

Evolution of Hydrothermal Circulation

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Abstract

The transfer of heat and mass through hydrothermal circulation is a fundamental Earth system influencing the accretion and aging of oceanic crust, and shapes tectonic, magmatic, microbial and biogeochemical properties on a global scale. Understanding hydrothermal circulation has societal relevance through its relationship with geodynamic processes, the deep biosphere, crustal alteration, global geochemical cycles, and is a prerequisite to the geological sequestration of greenhouse gases within the oceanic crust. Many aspects of hydrothermal circulation, and its evolution, are addressable through scientific drilling. Factors important to the vigor, style, and evolution of hydrothermal circulation include local permeability structure, background heat flow, bathymetric relief, and the nature of exposed basement or sediment cover, lithology, and thickness. We contend that the best route toward understanding hydrothermal circulation, its evolution, and other geologically important processes is to drill a series of holes along a crustal “flow line” and craft a multidisciplinary research program involving surface and subsurface studies (mapping, seismic, heat flow, chemistry, microbiology, observatories). Such a series of boreholes allows driving forces and permeability to be investigated in a systematic way and will elucidate relationships between hydrothermal circulation, and the physical, chemical and biological properties of oceanic crust. An overarching objective of this research is to develop an integrated physical, chemical, and biological model of ridge flank hydrothermal systems and its evolution with time.

Introduction

Hydrothermal circulation is an intrinsic characteristic of seafloor influencing the accretion and aging of oceanic crust, and impacting tectonic, magmatic, microbial and biogeochemical properties and processes on a global scale. Understanding hydrothermal circulation is fundamental to achieving high priority goals listed under two of the three primary themes in the Initial Science Plan (ISP) to IODP, the Deep Biosphere and Subseafloor Ocean, and Solid Earth Cycles and Geodynamics. Fluid flow is also relevant to the third IODP science theme discussed in the ISP, Environmental Change, through its influence on hydrate systems and climatically sensitive isotopes within sediments. Understanding hydrothermal circulation has societal relevance through its role in fundamental Earth processes and because of the potential for geological sequestration of greenhouse gases within the oceanic crust [e.g., *Goldberg and Slagle, 2008*].

Hydrothermal chemical exchange between the crust and oceans is a basic component of global geochemical cycles, affecting the composition of the crust, oceans and, through subduction, the mantle. Seawater chemistry reflects the balance between riverine, hydrothermal and sedimentary fluxes to and from the oceans. Since the magnitudes of these fluxes depend on

key global geologic processes including plate tectonics, climatic conditions, and biological processes, temporal variations in seawater chemistry can provide insights into fundamental Earth processes. However, reconstructing reliable records of past seawater chemistry and deconvolving the processes responsible for temporal variations in such records remain major challenges. Recent studies have demonstrated that altered sections of oceanic basement can be used to reconstruct past seawater chemistry and to investigate the processes responsible for changing ocean chemistry [Coogan, 2009, Vance *et al.* 2009]. Improved understanding of the controls (e.g. spreading rate, crustal age, and sedimentation history) on the nature and extent of hydrothermal alteration, combined with estimates of past crustal production, could be used to predict past hydrothermal contributions to the oceans and estimate the riverine fluxes required to balance past variations in ocean chemistry.

The temporal evolution of hydrothermal circulation is poorly understood, although it is thought that fluxes are generally greatest within the young seafloor, and decrease with time and increasing distance from the ridge. Near seafloor spreading centers, hydrothermal circulation dominates heat transfer, accounting for essentially all of the expected latent heat and heat of cooling within the upper two kilometers of crust [Baker, 2007]. Where the seafloor is young, basement permeability is high and the volcanic rocks are exposed to the ocean across large areas, numerous pathways exist for fluids to enter and exit the crust. The extent of crustal heat loss by fluid flow decreases with time as lithospheric heat input from below and crustal permeability diminish, and the accumulation of low permeability sediment isolates the crustal aquifer.

Many aspects of hydrothermal circulation and its impacts on crustal evolution remain poorly understood. For example:

- How long does geothermally and geochemically significant flow continue through the oceanic crust and what controls the waning of this flow?
- What is the nature of the transition between ridge-axis and ridge-flank hydrothermal circulation? Are these two systems isolated, or are mass, heat, solutes, and microbiological material exchanged between ridges and flanks?
- What are the characteristic geometries of ridge flank hydrothermal circulation, including typical lengths, depths, and orientations of flow?
- What controls the nature, extent and intensity of hydrothermal alteration, and its temporal evolution as the crust matures?
- How do microbial communities in the crust evolve – functionally and genetically – as a function hydrothermal circulation?
- What are the geochemical flank fluxes into and out of the crust and what is their impact on global geochemical budgets?
- To what extent can changes in ocean chemistry and consequently the wider Earth system processes be resolved from the record of crustal alteration?

Answering these questions requires scientific drilling into basement to provide access to rock samples and opportunities for high-resolution downhole observations and experiments, coupled with detailed transects of closely spaced heat flow measurements, pore-water geochemical analyses and environmental information from seismic and swath mapping.

As hydrothermal circulation redistributes heat and fluids its evolution influences the temporal and spatial variability of many basement characteristics and processes. These include the thermal state, seismic and magnetic properties, porosity and permeability, alteration state, geochemistry and microbiology. We argue that understanding hydrothermal circulation and its evolution are important targets for scientific drilling and advocate the drilling, sampling, and instrumentation

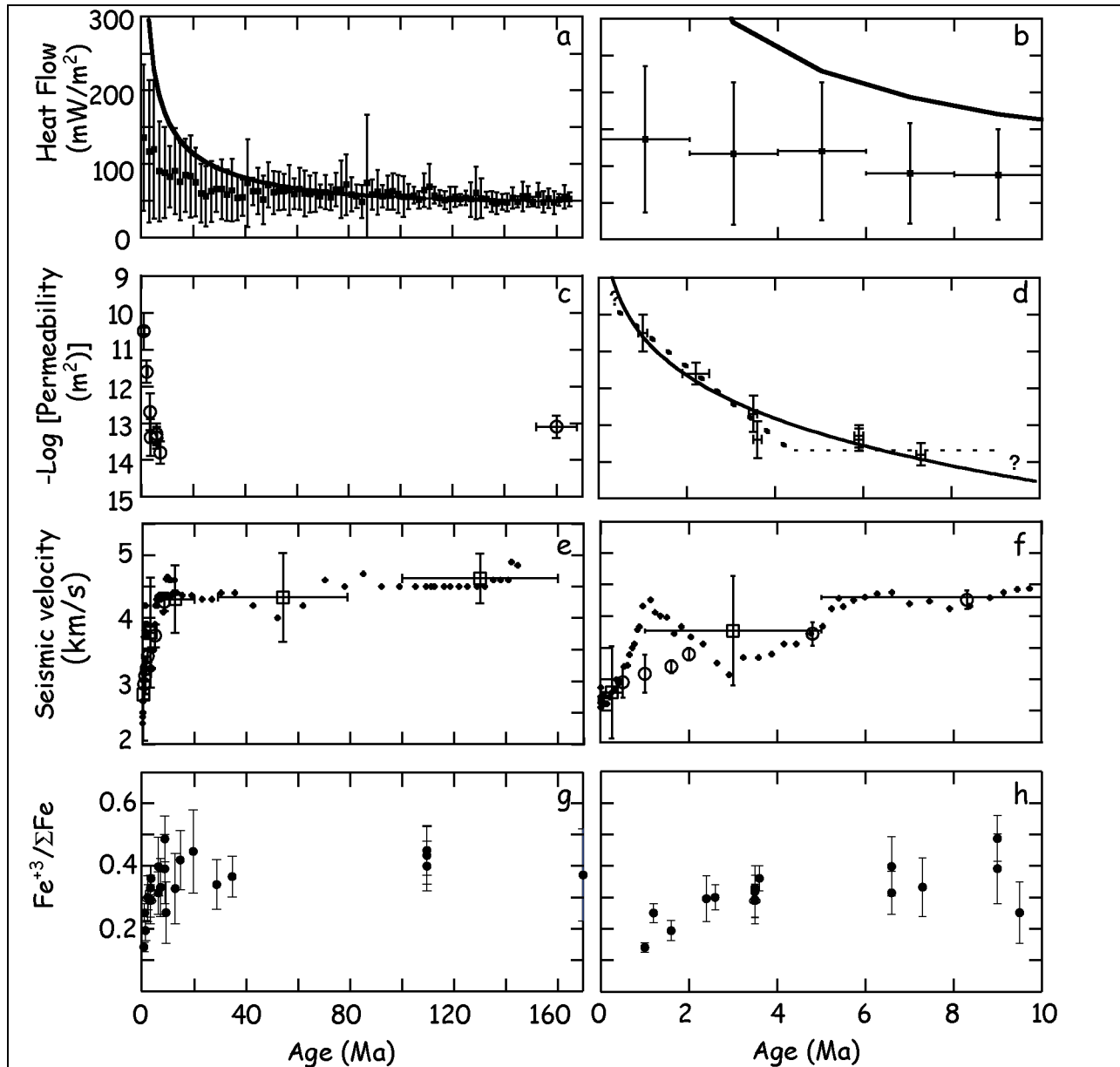


Figure 1. Heat flow and hydrologic measures of the upper oceanic lithosphere. Figure modified from *Fisher and Becker* [2000]. (a) Heat flow grouped in 2-Myr bins with standard deviations. Solid line show cooling reference model. (b) Expanded view showing heat flow deficit between 0 and 10 Ma. (c) Global dataset of upper crustal permeabilities based on drillstring packer tests. (d) Borehole permeability measurements showing a systematic decrease in permeability between 0 and 10 Ma. (e) Seismic velocities (dots). Horizontal bars show age range of averages and vertical bars show standard deviations. (f) Expanded view showing increase in average seismic velocity between 0 and 10 Ma. bars show standard deviations. (g) Plot of average $Fe^{+3}/\Sigma Fe$ of altered basalts [Johnson and Semyan, 1994; Bach and Edwards, 2003]. Each circle represents unweighted average for entire borehole with 2σ standard deviation. These data suggest that the oxidation state of altered crust increases in the first 10 Ma. (h). Expanded view showing increase of $Fe^{+3}/\Sigma Fe$ in first 10 Ma.

of a series of basement holes along a crustal flow line as the best route towards a better understanding of fluid flow, its evolution, and impact on the Earth system. Such a series of

boreholes will elucidate relationships between hydrothermal circulation, and the physical, chemical and biological properties of the crust. Through interactive experimentation, we can reveal the interplay and feedback between these properties, thereby establishing functional relationships; for example, establishing knowledge of the functional relationship between the size, activity, and properties of indigenous microbes and alteration style and extent, and their relationship to physical and hydrological properties of the crust. An overarching objective of this research is to develop an integrated physical, chemical, and biological model of ridge flank hydrothermal systems and its evolution with time.

The Global View

Figure 1 shows global compilations of four hydrologically relevant data sets as a function of crustal age. The most common measure of global heat loss from hydrothermal circulation is the difference between reference cooling models of oceanic lithosphere and measurements of the conductive heat flow [Sclater *et al.*, 1980, Stein and Stein, 1994]. These comparisons show that the heat flow deficit is greatest when the seafloor is young, and extends on average to ~65 Ma. Permeability measurements in the upper oceanic crust decrease from 10^{-10} to 10^{-13} m² in the first 10 Myr or so. Only one hole has been hydrologically tested that has a basement older than 8 Ma, Hole 801C in 165 Ma crust of the western Pacific Ocean, yielding a bulk permeability of 10^{-13} m² [Larson *et al.*, 1993]. A numerical analysis of hydrothermal conditions within 106 Ma seafloor of the Madeira Abyssal Plain, north Atlantic Ocean, suggests permeability on the order of 10^{-11} m² [Fisher and Von Herzen, 2005]. Thus it appears, from the limited number of available estimates, that permeability in the upper oceanic crust remains sufficiently high so as to sustain hydrothermal circulation out to great age. Seismic velocities of the upper oceanic crust are related to the porosity and alteration state of basement, and like permeability, they decrease in the first 10 Myr but then show little change thereafter. Fisher and Becker [2000] interpret these trends as suggesting that small pores fill rapidly in the earliest stages of crustal evolution but that large-scale fractures remain open during the life of oceanic crust. Correlation with alteration state of the ocean crust corroborate these data; Bach and Edwards [2003] show via examination of the oxidation state of the upper ocean crust that most oxidative alteration occurs in the first 10 Myr and, thereafter, slow or cease. These three data sets are consistent if flow channeling is important such that heat is advected through fractures. Unexplained however by this data set is the apparent cessation of advective fluid flow at 65 Ma, on average, or which processes are responsible for it. A limitation of these analyses for understanding the evolution of hydrothermal circulation is that crustal age is likely a poor proxy for driving forces, crustal properties and architecture, the spacing between basement outcrops, sedimentation history and other site specific factors.

The Regional View

Detailed regional studies of hydrothermal circulation such as those on the flanks of the Juan de Fuca Ridge [Davis *et al.*, 1992; Wheat and Mottl, 1994; Davis *et al.*, 1999; Elderfield *et al.*, 1999; Wheat and Mottl, 2000; Fisher *et al.*, 2003; Wheat *et al.*, 2004; Hutnak, *et al.*, 2006], East Pacific Rise [Grevemeyer *et al.*, 1998, 1999; Villinger *et al.*, 2002; Fisher *et al.*, 2003; Hutnak *et al.*, 2008], and Mid-Atlantic Ridge [Langseth *et al.*, 1984; 1992] indicate the profound influence that local environmental factors such as permeability, bathymetric relief, exposed basement or sediment cover, lithology, and thickness, have on influencing the vigor and pattern of hydrothermal circulation. Although these sites vary in environmental setting commonalities include vigorous fluid flow that homogenizes temperature in the crustal aquifer, modest to low

driving forces, and a high permeability crustal aquifer. Differences between regions and across regions include the magnitude of the heat flow deficit, the patterns of flow, and the temperature of venting fluids. Because most ridge flank studies have been conducted on young seafloor (< 25 Ma), it is not clear how these results can be extrapolated to older seafloor to understand the further evolution of hydrothermal circulation. Although there is evidence for hydrothermal circulation in older crust in many settings [Von Herzen, 2004; Jarrard et al., 2003], to date surveys of these areas lack the detail and spatial coverage needed to resolve key parameters and processes. In addition, because these sites are scattered across the seafloor in different basins, it is difficult to resolve differences that occur because of crustal setting versus crustal age.

The Case For Drilling Along a Crustal Flow Line

We contend that our best opportunity for understanding the evolution of hydrothermal circulation is to select an appropriate corridor along a crustal "flow line" (perpendicular to the spreading center), and craft a research program involving surface and subsurface studies (mapping, seismic, heat flow, chemistry, drilling, observatories). This strategy incorporating a combination of regional seismic lines in addition to "postage stamp" detailed surveys including heat flow, coring, and drilling was set out in a 1990 ONR/USSSP-sponsored workshop report [Purdy and Fryer, 1990]. The workshop led to a highly rated drilling proposal [Purdy et al., 1992] that ultimately was not considered for scheduling because of a lack of site surveys. Selection of a seafloor flow line created along a single ridge segment will help reduce spatial variability in crustal magmatic, accretion, and tectonic processes, helping to isolate factors related to aging. This sequence of boreholes could also be used to investigate temporal variations in accretion processes. Environmental factors that are important to hydrothermal circulation include local permeability structure, background heat flow, bathymetric relief, and the nature of exposed basement or sediment cover and thickness. This strategy allows driving forces and permeability to be investigated in a systematic way. Boreholes can be sited to take advantage of significant variations in some of these factors while minimizing variations in others. Ideally these sites would be on intermediate to older crust that at least partially infills the data void between ~10 and 160 Ma (Figure 1). Studies across a range of sites will permit examination of relationships between hydrothermal circulation, permeability, geochemistry, microbial community structure, an alteration, in order to understand functional relationships, and potentially reveal causal relationships.

References

- Bach, W. and K. J. Edwards, 2003, Iron and sulfide oxidation within the basaltic ocean crust: Implications for chemolithoautotrophic microbial biomass production. *Geochim Cosmochim Acta*, 3871-3887.
- Baker, E. T., 2007, Hydrothermal cooling of midocean ridge axes: Do measured and modeled heat fluxes agree, *Earth Planet. Sci. Lett.*, 263 (1-2), 140-150.
- Baker, P.A., P. M. Stout, M. Kastner and H. Elderfield., 1991, Large-scale lateral advection of seawater through oceanic crust in the central equatorial Pacific. *Earth Planet. Sci. Lett.*, **105**: 522-533.
- Coogan L. A., 2009, Altered oceanic crust as an inorganic record of paleoseawater Sr concentration, *Geochem. Geophys. Geosyst.*, 10, Q04001, doi:10.1029/2008GC002341.

- Davis E. E., D. S. Chapman K. Wang, 1999, 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*, 17,675-617,688.
- Davis E. E., D. S. Chapman, M. J. Mottl, et al., 1992, FlankFlux: an experiment to study the nature of hydrothermal circulation in young oceanic crust. *Can. J. Earth Sci.*, *29*, 925-952.
- Fisher A. T., and K. Becker, 2000, Channelized fluid flow in oceanic crust reconciles heat-flow and permeability data. *Nature* *403*, 71-74.
- Fisher A. T., E. E. Davis, M. Hutnak, et al., 2003, Hydrothermal recharge and discharge across 50 km guided by seamounts on a young ridge flank. *Nature* *421*, 618-621.
- Fisher, A. T., and R. Von Herzen, 2005, Models of hydrothermal circulation within 106 Ma seafloor: constraints on the vigor of fluid circulation and crustal properties below the Madeira Abyssal Plain, *Geochemistry Geophysics Geosystems*, *6*, doi:10.1029/2005GC001013.
- Goldberg, D. and A. Slagle, 2008, A global assessment of deep-sea basalt sites for carbon sequestration. Available from *Nature Precedings* <<http://dx.doi.org/10.1038/npre.2008.2640.1>>.
- Grevenmeyer, I., W. Weigel, and C. Jennrich, 1998, Structure and ageing of oceanic crust at 14° S on the East Pacific Rise, *Geophys. J. Int.*, *135*, 573-584.
- Grevenmeyer, I., N. Kaul, H. Villinger, and W. Weigel, 1999, Hydrothermal activity and the evolution of seismic properties of upper oceanic crust, *J. Geophys. Res.*, *104*, 5069-5079.
- Hutnak M, A. T. Fisher, L. Zühlsdorff, et al., 2006, Hydrothermal recharge and discharge guided by basement outcrops on 0.7-3.6 Ma seafloor east of the Juan de Fuca Ridge: observations and numerical models. *Geochem. Geophys. Geosys.* *7*, doi:10.1029/2006GC001242.
- Hutnak M, A. T. Fisher, R. Harris, et al., 2008, Large heat and fluid fluxes driven through mid-plate outcrops on ocean crust. *Nature Geosci.*, doi: 10.1038/ngeo264.
- Hutnak M, A. T. Fisher, C. A. Stein, et al., 2007, The thermal state of 18-24 Ma upper lithosphere subducting below the Nicoya Peninsula, northern Costa Rica margin. *MARGINS Theoretical Institute: SIEZE Volume*, (Dixon T, Moore C, Silver E, Stein S, Furlong K & Brown K, eds.), pp. 86-122. Columbia University Press, New York.
- Jarrard, R. D., L. J. Abrams, R. Pockalny, et al., 2003, Physical properties of upper oceanic crust: Ocean Drilling Program Hole 801C and the waning of hydrothermal circulation, *J. Geophys. Res.*, *108*, 2188, doi:10.1029/2001JB001727.
- Langseth, M. G., K. Becker, R. P. Von Herzen, and P. Schultheiss, 1992, Heat and fluid flux through sediment on the western flank of the Mid-Atlantic Ridge: a hydrogeological study of North Pond, *Geophys. Res. Lett.*, *19*, 517-520.
- Langseth, M. G., R. D. Hyndman, K. Becker, S. H. Hickman, and M. H. Salisbury, 1984, *The hydrogeological regime of isolated sediment ponds in mid-oceanic ridges*, in Init. Repts., DSDP, edited by R. H. Hyndman and M. H. Salisbury, pp. 825-837, U. S. Govt. Printing Office, Washington, D. C.
- Purdy, G. M., and G. J. Fryer, 1990, *Proceeding of a workshop on the physical properties of volcanic seafloor*, April 24-26, 1990. Woods Hole Oceanographic Institution, 278 pp.
- Purdy, G. M., D. Abbott, K. Becker, N. Christensen, A. Fisher, G.J. Fryer, H. P. Johnson, J. Karson, J. Karsten, M. Kastner, M. Langseth, D. Lavoie, G. Thompson, and R. Wilkens, 1992, *The Evolution of Oceanic Crust*, JOIDES proposal 420.
- Stein C and S. Stein, 1994, Constraints on hydrothermal heat flux through the oceanic lithosphere from global heat flow. *J. Geophys. Res.*, *99*, 3081-3095.

- Vance, D., D. A. H. Teagle, and G. L. Foster, 2009, Variable Quaternary chemical weathering fluxes and imbalances in marine geochemical budgets: *Nature*, 458, 493-496.
- Villinger, H., I. Grevemeyer, N. Kaul, and M. Pfender, 2002, Hydrothermal heat flux through aged oceanic crust: where does the heat escape? *Earth Planet. Sci. Lett.* 202, 159-170.
- Wheat C. G. and M. J. Mottl, 1994, Hydrothermal circulation, Juan de Fuca Ridge eastern flank: factors controlling basement water composition. *J. Geophys. Res.*, 99, 3067-3080.
- Wheat C. G. and M. J. Mottl, 2000, Composition of pore and spring waters from Baby Bare: global implications of geochemical fluxes from a ridge flank hydrothermal system. *Geochimica Cosmochimica Acta* 64, 629-642.