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Hydrothermal cooling of the ocean crust: Insights from ODP Hole 1256D

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ABSTRACT

The formation of new ocean crust at mid-ocean ridges is a fundamental component of the plate tectonic cycle and involves substantial transfer of heat and mass from the mantle. Hydrothermal circulation at mid-ocean ridges is critical for the advection of latent and sensible heat from the lower crust to enable the solidification of ocean crust near to the ridge axis. The sheeted dike complex (SDC) is the critical region between the eruptive lavas and the gabbros through which seawater-derived recharge fluids must transit to exchange heat with the magma chambers that form the lower ocean crust.

ODP Hole 1256D in the eastern equatorial Pacific Ocean provides the only continuous sampling of in-situ intact upper ocean crust formed at a fast spreading rate, through the SDC into the dike–gabbro transition zone. Here we exploit a high sample density profile of the Sr-isotopic composition of Hole 1256D to quantify the time-integrated hydrothermal recharge fluid flux through the SDC. Assuming kinetically limited fluid–rock Sr exchange, a fluid flux of $1.5–3.2 \times 10^6$ kg m^{-2} is required to produce the observed Sr-isotopic shifts. Despite significant differences in the distribution and intensity of hydrothermal alteration and fluid/rock Sr-isotopic exchange between Hole 1256D and SDC sampled in other oceanic environments (ODP Hole 504B, Hess Deep and Pito Deep), the estimated recharge fluid fluxes at all sites are similar, suggesting that the heat flux extracted by the upper crustal axial hydrothermal system is relatively uniform at intermediate to fast spreading rates.

The hydrothermal heat flux removed by fluid flow through the SDCs, is sufficient to remove only ~20 to 60% of the available latent and sensible heat from the lower crust. Consequently, there must be additional thermal and chemical fluid–rock exchange deeper in the crust, at least of comparable size to the upper crustal hydrothermal system. Two scenarios are proposed for the potential geometry of this deeper hydrothermal system. The first requires the downward expansion of the upper crustal hydrothermal system ~800 m into the lower crust in response to a downward migrating conductive boundary layer. The second scenario invokes a separate hydrothermal system in the lower crust for which fluid recharge bypasses reaction with the sheeted dikes, perhaps via flow down faults.

1. Introduction

Hydrothermal circulation is a key process in the formation and evolution of the ocean crust and impacts the broader Earth system through the modification of seawater chemistry and the subduction of altered ocean crust (Kelemen and Manning, 2015; Palmer and Edmond, 1989). At the ridge axis, hydrothermal circulation is intimately involved in the magmatic accretion of new crust through the advection of sensible and latent heat (e.g., Kelemen et al., 1997). Knowledge of the hydrothermal fluid fluxes and pathways through the crust are crucial to understanding the size, shape and distribution of magma bodies, and the processes of magma emplacement during the accretion of the ocean crust in the axial region.

The deficit between the predicted and observed conductive heat flow across the ocean basins persists on average until 65 ± 10 Ma, and implicates the cooling of the ocean crust by hydrothermal circulation. However, ~30% of the hydrothermal heat flux is advected from crust less than 1 million years old (Stein and Stein, 1994). In the axial region the magmatic heat released during the formation of the lower crust drives high-temperature (up to ~400 °C)

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hydrothermal circulation, which manifests at the seafloor as black-smoker vents, and transports large heat and chemical fluxes to the oceans. Observations of the lower ocean crust by remote geophysical methods and drilling, and from tectonic windows and ophiolites have been essential in developing our understanding of the subsurface fluid/rock reactions and fluid pathways during hydrothermal circulation. However, long-standing questions remain about how the lower crust is cooled.

The axial high temperature fluid flux is recorded in the subsurface through the fluid/rock reactions within the sheeted dike complex that form secondary minerals, either in fractures or replacing primary igneous minerals. The sheeted dike complex has been sampled in four locations from in-situ ocean crust formed at intermediate to fast spreading rates: ODP Holes 504B and 1256D, and in the tectonic windows of Hess Deep and Pito Deep (Alt et al., 1996; Barker et al., 2008; Gillis et al., 2005; Wilson et al., 2006). ODP Holes 504B and 1256D sample intact ocean crust, providing continuous sections through the overlying volcanic sequences and the sheeted dikes, whereas at Hess and Pito Deep, local triple junction-related tectonics expose the deeper levels of the upper and lower crust at the seafloor. These contrasting methods of sampling the sheeted dikes yield differing perspectives. Drill cores enable high resolution vertical sampling that is complemented by the two dimensional but discontinuous sampling afforded in tectonic windows.

The relationship between the upper crustal hydrothermal system in the lavas and dikes, and the accretion of the lower oceanic crust remains poorly constrained, despite this zone being significant for the exchange of heat. Two end member models for the accretion of the lower oceanic crust have been proposed; the gabbro glacier (Henstock et al., 1993; Phipps Morgan and Chen, 1993; Quick and Denlinger, 1993) and the multiple sills models (Boudier et al., 1996; Kelemen et al., 1997; MacLeod and Yoauancq, 2000). These models have contrasting requirements for the magnitude and distribution of hydrothermal circulation to extract the latent and sensible heat released from the cooling and crystallisation of the lower crust. In the simplest, gabbro glacier, geometry the upper crustal hydrothermal system extracts much of the heat available from the lower crust, because all solidification occurs in a high-level magma chamber. In contrast, the multiple sills model requires deep hydrothermal heat advection to extract latent heat (Coogan et al., 2006). Hence, the thermal predictions of the models can be evaluated by quantifying the hydrothermal fluid flux through the sheeted dike complex that is driven by heat supplied from the lower crust.

Global hydrothermal fluid fluxes have been estimated directly through the extrapolation of modern vent fluxes (e.g., Baker et al., 1996) and indirectly from oceanic chemical budgets (e.g., Sr, Mg; Elderfield and Schultz, 1996; Palmer and Edmond, 1989) and the thermal balance of mid-ocean ridges (e.g., Morton and Sleep, 1985). Another approach is through the quantification of the total fluid/rock exchange that occurs between seawater and ocean crust during hydrothermal circulation using Sr isotopes as a tracer (Barker et al., 2008; Bickle and Teagle, 1992; Gillis et al., 2005; Teagle et al., 2003). The Hole 1256D and 504B whole rock $^{87}Sr/^{86}Sr$ profiles through the volcanic sequence and sheeted dike complex reveal clear differences in the distribution and intensity of Sr isotope exchange. Hole 1256D shows only limited seawater strontium exchange in the lavas but extensive isotopic re-equilibration in the sheeted dikes. In contrast, Hole 504B exhibits significant exchange in the lavas, but only slight $^{87}Sr/^{86}Sr$ increases in most of the dike section (Harris et al., 2015). These profiles may reflect significant differences in the timing and intensity of hydrothermal alteration and affect the global seawater–basalt exchange fluxes calculated for some elements.

In this paper we will investigate whether the contrasting extent of Sr-isotopic exchange in the sheeted dikes reflects different amounts of hydrothermal fluid recharge. We use the high sample density Sr isotope profile of ODP Hole 1256D (Harris et al., 2015) as a record of seawater–basalt exchange during hydrothermal recharge, to calculate the time integrated fluid flux through the sheeted dike complex. This fluid flux is compared to those calculated from the sheeted dike complex in Hole 504B, Hess Deep and Pito Deep to evaluate previous suggestions that hydrothermal recharge fluxes are uniform in sheeted dike complexes formed at intermediate to fast spreading rates (Barker et al., 2008). Our fluid flux is then converted into a hydrothermal heat flux to evaluate the thermal budgets implied by contrasting models of ocean crust accretion.

2. Geological setting

ODP Hole 1256D is located in the eastern equatorial Pacific and is the only complete sampling of intact in-situ upper oceanic crust down to the dike/gabbro transition (Fig. 1; Teagle et al., 2006, 2012; Wilson et al., 2006). Site 1256 formed at the East Pacific Rise 15 myr-ago during an interval of superfast spreading (>200 mm/yr full rate; Wilson, 1996). The ocean crust at Site 1256 is covered by 250 m of sediments and Hole 1256D samples 750 m of extrusive volcanic rocks, a thin mineralized lava-dike transition, 350 m of sheeted dikes, and 120 m into the dike/gabbro transition where two thin gabbro sills are intruded into contact metamorphosed sheeted dikes (Teagle et al., 2006, 2012; Wilson et al., 2006).

The assemblages of secondary minerals document a downhole transition from low temperature phases (e.g., clays, oxyhydroxides, carbonates) in the volcanic sequence to greenschist facies phases (e.g., chlorite, actinolite, albite) in the sheeted dike complex (Alt et al., 2010). This alteration is broadly similar to the only other penetration of intact in-situ upper ocean crust drilled in Hole 504B (Alt et al., 1996). Studies of tectonic windows also record greenschist facies alteration in the sheeted dike complex, although at Pito Deep amphibole dominates the alteration assemblage (Heft et al., 2008) whereas at Hess Deep chlorite is more dominant (Gillis et al., 2005). Careful inspection of the Hole 1256D drill core and thin sections allows the classification of dike samples into: background alteration, alteration patches and vein halos, and dike margin categories. In the dike/gabbro transition early amphibole alteration is overprinted by granulite facies contact metamorphism and later lower temperature hydrothermal alteration at greenschist facies conditions and below (Alt et al., 2010).

The whole rock Sr isotope profile of Hole 1256D records the evolution of fluid pathways in the hydrothermal system and shows distinct variation between the main stratigraphic sequences (Fig. 1; Harris et al., 2015). The volcanic sequence has limited increases in $^{87}Sr/^{86}Sr$ except along brecciated horizons and the margins of anomalously thick massive flows. This suggests that the hydrothermal recharge fluid reaching the top of the sheeted dikes had undergone only minor modification from seawater $^{87}Sr/^{86}Sr$. Large increases in $^{87}Sr/^{86}Sr$ in the lava-dike transition are restricted to mineralized, brecciated horizons and reflect the sub-surface mixing of upwelling and downwelling fluids.

The sheeted dike complex provides pathways for both downwelling recharge fluids and upwelling hydrothermal discharge (Harris et al., 2015), and dikes display strongly elevated $^{87}Sr/^{86}Sr$ towards our estimated end member hydrothermal fluid composition, indicating extensive fluid/rock exchange at greenschist facies conditions (Fig. 1). The Sr-isotopic composition of the upwelling hydrothermal fluid is estimated from analyses of hydrothermal epidote ($n = 5$) that precipitated in veins and alteration patches. Epidote is selected as it has high Sr concentrations (>500 ppm) so is robust to overprinting, and it is commonly associated with