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Cool seafloor hydrothermal springs reveal global geochemical fluxes

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ABSTRACT

We present geochemical data from the first samples of spring fluids from Dorado Outcrop, a basaltic edifice on 23 M.y. old seafloor of the Cocos Plate, eastern Pacific Ocean. These samples were collected from the discharge of a cool hydrothermal system (CHS) on a ridge flank, where typical reaction temperatures in the volcanic crust are low (2–20 °C) and fluid residence times are short. Ridge-flank hydrothermal systems extract 25% of Earth's lithospheric heat, with a global discharge rate equivalent to that of Earth's river discharge to the ocean; CHSs comprise a significant fraction of this global flow. Upper crustal temperatures around Dorado Outcrop are ∼15 °C, the calculated residence time is <3 y, and the composition of discharging fluids is only slightly altered from bottom seawater. Many of the major ions concentrations in spring fluids are indistinguishable from those of bottom seawater; however, concentrations of Rb, Mo, V, U, Mg, phosphate, Si and Li are different. Applying these observed differences to calculated global CHS fluxes results in chemical fluxes for these ions that are ≥15% of riverine fluxes. Fluxes of K and B also may be significant, but better analytical resolution is required to confirm this result. Spring fluids also have ∼50% less dissolved oxygen (DO) than bottom seawater. Calculations of an analytical model suggest that the loss of DO occurs primarily (>80%) within the upper basaltic crust by biotic and/or abiotic consumption. This calculation demonstrates that permeable pathways within the upper crust can support oxic water–rock interactions for millions of years.

1. Introduction

Observed differences between measured and predicted lithospheric heat flux values from the deep seafloor are attributed to advective cooling of the crust by hydrothermal fluids (e.g., Lister, 1972). This process extracts ∼10 TW (25%) of the Earth's lithospheric heat (Sclater et al., 1980; Stein and Stein, 1994; Mottl, 2003). Although high-temperature hydrothermal systems have been discovered and sampled at many seafloor spreading centers, where fluid flow at high temperatures (∼250–400 °C) is driven by crustal cracking and the intrusion of magma (e.g., Corliss et al., 1979), such systems account for at most 20% of the global advective heat loss with the remainder occurring on ridge flanks at much lower temperatures (Mottl, 2003). In contrast, ridge flank hydrothermal systems are driven by conductive heat loss from the lithosphere. Sites of discharge and recharge in ridge flank systems are determined by (a) the permeability structure of the upper basaltic crust, (b) topographic relief, and (c) the distribution and properties of sediment above the crustal aquifer (e.g., Langseth et al., 1984; Davis et al., 1992; Fisher and Wheat, 2010). On ridge flanks, sediment acts as a low-permeability barrier that limits direct fluid exchange between the crustal aquifer and bottom seawater (Spinelli et al., 2004). In contrast, seamounts and other basaltic outcrops provide highly permeable channels for efficient fluid exchange between volcanic crustal rocks and the overlying ocean (e.g., Davis et al., 1992; Hutnak et al., 2008). Because the magnitude of ridge flank discharge is equal to the discharge of Earth's rivers to the ocean (Wheat et al., 2003), even a small change in the chemical composition of circulating fluids within the basaltic crust could impact global geochemical budgets (e.g., Elderfield and Schultz, 1996; Wheat and Mottl, 2004), yet no pristine samples of CHS fluids from ridge flanks have been collected.

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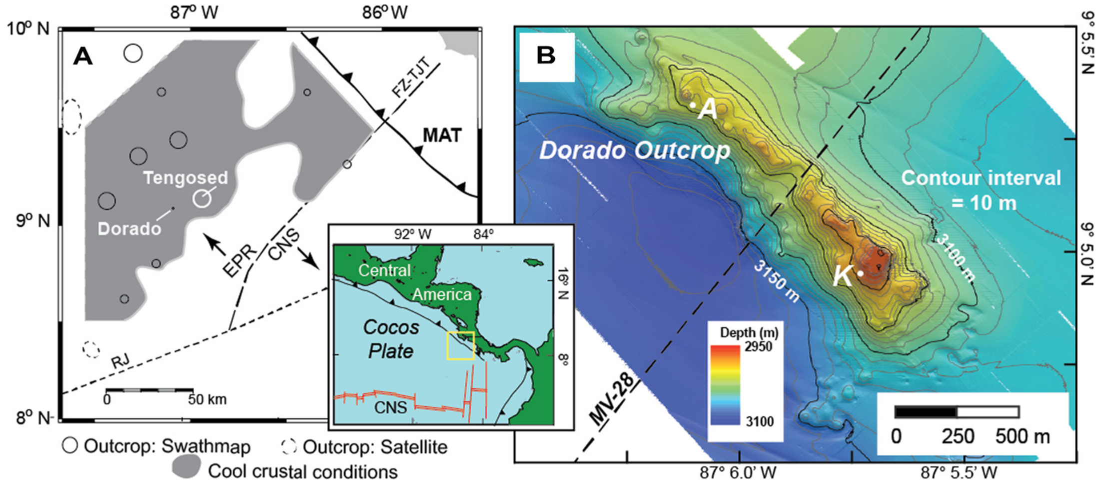

Wheat et al. (2017)

Fig. 1. A. Dorado outcrop is located on 23 M.y. old seafloor west of Costa Rica, on the Cocos Plate, in a region (gray area) where the heat flow is 10–40% of lithospheric predicted values, consistent with rapid hydrothermal circulation and advective heat loss (Fisher et al. 2003; Hutnak et al., 2008). Circles represent locations of know basaltic exposures, potential sites of fluid recharge and discharge. EPR – Lithosphere generated on the East Pacific Rise; CNS – Lithosphere generated on the Cocos-Nazca Spreading Center; RJ – Ridge Jump; MAT – Mid-America Trench; FZ-TJT – Fracture Zone-Triple Junction Trace. B. Bathymetric map of Dorado Outcrop from multibeam sonar data collected by the AUV *Sentry*. Contours are 10 m. The outcrop rises about 150 m above a sediment sequence that ranges from 200 to 400 m thick. "A" and "K" mark locations where long-term and numerous discrete fluid samples were collected. The dashed line shows the location of a seismic reflection profile (Fig. 2).

Much of the global ridge flank fluid flow occurs through young crust within cool (<20 °C) hydrothermal systems (CHS), where the difference between measured seafloor and lithospheric heat flux is greatest (Stein and Stein, 1994). In these regions, the lack of a continuous sediment cover allows many pathways for seawater to flow into and out of the volcanic oceanic crust. The ubiquity of basaltic exposure on many young ridge flanks (e.g., abyssal hills, fracture zones, seamounts and other outcrops; Macdonald et al., 1996) and the low temperature of discharge from CHS make it difficult to locate and sample fluids that are characteristic of these systems. Hydrothermal circulation on ridge flanks also occurs where thicker and more continuous sediment cover limits areas of basaltic exposure, resulting in slower fluid flow through the crust, longer residence times, and higher reaction temperatures (e.g., Mottl et al., 1998; Elderfield et al., 1999). However, the same processes and conditions that raise reaction temperatures during circulation result in a distinctive hydrothermal fluid composition that make these systems easier to locate and sample, but they are not globally representative, thus their global impact is limited (Mottl, 2003). Despite decades of searching, CHS on ridge-flanks have not been sampled, making it difficult to quantify the influence of ridge flank hydrothermal systems on crustal alteration and global geochemical fluxes.

On the eastern flank of the East Pacific Rise, on 18–23 M.y. old seafloor of the Cocos Plate (Fig. 1), the regional seafloor heat flux within a 14,500 km^2 area is 60–90% lower than lithospheric predictions (Fisher et al., 2003; Hutnak et al., 2007, 2008). Low values of conductive heat flux in this area are attributed to advective cooling as a result of vigorous hydrothermal circulation. Bathymetric mapping, seismic reflection, heat flux, and sediment pore water data were combined to identify areas of CHS recharge and discharge through basaltic edifices that penetrate up to 450 m of sediment in this area (Fisher et al., 2003; Spinelli and Underwood, 2004; Hutnak et al., 2007, 2008; Wheat and Fisher, 2008). Eleven basement highs were mapped in this region of low seafloor heat flux; one of the smallest basement edifices, Dorado Outcrop, was hypothesized to be a site of CHS discharge on the basis of heat flux measurements and the pore fluid geochemistry of sediments immediately adjacent to the outcrop (Hutnak et al., 2007; Wheat and Fisher, 2008). However, these surveys with conventional oceanographic vessels could not identify sites of direct CHS discharge, and neither did they permit sampling of pristine CHS fluids.

Fluids that discharge from Dorado Outcrop are thought to have recharged through Tengosed Seamount, located ~20 km to the east, where there are anomalously low heat flux values adjacent to the edge of the seamount (Hutnak et al., 2007, 2008). Thermal and sediment pore water geochemical data from earlier surveys, and one-dimensional analytical models of coupled fluid-heat and fluid-solute transport, suggest that upper basement temperatures are ≤20 °C between Tengosed and Dorado, and that fluid flow is rapid, with a fluid residence time in the basaltic crust of 0.6 to 3 y (Wheat and Fisher, 2008; Hutnak et al., 2008). Laboratory studies of seawater–basalt interactions at low temperatures (25 °C) indicate slow reaction rates (Seyfried, 1977). Thus, the low upper-crustal temperatures and the short residence time of fluids discharging from Dorado Outcrop should result in a fluid composition that is only slightly modified from bottom seawater, but even small changes in fluid composition could result in globally significant geochemical fluxes because of the enormity of such discharge from the oceanic crust. Thus, given that the Dorado Outcrop is located in a ridge-flank setting where the basaltic crust is generally covered with thick sediments, much of the lithospheric heat is lost to advection in this region, and there are only a few sites of basaltic exposure where such hydrothermal exchange could occur with bottom seawater, the Dorado Outcrop was a promising target for locating and sampling fluids that discharge from CHS.

On this basis, we embarked on two expeditions to Dorado Outcrop to locate sites of CHS discharge and collect the first pristine samples of CHS fluids from a ridge flank. The first expedition (AT26-09) focused on the use of the autonomous underwater vehicle *Sentry* and the remotely operated vehicle *Jason II*, to map the outcrop, survey the area for springs, and sample spring sites. Long-term instruments were deployed to measure discharge temperatures and collect spring fluids. A second expedition (AT26-24), about one year later, recovered these instruments and collected additional samples at spring discharge sites with the submersible *ALVIN*.