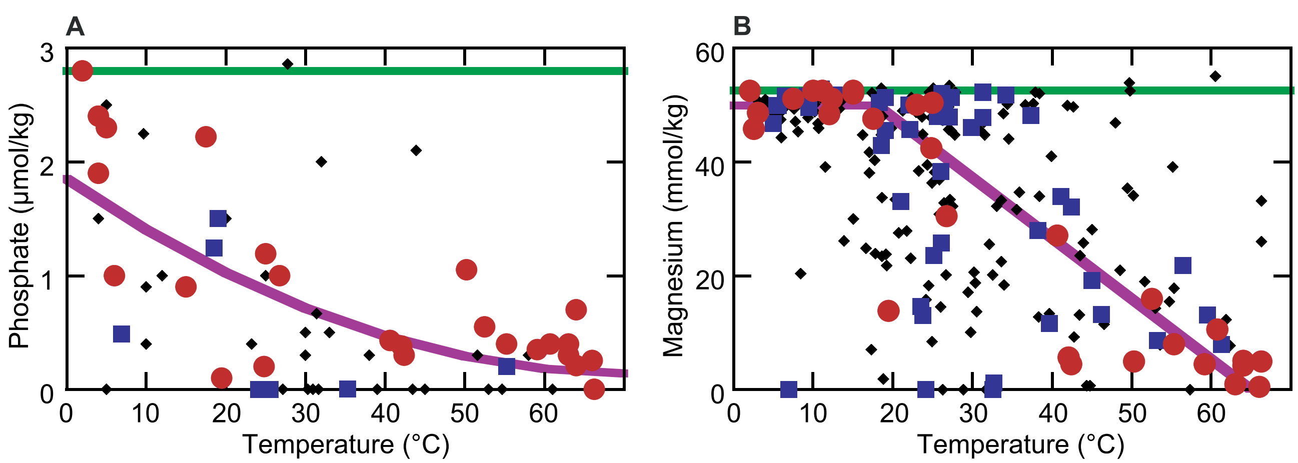


Figure 4. Concentrations of (A) phosphate and (B) magnesium versus temperature in ridge-flank fluids from the upper basaltic crust. These plots comprise a global compilation of pore water and borehole samples collected during scientific ocean drilling, by gravity/piston coring near basaltic outcrops, and by sampling seafloor seeps and springs. Phosphate data were published previously (Wheat et al., 2003), whereas the magnesium data were compiled for the present study. Data are classified qualitatively to indicate quality, as assessed by the authors: red circle = highest quality, blue square = moderate quality, and black diamond = fair quality. Factors involved in this analysis include the number of samples, the proximity of samples to the sediment-basalt interface, magnitude of pore water gradients, errors in estimated gradients, and availability of thermal data at the same location as concentration data to estimate the temperature of upper basaltic rocks. Purple lines indicate trends consistent with the highest-quality data. Horizontal green lines indicate typical concentrations in bottom seawater, which is generally at a temperature of ~ 2°C.

between the advective seawater flux and the diffusional exchange with overlying sediment pore waters, with only the most reactive solutes showing any significant alteration relative to bottom seawater (e.g., phosphate; Figure 4A). In contrast, reaction rates at warmer temperatures (40–60°C) are faster, generally doubling with every 10°C increase, and hydrothermal fluids rapidly become altered relative to seawater (e.g., Mg; Figure 4B). The importance of reaction temperature to the composition of ridge-flank hydrothermal fluids is illustrated in the next section, through comparison of conditions and fluid compositions from contrasting cool and warm ridge-flank hydrothermal systems guided by seamounts.

EXAMPLES OF RIDGE-FLANK HYDROTHERMAL CIRCULATION THROUGH SEAMOUNTS

3.5 Million-Year-Old Seafloor on the Eastern Flank of the Juan de Fuca Ridge

Numerous physical and chemical surveys have been completed on 0.7–3.6 million-year-old seafloor on the eastern flank of the Juan de Fuca Ridge (e.g., Davis et al., 1992; Hutnak et al., 2006). Turbidites that flowed from the nearby North American continent during sea level low stands in the Pleistocene have blanketed the basaltic crust with thick sediment at an unusually young age. Volcanic crustal rocks remain exposed over large areas close to the active spreading center, and on seamounts found up to 100 km to the east. Three seamounts were identified in this area initially: Papa Bare, Mama Bare, and Baby Bare (Figure 5A; Davis et al., 1992; Mottl et al., 1998).

Baby Bare is the most extensively surveyed and the smallest of the three features, rising 70 m above the surrounding seafloor with an area of 0.5 km^2. Although the outcrop area is currently small, the buried Baby Bare edifice rises ~ 600 m above the regional

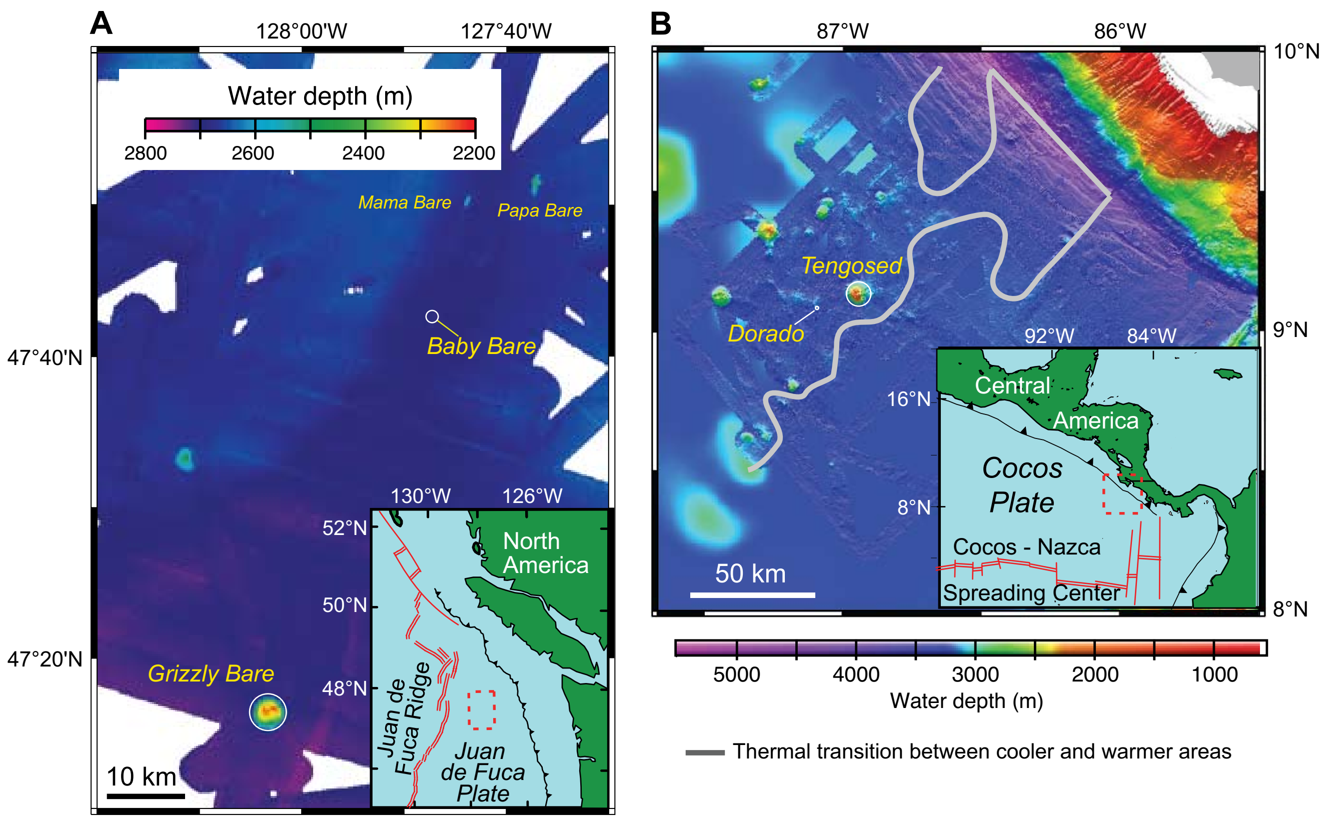


Figure 5. Bathymetric maps showing field areas for two example recharging and discharging seamount pairs. The primary seamounts discussed in this paper are circled in each panel. (A) Grizzly Bare (recharging) and Baby Bare (discharging) on 3.5 million-year-old seafloor on the eastern flank of the Juan de Fuca Ridge. (B) Tengosed (recharging) and Dorado (discharging) on 22.5 million-year-old seafloor on the eastern flank of the East Pacific Rise. The gray line on (B) separates the area of cooler seafloor (greater advective heat loss) to the northwest from the area of warmer seafloor to the southeast (greater conductive heat loss) (Hutnak et al., 2008).

top of volcanic crustal rocks. Analysis of altered basaltic rocks, sediment pore fluids, and shallow thermal gradients on Baby Bare demonstrate that the edifice discharges 5–20 L s^{-1} of hydrothermal fluid and releases 2–3 MW of heat (Mottl et al., 1998; Wheat et al., 2004b). Mama and Papa Bare are also known sites of hydrothermal discharge.

No hydrothermal recharge sites have been identified on these three features. Instead, fluids recharge through Grizzly Bare, 52 km to the south (Figure 5A). Grizzly Bare is conical in shape, 3.5 km in diameter, and rises 450 m above the surrounding seafloor. Fluid flow in basement between Grizzly Bare and Baby Bare may be facilitated by enhanced basement permeability in a direction parallel to the primary crustal fabric, as expressed by abyssal hill topography (Wheat et al., 2000; Fisher et al., 2003a, 2008).

Grizzly Bare was identified initially as a site of regional hydrothermal recharge based on patterns of seafloor heat flow immediately adjacent to the edifice. Seafloor heat flow is depressed within a few kilometers of the edge of basalt exposure along several transects of measurements (Fisher et al., 2003a). Seismic reflection data allow determination of sediment thicknesses at locations where heat flow was measured, and downward continuation of thermal conditions shows that isotherms are swept downward by cold, recharging fluid in shallow crust adjacent to the outcrop edge. In contrast, warm fluid discharge from Baby Bare causes extremely high seafloor heat flow, and an upward sweeping of isotherms, adjacent to the area of exposed volcanic rocks (Davis et al., 1992; Fisher et al., 2003a).

Driving forces available to sustain this flow are quantified through consideration of fluid properties and pressures at recharge and discharge sites (Figure 3). Given a regional basement fluid temperature of ~ 64°C, bottom water (fluid recharge) temperature of ~ 2°C, and a typical sediment thickness of ~ 600 m, the available driving pressure for hydrothermal flow between Grizzly Bare and Baby Bare is ~100 kPa. This calculation assumes that crustal permeability along the recharging and discharging flow paths is no lower than 10^{-12} m^2, consistent with regional measurements (e.g., Becker and Davis, 2004; Fisher et al., 2003a, 2008) and results of numerical modeling experiments (Hutnak et al., 2006).

Hydrothermal circulation between Grizzly Bare and Baby Bare has virtually no regional influence on lithospheric heat loss (Davis et al., 1999; Fisher et al., 2003a; Hutnak et al., 2006). Suppressed and elevated seafloor heat flow adjacent to Grizzly Bare and Baby Bare, respectively, extend only a few kilometers from the edge of exposed basalt, and regional (background) heat flow away from outcrops is constant along a swath of 3.5–3.6 million-year-old seafloor extending 100 km to the north and south (Hutnak et al., 2006). It is likely that the hydrothermal circulation system between the two seamounts was considerably more active, and had a larger regional influence on lithospheric heat loss, when sediment cover was thinner and less complete in this area, prior to the recent phase of rapid sedimentation in the Pleistocene. It is the relatively slow and restricted nature of fluid flow today between Grizzly Bare and Baby Bare that allows the circulating fluids to be warmed and react extensively with basalt and overlying sediment pore waters while in transit (e.g., Mottl et al., 1998; Elderfield et al., 1999; Wheat et al., 2000).

The hydrothermal fluid seeping from Baby Bare is almost completely depleted in Mg (having exchanged Mg for Ca during water-rock reaction) and has lost most of its initial seawater alkalinity. This composition is consistent with an extensive reaction time in basement, as suggested by a measured radiocarbon age of thousands of years (Elderfield et al., 1999; Walker et al., 2007). The actual travel time may be decades to centuries because dispersive exchange with regions containing old carbon adjacent to primary flow paths causes the fluid to appear older (Sanford, 1997; J. Stein and Fisher, 2003). Reaction for decades to centuries at 64°C would alter the fluid as observed, based on seawater-basalt experimental data (Seyfried and Bishoff, 1979).

In most ridge-flank settings, the composition of hydrothermal crustal fluids is inferred mainly from the composition and compositional gradients observed in pore fluids from basal sediment. But for Baby Bare, data also are available from springs on the seamount (Mottl et al., 1998; Wheat and Mottl, 2000) and from nearby boreholes (Elderfield et al., 1999; Wheat et al., 2004a). Mg concentrations from shallow sediment pore waters on and around Baby Bare show upward curvature indicative of fluid seepage at a range of speeds (Figure 6). The speed of fluid seepage is great relative to the time required for molecular diffusion of solutes to affect chemical profiles, but generally too slow to have an influence on conductive heat transport.

Similar to Mg, redox-sensitive ions

such as nitrate and dissolved oxygen are absent in Baby Bare basement fluids, likely lost as a result of diffusion into the overlying sediment pore waters and consumption by microbial processes. Because reactions involving nitrate in the sediment are relatively rapid, nitrate in bottom seawater is entirely consumed within the upper few centimeters of sediment. Likewise, nitrate that diffuses from the basaltic formation fluid upward and into overlying sediment is consumed rapidly. This explains why sediment pore water nitrate profiles from Baby Bare are not influenced significantly by the different speeds of upward seepage (Figure 6).

22.5 Million-Year-Old Seafloor on the Eastern Flank of the East Pacific Rise

The Cocos Plate seafloor offshore the Nicoya Peninsula, Costa Rica (Figure 5B), comprises a northern region formed at the East Pacific Rise (EPR), and a southern region formed at the Cocos-Nazca Spreading Center (CNS) (e.g., Meschede et al., 1998; Barckhausen et al., 2001). Recent surveys of the area included swath mapping to locate seamounts, and multichannel seismic reflection data to delineate regional tectonic features, sediment thickness, and crustal relief (Fisher et al., 2003b; Hutnak et al., 2007). Multipenetration heat flow data were collocated on seismic reflection profiles to assess heat transport and determine temperatures at the sediment-crust contact; additional heat flow measurements were made with autonomous temperature probes attached to core barrels. Gravity coring in this area targeted edges of seamounts, especially where there was thermal

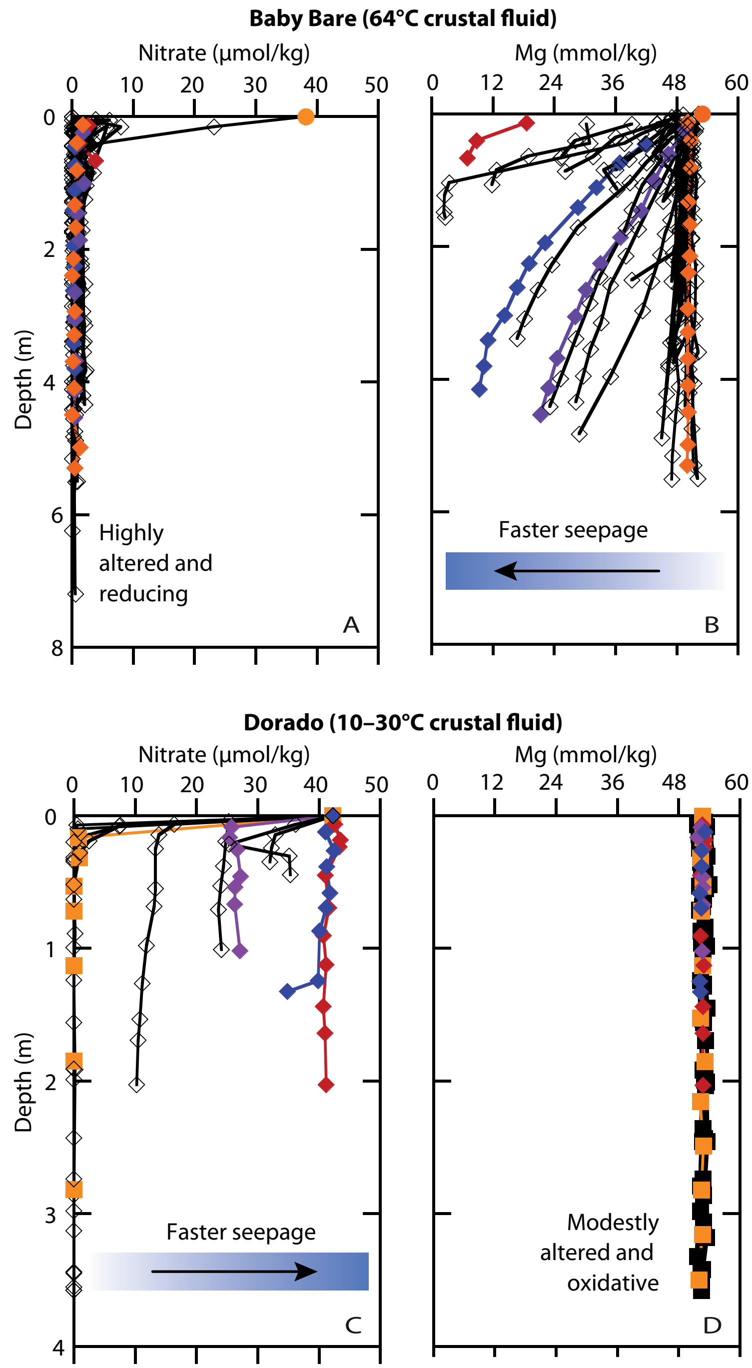


Figure 6. Pore water profiles from gravity and piston cores collected on and near Baby Bare and Dorado (locations shown in Figure 5; data from Wheat and Fisher, 2008; Wheat et al., 2004b). Nitrate (A) and Mg (B) data from pore fluids collected near and on Baby Bare. Basement formation fluid within Baby Bare is highly altered relative to bottom seawater, having exchanged Mg for Ca almost entirely, and having all nitrate lost during lateral transport, probably as a result of diffusive exchange with overlying sediment. Where there is rapid upward seepage, pore fluid compositions in shallow sediments are similar to basement fluids sampled from nearby springs and boreholes. Nitrate (C) and Mg (D) data from pore fluids collected near and on Dorado. The composition of basement formation fluids in this area is similar to bottom seawater, so rapid upward seepage results in nearly constant Mg and nitrate concentrations in shallow sediment. In contrast, where seepage is slow or there is no seepage, microbial processes remove much of the nitrate in sedimentary pore waters, but have no effect on Mg concentrations.

evidence for upward fluid seepage (Wheat and Fisher, 2008).

These surveys documented an abrupt thermal transition between warm and cool areas of the plate, consistent with shallow fluid circulation in the volcanic crust (Figure 5B; Fisher et al., 2003b; Hutnak et al., 2007). Regional maps include ten seamounts in 14,500 km^2 of cool seafloor, comprising just 260 km^2 of basalt exposure, less than 2% of the cool region. Surveys show that some seamounts recharge, whereas others discharge (Hutnak et al., 2007, 2008). As in the Baby Bare/Grizzly Bare area, cold fluid recharge is indicated by lower seafloor heat flow and downward-sweeping isotherms where sediment thins in proximity to basement exposure. In contrast, warm fluid discharge causes extremely high seafloor heat flow, and upward-sweeping isotherms, adjacent to areas of exposed basement. In the latter case, the temperature of the sediment-basalt contact often remains nearly isothermal as the contact shallows toward the seafloor. Surveys of five of the ten mapped seamounts on the cool part of the Cocos Plate indicate recharge through two, discharge through one (Dorado), one that both recharges and discharges, and one that shows evidence neither for recharge nor discharge (Hutnak et al., 2008).

Dorado is physically similar to Baby Bare, the small surface expression of a larger volcanic edifice that is mostly buried by thick sediment. Heat flow around Dorado is generally less than 20 mW m^{-2} (about one-fifth of lithospheric model predictions), but rises to 1000 mW m^{-2} (ten times lithospheric model predictions) along the outcrop edge as hydrothermal fluid rises rapidly. In contrast, heat flow is locally suppressed adjacent to the much larger Tengosed Seamount (the nearest mapped basement edifice; Figure 5B), located 20 km to the east, because of the rapid penetration of cold bottom water into exposed crustal rocks (Hutnak et al., 2008). Large-scale fluid flow in this area extracts lithospheric heat and results in a regional conductive deficit of 800–1,400 MW. The estimated power output per discharging outcrop is 200–350 MW, similar to that determined from plume and point studies of high-temperature vent fields at seafloor spreading centers (E. Baker, 2007). But, in contrast to high-temperature systems, the heat advected from Dorado and other outcrops in this area is conveyed by fluids that are moderately warmer than bottom seawater (Wheat and Fisher, 2008). Data from this area suggest a regional fluid flow of 4 to 80 x 10^3 L s^{-1} through discharging seamounts, equivalent to 1 to 20 x 10^3 L s^{-1} through Dorado and similar features (Hutnak et al., 2008). This fluid-flow rate is ~ 1000 times greater than that inferred to be seeping from Baby Bare (Mottl et al., 1998; Wheat et al., 2004b).

Driving forces available to sustain flow between Tengosed and Dorado are estimated based on the hydrothermal siphon concept described earlier (Figure 3). Given typical hydrothermal fluid temperatures in the upper volcanic crust around Dorado of 10–30°C, and a regional sediment thickness of 500 m, the maximum pressure difference available to drive fluid from Tengosed to Dorado is ≤ 30 kPa. This pressure difference is smaller than was calculated between Grizzly Bare and Baby Bare, despite the much greater fluid flux through seafloor around Tengosed and Dorado, requiring that basement permeability be considerably greater in the latter area, perhaps by two to three orders of magnitude (Fisher et al., 2003a; Hutnak et al., 2008). The reason for higher crustal permeability in this area is not known, but may be a consequence of the crust being formed at a fast rate, with longer periods of magmatic activity at the spreading center and greater horizontal continuity in the crust.

The rapid rate of fluid flow around Dorado is evident in the radiocarbon age of the basement fluid, only a few hundred years older than bottom

> "SEAMOUNTS ARE IDEAL PLACES TO SAMPLE CRUSTAL FLUIDS AS THEY EXIT THE CRUST AND ENTER THE OCEAN, TO DETERMINE THEIR CHEMICAL AND MICROBIAL CHARACTERISTICS, AND TO ASSESS THE IMPORTANCE OF THIS GLOBAL HYDROGEOLOGIC SYSTEM ON THE EVOLUTION OF EARTH'S LITHOSPHERE, OCEAN, AND BIOSPHERE."

seawater, considerably younger than crustal fluids recovered from near Baby Bare (Wheat and Fisher, 2008). The short residence time of crustal hydrothermal fluids near Dorado, coupled with low crustal temperatures, explains why crustal fluid alteration is modest. Pore water profiles from sediments at the edge of Dorado generally show little difference from seawater values, whether or not there is significant fluid seepage (Wheat and Fisher, 2008; Figure 6D). One exception to this rule is nitrate, which reacts rapidly in the sediment because of microbially mediated processes. As a result, nitrate concentrations in sediment pore fluids around Dorado are lower than those of bottom seawater, with profile shapes affected by the rate of fluid seepage (Figure 6C).

There has been no direct sampling of low-temperature fluids discharging from Dorado. Collecting pristine fluids as they exit exposed basalt would allow determination of formation-fluid composition without sedimentary (and associated sampling and processing) artifacts. For many elements, this fluid composition may be only 1% or 2% different from seawater, differences that approach analytical limits. These subtle differences in fluid composition could have a significant influence on global geochemical budgets because the associated fluid flows are so large (Hutnak et al., 2008; Wheat and Fisher, 2008).

SYNTHESIS AND IMPLICATIONS

Figure 3D summarizes the key characteristics of ridge-flank hydrothermal circulation guided by seamounts. Networks of seamounts permit rapid fluid circulation to bypass thick and relatively continuous sediment across much of the deep seafloor. Fluid recharges into the crust as oceanic bottom seawater, being relatively cold and dense. As the fluid penetrates more deeply into the crust, it warms and reacts with the surrounding basalt, and interacts with the overlying sediments through diffusive exchange across the sediment-basalt interface. Fluid can flow laterally for tens of kilometers through the oceanic crust, with the extent of heating and reaction dependent on the flow rate, crustal age, and other factors. Where the flow rate is rapid and residence time is short, circulating fluid becomes only slightly warmer than bottom seawater, and changes to the formation fluid composition are small. These systems can still result in large solute fluxes because so much fluid is transported.

In contrast, when the flow rate is slow and fluid has a longer residence time in the crust, the fluid becomes warm and reactive. Weaker circulation systems can result in significant local rock alteration and heat extraction, but are unlikely to have a large impact on lithospheric heat loss on a regional scale. Most ridge-flank hydrothermal systems are likely to evolve between these two end members, beginning as low-temperature, rapid-flow systems and moving toward higher-temperature, slower-flow conditions, as seamounts become buried by ridge-flank sediment and the oceanic crust becomes altered and less permeable. Without seamounts and other basement outcrops, it would not be possible for ridge-flank hydrothermal circulation to mine a significant fraction of lithospheric heat once sediments become thick and continuous on a regional basis. Thus, ridge-flank hydrothermal activity would be very different on an Earth without seamounts.

End-member systems represented by Baby Bare (warm, highly altered, low fluid fluxes) and Dorado (cool, minor alteration, massive fluid fluxes) influence global geochemical budgets in different ways. If 15% of the oceanic advective heat loss were carried by warm, altered fluids, then the removal rate of Mg from such hydrothermal systems would equal the global river input (Wheat and Mottl, 2000). Similar calculations suggest that significant solute fluxes (> 25% of river values) for K, Ca, sulfate, and B could be associated with warm ridge-flank hydrothermal systems. The partitioning of geochemical fluxes among seawater-basalt reactions, diffusive exchange with overlying sediment, and microbial processes across a range of operating temperatures remains to be quantified. Given the abundant cool ridge-flank hydrothermal systems (like Dorado) that must exist globally, diffusive exchange with overlying sediments may be of primary importance to geochemical budgets for sediment-reactive elements.

Although there is clear evidence for thriving microbial communities in marine sediments, it is not known whether microbial populations within basaltic crust have a significant influence on basement fluid compositions. There have been relatively few studies of microbial communities from the basaltic aquifer on ridge flanks, and most of these have focused on samples recovered from Ocean Drilling Program (ODP) Hole 1026B and nearby Baby Bare (Cowen et al., 2003; Huber et al., 2006; Nakagawa et al., 2006). These studies indicate that organisms within crustal fluids comprise a mixture of microbes commonly found in seawater, marine sediments, and elsewhere in the crust, including thermophilic bacteria and archaea. Little is known about the potential for crustal microbial populations at Dorado. Collection of pristine discharging fluids from Dorado would assist with characterizing microbial processes and community structure under conditions that are common within global ridge-flank hydrothermal systems.

Analyses of satellite gravimetric and ship track data suggest that there could be as many as 10^5 seamounts having a radius of ≥ 3.5 km and height ≥ 2 km (Wessel, 2001), and perhaps 10^6 to 10^7 features > 100 m in height (Hillier and Watts, 2007). Given the ubiquity of these features on ridge flanks, it is surprising how little we know about which seamounts are hydrologically active—how many recharge and how many discharge. Observational and modeling studies suggest that smaller features are favored sites of discharge, perhaps because it is easier to maintain warm conditions during upflow when that flow occurs through a smaller edifice, whereas larger features are more likely to remain cold (Fisher et al., 2003a; Hutnak et al., 2007, 2008). Only two field studies have been completed so far that allow identification of specific hydrothermal recharge and discharge sites, separated laterally by tens of kilometers, and only one field site has been sampled to characterize microbial processes and community structure. At each of these two sites, work has focused on a single pair of features, leading to a highly idealized view of fluid flow patterns. We don't know how seamounts make the hydrogeologic transition between an early stage dominated by volcanic construction and magmatic heating, and a later stage in which lithospheric cooling provides the primary heat source to drive hydrothermal circulation. Researchers have not resolved the influence of hydrothermal circulation through seamounts on subduction processes and recycling of elements from the ocean and crust into the mantle. These and many other aspects of seamount evolution, hydrogeology, geochemistry, and microbiology remain intriguing frontiers in oceanographic research.

ACKNOWLEDGMENTS

We thank *Oceanography* guest editors Hubert Staudigel and Anthony Koppers for encouragement, critical questions, and thoughtful suggestions as this manuscript was being prepared and revised. J. Alt, K. Becker, and C. Stein provided helpful reviews. This research was supported by National Science Foundation grants OCE–0550713 and OCE–0727952 (ATF) and OCE–0727119 and OCE–0727120 (CGW).

REFERENCES

Alt, J.C., 2004. Alteration of the upper oceanic crust: Mineralogy, chemistry, and processes. Pp. 495–533 in *Hydrogeology of the Oceanic Lithosphere*. E.E. Davis and H. Elderfield, eds, Cambridge University Press, Cambridge, UK.

Baker, E.T. 2007. Hydrothermal cooling of midocean ridge axes: Do measured and modeled heat fluxes agree. *Earth and Planetary Science Letters* 263(1–2):140–150.

Baker, E.T., and G.J. Massoth. 1987. Characteristics of hydrothermal plumes from two vent fields on the Juan de Fuca Ridge, northeast Pacific Ocean. *Earth and Planetary Science Letters* 85:59–73.

Baker, P., P. Stout, M. Kastner, and H. Elderfield. 1991. Large-scale lateral advection of seawater through oceanic crust in the central equatorial Pacific. *Earth and Planetary Science Letters* 105:522–533.

Barckhausen, U., C. Renaro, R. von Huene, S.C. Cande, and H.A. Roeser. 2001. Revised tectonic boundaries in the Cocos Plate off Costa Rica: Implications for the segmentation of the convergent margin and for plate tectonic models. *Journal of Geophysical Research* 106(B9):19,207–19,220.

Becker, K., and E. Davis. 2004. In situ determinations of the permeability of the igneous oceanic crust. Pp. 189–224 in *Hydrogeology of the Oceanic Lithosphere*. E.E. Davis and H. Elderfield, eds, Cambridge University Press, Cambridge, UK.

Cowen, J.P., S.J. Giovannoni, F. Kenig, H.P. Johnson, D. Butterfield, M.S. Rappé, M. Hutnak, and P. Lam. 2003. Fluids from ageing ocean crust that support microbial life. *Science* 299:120–123.

Davis, E.E., and C.R.B. Lister. 1974. Fundamentals of ridge crest topography. *Earth and Planetary Science Letters* 21:405–413.

Davis, E.E., D.S. Chapman, M.J. Mottl, W.J. Bentkowski, K. Dadey, C. Forster, R. Harris, S. Nagihara, K. Rohr, G. Wheat, and others. 1992. FlankFlux: An experiment to study the nature of hydrothermal circulation in young oceanic crust. *Canadian Journal of Earth Sciences* 29(5):925–952.

Davis, E.E., D.S. Chapman, K. Wang, H. Villinger, A.T. Fisher, S.W. Robinson, J. Grigel, D. Pribnow, J. Stein, and K. Becker. 1999. Regional heat-flow variations across the sedimented Juan de Fuca Ridge eastern flank: Constraints on lithospheric cooling and lateral hydrothermal heat transport. *Journal of Geophysical Research* 104(B8):17,675–17,688.

Donnelly, T.W., R.A. Pritchard, R. Emmermann, H. Puchelt, and T.H. Karlsruhe. 1980. The aging of oceanic crust: Synthesis of the mineralogical and chemical results of Deep Sea Drilling Project Legs 51 through 53. Pp. 1,563–1,577 in *Initial Reports of the Deep Sea Drilling Project*. US Government Printing Office, Washington, DC.

Edwards, K.J., W. Bach, and T.M. McCollom. 2005. Geomicrobiology in oceanography: Microbe-mineral interactions at and below the seafloor. *Trends in Microbiology* 13(9):449–456.

Elderfield, H., C.G. Wheat, M.J. Mottl, C. Monnin, and B. Spiro 1999. Fluid and geochemical transport through oceanic crust: A transect across the eastern flank of the Juan de Fuca Ridge. *Earth and Planetary Science Letters* 172:151–165.

Embley, R.W., E.T. Baker, D.A. Butterfield, W.W. Chadwick Jr., J.E. Lupton, J.A. Resing, C.E.J. de Ronde, K.-I. Nakamura, V. Tunnicliffe, J.F. Dower, and S.G. Merle. 2007. Exploring the submarine ring of fire: Mariana Arc–Western Pacific. *Oceanography* 20(4):68–79.

Fisher, A.T., E.E. Davis, and K. Becker. 2008. Borehole-to-borehole hydrologic response across 2.4 km in the upper oceanic crust: Implications for crustal-scale properties. *Journal of Geophysical Research* 113, doi:10.1029/2007JB005447.

Fisher, A.T., E.E. Davis, M. Hutnak, V. Spiess, L. Zühlsdorff, A. Cherkaoui, L. Christiansen, K.M. Edwards, R. Macdonald, H. Villinger, and others. 2003a. Hydrothermal recharge and discharge across 50 km guided by seamounts on a young ridge flank. *Nature* 421:618–621.

Fisher, A.T., C.A. Stein, R.N. Harris, K. Wang, E.A. Silver, M. Pfender, M. Hutnak, A. Cherkaoui, R. Bodzin, and H. Villinger. 2003b.

Abrupt thermal transition reveals hydrothermal boundary and role of seamounts within the Cocos Plate. *Geophysical Research Letters* 30(11), 1550, doi:1510.1029/2002GL016766.
Harris, R.N., A.T. Fisher, and D. Chapman. 2004. Fluid flow through seamounts and implications for global mass fluxes. *Geology* 32(8):725–728, doi:710.1130/G20387.20381.
Hillier, J.K., and A.B. Watts. 2007. Global distribution of seamounts from ship-track bathymetry data. *Geophysical Research Letters* 34 (L13304), doi:10.1029/2007GL029874.
Huber, J.A., D.A. Butterfield, H.P. Johnson, and J.A. Baross. 2006. Microbial life in ridge flank crustal fluids. *Environmental Microbiology* 8(1):88–99, doi:10.1111/j.1462-2920.2005.00872.x.
Hutnak, M., A.T. Fisher, R. Harris, C. Stein, K. Wang, G. Spinelli, M. Schindler, H. Villinger, and E. Silver. 2008. Large heat and fluid fluxes driven through mid-plate outcrops on ocean crust. *Nature Geoscience*, doi:10.1038/ngeo264.
Hutnak, M., A.T. Fisher, C.A. Stein, R. Harris, K. Wang, E. Silver, G. Spinelli, M. Pfender, H. Villinger, R. MacKnight, and others. 2007. The thermal state of 18–24 Ma upper lithosphere subducting below the Nicoya Peninsula, northern Costa Rica margin. Pp. 86–122 in *MARGINS Theoretical Institute: SIEZE Volume*. T. Dixon, C. Moore, E. Silver, S. Stein, K. Furlong, and K. Brown, eds, Columbia University Press, New York.
Hutnak, M., A.T. Fisher, L. Zühlsdorff, V. Spiess, P. Stauffer, and C.W. Gable. 2006. Hydrothermal recharge and discharge guided by basement outcrops on 0.7–3.6 Ma seafloor east of the Juan de Fuca Ridge: Observations and numerical models. *Geochemistry, Geophysics, Geosystems* 7, doi:10.1029/2006GC001242.
Menard, H.W., and H.S. Ladd. 1963. Oceanic islands, seamounts, guyots and atolls. Pp. 365–387 in *The Sea: The Earth Beneath the Sea*. M.N. Hill, ed., Robert E. Krieger, Huntington, NY.
Meschede, M., U. Barckhausen, and H.-U. Worm. 1998. Extinct spreading on the Cocos Ridge. *Terra Nova* 10:211–216.
Mottl, M.J. 2003. Partitioning of energy and mass fluxes between mid-ocean ridge axes and flanks at high and low temperature. Pp. 271–286 in *Energy and Mass Transfer in Submarine Hydrothermal Systems*. P. Halbach, V. Tunnicliffe, and J. Hein, eds, Dahlem University Press, Berlin, Germany.
Mottl, M.J., and C.G. Wheat. 1994. Hydrothermal circulation through mid-ocean ridge flanks: Fluxes of heat and magnesium. *Geochimica Cosmochimica Acta* 58:2,225–2,237.
Mottl, M.J., C.G. Wheat, E. Baker, N. Becker, E. Davis, R. Feeley, A. Grehan, D. Kadko, M. Lilley, G. Massoth, and others. 1998. Warm springs discovered on 3.5 Ma oceanic crust, eastern flank of the Juan de Fuca Ridge. *Geology* 26:51–54.
Nakagawa, S., F. Inagaki, Y. Suzuki, B.O. Steinsbu, M.A. Lever, K. Takai, B. Engelen, Y. Sako, C.G. Wheat, and K. Horikoshi. 2006. Microbial community in black rust exposed to hot ridge-flank crustal fluids. *Applied and Environmental Microbiology* 72(10):6,789–6,799.
Parsons, B., and J.G. Sclater. 1977. An analysis of the variation of ocean floor bathymetry and heat flow with age. *Journal of Geophysical Research* 82:803–829.
Pollack, H.N., S.J. Hunter, and J.R. Johnson. 1993. Heat flow from the earth's interior: Analysis of the global data set. *Reviews of Geophysics* 31(3):267–280.
Sanford, W.E. 1997. Correcting for diffusion in Carbon-14 dating of ground water. *Ground Water* 35(2):357–361.
Schmidt, R., and H.-U. Schmincke. 2000. Seamounts and Island Building. Pp. 383–402 in *Encyclopedia of Volcanoes*. H. Sigurdsson, ed., Academic Press, San Diego, CA.
Sclater, J.G., C. Jaupart, and D. Galson. 1980. The heat flow through oceanic and continental crust and the heat loss of the earth. *Reviews of Geophysics and Space Physics* 18:269–311.
Seyfried, W.E. Jr., and J.L. Bishoff. 1979. Low temperature basalt alteration by seawater: An experimental study at 70°C and 150°C. *Geochimica Cosmochimica Acta* 43:1,937–1,947.
Spinelli, G.A., E.G. Giambalvo, and A.T. Fisher. 2004. Hydrologic properties and distribution of sediments. Pp. 151–188 in *Hydrogeology of the Oceanic Lithosphere*. E.E. Davis and H. Elderfield, eds, Cambridge University Press, Cambridge, UK.
Staudigel, H., and D.A. Clague. 2010. The geological history of deep-sea volcanoes: Biosphere, hydrosphere, and lithosphere interactions. *Oceanography* 23(1):58–71.
Staudigel, H., S.R. Hart, and S.H. Richardson. 1981. Alteration of oceanic crust: Processes and timing. *Earth and Planetary Science Letters* 52:311–327.
Staudigel, H., T. Plank, B. White, and H.-U. Schmincke. 1996. Geochemical fluxes during seafloor alteration of the basaltic upper oceanic crust: DSDP Sites 417 and 418. Pp 19–38 in *Subduction: Top to bottom*. American Geophysical Union, Washington, DC.
Stein, C.A., S. Stein, and A.M. Pelayo. 1995. Heat flow and hydrothermal circulation. Pp. 425–445 in *Seafloor Hydrothermal Systems: Physical, Chemical, Biological and Geological Interactions*. S.E. Humphris, R.A. Zierenberg, L.S. Mullineaux, and R.E. Thompson, eds, American Geophysical Union, Washington, DC.
Stein, J.S., and A.T. Fisher. 2003. Observations and models of lateral hydrothermal circulation on a young ridge flank: Numerical evaluation of thermal and chemical constraints. *Geochemistry, Geophysics, Geosystems*, doi:10.1029/2002GC000415.
Villinger, H., I. Grevemeyer, N. Kaul, J. Hauschild, and M. Pfender. 2002. Hydrothermal heat flux through aged oceanic crust: Where does the heat escape? *Earth and Planetary Science Letters* 202(1):159–170.
Walker, B.D., M.D. McCarthy, A.T. Fisher, and T.P. Guilderson. 2007. Dissolved inorganic carbon isotopic composition of low-temperature axial and ridge-flank hydrothermal fluids of the Juan de Fuca Ridge. *Marine Chemistry* (108), doi:10.1016/j.marchem.2007.1011.1002.
Wessel, P. 2001. Global distribution of seamounts inferred from gridded Geosat/ERS-1 altimetry. *Journal of Geophysical Research* 106(B9):19,431–19,442.
Wheat, C.G., and A.T. Fisher. 2008. Massive, low-temperature hydrothermal flow from a basaltic outcrop on 23 Ma seafloor of the Cocos Plate: Chemical constraints and implications. *Geochemistry, Geophysics, Geosystems* 9, Q12O14, doi:10.1029/2008GC002136.
Wheat, C.G., and M.J. Mottl. 2000. Composition of pore and spring waters from Baby Bare: Global implications of geochemical fluxes from a ridge flank hydrothermal system. *Geochimica Cosmochimica Acta* 64(4):629–642.
Wheat, C.G., and M.J. Mottl. 2004. Geochemical fluxes through mid-ocean ridge flanks. Pp. 627–658 in *Hydrogeology of the Oceanic Lithosphere*. E.E. Davis and H. Elderfield, eds, Cambridge University Press, Cambridge, UK.
Wheat, C.G., H. Elderfield, M.J. Mottl, and C. Monnin. 2000. Chemical composition of basement fluids within an oceanic ridge flank: Implications for along-strike and across-strike hydrothermal circulation. *Journal of Geophysical Research* 105(B6):13,437–13,447.
Wheat, C.G., H.W. Jannasch, M. Kastner, J.N. Plant, E. DeCarlo, and G.T. Lebon 2004a. Venting formation fluids from deep-sea boreholes in a ridge flank setting: ODP Sites 1025 and 1026. *Geochemistry, Geophysics, Geosystems* 5(8), Q08007, doi:08010.01029/02004GC000710.
Wheat, C.G., J. McManus, M.J. Mottl, E.G. Giambalvo. 2003. Oceanic phosphorus imbalance: Magnitude of the mid-ocean ridge flank hydrothermal sink. *Geophysical Research Letters*, doi:10.1029/2003GL017318.
Wheat, C.G., M.J. Mottl, E.T. Baker, and R.A. Feely. 1997. Chemical anomalies in the water column from low-temperature hydrothermal venting on the eastern flank of the Juan de Fuca ridge. *Journal of Geophysical Research* 102(B7):15,433–15,446.
Wheat, C.G., M.J. Mottl, A.T. Fisher, D. Kadko, E.E. Davis, and E. Baker. 2004b. Heat and fluid flow through a basaltic outcrop on a ridge flank. *Geochemistry, Geophysics, Geosystems* 5(12), doi:10.1029/2004GC000700.
Wilkens, R.H., G.J. Fryer, and J. Karsten. 1991. Evolution of porosity and seismic structure of upper oceanic crust: Importance of aspect ratios. *Journal of Geophysical Research* 96:17,981–17,995.