Fluid Flow and Fluid-Rock Interaction Within Ocean Crust: Reconciling Geochemical, Geological, and Geophysical Observations

Wolfgang Bach

Department of Marine Chemistry and Geochemistry, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts

Susan E. Humphris

Department of Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts

Andrew T. Fisher

Earth Sciences Department and Institute for Geophysics and Planetary Physics, University of California, Santa Cruz, California

Fluid flow governs heat and mass transport in subseafloor hydrothermal systems and exerts control on the nature and distribution of deep microbial ecosystems in oceanic crust. We have integrated geophysical, petrographical, and geochemical data from key DSDP and ODP drill holes to assess fluid circulation pathways, fluid flow rates, and fluid-rock interaction in the oceanic lithosphere. Fluid ingress into the deep lithosphere is controlled by the development of faults and ductile shear zones, magmatic injection into the shallow crust, and downward propagation of a front of brittle fracturing into hot rock. Seawater circulation in the ridge flanks is governed by the crustal permeability structure, the availability of heat, and the existence of open pathways between the crustal aquifer and the overlying ocean. Rocks from drill holes representing basaltic crust of various ages and geological settings exhibit a uniform first-order sequence of alteration stages. An early stage of oxidative alteration and open seawater circulation is followed by restricted fluid circulation under varying conditions. Zones of high degrees of alteration often correspond to zones of high permeability, indicating that rock alteration and mineral precipitation do not completely seal the large-scale, most-permeable fluid pathways. On the scale of tens to hundreds of meters, fluid flow is controlled by the distribution of permeable lithologies: breccias, fractured pillow basalts and faults act as aquifers, while massive flows of considerable areal extent may act as fluid flow barriers. Flow boundaries, pillow margins and large cooling cracks are the main fluid conduits at the meter-scale, while at the smallest scale, micro-cracks and grain boundaries control fluid flow. Hence, fluid flow is highly channelized and only a small fraction of basement communicates with the

The Subseafloor Biosphere at Mid-Ocean Ridges
Geophysical Monograph Series 144

10.1029/144GM07

oceans. Fluid-rock interactions away from these main fluid conduits are dominantly diffusion-controlled, making the largest fraction of basement less desirable for microorganisms that rely on supply of nutrients by circulating fluids.

INTRODUCTION

Fluid flow within ocean crust has important consequences for the global heat budget, the chemical evolution of the Earth, and the depth extent and nature of subseafloor microbial ecosystems. It is controlled by a combination of driving forces, sources and sinks, and hydrogeological properties. Considerable effort during the last thirty years has focused on estimating or measuring these parameters, particularly permeability — the ease with which fluid can move through rock. Permeability is scale dependent: values determined from hand samples of oceanic basement are generally on the order of 10^{-17} to 10^{-19} m^2 or less [e.g., *Hamano*, 1979; *Karato*, 1983], while in situ measurements made at bore hole length scales of hundreds of meters vary from 10^{-17} to 10^{-10} m^2 [e.g., *Anderson and Zoback*, 1982; *Becker*, 1996]. The best explanation for this difference is that the most important flow pathways in oceanic crust are fractures, cracks and other irregular channels.

About 9-11 TW of heat (about one-third of the total ocean lithosphere heat flux and 20-25% of the global heat loss) are lost through hydrothermal circulation that occurs from the mid-ocean ridge axis out to basement with ages up to 65 Ma [*Elderfield and Schultz*, 1996; *Stein and Stein*, 1994]. Magmatic heat input constrains the axial hydrothermal heat flux to 2-4 TW, of which only a fraction is related to discrete high-temperature venting. The bulk of the heat is transported by moderate temperature (<60°C), diffuse venting fluids that often represent mixtures of vent fluids and seawater that was entrained in the crust [*Baker et al.*, 1993; *James and Elderfield*, 1996; *Rona and Trivett*, 1992; *Schultz et al.*, 1992]. The remaining hydrothermal flux takes place in ridge flanks where fluid temperatures are much lower. To account for a hydrothermal ridge flank heat flux of 7 TW by fluids with a temperature anomaly between 5 and 15°C, water flux rates between 4 and 11×10^{12} m^3/yr are required [*Elderfield and Schultz*, 1996]. At these rates, the total water volume of the oceans could be cycled through ridge flank crust in less than 350 kyrs. Such enormous fluid fluxes, together with the observation that bulk permeability in the upper 100 m of basaltic crust decreases most rapidly within the first few million years of crustal evolution [*Fisher and Becker*, 2000], suggest that fluid flow within oceanic crust must be highly channelized. This interpretation is consistent with observations of crustal petrophysical properties [e.g., *Mathews et al.*, 1984] and patterns of seafloor alteration [e.g., *Alt*, 1995] that indicate considerable heterogeneity in seafloor fluid flow.

Chemical reactions between fluid and basement change the composition of both the aging ocean crust and seawater. At the ridge axis, focused discharge of high-temperature hydrothermal fluids delivers base metals, H_2S, and other chemical species to the seafloor, resulting in the formation of sulfide deposits and supporting unique ecosystems [e.g., *Holden et al.*, 1998; *Jannasch*, 1995; *Karl*, 1995]. In addition, magma degassing and fluid-rock interaction release volatiles, such as H_2, CO_2, and CH_4, that can serve as energy sources for chemosynthetic microorganisms [e.g., *Kelley and Früh-Green*, 1999]. In fact, chemical disequilibrium during interaction of circulating seawater with rocks and mixing of seawater with upwelling hydrothermal fluids constitutes the principal source of metabolic energy and organic species for chemolithoautotrophic microorganisms in hydrothermal systems [e.g., *McCollom and Shock*, 1997; *Shock*, 1992; *Shock and Schulte*,1998]. Ridge flanks also play a large role in the elemental exchange between crust and seawater [*Elderfield et al.*, 1999; *Hart and Staudigel*, 1982; *Mottl and Wheat*, 1994; *Wheat and Mottl*, 2000]. In addition, textural analyses and whole rock stable isotope data of partially altered basalt glass have been interpreted to suggest that ridge flanks may host microbial ecosystems [*Fisk et al.*, 1998; *Furnes et al.*, 2001; *Furnes and Staudigel*, 1999; *Torsvik et al.*, 1998].

Fluid flow and water-rock reactions clearly play a critical role in determining the nature and extent of the subsurface biosphere. In this paper, we examine the controls on the patterns and rates of fluid flow in the oceanic crust by integrating geological, geochemical, and geophysical observations. We use data collected from Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP) drill holes (Figure 1). Only a few drill sites have detailed geophysical logs and sufficiently well documented downhole alteration mineralogy and chemistry to permit a detailed examination of the evolution of physical and chemical characteristics. However, other sites provide either geophysical or geochemical information that allows the continuum of fluid-rock processes in aging crust to be evaluated. Rather than provide a comprehensive review of all drill sites, we have selected key drill holes that allow us to compare the distribution and evolution of alteration reactions and physical properties for different portions of the oceanic lithosphere.

LOWER CRUST AND UPPER MANTLE

Deep hydrothermal circulation plays an important role in accretion and cooling of the ocean crust [e.g., *Phipps*

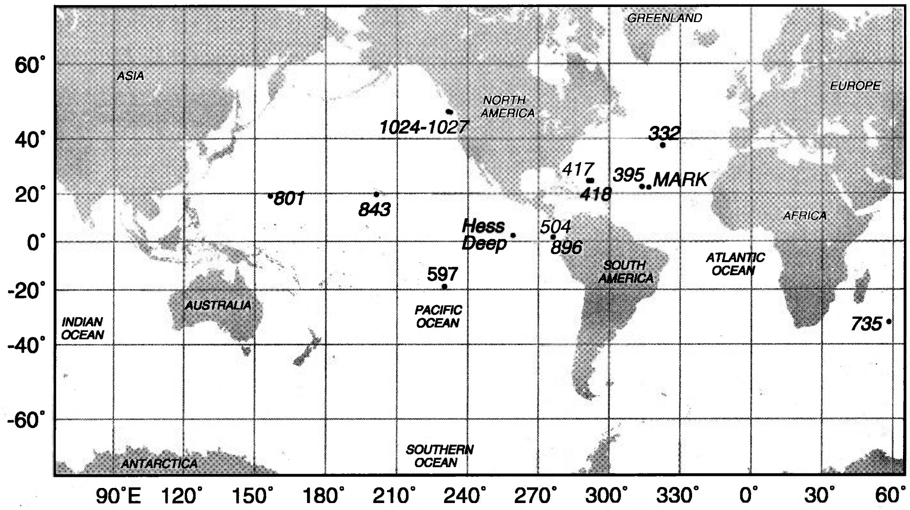

Figure 1. Map with locations of DSDP and ODP drill sites that are discussed in the text.

Morgan and Chen, 1993]. In the last decade, it has become clear that a simple layered model for crustal architecture suggested by seismic refraction studies and ophiolite analogs does not always apply as magma budgets and spreading rate decrease. Amagmatic extension and tectonic processes along slow-spreading ridges (which constitute 52% by length of the global mid-ocean ridge system) expose lower crust and upper mantle rocks. In fact, *Cannat et al.* [1995] have estimated that mantle rocks make up a significant fraction of the seafloor (e.g., 23% of the seafloor in the MARK area at 23°N on the Mid-Atlantic Ridge), and reaction between heated seawater and ultramafic rocks is common [e.g., *Charlou and Donval*, 1993; *German et al.*, 1996; *Kelley et al.*, 2001]. Hydrothermal plume mapping reveals that ultraslow spreading ridges are more hydrothermally active than predicted based on their low magma budgets [*German et al.*, 1998; *Edmonds et al.*, 2001; *Bach et al.*, 2002]. Experiments and field observations indicate that serpentinization may result in the production of significant quantities of volatiles, particularly CH_4 and H_2 [*Abrajano et al.*, 1988; *Charlou and Donval*, 1993; *Janecky and Seyfried*, 1986; *Horita and Berndt*, 1999]. In addition, abundant methane-rich fluid inclusions found in core material from Atlantis Bank and the MARK area provide evidence for the generation of abiotic methane in deep hydrothermal systems [*Vanko and Stakes*, 1991; *Kelley*, 1996; *Kelley and Früh-Green*, 1999]. These volatiles can be used as energy sources by chemosynthetic microorganisms as exemplified by the microbial communities supported by warm fluids (40-75°C) discharging from carbonate-brucite chimneys in an off-axis vent field on 1.5 Ma MAR lithosphere at 30°N [*Kelley et al.*, 2001].

Atlantis Bank

The longest section of lower ocean crust recovered to date is ODP Hole 735B, which penetrates more than 1500 m into 12 Ma gabbro. The crust was generated at the very slow spreading Southwest Indian Ridge, and was later unroofed along a detachment fault to form the Atlantis Bank [*Dick et al.*, 1991b].

The rocks preserve a complex record of deformation and hydrothermal alteration [*Dick et al.*, 2000; *Stakes et al.*, 1991; *Vanko and Stakes*, 1991]. Localized, narrow zones of crystal-plastic deformation that cut igneous fabrics indicate high temperature metamorphism (800-1000°C). A later, static background alteration is generally manifest as coronitic alteration halos around olivine grains and common replacement of clinopyroxene by variable amounts of amphibole. Subvertical amphibole veins are probably related to cooling and cracking of the rocks in the axial environment. The intensities of crystal plastic deformation and amphibolitization correlate in the uppermost 500 m of basement at 735B, suggesting a relationship between ductile deformation and fluid penetration into the gabbroic lower ocean crust [*Cannat et al.*, 1991; *Dick et al.*, 1991a; *Stakes et al.*, 1991]. Deeper in the hole, significant hydrothermal alteration is generally restricted to local zones of ductile and brittle deformation, i.e., in mylonitic and cataclastic shear zones or in highly fractured regions [*Dick et al.*, 2000]. In addition, the lower crust at 735B has been affected by a multistage history of low-temperature (<250°C) alteration, typically confined to fractured regions, and probably related to the tectonic uplift of the basement [*Bach et al.*, 2001; *Shipboard Scientific Party*, 1999].

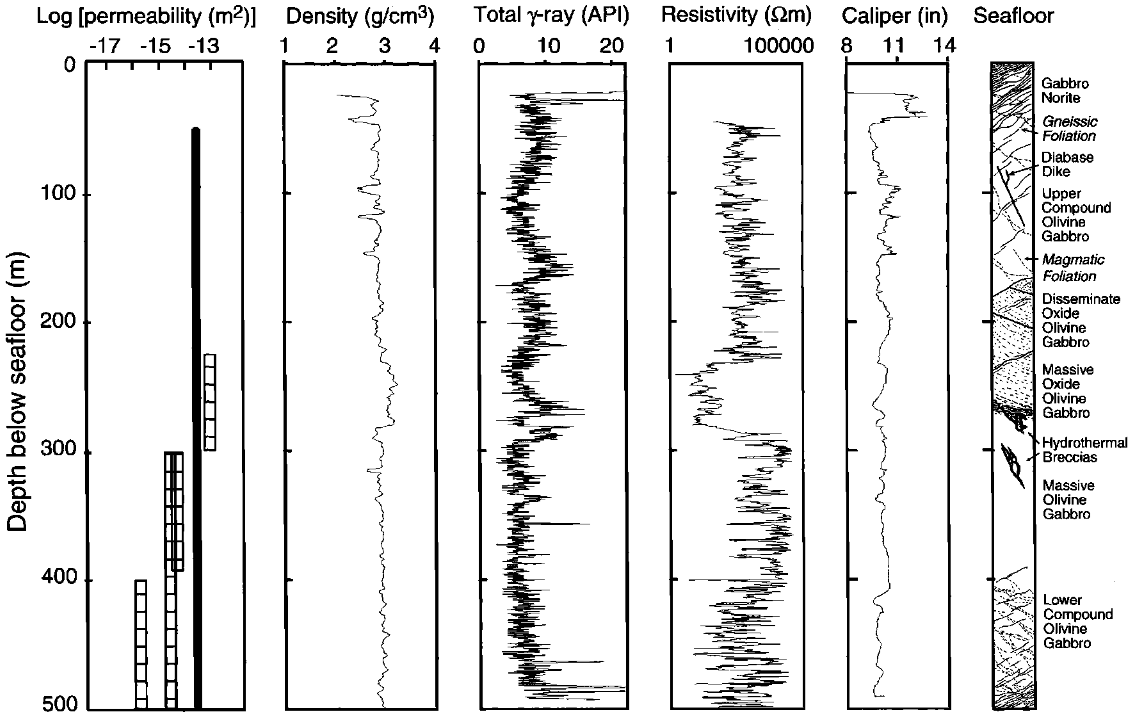

Figure 2. Hole 735B permeability data [*Becker*, 1991], wire line logging data (density, γ-ray intensity, electrical resistivity [*Goldberg et al.*, 1991]) and lithological summary [*Dick et al.*, 1991a] deduced from core descriptions plotted versus depth subbasement. In this and subsequent Figures, wire line logging data for rock density, γ-ray, and electrical resistivity are plotted next to packer permeability measurements and a lithologic column that is based on visual core descriptions. Core recovery is also shown and reflects the degree of certainty with which given intervals can be classified based on the recovered material. Caliper data are shown to help interpret the logs because the caliper of the drill holes affects the wire line logging data (e.g., a large drillhole caliper may result in artificially low density and γ-ray readings electrical resistivity logs based on widely spaced electrodes are less influenced by borehole washouts). The wire line logs are interpreted in the following manner: (a) density reflects degree of alteration (i.e. density is low in highly altered rocks), (b) total γ-ray count indicates primarily K and U concentrations (i.e. both are high in oxidatively altered rocks), and (c) resistivity reflects the extent of alteration and of well-connected pathways (i.e. resistivity is lowest in highly altered and permeable rocks).Note that the resistivity values are, on average, much greater than in basaltic crust. Zones of increased γ-ray intensity are developed where hydrothermal breccias are abundant and faults have provided pathways for cold seawater to penetrate deep into the Atlantis Bank massif. A zone of intense shearing and brecciation coincides with the interval of highest permeability and lowest resistivity (dashed lines).

Hole 735B is the only hole in lower crust/upper mantle in which downhole logging and packer experiments have been successfully conducted; however, these data are limited to the upper 500 m of the basement (Figure 2). Bulk permeabilities decrease by two orders of magnitude with depth, ranging from 2 x 10^{-14} m^2 for the lower 450 m to 2 x 10^{-16} m^2 for the lower 111 m of Hole 735B [*Becker*, 1991]. The downhole logs indicate that most of the permeability can be attributed to a few zones of open fractures within sheared gabbros between 170-270 m below the seafloor [*Goldberg et al.*, 1991]. Within this interval, there are abundant veins and other indications of post-emplacement fluid flow and alteration [*Dick et al.*, 1991a]. On this basis, *Becker* [1991] suggested that the lower permeabilities measured in Hole 735B may be more representative of in situ oceanic gabbro.

The MARK Area

ODP Legs 106/109/153 recovered both lower crustal and upper mantle rocks from the MARK area south of the Kane Fracture Zone on the MAR at 23°N. Gabbroic rocks in the MARK area occur several km west of the spreading axis, indicating rapid unroofing (500 to 900 kyrs) via faulting and block uplifting [*Gillis et al.*, 1993; *Karson and Dick*, 1983; *Mével et al.*, 1991]. The metamorphic evolution of the gabbros is complex and multistage [*Gillis et al.*, 1993; *Kelley*, 1997; *Mével et al.*, 1991]. Plastic deformation in discrete shear zones is accompanied by formation of hornblende and recrystallization of olivine, plagioclase, and pyroxene at temperatures >700°C [*Mével et al.*, 1991]. The relationship of these shear zones to the detachment fault is uncertain.

The shear zones commonly exhibit varying degrees of retrograde overprinting under greenschist-facies conditions. Greenschist-facies alteration and the development of chlorite-bearing vein assemblages is abundant but largely localized to fractures and cataclastic shear zones that provided fluid pathways throughout the period of cooling and uplifting. Late cataclastic zones mineralized with greenschist to subgreenschist-facies mineral assemblages probably represent extension faults related to the uplift of the ridge-transform intersection (RTI) massif. Rock samples from the MARK area also include quartz and sulfide impregnated basalt breccias, which probably represent zones of focused upflow of hydrothermal vent fluids [*Delaney et al., 1987*; *Kelley et al.*, 1993].

The textures and mineralogical compositions of oceanic serpentinites from drill holes in the MARK area record the polyphase metamorphic history of the exposed mantle. The earliest stage is usually a pervasive replacement of olivine and pyroxene by lizardite (±brucite) and subordinate talc and magnetite. According to phase equilibria considerations and O isotope studies, this intense interaction between fluid and peridotite probably occurred at high temperatures (>350°C) and comparatively low fluid-to-rock ratios [*Agrinier and Cannat*, 1997; *Dilek et al.*, 1997]. The pervasive serpentinization imposed a mesh texture to the rock, characterized by structureless serpentine replacing olivine, and pseudomorphs of lizardite after pyroxene (bastite). This mesh texture may provide permeability for continued fluid flow and fluid-rock interaction [*Hébert et al.*, 1990], although it is not clear how permeability is maintained during the volume change associated with serpentinization. Subsequent periods of dilatation and shearing resulted in the formation of chrysotile and lizardite veins and antigorite in shear zones, with chlorite, tremolite, magnetite, sulfides and carbonate as minor phases [*Dilek et al.*, 1997; *Hébert et al.*, 1990; *Prichard*, 1979]. The latest dilatation fractures to form are filled with clay minerals, carbonate and more rarely sulfides, reflecting low-temperature fluid flow during emplacement of serpentinites along the rift valley walls. Weathering of serpentine minerals to clay, oxidation of magnetite, dissolution of brucite, and formation of aragonite reflect ongoing reaction with seawater after emplacement of the serpentinites at the seafloor.

Hess Deep

Lower crust and upper mantle representing lithosphere generated at the fast spreading East Pacific Rise (EPR) are exposed in the Hess Deep, 50 to 100 km west of the present-day EPR, and sections within both gabbros and peridotites have been recovered. Gabbros from ODP Site 894 record several alteration stages, including early high temperature (500-750°C) pervasive alteration, localized strong greenschist facies overprint (T=250-400°C), and rare late zeolite-calcite veining [e.g., *Früh-Green et al.*, 1996a]. Gabbros recovered from fault scarps that bound the Hess Deep rift valley show minor cataclastic deformation and late-stage hydrothermal overprint [*Gillis*, 1995]. In contrast to the lower crustal rocks from the MAR and SWIR, the Hess Deep gabbros lack significant crystal plastic deformation, and ingress of very high temperature (T>500°C) hydrothermal fluids was solely controlled by microfractures [e.g., *Gillis*, 1995; *Manning et al.*, 1996]. Low oxygen isotope values of early secondary plagioclase [*Früh-Green et al.*, 1996a; *Lecuyer and Reynard*, 1996] suggest significant mass flux of fluids. The timing of fluid ingress was probably related to the magmatic evolution, and fluids were able to penetrate to deep crustal levels only after complete solidification of the magma several kilometers off–axis [e.g., *Gillis*, 1995; *Manning et al.*, 1996].

Mantle rocks in Hess Deep (Site 895) are extensively serpentinized and show localized greenschist and zeolite facies overprint [*Früh-Green et al.*, 1996b]. Temperatures of serpentinization are estimated to be greater than 350°C [*Agrinier et al.*, 1995; *Früh-Green et al.*, 1996b], similar to the serpentinites from the MARK area [*Agrinier and Cannat*, 1997].

UPPER AND MIDDLE CRUSTAL SECTION

Drilling has provided a series of holes in crust ranging from essentially zero-age to 170 Ma that record the effects of both axial high-temperature alteration and off-axis, lower temperature water-rock reactions that continue as the crust ages.

Near a ridge axis, hydrothermal processes are closely related to the spatial and temporal evolution of the lithosphere. At slow spreading ridges, the development of axial hydrothermal circulation cells seems to be dominantly tectonically controlled, with fault and shear zones likely acting as networks of fluid conduits [e.g., *German and Parson*, 1998; *Karson and Rona*, 1990; *Kleinrock and H umphris*, 1996]. The depth distribution of earthquakes at slow spreading ridges suggests that brittle faulting, and hence permeability that may facilitate fluid flow, extends to great depths [e.g., *Toomey et al.*, 1985; *Huang and Solomon*, 1988]. In contrast, at fast spreading ridges, permeability for hydrothermal convection appears to be created mainly by magmatic diking events [*Gillis*, 1995; *Von Damm et al.*, 1995]. It may be sustained through downward propagation of a cracking front developed when the deep basement is cooled efficiently by a convective heat removal front [*Lister*, 1983; *Wilcock and Delaney*, 1996; *Sohn et al.*, 1998]. Consistent with the earthquake data, a first-order correlation between the Sr and O isotope composition of hydrothermal vent fluids and spreading rate suggests that circulation cells may reach deeper at slow spreading ridges [*Bach and Humphris*, 1999].

An excellent review of the conceptual model of hydrothermal circulation and the attendant water-rock reactions within the ocean crust is given by *Alt* [1995]. Seawater circulation in permeable upper ocean crust leads to oxidative alteration of the basalt to Fe-oxyhydroxides, ferric mica (celadonite), smectite and carbonate. During this low-temperature oxidative alteration, the fluid becomes anoxic, loses some Mg and alkalis, and gains some Ca and Si. At greater depths, the chemically modified fluid reacts with less permeable crust at somewhat elevated temperatures to form Mg-smectite (saponite), pyrite, and carbonate. In addition, anhydrite may precipitate out of the fluid at temperatures $\geq 150°C$ [*Bischoff and Seyfried*, 1978]. Some fluids penetrate into the underlying, less permeable sheeted dike complex and, under increasing temperatures and reaction rates, interact with the rocks to form greenschist-facies minerals such as chlorite, actinolite, albite, and titanite. At this point, the fluid has lost virtually all its Mg and sulfate owing to precipitation of Mg-silicates and anhydrite. As temperatures increase, the fluids leach components like alkali metals, base metals and sulfur out of the basement. The zone where this leaching is most pronounced is called the root zone of axial hydrothermal systems. There, the fluid-to-rock ratios are small (about unity), temperatures are greater than 400°C, and the fluid is equilibrated with a metamorphic mineral assemblage consisting mainly of plagioclase, amphibole, quartz, chlorite, sulfide, and oxide [e.g., *Bowers and Taylor*, 1985; *Seyfried and Ding*, 1995].

Phase separation and thermal expansion of the hydrothermal fluid [*Bischoff and Rosenbauer*, 1985], in concert with the creation of near-vertical fluid conduits by some combination of fracturing, faulting, and magmatic diking, allow the fluid to rise rapidly in the discharge zone. Permeability in these upflow zones changes dynamically due to wall rock dissolution and replacement and precipitation of minerals (quartz, sulfides, anhydrite) in fractures and voids [*Humphris et al.*, 1995; *Lowell et al.*, 1993]. Although upwelling is rapid, the fluid may undergo varying degrees of conductive cooling and/or subseafloor mixing with seawater before reaching the seafloor. While fluids venting discretely to form sulfide/sulfate chimneys are affected by subseafloor mixing and cooling to some extent [*Seewald and Seyfried*, 1990; *Tivey et al.*, 1995], diffuse fluids ranging in temperature between 5 and 60°C have been shown to also represent mixtures of seawater and hydrothermal fluids [*Edmond et al.*, 1979; *James and Elderfield*, 1996; *Schultz and Elderfield*, 1997]. It has been suggested that these diffuse fluids transport an order of magnitude more heat than discrete venting fluids [*Baker et al.*, 1993; *Rona and Trivett*, 1992; *Schultz et al.*, 1992]. This implies that subsurface mixing may be very common, and mixing zones may provide habitats for a large subsurface biosphere [*Deming and Baross*, 1993].

Hydrothermal Upflow Zones

Results from ocean drilling have most profoundly influenced our understanding of hydrothermal processes in upflow zones. They have demonstrated that one of the most distinct processes in shallow upflow zones is the massive precipitation of anhydrite, which is common during subsurface mixing of hydrothermal fluids and seawater. ODP has drilled into upflow zones of three hydrothermal systems in distinct geotectonic settings: a volcanic-hosted deposit on the Mid-Atlantic Ridge (TAG), sediment-hosted deposits on the Juan de Fuca Ridge (Middle Valley), and a felsic-hosted deposit in a convergent margin setting (PACMANUS). Although no borehole geophysical data were collected during drilling operations at TAG, we focus on the TAG upflow zone because it is hosted in basalt and is hence probably most representative of a typical mid-ocean ridge axial system upflow zone in slow spread crust.

The most common reaction in the TAG basement is replacement of basalt by chlorite, Na-mica (paragonite), silica and sulfide, with chlorite being most abundant deep in the system and silica-sulfide replacement most pronounced in anhydrite-cemented breccias in the shallow basement [*Humphris et al.*, 1995; *Humphris and Tivey*, 2000]. The TAG drill holes also provide useful insights into fluid flow in the marginal areas of a seafloor sulfide deposit. In the SE part of the mound, pillow rind breccias at the contact between the lavas and overlying sulfides are composed of Mg-rich chlorite and have high (i.e., seawater-like) Sr isotope composition indicating reaction with conductively heated seawater. This suggests that the lava-sulfide contact acts as a conduit for seawater inflow into the hydrothermal system. In contrast, chlorite in the altered basalt in the NW part of the TAG mound is Fe-rich and has low Sr isotope ratios expected for rocks that have reacted with a hydrothermal fluid rather than a seawater dominated fluid [*Alt and Teagle*, 1998; *Honnorez et al.*, 1998]. Oxygen isotope compositions of chlorites from both locations suggest similar formation temperatures (250-310°C; *Alt and Teagle* [1998]). Hence, although rocks at both sites show low-temperature overprint [*Honnorez et al.*, 1998], it can be concluded that both conductive cooling of hydrothermal fluids (on the NW side of the mound) as well as rapid heating of entrained seawater (on the SE side of the mound) is taking place in the subsurface.

RIDGE FLANK HYDROTHERMAL SYSTEMS

Interaction between circulating seawater and ocean crust continues in the ridge flanks away from the ridge. Long-lived hydrothermal circulation systems in volcanic ridge flanks are well recognized from geological studies on drill core samples [e.g., *Alt and Honnorez*, 1984; *Muehlenbachs*, 1979; *Alt et al.*, 1996a] and ophiolites [*Gillis and Robinson*, 1990], as well as from geophysical measurements [*Davis et al.*, 1992; 1999; *Embley et al.*, 1983; *Noel*, 1985; *Sclater et al.*, 1980; *Stein and Stein*, 1994]. In terms of advective heat loss [*Stein and Stein*, 1994], solute fluxes [*Mottl and Wheat*, 1994], and crustal alteration [*Alt*, 1995], ridge flank circulation is at least as important as fluid circulation in axial hydrothermal systems. However, the relative importance of advective heat transport diminishes as basement age increases. Crustal heat loss is usually dominantly conductive in seafloor older than 65 Myrs [*Stein and Stein*, 1994], although advective redistribution of heat has been observed in some regions with crustal ages >65Ma [*Embley et al.*, 1983; *Noel*, 1985]. Even where crustal heat loss is conductive, there can be local or regional chemical and biological interaction between basement and fluids, including some of the oldest seafloor.

Drill hole data from seafloor produced at a range of spreading rates and at various stages of evolution reveal a remarkably coherent set of apparent permeabilities [*Fisher*, 1998; *Wilcock and Fisher*, this volume]. Values within the upper 100-300 m of basement generally range from 10^{-14} and 10^{-12} m^2 for seafloor from 0.2 to 170 Ma. The highest values are found within the youngest, shallowest crust and within zones that are tens of meters thick or less. These general trends are consistent with drill hole data collected in fractured aquifers on land [e.g., *Manning and Ingebritsen*, 1999]. Data from below the upper 500 meters of basement, restricted to Hole 504B, suggest that bulk permeabilities within the sheeted dikes on ridge flanks are generally on the order of 10^{-17} m^2. *Fisher* [1998] has also shown that geochemical estimates for water-to-rock ratios reveal a depth distribution resembling that of bulk permeability. This observation suggests that intensity and style of rock alteration are consistent with present-day permeability. Such a relationship is surprising because rock alteration reflects the time-integrated effects of fluid-rock interaction over a range of temperatures and fluid compositions, while drill hole measurements provide a snapshot of the current crustal permeability. Moreover, a common perception is that alteration and vein formation result in a drastic decrease in permeability and ultimately the shut-down of hydrothermal circulation. If this were the case, one would predict a reverse relation between permeability and rock alteration, i.e., low permeability in highly altered rocks. Hydrothermal circulation and mineral precipitation in ridge flanks are believed to be the main reasons for changes in upper basement seismic properties [*Houtz and Ewing*, 1976; *Jacobson*, 1992]. However, the relationship between upper crustal sonic velocities and hydrothermal processes is problematic, because upper crustal sonic velocities increase mainly in the first 10 Myrs of crustal evolution, while the heat flow anomaly persists for 65 Myrs, [*Carlson*, 1998; *Fisher and Becker*, 2000].

Vigorous hydrothermal circulation in the early stages of ridge flank evolution is consistent with age dating results that suggest the secondary minerals are usually only a few million years older than the primary basalt [e.g., *Peterson et al.*, 1986; *Richardson et al.*, 1980; *Staudigel et al.*, 1981]. However, the rock record, reviewed for selected drill holes in this section, clearly shows that alteration is multistage and that fluids circulating through ridge flanks can have a range of temperatures and chemical compositions [*Alt and Honnorez*, 1984; *Alt et al.*, 1986; 1996a; 1996b; *Gillis and Robinson*, 1990; *Teagle et al.*, 1996].

Holes 504B and 896A

A key section in understanding the progressive sequence of alteration is Hole 504B drilled to 2111 m below the seafloor in 6.6 Ma oceanic basement located ~200 km south of the Costa Rica Rift in the eastern equatorial Pacific. Hole 896A is located 1 km southeast of Hole 504B and penetrated 290 m of basement. Its position at basement and heat flow highs in a zone of present-day upwelling fluid contrasts with the location of Hole 504B on the flank of a buried basement ridge.

Alt et al. [1996b] and *Teagle et al.* [1996] distinguished four different alteration stages. The oldest secondary phases are celadonite and Fe-oxyhydroxides that formed at temperatures less than 50°C when the crust was open to free circulation of seawater under oxidizing alteration conditions. This was followed by circulation of large quantities of seawater which resulted in oxidation and the formation of celadonite, smectite, and Fe-oxyhydroxides in reddish alteration halos at low temperatures (<25°C). Subsequently, saponite and pyrite formed during restricted circulation of evolved seawater, less oxidizing conditions, and temperatures >40°C. Carbonates and zeolites are the youngest secondary phases. At Site 896, the younger generation of carbonates formed at temperatures between 50 and 70°C from reacted seawater in a ridge flank hydrothermal upflow zone.

Pezard and Anderson [1989] used geochemical logging data to estimate the proportions of clayey alteration products in Hole 504B and found that high degrees of alteration are bound to zones of high permeability (i.e., low electrical resistivity). They concluded that certain massive lava flows may be efficient flow barriers, while breccias and highly fractured flows channelize fluid flow.

The main differences between alteration in Holes 504B and 896A reflect the variability in the present thermal regimes in this area. Breccias, which are the loci of intense geochemical changes as indicated by extreme enrichments in Mg, alkalis, and CO_2, are much more abundant in Hole 896A, and the crust also appears to be more tightly cemented. In addition, veins are more abundant and include aragonite as a vein-filling in Hole 896A. These differences are consistent with Hole 896A being located in an upflow zone.

Density, resistivity, and γ-ray logs for the upper 500 m of basement in Hole 504B (Figure 3A) appear largely unrelated to the caliper log. Massive flows correlate with high density and resistivity values, and those at sub-basement depths of about 40, 270, and 290 m exhibit low γ-ray counts. These variations are indicative of less alteration (and probably lower permeabilities) in the massive flows than in the adjacent pillow lavas. The transition from dominantly oxidative alteration conditions above 250-300 m sub-basement to dominantly non-oxidative alteration below that depth is reflected in the γ-ray log by a drop in the background values by a factor of 2 (Figure 3A), and in downhole chemical profiles that show marked decreases in K_2O contents and Fe^{3+}/Fe_T ratios (Figure 3B). In addition, permeability measurements indicate a marked decrease at this alteration transition. A thick massive flow sequence between 300 and 320 m sub-basement appears to constitute the base of the oxidatively altered sequence. This may have acted to restrict fluid flow, thereby resulting in non-oxidative alteration below.

Alteration, however, is extremely variable on the meter-scale throughout the drill hole. Spikes in γ-ray counts in the upper part of the section, most notably at 195, 270, and 290 m sub-basement, can be correlated with boundaries between pillow lavas and massive flows or phyric and aphyric pillow lavas. Spikes of high γ-ray counts can also be found within pillow lava and breccia sequences at greater depths (e.g., at 420 and 440 m subbasement). This variability is also reflected in the considerable meter-scale scatter in the K_2O concentrations and degree of oxidation (Fe^{3+}/Fe_T ratios), and appears to be most pronounced near flow boundaries (Figure 3B).

Hole 504B also penetrated about 1400 m into the sheeted dike section of the oceanic crust. The alteration mineralogy suggests a steep temperature gradient downward from ~100-150°C in the lower volcanics to ~250-350°C in the uppermost dikes [*Alt et al.*, 1986]. In the upper sheeted dikes,

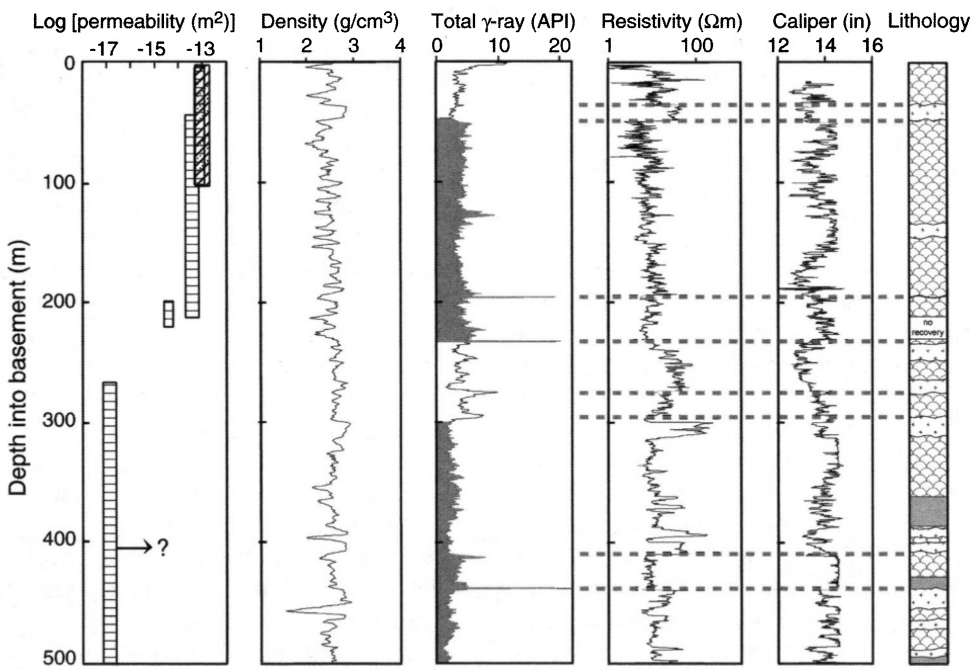

Figure 3. (A) Hole 504B permeability data [*Anderson and Zoback*, 1982; *Anderson et al.,* 1985; *Becker et al*., 1989; *Becker*, 1996], wire line logging data (density, γ-ray intensity, electrical resistivity; [*Becker et al*., 1988]), and lithological summary [*Cann et al*., 1983] deduced from core descriptions plotted versus depth subbasement. Horizontal lines indicate packer experiments, diagonal lines indicate permeabilities inferred from temperature logs. The tested intervals extend below the bases of these plots in many cases. The arrow in the deeper part of the 504B data is because of a reinterpretation of earlier data [*Anderson et al*., 1985] by *Becker* [1996]. Note that spikes in the γ-ray intensity, density, and electrical resistivity commonly coincide with flow boundaries, some of which are marked by dashed lines. Also note that the background γ-ray intensity drops to lower values below 300 m subbasement where permeability is decreased. Bulk density data were boxcar-filtered with a 3-m window to smooth small-scale variability.

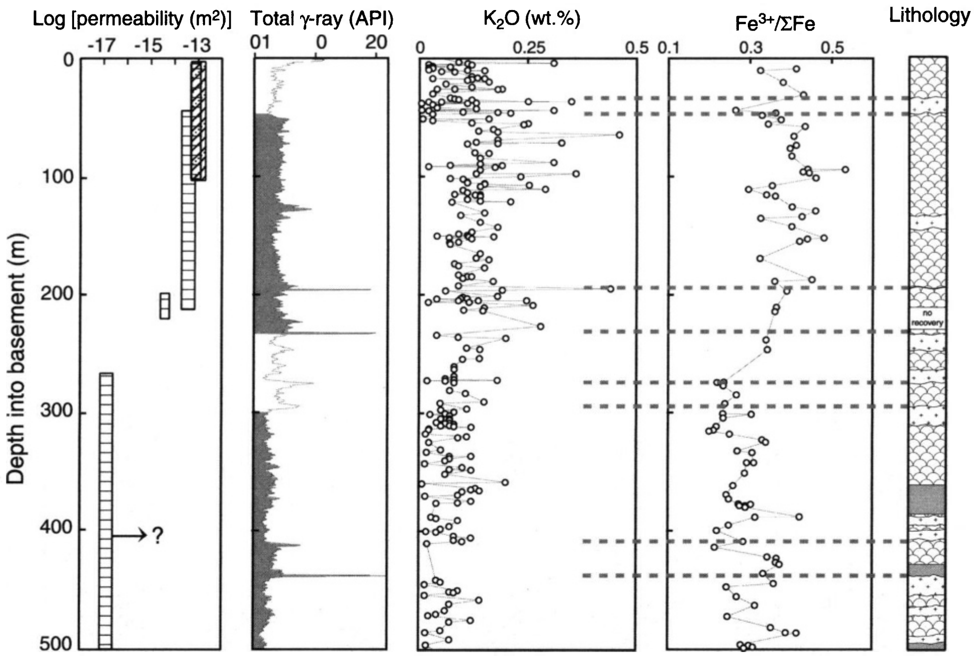

Figure 3. (B) Permeability data, γ-ray log, K_2O concentration and fraction of ferric iron (degree of oxidation) and lithological summary deduced from core descriptions plotted versus depth plotted versus depth subbasement. The downhole plot of K_2O concentrations shows the same principal pattern as the γ-ray intensity log, providing some groundtruthing for the use of γ-ray intensity logs as proxy for alteration chemistry. Note that the degree of oxidation is highest in the uppermost 200 m subbasement where permeability is greatest.

lower greenschist facies assemblages occur, with albite partially replacing plagioclase; chlorite and actinolite replacing olivine and glass and filling fractures and pore space, and actinolite replacing clinopyroxene [*Alt et al.*, 1986]. Alteration mineralogy in the lower 500-600 m of sheeted dikes in Hole 504B suggest that it may represent conditions within a high-temperature hydrothermal reaction zone [*Alt et al.*, 1996b]. Late-stage deposition of Ca-zeolites and anhydrite as fracture-fill in the sheeted dike complex is probably due to deep circulation of seawater in an off-axis recharge zone [*Alt et al.*, 1996b; *Teagle et al.*, 1998].

Hole 395A

A remarkable wealth of borehole geophysical data is available from DSDP/ODP Hole 395A on the west flank of the Mid-Atlantic Ridge (Figure 4). Some of the downhole variability observed in density and γ-ray counts can be accounted for by differences in hole size (see caliper log), but the resistivity measurements are much less sensitive to variations in hole size. In addition, there are distinct zones in which γ-ray counts and resistivity are inversely correlated and exhibit distinct saw-tooth patterns, suggesting that the γ-ray signal overcomes environmental noise caused by differences in borehole diameter. Shipboard comparison of lithologic and electrical resistivity logs for Hole 395A suggested a series of vertically distinct, basaltic flows [*Mathews et al.*, 1984]. Each flow unit is characterized by a decrease in electrical resistivity and an increase in γ-ray counts from its base to its top. This may indicate an increase in porosity in rocks deposited during the final stages of each effusive event. Many of the low-resistivity intervals at the tops of the flow units correspond to recovery of cobbles or breccia, although it should be noted that recovery within the upper few hundred meters of basement was extremely low.

Temperature logs collected soon after drilling [*Becker et al.*, 1984] indicated that bottom water was being drawn down Hole 395A at 10-100 m/hr because of low formation pressures, and this flow continued for many years after drilling. These results suggest that breccias developed between major flow units have a high present-day fluid permeability. The correlation between alteration chemistry and permeability (Figure 4) indicates that the flow boundaries acted as fluid conduits throughout the hydrological history of the basement at Site 395. Logging and packer results suggest that permeability at Site 395 decreases below 400 m subbasement [*Hickman et al.*, 1984; *Mathews et al.*, 1984] where temperature increases [*Becker et al.*, 1984].

Additional geophysical experiments were conducted in Hole 395A in 1998, including collection of bulk density, temperature, and spontaneous potential (SP) logs in the open hole [*Becker et al.*, 1998]. The SP log is used in the petroleum

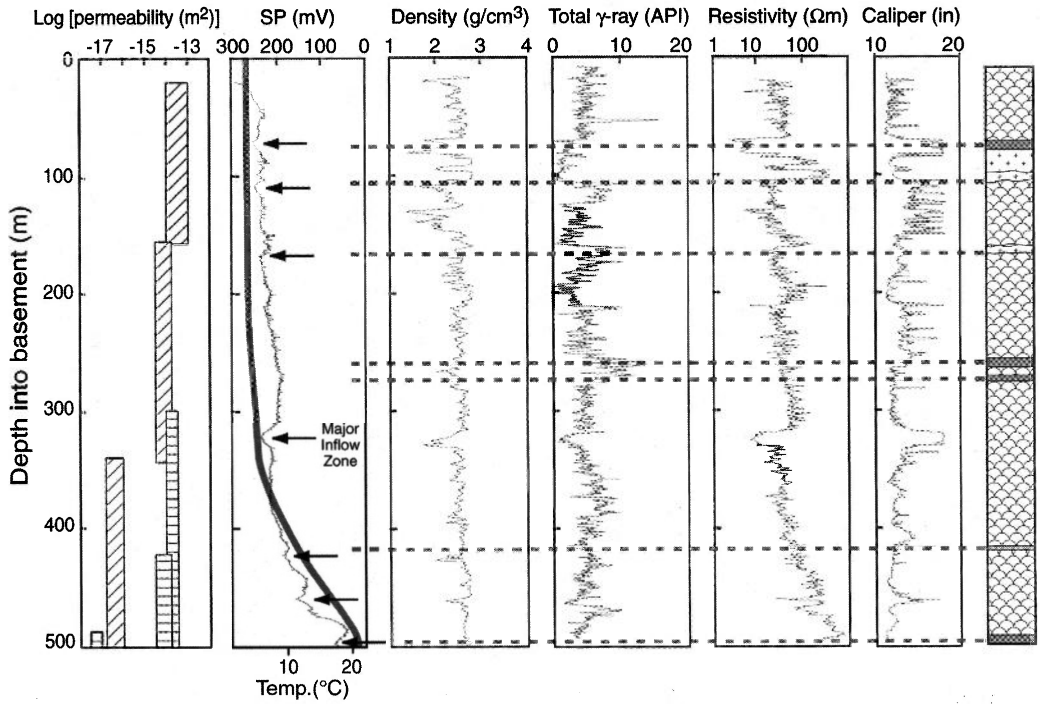

Figure 4. Comparison of lithology and geophysical log data from Hole 395A. Permeability data are from *Hickman et al.* [1984] and *Becker* [1990], graphic lithology and resistivity data are from *Mathews et al.* [1984], and other logging data are from *Detrick et al.* [1988]. Resistivity-decreasing-up sequences (bold, dashed lines) interpreted are to indicate individual effusive events, with greater porosity at the top. Temperature, spontaneous potential (SP), and bulk density data from *Becker et al.* [1998]. Concave-down temperature log (bold line) indicates flow of cold bottom water into the open hole at depth. Deflections in the SP log are interpreted to indicate locations of intervals into which water is being drawn into basement by differential pressure. Arrows illustrate correlations between these intervals and tops of resistivity units, suggesting that these are the most hydrologically active intervals of the formation. Note the relative thickness of these intervals compared to hydrologically less important intervals. Bulk density data were boxcar-filtered with a 3-m window to smooth small-scale variability.

industry to infer the locations of intervals within a borehole that receive or produce fluids. Deflections in the SP log (Figure 4) clearly correlate with the tops of individual resistivity sequences, suggesting that these thin intervals, interpreted independently on the basis of resistivity and lithologic data to have higher porosity, are also the most hydrologically active intervals. Many of these zones also correlate with intervals of low bulk density. The typical ratio in thicknesses of the most and least hydrologically active sections of this borehole is on the order of 1:10 to 1:100, suggesting that most of the fluid that entered the formation surrounding Hole 395A passed through a small fraction of the exposed rock.

Other Drill Holes

Space does not permit us to discuss all drill holes in detail, but results for other Holes 418A and 801C show similar relationships between basement lithology and alteration intensity [*Donelly et al.*, 1979; *Johnson*, 1979; *Jarrard et al.*, 1995; *Shipboard Scientific Party*, 2000]. Other drilled upper crustal sections (e.g., Holes 332, 418A, 597C, 843B, and 801C), covering a range of spreading rates and basement ages, also show similar sequences of alteration [*Andrews*, 1980; *Alt and Honnorez*, 1984; *Peterson et al.*, 1986; *Alt*, 1993; *Alt et al.*, 1992]. The transition from oxidative alteration (celadonite, Fe-oxyhydroxides) to non-oxidative alteration (saponite, pyrite) is developed in all sections of ages greater than 3.5 Ma. The earliest vein fills are sequences of Fe-oxyhydroxides, celadonitic clay, and smectite, while the late veins are zeolite-, sulfide- and carbonate-filled. Invariably, carbonate veins are the latest to form. Oxidative alteration assemblages, such as observed at Sites 395 and 417 [*Alt and Honnorez*, 1984; *Lawrence et al.*, 1978], indicate alteration at temperatures below 20°C. Later-stage smectite formed at temperatures of 30-50°C [*Alt and Honnorez*, 1984; *Lawrence et al.*, 1978]. Temperatures derived for late calcite veins vary between 5 and 40°C [e.g., *Alt*, 1993; *Lawrence*, 1979]. Higher temperatures of calcite formation (35 to 70°C) were deduced for sedimented ridge flanks [*Teagle et al.*, 1996; *Hunter et al.*, 1999] and reflect conductive reheating of the shallow basement at these sites. *Marescotti et al.* [2000] find that the transition between oxidative and non-oxidative alteration is somewhere between 1 and 3.5 Ma on the eastern flank of the Juan de Fuca Ridge flank, where sedimentation rates are high. In contrast, K-Ar dating of celadonite from the flank of the southern EPR, where sedimentation rate is low, suggests that oxidative alteration continued in 10 to 16 Ma crust – or up to 1000 km off axis [*Peterson et al.*, 1986].

Several examples demonstrate a significant local variability in basement alteration that probably reflects long-term fluid flow patterns. Rocks from Hole 417D drilled on a basement topographic high, are more fractured and altered than rocks from nearby Holes 417A and 418A [*Donnelly et al.*, 1979]. Similar to 504B/896A, the discrepancy in veining and alteration is believed to reflect the hydrogeological situation of focused and long-lived upflow at the location of the basement highs (417D, 896A). In Hole 801C, oxidized units intercalate with non-oxidized flows throughout the hole, and an age progression in alteration style is less obvious than in the other drilled sections [*Alt*, 1992; *Shipboard Scientific Party*, 2000]. A detailed discussion of all these drill holes is beyond the scope of this paper, but it is apparent that lithology, basement topography, and sedimentation history greatly affect the patterns and duration of fluid circulation.

Fluid Flow and Aging of Ocean Crust

Results from drilling indicate a common sequence of alteration in shallow oceanic crust, i.e. early oxidative alteration followed by alteration under non-oxidizing conditions. Interestingly, there is no simple relationship between the alteration sequence and age. Where the sedimentation rate is high, and hence fluid circulation becomes restricted relatively rapidly, the transition from oxidative to non-oxidative alteration is observed in very young crust (1-3.5 Myrs; *Marescotti et al.* [2000]). In areas where sedimentation rates are low, for example in the central Pacific, oxidative alteration may prevail in crust up to 10-16 Ma [*Peterson et al.*, 1986]. The progression from oxidative to non-oxidative alteration is hence not simply age-dependent, but is also influenced by factors that control the local fluid circulation. Age dating indicates that most alteration is completed after 10 to 15 Ma, despite the fact that fluid circulation in basement older than 15 Ma is required to explain the heat flow data. Prolonged seawater circulation has been invoked to account for the apparent correlation between basement age and carbonate abundance [*Alt and Teagle*, 1999].

Bulk permeability of the upper 100 m of basaltic crust formed at non-sedimented, mid-ocean ridges tends to decrease most rapidly within the first few million years of crustal evolution [*Fisher and Becker*, 2000]. The overall distribution of permeabilities within basaltic crust is broadly consistent with our understanding of alteration zones within shallow oceanic basement. The highest permeabilities are found within the region of dominantly oxidative alteration and high water/rock ratios, and lower values are found in a region of non-oxidative alteration and low water/rock ratios. But it is important to note that oxidative alteration may take place locally in crustal sections of generally low permeability. Such an example is Hole 735B in lower ocean crust that exhibits various zones of intense low-temperature veining and low-temperature rock alteration [*Bach et al.*, 2001; *Dick et al.*, 2000]. The overall alteration intensity in Hole 735B is an order of magnitude lower than in a volcanic ridge flank setting [*Bach et al.*, 2001], and this likely reflects the generally low permeability. Locally intensive seawater alteration, however, suggests that late-stage circulation of seawater in uplifted lower crust may penetrate surprisingly deep into the section. In contrast to volcanic ridge flanks, permeability in uplifted lower ocean crust is not controlled by the primary lithology, but by fractures and faults. It is interesting to note that the rough basement topography of amagmatically spread crust may promote continued basement-seawater interaction, which is largely inhibited by a sediment blanket covering volcanic ridge flanks [*Bach et al.*, 2001].

The restriction of significant oxidative alteration to the uppermost 300 m of the oceanic basement suggests that oxygenated fluids usually do not penetrate deep into the basement, probably because the oxidizing capacity gets exhausted rapidly along the fluid flow path. Furthermore, oxidation within the upper 300 m of basement is not pervasive, but is focused along fractures that acted as conduits for oxygenated seawater. Along fractures that formed during cooling of lava flows, red alteration halos are developed that grade into greenish and grayish zones, indicating oxygen consumption as the fluid moves into the rock. Oxidation halos are typically 10 to 20 times wider than the vein [*Andrews et al.*, 1977]. The development of these halos suggests diffusion-controlled transport away from the fluid conduits. Fractures without oxidized halos are likely related to faulting and compaction of the lava piles in off-axis environments. The gradation from oxidative to non-oxidative alteration in time and on different spatial scales suggests that oxidative alteration is a transient phenomenon of restricted spatial extent. Hence, the largest fraction of oceanic basement is habitable only by anaerobes.

Rates and Distribution Characteristics of Ridge Flank Circulation

Surveys on the flanks of numerous mid-ocean ridges reveal large regions where seafloor heat flow is suppressed relative to that predicted by conductive lithospheric cooling models [e.g., *Sclater et al.*, 1974; *Langseth et al.*, 1984; *Fisher et al.*, 1990; *Davis et al.*, 1992].

Langseth and Herman [1981] presented a one-dimensional ("well-mixed aquifer," WMA) model of lateral fluid and heat flow within a ridge flank that allows rough estimation of fluid specific discharge (volume flux/cross-sectional area) within a basement aquifer. Such estimates depend on the depth and thickness of the zone through which rapid flow occurs, the thermal conductivity of the basalt and sediment, and the distance between recharge and discharge sites. *Langseth and Herman* [1981] used the WMA model to estimate specific discharge in the Brazil Basin on the order of meters/year. *Baker et al.* [1991] applied the WMA model to the eastern Equatorial Pacific Ocean, yielding similar values. *Fisher and Becker* [2000] conducted an analysis of global heat flow data using the same model, and estimates of available driving forces, and calculated that flow rates of meters/year to tens of meters/year are required over large areas to explain the difference between observed and expected seafloor heat flow values.

Elderfield et al. [1999] analyzed several chemical tracers from basement waters on the east flank of the Juan de Fuca Ridge, and concluded that average linear velocities are on the order of meters per year. *Davis et al.* [1999] and *Stein and Fisher* [2000] completed numerical models of the same ridge flank and found that lateral specific discharge of basement fluid at meters/year to tens of meters/year is required to explain the observed suppression of heat flow. The average linear velocity (v_L) relates to specific discharge (q) as $v_L = q/n_e$, where n_e = effective porosity (the well connected pore space through which most fluid travels). Although the bulk porosity of uppermost oceanic crust may be close to 10% on many ridge flanks, the effective porosity is likely to be considerably lower [*Fisher and Becker*, 2000; *Wilcock and Fisher*, this volume]. Thus there is a discrepancy between geochemical and geothermal estimates of fluid flow rates on the east flank of the Juan de Fuca Ridge by a factor of 10-100. *Stein and Fisher* [2000] proposed that these estimates can be reconciled if diffusive loss of solutes, as is common within heterogeneous, fractured aquifers [e.g., *Sanford*, 1997], is considered. This interpretation is consistent with both variability in rock alteration and the restriction of high permeabilities to thin zones within uppermost basement, as described earlier.

A review of geological, geophysical, and geochemical data reveals that fluid flow is highly channelized and, at one time, only a small fraction of basement is communicating with the oceans. How can this interpretation be reconciled with heat flow measurements that indicate efficient mining of heat through hydrothermal convection away from the ridge axis? Heat flow (H) and fluid flow (F) are related by the equation $H=F/(c_p\ \Delta T)$, where c_p is the heat capacity of seawater (about 4 J K^{-1} kg^{-1} at temperatures below 200°C [*Bischoff and Rosenbauer*, 1985]) and ΔT is the temperature anomaly of the fluid, i.e. the difference between recharging and discharging fluid. Using this relationship, *Elderfield and Schultz* [1996] showed that water flux rates greater than 4×10^{12} m^3 yr^{-1} are required to account for a hydrothermal ridge flank heat flux of 7 TW by advection of low-temperature fluids ($\Delta T<15°C$).

What is the implication of these high fluid fluxes for residence times of fluids circulating in ridge flanks? If it is assumed that the area of the seafloor affected by advective cooling is 2×10^{14} m^2 (i.e., 2/3 of the ocean basins), the depth extent of flank circulation cells is 400 m [e.g., *Langseth et al.*, 1984], the effective porosity of the upper crust is 1 to 5%, then the steady state volume of basement fluid circulating in the ridge flanks is 8×10^{15} to 4×10^{16} m^3. Hence, to achieve flux rates of > 4×10^{12} m^3 yr^{-1}, fluid residence times of only 2 to 10 kyrs are required. For a flow rate of 1 to 10 m yr^{-1}, the average spacing between downflow and upflow zones must be 2 to 100 km. Basement outcrops are the most likely areas of fluid recharge and discharge [*Baker et al.*, 1991]. Although minor downflow in sediments has also been reported [*McDuff*, 1981], the rates of flow that occur through sediments are trivial compared to that needed to mine heat. If the fluids are allowed to penetrate deeper into the basement, longer residence times and greater lateral extents of off-axis circulation systems become viable. Alternatively, the fluid flow rates are much greater than 1-10 m/yr [*Stein and Fisher*, 2000]. Deeper circulation can be more efficient than shallow circulation in mining heat from ridge flanks, assuming that the difference in temperature between recharging and ambient (crustal) fluids scales with the depth of flow [*Rosenberg et al.*, 2000]. The chemistry of basement fluids sampled in 2.6 Ma Juan de Fuca Ridge flank crust may imply upflow of reacted fluids, which mix with seawater-like fluids in shallow aquifers [*Elderfield et al.*, 1999]. However, it remains difficult to understand how fluid penetrates deeply into the crust on ridge flanks without losing considerable energy that might otherwise be used to drive lateral flow.

SUMMARY

The lower crustal sections reviewed above show similarities in the way that tectonic and hydrothermal processes are related. In Hole 735B, a large fraction of the ductile shear zones were metamorphosed under granulite-facies conditions, i.e. without significant hydration of the igneous mineral assemblages [*Cannat et al.*, 1991; *Dick et al.*, 1991a, 2000]. In addition, greenschist-facies alteration is not volumetrically the most abundant alteration style in Hole 735B, but is very localized and generally quite sparse [*Dick et al.*, 2000; *Stakes et al.*, 1991], possibly reflecting the unusually rapid exhumation of Atlantis Bank basement [*Dick et al.*, 1991b]. Observations on drill core from Hess Deep suggest that plastic deformation is less important at faster spreading ridges where fluids penetrate into the lower crust along downward propagating fracture networks [*Manning et al.*, 1996]. Both the static alteration in the Hess Deep section, as well as dynamic recrystallization in slow spread lower crust, initially take place at very high temperatures (T>600°C), but later lower temperature overprint is developed as a consequence of tectonic unroofing.

At slow spreading rates, introduction of water into the lower ocean crust generally appears to be coupled to the development of deep fault zones [*Cannat et al.*, 1991; *Gillis et al.*, 1993; *Ito and Clayton*, 1983; *Mével and Cannat*, 1991; *Stakes et al.*, 1991; *Stakes and Vanko*, 1986]. This deep faulting allows fluids to penetrate into the upper mantle where reactions with mafic minerals may occur to form serpentine, magnetite, and hydrogen. Hydrogen can then possibly further react with CO and CO_2 to form methane and other hydrocarbons [e.g., *Horita and Berndt*, 1999]. If serpentinization and abiogenic generation of methane along slow spreading ridges is common, it may have major implications for the global carbon cycle, and for the distribution and extent of the subsurface biosphere.

Based on our synthesis of logging data, packer results, and core descriptions, we conclude that the observed permeability pattern is not the result of alteration-related cementation that has obscured the original pattern of permeability. In most cases, it is possible to link high degrees of alteration with zones that have high permeability that has persisted over the long-term. This is best seen in the permeability and logging data from Hole 504B and in the SP log from Hole 395A, but has also been observed in core samples from Holes 417D, 418A, and 504B [*Hamano*, 1979; *Johnson*, 1979; *Karato*, 1983]. *Johnson* [1979] and *Jarrard et al.* [1995] demonstrated that alteration can lower permeability due to clogging of microfractures by clay minerals. *Fisher and Becker* [2000] have argued that this fine-scale permeability may be typical of most of the upper crust, but it does not include the pathways responsible for the greatest fluid, heat and solute fluxes.

Pezard and Anderson [1989] used geochemical logging data to estimate the proportions of clayey alteration products in Hole 504B and found that high degrees of alteration are bound to zones of high permeability (i.e., low electrical resistivity). They concluded that certain massive lava flows may be efficient flow barriers, while breccias and highly fractured flows channelize fluid flow. Massive lava flows may have considerable lateral extension [*Gregg and Fornari*, 1998; *Macdonald et al.*, 1989] and hence effectively control lateral fluid flow in ridge flanks, particularly at fast spreading rates. Likely, these different lithological units maintain their fluid transmissive properties throughout most processes of crustal evolution. If this is so, then assessing permeability patterns and crustal fluid flow requires understanding the volcanic architecture of ocean crust [e.g., *Smith and Cann*, 1992] and its dependence on spreading and magma supply rates. Likewise, deformation due to lava flow loading [*Schouten and Denham*, 2000] will alter the permeability structure of young upper crust.

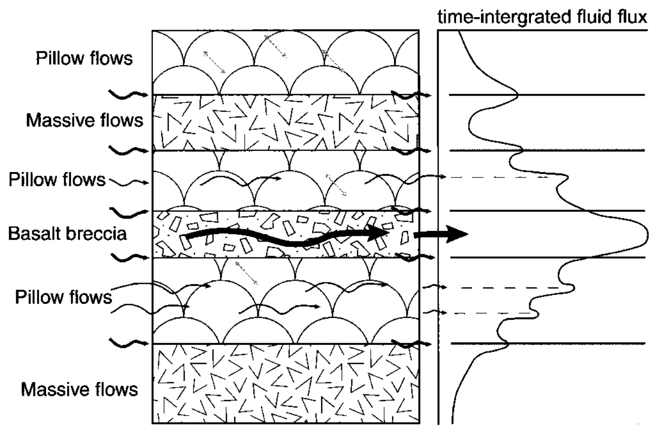

Figure 5. Schematic profile of pillow basalts, massive flows and a breccia zone. Time-integrated fluid flux (qualitatively deduced from the rock record) is highest in the breccia zone which is the zone of highest present-day permeability based on electrical resitivity logs and packer permeability measurements. Flow boundaries and pillow margins provide subordinate fluid pathways, while massive flows are fluid flow barriers. Small, gray arrows indicate slow (diffusion-controlled) exchange of fluid between the main channels and surrounding rock. Note that this sketch is not to scale: vertical scale is 1's to 10s of m for flow paths, 10s to 100s of m for flow barriers, and lateral scale would be 100s of m to 10s of km.

Our observations of crustal petrophysical properties and patterns of seafloor alteration indicate considerable heterogeneity in seafloor fluid flow. The meter-scale variability common to these measurements is not experimental noise, but indicates extreme actual heterogeneity in properties and the extent and nature of water/rock interaction.

Logging data and drill core descriptions suggest that permeability and fluid flow are controlled by different geological features at different scales (Figure 5). At a scale of tens to hundreds of meters, breccias appear to be most permeable, while massive flow units act as barriers to fluid flow. At a meter-scale, pillow margins, flow boundaries, and radial and concentric cooling cracks may control fluid flow, leading to the development of alteration halos along these features. Within these halos, mass transport is limited by diffusion and hence chemical gradients are large. At the smallest scale, fluid flow is focused along micro-cracks and grain boundaries. If these features are the only source of permeability, fluid flow may be extremely limited and the bulk of the rocks will remain virtually unaltered. Strong changes in vein mineralogy often observed along sealed micro-cracks indicate that fluid flow rates are extremely small and that diffuse transport is dominant in such rock-dominated systems.

The hypothesis that fluid flow is channelized and limited to highly permeable features has consequences for microbial ecosystems in ridge flanks. Although ridge flank crust constitutes an enormous volume and may be one of the largest habitats for microorganisms [*Macleod et al.*, 1994; *Furnes and Staudigel*, 1999], at one time only a small fraction of that volume is affected by fluid flow and hence habitable by microorganisms.

Acknowledgments. This research used data provided by the Ocean Drilling Program (ODP). The ODP is sponsored by the U.S. National Science Foundation (NSF) and participating countries under management of Joint Oceanographic Institutions (JOI), Inc. Kathy Gillis and Gretchen Früh-Green provided helpful reviews. We thank M. Sulanowska for help in figure preparation. Funding for this research was in part provided by NSF Grant OCE-9907070 (WB, SEH), and by CULAR/UCSC program (STB-UC 98-181) and NSF/OCE-9819242 (ATF). WB acknowledges support from J. Lamar Worzel and Penzance Endowed Funds. This is WHOI contribution number 10597.

REFERENCES

Abrajano, T.A., N.C. Sturchio, J.K. Böhlke, G.L. Lyon, R.J. Poreda, and C.M. Stevens, Methane-hydrogen gas seeps, Zambales Ophiolite, Philippines: Deep or shallow origin?, *Chem. Geol.*, 71, 211-222, 1988.

Agrinier, P., R. Hekinian, D. Bideau, and M. Javoy, O and H stable isotope compositions of oceanic crust and upper mantle rocks exposed in the Hess Deep near the Galapagos Triple Junction, *Earth Planet. Sci. Lett.*, 136, 183-196, 1995.

Agrinier, P., and M. Cannat, Oxygen-isotope constraints on serpentinization processes in ultramafic rocks from the Mid-Atlantic Ridge (23°N), in *Proc. ODP Sci. Results 153*, edited by J.A. Karson, M. Cannat, D.J. Miller, and D. Elthon, pp. 381-388, Ocean Drilling Program, College Station, 1997.

Alt, J.C., Low-temperature alteration of basalts from the Hawaiian Arch, Leg 136, in *Proc. ODP Sci. Results 136*, edited by R.H. Wilkens, *et al.*, pp. 133-146, Ocean Drilling Program, College Station, TX, 1993.

Alt, J.C., Subseafloor processes in mid-ocean ridge hydrothermal systems, in *Seafloor Hydrothermal Systems: Physical, Chemical, Biological and Geological Interactions*, edited by S.E. Humphris, R.A. Zierenberg, L.S. Mullineaux, and R.E. Thomson, pp. 85-114, AGU, Washington, D.C., 1995.

Alt, J.C., C. France-Lanord, P.A. Floyd, P. Castillo, and A. Galy, Low-temperature hydrothermal alteration of Jurassic ocean crust, Site 801, in *Proc. ODP, Sci. Results*, edited by R.L. Larson, and Y. Lancelot, pp. 415-427, Ocean Drilling Program, College Station, TX, 1992.

Alt, J.C., and J. Honnorez, Alteration of the upper oceanic crust, DSDP site 417: mineralogy and chemistry, *Contrib. Mineral. Petrol.*, 87, 149-169, 1984.

Alt, J.C., J. Honnorez, C. Laverne, and R. Emmermann, Hydrothermal alteration of a 1 km section through the upper oceanic crust. DSDP Hole 504B: Mineralogy, chemistry and evolution of seawater-basalt interactions, *J. Geophys. Res.*, 91, 309-335, 1986.

Alt, J.C., C. Laverne, D. Vanko, P. Tartarotti, D.A.H. Teagle, W. Bach, E. Zuleger, J. Erzinger, and J. Honnorez, Hydrothermal alteration of a section of upper oceanic crust in the eastern equatorial Pacific: A synthesis of results from DSDP/ODP Legs 69, 70, 83, 111, 137, 140, and 148 at Site 504B, in *Proc. ODP, Sci. Results*, edited by J.C. Alt, H. Kinoshita, L.B. Stokking, and P.J. Michael, pp. 417-434, Ocean Drilling Program, College Station, TX, 1996a.

Alt, J.C., and D.A.H. Teagle, Probing the TAG hydrothermal mound and stockwork: oxygen-isotopic profiles from deep ocean drilling, in *Proc. ODP Sci. Results 158*, edited by S.E. Humphris, P.M. Herzig, D.J. Miller, and R.A. Zierenberg, pp. 285-295, Ocean Drilling Program, College Station, TX, 1998.

Alt, J.C., and D.A.H. Teagle, The uptake of carbon during alteration of ocean crust, *Geochim. Cosmochim. Acta*, 63, 1527-1535. 1999.

Alt, J.C., D.A.H. Teagle, C. Laverne, D. Vanko, W. Bach, J. Honnorez, and K. Becker, Ridge flank alteration of upper oceanic crust in the eastern Pacific: A synthesis of results for volcanic rocks of Holes 504B and 896A., in *Proc. ODP, Sci. Results*, edited by J.C. Alt, H. Kinoshita, L.B. Stokking, and P.J. Michael, pp. 435-450, Ocean Drilling Program, College Station, TX, 1996b.

Anderson, R.N., and M.B. Zoback, Permeability, underpressures, and convection in the oceanic crust near the Costa Rica Rift, eastern equatorial Pacific, *J. Geophys. Res.*, 87, 2860-2868, 1982.

Anderson, R.N., M.D. Zoback, S.H. Hickman, and R.L. Newmark, Permeability versus depth in the upper oceanic crust: in situ measurements in DSDP Hole 504B, eastern equatorial Pacific, *J. Geophys. Res.*, 90, 3659-3669, 1985.

Andrews, A.J., R.L. Barnett, B.A.E. MacClement, W.S. Fyfe, G. Morrison, N.D., MacRae, and J. Starkey, Zeolite facies metamorphism, geochemistry, and some aspects of trace element redistribution in altered basalts of DSDP, Leg 37, in *Init. Repts. DSDP 37*, edited by F. Aumento, *et al.*, pp. 795-810, US Government Printing Office, Washington, D.C., 1977.

Andrews, A.J., Saponite and celadonite in layer 2 basalts, DSDP Leg 37, Contrib. Mineral. Petrol., 73, 323-340, 1980.

Bach, W., J.C. Alt, Y. Niu, S.E. Humphris, J. Erzinger, and H.J.B. Dick, The geochemical consequences of late-stage low-grade alteration of lower ocean crust at the SW Indian Ridge: Results from ODP Hole 735B (Leg 176), *Geochim. Cosmochim. Acta*, 65, 3267-3287, 2001.

Bach, W., N.R. Banerjee, H.J.B.Dick, and E.T. Baker, Discovery of ancient and active hydrothermal system along the southwest Indian Ridge 10-16°E. Geochemistry, Geophyscis, Geosystems 3(7), 10.1029/2001GC000279, 2002.

Bach, W., and S.E. Humphris, Relationship between the Sr and O isotope compositions of hydrothermal fluids and the spreading and magma supply rates of oceanic spreading centers, *Geology*, 27, 1067-1070, 1999.

Baker, E.T., G.J. Massoth, S.L. Walker, and R.W. Embley, A method for quantitatively estimating diffuse and discrete hydrothermal discharge, *Earth and Planetary Science Letters*, 118, 235-249, 1993.

Baker, P.A., P.M. Stout, M. Kastner, and H. Elderfield, Large-scale lateral advection of seawater through oceanic crust in the central equatorial Pacific, *Earth Planet. Sci. Lett.*, 105, 522-533, 1991.

Becker, K., In-situ bulk permeability of oceanic gabbros in Hole 735B, ODP Leg 118, in *Proc. ODP, Sci. Results*, edited by P.T. Robinson, R.P. Von Herzen, *et al.*, pp. 333-347, Ocean Drilling Program, College Station, Texas, 1991.

Becker, K., Permeability measurements in Hole 896A and implications for the lateral variability of upper crustal permeability at Sites 504 and 896, in *Proc. ODP, Sci. Res. 140*, edited by J.C. Alt, H. Kinoshita, and L. Stokking, Ocean Drilling Program, College Station, TX, 1996.

Becker, K., M.G. Langseth, and R.D. Hyndman, Temperature measurements in Hole 395A, Leg 78B, in *Init. Repts., DSDP, Volume 78B*, edited by R. Hyndman, and Salisbury, M, pp. 689-698, U. S. Govt. Printing Office, Washington, D. C, 1984.

Becker, K., H. Sakai, C. *et al.* Drilling deep into young oceanic crust, Hole 504B, Costa Rica Rift, *Rev. Geophys.*, 27, 79-102, 1989.

Becker, K., Permeability measurements in Hole 896A and implications for the lateral variability of upper crustal permeability at Sites 504 and 896, in *Proc. ODP, Sci. Res. 140*, edited by J.C. Alt, H. Kinoshita, and L. Stokking, Ocean Drilling Program, College Station, TX, 1996.

Becker, K., Measurement of the permeability of the upper oceanic crust at Hole 395A, ODP Leg 109, in *Proc. ODP, Sci. Results*, edited by R. Detrick, J. Honnorez, W.B. Bryan, T. Juteau, *et al.*, pp. 213-222, Ocean Drilling Program, College Station, TX, 1990.

Becker, K., L.B.S. Party, and E.E. Davis, Leg 174B revisits Hole 395A: logging and long-term monitoring of off-axis hydrothermal processes in young oceanic crust, *JOIDES Journal*, 24(1), 1-3,13, 1998.

Becker, K., H. Sakai, *et al.*, *Proc. ODP*, *Init. Repts. 111*, College Station, TX, 1988.

Bischoff, J.L., and W.E. Seyfried, Hydrothermal chemistry of seawater from 25° to 350°C, *Am. J. Sci.*, 278, 838-860, 1978.

Bischoff, J.L., and R.J. Rosenbauer, An empirical equation of state for hydrothermal seawater (3.2 percent NaCl), *Am. J. Sci.*, 285, 725-763, 1985.

Bowers, T.S., and H.P. Taylor, Jr., An intergrated chemical and stable-isotope model of the origin of mid-ocean ridge hot spring systems, *J. Geophys. Res.*, 90, 12,583-12,606, 1985.

Cann, J.R., M.G. Langseth, J. Honnorez, R.P. Von Herzen, S.M. White, *et al.*, *Init. Repts. DSDP 69*, U.S. Govt. Printing Office, Washington, D.C., 1983.

Cannat, M., C. Mével, M. Maia, C. Deplus, C. Durand, P. Gente, P. Agrinier, A. Belarouchi, G. Dubuisson, E. Humler, and J. Reynolds, Thin crust, ultramafic exposures, and rugged faulting patterns at the Mid-Atlantic Ridge (22°-24°N), *Geology*, 23, 49-52, 1995.

Cannat, M., C. Mével, and D. Stakes, Normal ductile shear zones at an oceanic spreading ridge: tectonic evolution of Site 735 gabbros (southwest Indian Ocean), *Proc. ODP Sci. Results*, 118, 415-429, 1991.

Carlson, R.L., Seismic velocities in the uppermost oceanic crust: Age dependence and the fate of layer 2A, *J. Geophys. Res.*, 103, 7069-7077, 1998.

Charlou, J.-L., and J.-P. Donval, Hydrothermal methane venting between 12°N and 26°N along the Mid-Atlantic Ridge, *J. Geophys. Res.*, 98, 9625-9642, 1993.

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 M. Whiticar, FlankFlux: an experiment to study the nature of hydrothermal circulation in young oceanic crust, *Can. J. Earth Sci.*, 29, 925-952, 1992.

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, Regional heat-flow variations across the sedimented Juan de Fuca Ridge eastern flank: constraints on lithospheric cooling and lateral hydrothermal heat transport, *J. Geophys. Res.*, 104(8), 17675-17688, 1999.

Delaney, J.R., D.W. Mogk, and M.J. Mottl, Quartz-cemented breccias from the mid-Atlantic ridge: samples of a high-salinity hydrothermal upflow zone, *J. Geophys. Res.*, 92, 9174-9192, 1987.

Deming, J.W., and J.A. Baross, Deep-sea smokers: windows to a subsurface biosphere?, *Geochim. Cosmochim. Acta*, 57, 3219-3230, 1993.

Detrick, R., J. Honnorez, W.B. Bryan, T. Juteau, *et al.*, *Proc. ODP*, *Init. Repts. 106/109*, Ocean Drilling Program, College Station, TX, 1988.

Dick, H.J.B., P.S. Meyer, S. Bloomer, S. Kirby, D. Stakes, and C. Mawer, Lithostratigraphic Evolution of an *In-Situ* Section of Oceanic Layer 3, in *Proc. ODP Sci. Results*, edited by R.P. Von Herzen, P.T. Robinson, *et al.*, pp. 439-538, Ocean Drilling Program, College Station, TX, 1991a.

Dick, H.J.B., J.H. Natland, *et al.* A long in situ section of the lower ocean crust: Results of ODP Leg 176 Drilling at the Southwest Indian Ridge, *Earth Planet. Sci. Lett.*, 179, 31-51, 2000.

Dick, H.J.B., H. Schouten, P.S. Meyer, D.G. Gallo, H. Bergh, R. Tyce, P. Patriat, K.T.M. Johnson, J. Snow, and A. Fisher, Tectonic evolution of the Atlantis II Fracture Zone, in *Proc. ODP Sci. Results*, edited by R.P. Von Herzen, *et al.*, pp. 359-398, 1991b.

Dilek, Y., A. Coulton, and S.D. Hurst, Serpentinization and hydrothermal veining in peridotites at Site 920 in the MARK area, in *Proc. ODP Sci. Results 153*, edited by J.A. Karson, M. Cannat, D.J. Miller, and D. Elthon, pp. 35-59, Ocean Drilling Program, College Station, 1997.

Donnelly, T.W., R.A. Pritchard, R. Emmermann, and H. Puchelt, The aging of oceanic crust: synthesis of the mineralogical and chemical results of Deep Sea Drilling Project, Legs 51 through 53, in *Init. Repts. DSDP*, edited by T.W. Donnelly, *et al.*, pp. 1563-1577, U.S. Government Printing Office, Washington, D.C., 1979.

Edmond, J.M., C. Measures, B. Mangum, B. Grant, F.R. Sclater, R. Collier, and A. Hudson, On the formation of metal-rich deposits at Ridge crests, *Earth Planet. Sci. Lett.*, 46, 19-30, 1979.

Edmonds, H.N., P.J. Michael, E.T. Baker, D.W. Graham, M. Vock, J. Snow, R. Mühe, D.P. Connelly, C.R. German, Healy0102 Scientific Party, and ARKVII/2 Scientific Party, Hot springs in a cold ocean: abundant hydrothermal venting on the ultra-slow-spreading Gakkel Ridge, Eos Trans. AGU, 82(47), Fall Meet. Suppl., Abstract OS32C-04, 2001.

Elderfield, H., and A. Schultz, Mid-ocean ridge hydrothermal fluxes and the chemical composition of the ocean, *Annu. Rev. Earth Planet. Sci.*, 24, 191-224, 1996.

Elderfield, H., C.G. Wheat, M.J. Mottl, C. Monnin, and B. Spiro, Fluid and geochemical transport through oceanic crust: a transect across the eastern flank of the Juan de Fuca Ridge, *Earth Planet. Sci. Lett.*, 172, 151-165, 1999.

Embley, R., M. Hobart, R. Anderson, and D. Abbott, Anomalous heat flow in the northwest Atlantic, a case for continued hydrothermal circulation in 80 MY crust, *J. Geophys. Res.*, 88, 1067-1074, 1983.

Fisher, A.T., Permeability within basaltic oceanic crust, *Rev. Geophys.*, 36, 143-182, 1998.

Fisher, A.T., and K. Becker, Channelized fluid flow in oceanic crust reconciles heat-flow and permeability data, *Nature*, 403, 71-74, 2000.

Fisher, A.T., K. Becker, T.N. Narasimhan, M.G. Langseth, and M.J. Mottl, Passive, off-axis convection through the southern flank of the Costa Rica Rift, *J. Geophys. Res.*, 95, 9343-9370, 1990.

Fisk, M.R., S.J. Giovannoni, and I.H. Thorseth, The extent of microbial life in volcanic crust of the ocean basins, *Science*, 281, 978-980, 1998.

Früh-Green, G.L., A. Plas, and L.N. Dell'Angelo, Mineralogic and stable isotope record of polyphase alteration of upper crustal gabbros of the East Pacific Rise (Hess Deep, Site 894), in *Proc. ODP Sci. Results 147*, edited by C. Mevel, K.M. Gillis, J.F. Allan, and P.S. Meyer, pp. 235-254, Ocean Drilling program, College Station, 1996a.

Früh-Green, G.L., A. Plas, and C. Lecuyer, Petrologic and stable isotopic constraints on hydrothermal alteration and serpentinization of the EPR shallow mantle at Hess Deep, Site 895, in *Proc. ODP Sci. Results 147*, edited by C. Mevel, K.M. Gillis, J.F. Allan, and P.S. Meyer, pp. 109-163, Ocean Drilling program, College Station, 1996b.

Furnes, H., K. Muehlenbachs, T. Torsvik, I.H. Thorseth, and O. Tumyr, Microbial fractionation of carbon isotopes in altered basaltic glass from the Atlantic Ocean, Lau Basin and Costa Rica Rift, *Chem. Geol.*, 173, 313-330, 2001.

Furnes, H., and H. Staudigel, Biological mediation in ocean crust alteration: how deep is the deep biosphere, *Earth Planet. Sci. Lett.*, 166, 97-103, 1999.

German, C.R., G.P. Klinkhammer, and M.D. Rudnicki, The Rainbow hydrothermal plume, 36°15'N, MAR, *Geophys. Res. Lett.*, 23, 2979-2982, 1996.

German, C.R., E.T. Baker, C. Mevel, K. Tamaki, and F.S. Team, Hydrothermal activity along the southwest Indian ridge, *Nature*, 395, 490-493, 1998.

German, C.R., and L.M. Parson, Distribution of hydrothermal activity along the Mid-Atlantic Ridge: interplay between magmatic and tectonic controls, *Earth Planet. Sci. Lett.*, 160, 327-341, 1998.

Gillis, K.M., Controls on hydrothermal alteration in a section of fast-spreading oceanic crust, *Earth Planet. Sci. Lett.*, 134, 473-489, 1995.

Gillis, K.M., and P.T. Robinson, Patterns and processes of alteration in the lavas and dikes of the Troodos ophiolite, Cyprus, *Journal of Geophysical Research*, 95, 21523-21548, 1990.

Gillis, K.M., G. Thompson, and D.S. Kelley, A view of the lower crustal component of hydrothermal systems at the Mid-Atlantic Ridge, *J. Geophys. Res.*, 98, 19597-19619, 1993.

Goldberg, D., C. Broglia, and K. Becker, Fracturing, alteration, and permeability: in-situ properties in Hole 735B, Atlantis II Fracture Zone, southwest Indian Ridge, in *Proc. ODP, Sci. Results*, edited by P.T. Robinson, R.P. Von Herzen, *et al.*, pp. 261-270, Ocean Drilling Program, College Station, Texas, 1991.

Gregg, T.K.P., and D.J. Fornari, Long submarine lava flows: Observations and results from numerical modeling, *J. Geophys. Res.*, 103, 27517-27531, 1998.

Hamano, Y., Physical properties of basalts from Holes 417D and 418A, in *Initial Reports of the Deep Sea Drilling Project*, edited by T.W.D.*et al.*, pp. 1457-1466, U.S. Government Printing Office, Washington, D.C., 1979.

Hart, S.R., and H. Staudigel, The control of alkalies and uranium in seawater by ocean crust alteration, *Earth Planet. Sci. Lett.*, 58, 202-212, 1982.

Hébert, R., A.C. Adamson, and S.C. Komor, Metamorphic Petrology of ODP Leg 106/109, Hole 670A, serpentinized peridotites: serpentinization processes at a slow-spreading ridge environment, in *Proc. ODP*, *Scientific Results 106/109*, edited by R. Detrick, *et al.*, pp. 103-116, Ocean Drilling Program, College Station, TX, 1990.

Hickman, S.H., M. Langseth, and J.F. Svitek, In situ permeability and pore pressure measurements near the Mid-Atlantic Ridge, Deep Sea Drilling Project Hole 395A, in *Init. Repts. DSDP 78B*, edited by R.D. Hyndman, M.H. Salisbury, *et al.*, pp. 699-708, U.S. Govenrment Printing Office, Washington, D.C., 1984.

Holden, J.F., M. Summit, and J.A. Baross, Thermophilic and hyperthermophilic microorganisms in 3-30°C hydrothermal fluids following a deep-sea volcanic eruption, *FEMS Microbiology Ecology*, 25, 33-41, 1998.

Honnorez, J., J.C. Alt, and S.E. Humphris, Vivisection and autopsy of active and fossil hydrothermal alterations of basalt beneath and within the TAG hydrothermal mound, in *Proc. ODP Sci. Results 158*, edited by S.E. Humphris, P.M. Herzig, D.J. Miller, and R.A. Zierenberg, pp. 231-254, Ocean Drilling Program, College Station, TX, 1998.

Horita, J., and M.E. Berndt, Abiogenic methane formation and isotopic fractionation under hydrothermal conditions, *Science*, 285, 1055-1057, 1999.

Houtz, R., and J. Ewing, Upper crustal structure as a function of plate age, *J. Geophys. Res.*, 81, 2490-2498, 1976.

Huang, P.Y., and S.C. Solomon, Centroid depths of mid-ocean ridge earthquakes: Dependence on spreading rate, *J. Geophys. Res.*, 93, 13445-13477, 1988.

Humphris, S.E., *et al.*, The internal structure of an active seafloor massive sulphide deposit, *Nature*, 377, 713-716, 1995.

Humphris, S.E., and M.K. Tivey, A synthesis of geological and geochemical investigations of the TAG hydrothermal field: insights into fluid-flow and mixing processes in a hydrothermal system, in *Ophiolites and Oceanic Crust*, edited by Y. Dilek, E.M. Moores, D. Elthon, and A. Nicolas, pp. 213-235, Geological Society of America, Special Paper, Boulder, CO, 2000.

Hunter, A.G., P.D. Kempton, and P. Greenwood, Low-temperature fluid-rock interaction – an isotopic and mineralogical perspective of upper crustal evolution, eastern flank of the Juan de Fuca Ridge (JdFR), ODP Leg 168, *Chem. Geol.*, 155, 3-28, 1999.

Ito, E., and R.N. Clayton, Submarine metamorphism of gabbros from the Mid-Cayman Rise: an oxygen isotopic study, *Geochim. Cosmochim. Acta*, 47, 535-546, 1983.

Jacobson, R.S., Impact of crustal evolution on changes of the seismic properties of the uppermost ocean crust, *Rev. Geophys.*, 30, 23-42, 1992.

James, R.H., and H. Elderfield, The chemistry of ore-forming fluids and mineral precipitation rates in active hydrothermal sulphide deposit on the Mid-Atlantic Ridge, *Geology*, 24, 1147-1150, 1996.

Janecky, D.R., and W.E. Seyfried, Jr., Hydrothermal serpentinization of peridotite within the oceanic crust: Experimental investigations of mineralogy and major element chemistry, *Geochim. Cosmochim. Acta*, 50, 1357-1378, 1986.

Jannasch, H.W., Microbial interactions with hydrothermal fluids, in *Seafloor Hydrothermal Systems*, edited by S.E. Humphris, R.A. Zierenberg, L.S. Mullineaux, and R.E. Thomson, pp. 273-296, American Geophysical Union, Washington, DC, 1995.

Jarrard, R.D., R.L. Larson, A.T. Fisher, and L.J. Abrams, Geophysical aging of oceanic crust: evidence from Hole 801C, in *Proc. ODP, Sci. Res. 125*, edited by J.A. Haggerty, I.P. Silva, F. Rack, and M.K. McNutt, pp. 649-662, Ocean Drilling Program, College Station, TX, 1995.

Johnson, D.M., Crack distribution in the upper oceanic crust and its effects upon seismic velocity, seismic structure, formation permeability, and fluid circulation, in *Init. Repts. DSDP 51-53*, edited by T.W.Donelly *et al.*, pp. 1479-1490, U.S. Government Printing Office, Washington, D.C., 1979.

Karato, S., Physical properties of basalts from Deep Sea Drilling Project Hole 504B, Costa Rica Rift, in *Init. Repts. DSDP 69*, edited by J.R. Cann, *et al.*, pp. 687-695, U.S. Government Printing Office, Washington, D.C., 1983.

Karl, D.M., Ecology of free-living, hydrothermal vent microbial communities, in *Microbiology of Deep-Sea Hydrothermal Vents*, edited by D.M. Karl, pp. 35-123, CRC Press, 1995.

Karson, J.A., and H.J.B. Dick, Tectonics of Ridge-transform intersections at the Kane Fracture Zone, *Mar. Geophys. Res.*, 6, 51-98, 1983.

Karson, J.A., and P.A. Rona, Block-tilting, transfer faults, and structural control of magmatic and hydrothermal processes in the TAG area, Mid-Atlantic Ridge 26°N, *Geol. Soc. Am. Bull.*, 102, 1635-1645, 1990.

Kelley, D.S., Methane-rich fluids in the oceanic crust, *J. Geophys. Res.*, 101, 2943-2962, 1996.

Kelley, D.S., Fluid evolution in slow-spreading environments, in *Proc. ODP Sci. Results 153*, edited by J.A. Karson, M. Cannat, D.J. Miller, and D. Elthon, pp. 399-415, Ocean Drilling Program, College Station, 1997.

Kelley, D.S., and G.L. Früh-Green, Abiogenic methane in deep-seated mid-ocean ridge environments: insights from stable isotope analyses, *J. Geophys. Res.*, 104, 10439-10460, 1999.

Kelley, D.S., K.M. Gillis, and G. Thompson, Fluid evolution in submarine magma-hydrothermal systems at the Mid-Atlantic Ridge, *J. Geophys. Res.*, 98, 19579-19596, 1993.

Kelley, D.S., J.A. Karson, D.K. Blackman, G.L. Früh-Green, D.A. Butterfield, M.D. Lilley, E.J. Olson, M.O. Schrenk, K.K. Roe, G.T. Lebon, P. Rivizzigno, An off-axis hydrothermal vent field near the Mid-Atlantic Ridge at 30 degrees N, *Nature*, 412, 127-128, 2001.

Kleinrock, M.C., and S.E. Humphris, Structural controls on the localization of seafloor hydrothermal activity at the TAG active mound, Mid-Atlantic Ridge, *Nature*, 382, 149-153, 1996.

Langseth, M.G., and B.M. Herman, Heat transfer in the oceanic crust of the Brazil Basin, *J. Geophys. Res.*, 86, 10805-10819, 1981.

Langseth, M.G., R.D. Hyndman, K. Becker, S.H. Hickman, and M. Salisbury, The hydrogeological regime of isolated sediment ponds in mid-ocean ridges, in *Init. Repts. DSDP 78*, edited by B. Biju-Duval, *et al.*, pp. 825-837, U. S. Government Printing Office, Washington, D.C., 1984.

Lawrence, J.R., J.J. Drever, and M. Kastner, Low temperature alteration of basalts predominates at DSDP Site 395, in *Init. Repts. DSDP 37*, edited by W.G. Melson, *et al.*, pp. 609-612, US Government Printing Office, Washington, D.C., 1978.

Lawrence, J.R. Temperatures of formation of calcite veins in the basalts from Deep Sea Drilling Project Holes 417A and 417D. in *Init. Repts. DSDP 51-53*, edited by T.W. Donnelly, *et al.*, pp. 1183-1184, U.S. Government Printing Office, Washington, D.C., 1979.

Lecuyer, C., and B. Reynard, High-temperature alteration of oceanic gabbros by seawater (Hess Deep, Ocean drilling Program Leg 147): Evidence from oxygen isotopes and elemental fluxes, *J. Geophys. Res.*, 101, 15883-13897, 1996.

Lister, C.R.B., The basic physics of water penetration into hot rocks, in *Hydrothermal processes at seafloor spreading centers*, edited by P.A. Rona, K. Boström, L. Laubier, and K.L. Smith, Jr., pp. 141-168, Plenum Press, New York, 1983.

Lowell, R.P., P. Van Cappellen, and L.N. Germanovich, Silica precipitation in fractures and the evolution of permeability in hydrothermal upflow zones, *Science*, 260, 192-194, 1993.

Macdonald, K.C., R. Haymon, and A. Shor, A 220 km^2 recently erupted lava field on the East Pacific Rise near lat 8°S, *Geology*, 17, 212-216, 1989.

Macleod, G., C. McKeown, A.J. Hall, and M.J. Russell, Hydrothermal and oceanic pH conditions of possible relevance to the origin of life, *Origins of Life & Evolution of the Biosphere*, 24(1), 19-41, 1994.

Manning, C.E., and S. Ingebritsen, Geological implications of a permeability-depth curve for the continental crust, *Geology*, 27, 1107-1110, 1999.

Manning, C.E., P.E. Weston, and K.I. Mahon, Rapid high-temperature metamorphism of East Pacific Rise gabbros from Hess Deep, *Earth Planet. Sci. Lett.*, 144, 123-132, 1996.

Marescotti, P., D.A. Vanko, and R. Cabella, From oxidizing to reducing alteration: mineralogical variations in pillow basalts from the east flank of the Juan de Fuca Ridge, in *Proc. ODP. Sci. Results 168*, edited by A. Fisher, E.E. Davis, and C. Escutia, pp. 119-136, Ocean Drilling Program, College Station, TX, 2000.

Mathews, M., M.H. Salisbury, and R.D. Hyndman, Basement logging on the Mid-Atlantic Ridge, Deep Sea Drilling Project Hole 395A, in *Init. Repts. DSDP 78*, edited by B. Biju-Duval, *et al.*, pp. 717-730, U. S. Government Printing Office, Washington, D.C., 1984.

McCollom, T.M., and E.L. Shock, Geochemical constraints on chemolithoautotrophic metabolism by microorganisms in seafloor hydrothermal systems, *J. Geophys. Res.*, 61, 4375-4391, 1997.

McDuff, R.E., Major cation gradients in DSDP interstitial waters: the role of diffusive exchange between seawater and upper oceanic crust, *Geochim. Cosmochim. Acta*, 45, 1705-1713, 1981.

Mével, C., and M. Cannat, Lithospheric stretching and hydrothermal processes in oceanic gabbros from slow spreading ridges, in *Ophiolite Genesis and the Evolution of the Oceanic Lithosphere*, edited by T. Peters, A. Nicolas, and R.G. Coleman, pp. 293-312, Kluwer Academics, Dordrecht, 1991.

Mével, C., M. Cannat, P. Gente, E. Marion, J.M. Auzende, and J.A. Karson, Emplacement of deep crustal and mantle rocks on the west median valley wall of the MARK area (MAR, 23° N), *Tectonophysics*, 190, 31-53, 1991.

Mottl, M.J., and C.G. Wheat, Hydrothermal circulation through mid-ocean ridge flanks: Fluxes of heat and magnesium, *Geochim. Cosmochim. Acta*, 58, 2225-2237, 1994.

Muehlenbachs, K., The alteration and aging of the basaltic layer of the seafloor: oxygen isotope evidence from DSDP/IPOD Legs 51, 52, and 53, in *Init. Repts. DSDP 51-53*, edited by T. Donnelly, *et al.*, pp. 1159-1167, U.S. Government Printing Office, Washington, D.C., 1979.

Noel, M., Heat flow, sediment faulting and pore water advection in the Madeira abyssal plain, *Earth Planet. Sci. Lett.*, 73, 398-406, 1985.

Peterson, C., R. Duncan, and K.F. Scheidegger, Sequence and longevity of basalt alteration at Deep Sea Drilling Project Site 597, in *Init. Repts. DSDP 92*, edited by M. Leinen, *et al.*, pp. 505-515, US Govt. Printing Office, Washington, D.C., 1986.

Pezard, P.A., and R.N. Anderson, Morphology and alteration of the upper oceanic crust from in situ electrical experiments in DSDP/ODP Hole 504B, in *Proc. ODP*, *Sci. Results*, edited by K. Becker, *et al.*, pp. 133-146, Ocean Drilling Program, College Station, TX, 1989.

Phipps Morgan, J., and Y.J. Chen, The genesis of oceanic crust: Magma injection, hydrothermal circulation, and crustal flow, *J. Geophys. Res.*, 98, 6283-6298, 1993.

Prichard, H.M., A petrographic study of the process of serpentinization in ophiolites and the ocean crust, *Contrib. Mineral. Petrol.*, 68, 231-241, 1979.

Richardson, S.H., S.R. Hart, and H. Staudigel, Vein mineral ages of old oceanic crust, *J. Geophys. Res.*, 85, 7195-7200, 1980.

Rona, P.A., and D.A. Trivett, Discrete and diffuse heat transfer at ASHES vent field, *Earth Planet. Sci. Lett.*, 109, 57-71, 1992.

Rosenberg, N.D., A.T. Fisher, and J.S. Stein, Large-scale lateral heat and fluid transport in the seafloor: revisiting the well-mixed aquifer model, *Earth Planet. Sci. Lett.*, 182, 93-101, 2000.

Sanford, W.E., Correcting for diffusion in Carbon-14 dating of ground water, *Ground Water*, 35, 357-361, 1997.

Schouten, H, and C.R. Denham, Comparison of volcanic contruction in the Troodos ophiolite and oceanic crust using paleomagnetic inclinations from Cyprus Crustal Study Project (CCSP) CY-1 and CY1A and Ocean Drilling Program (DOP) 504B drill cores, in *Ophiolites and Ocean Crust: New Insights From Field Studies and the Ocean Drilling Program*, edited by Y. Dilek, E.M. Moores, D. Elthon, and A. Nicolas, Geological Society of America Special Paper 349, pp. 181-194, 2000.

Schultz, A., J.R. Delaney, and R.E. McDuff, On the partitioning of heat flux between diffuse and point source seafloor venting, *J. Geophys. Res.*, 97, 12299-12314, 1992.

Schultz, A., and H. Elderfield, Controls on the physics and chemistry of seafloor hydrothermal circulation, Phil. Trans. R. Soc. London, A355, 384-422, 1997.

Sclater, J.G., C. Jaupart, and D. Galson, The heat flow through oceanic and continental crust and the heat loss of the Earth, *Rev. Geophys. Space Phys.*, 18, 269-311, 1980.

Sclater, J.G., R.P. Von Herzen, D.L. Williams, R.N. Anderson, and K. Klitgord, The Galapagos Spreading Center: heat flow on the north flank, *Geophys. J. R. Astr. Soc.*, 38, 609-626, 1974.

Seewald, J.S., and W.E. Seyfried, Jr., The effect of temperature on metal mobility in subseafloor hydrothermal systems: constraints from basalt alteration experiments, *Earth Planet. Sci. Lett.*, 101, 388-403, 1990.

Seyfried, W.E., and K. Ding, Phase equilibria in subseafloor hydrothermal systems: a review of the role of redox, temperature, pH and dissolved Cl on the chemistry of hot spring fluids on mid-ocean ridges, in *Seafloor Hydrothermal Systems*, edited by S.E. Humphris, R.A. Zierenberg, L.S. Mullineaux, and R.E. Thomson, pp. 248-272, American Geophysical Union, Washington, DC, 1995.

Shipboard Scientific Party, Site 735B, in *Proc. ODP*, *Init. Repts.*, *176*, edited by H.J.B. Dick, J.H. Natland, D.J. Miller, *et al.*, pp. 1-314, [CD-ROM]. Available from: Ocean Drilling Program, Texas A&M University, College Station, TX 77845-9547, U.S.A., 1999.

Shipboard Scientific Party, Leg 185 summary: inputs to the Izu-Mariana subduction system, in *Proc. ODP, Init. Repts. 185*, edited by T. Plank, *et al.*, Ocean Drilling Program, Texas A&M University, College Station, TX, 2000.

Shock, E.L., Chemical environments of submarine hydrothermal systems, in *Marine Hydrothermal Systems and the Origin of Life*, edited by N.G. Holm, pp. 67-107, Kluwer Academic, Dordrecht, 1992.

Shock, E.L., and M.D. Schulte, Organic synthesis during fluid mixing in hydrothermal systems, *J. Geophys. Res.*, 103, 28513-28527, 1998.

Smith, D.K., and J.R. Cann, The role of seamount volcanism in crustal construction at the Mid-Atlantic Ridge (24°-30°N), *J. Geophys. Res.*, 97, 1645-1658, 1992.

Sohn, R.A., D.J. Fornari, K.L. Von Damm, J.A. Hildebrand, and S.C. Webb, Seismic and hydrothermal evidence for a cracking event on the East Pacific Rise crest at 9°50'N, *Nature*, 396, 159-161, 1998.

Stakes, D., C. Mével, M. Cannat, and T. Chaput, Metamorphic stratigraphy of Hole 735B, in *Proc. ODP Sci. Results*, edited by R.P. Von Herzen, and P.T. Robinson, pp. 153-180, Ocean Drilling Program, College Station, TX, 1991.

Stakes, D., and D.A. Vanko, Multistage hydrothermal alteration of gabbroic rocks from the failed Mathematician Ridge, *Earth Planet. Sci. Lett.*, 79, 75-92, 1986.

Staudigel, H., S.R. Hart, and S.H. Richardson, Alteration of the oceanic crust: processes and timing, *Earth Planet. Sci. Lett.*, 52, 311-327, 1981.

Stein, C.A., and S. Stein, Constraints on hydrothermal heat flux through the oceanic lithosphere from global heat flow, *J. Geophys. Res.*, 99 (B2), 3081-3095, 1994.

Stein, J., and A.T. Fisher, Lateral hydrothermal circulation beneath the eastern flank of Juan de Fuca Ridge: thermal, chemical and modeling constraints, *Eos, Trans. AGU*, 81, F481, 2000.

Teagle, D.A.H., J.C. Alt, W. Bach, A. Halliday, and J. Erzinger, Alteration of the upper ocean crust in a ridge flank hydrothermal up-flow zone: Mineral, chemical, and isotopic constraints from ODP Hole 896A., in *Proc. ODP, Sci. Results*, edited by J.C. Alt, H. Kinoshita, L.B. Stokking, and P.J. Michael, pp. 119-150, Ocean Drilling Program, College Station, TX, 1996.

Teagle, D.A.H., J.C. Alt, and A.N. Halliday, Tracing the chemical evolution of fluids during hydrothermal recharge: Constraints from anhydrite recovered in ODP Hole 504B, *Earth Planet. Sci. Lett.*, 155, 167-182, 1998.

Tivey, M.K., S.E. Humphris, G. Thompson, M.D. Hannington, and P.A. Rona, Deducing patterns of fluid flow and mixing within the active TAG mound using mineralogical and geochemical data, *J. Geophys. Res.*, 100, 12,527-12,555, 1995.

Toomey, D.R., S.C. Solomon, G.M. Purdy, and M.H. Murray, Microearthquakes beneath the median valley of the Mid-Atlantic Ridge near 23°N; hypocenters and focal mechanism, *J. Geophys. Res.*, 90, 5443-5458, 1985.

Torsvik, T., H. Furnes, K. Muehlenbachs, I.H. Thorseth, and O. Tumyr, Evidence for microbial activity at the glass-alteration interface in oceanic basalts, *Earth Planet. Sci. Lett.*, 162, 165-176, 1998.

Vanko, D.A., and D.S. Stakes, Fluids in oceanic layer 3: evidence from veined rocks, Hole 735B, Southwest Indian Ridge, in *Proc. ODP Sci. Results*, edited by R.P. Von Herzen, and P.T. Robinson, pp. 181-215, Ocean Drilling Program, College Station, TX, 1991.

Von Damm, K.L., S.E. Oosting, R. Kozlowski, L.G. Buttermore, D.C. Colodner, H.N. Edmonds, J.M. Edmond, and J.M. Grebmeier, Evolution of East Pacific Rise hydrothermal vent fluids following a volcanic eruption, *Nature*, 375, 47-50, 1995.

Wheat, C.G., and M.J. Mottl, Composition of pore and spring waters from baby bare: Global implications of geochemical fluxes from a ridge flank hydrothermal system, *Geochim. Cosmochim. Acta*, 64, 629-642, 2000.

Wilcock, W.S.D., and J.R. Delaney, Mid-ocean ridge sulfide deposits: Evidence for heat extraction from magma chambers or cracking fronts?, *Earth Planet. Sci. Lett.*, 145, 49-65, 1996.

W. Bach, Department of Marine Chemistry and Geochemistry, Woods Hole Oceanographic Institution, 360 Woods Hole Road, Woods Hole, MA 02543, USA

A.T. Fisher, Earth Sciences Department and Institute for Geophysics and Planetary Physics, University of Santa Cruz, CA 95064, USA

S.E. Humphris, Department of Geology and Geophysics, Woods Hole Oceanographic Institution, 360 Woods Hole Road, Woods Hole, MA 02543, USA