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Subsurface conditions in hydrothermal vents inferred from diffuse flow composition, and models of reaction and transport

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ABSTRACT

Chemical gradients in the subsurface of mid-ocean ridge hydrothermal systems create an environment where minerals precipitate and dissolve and where chemosynthetic organisms thrive. However, owing to the lack of easy access to the subsurface, robust knowledge of the nature and extent of chemical transformations remains elusive. Here, we combine measurements of vent fluid chemistry with geochemical and transport modeling to give new insights into the under-sampled subsurface. Temperature–composition relationships from a geochemical mixing model are superimposed on the subsurface temperature distribution determined using a heat flow model to estimate the spatial distribution of fluid composition. We then estimate the distribution of Gibb's free energies of reaction beneath mid oceanic ridges and by combining flow simulations with speciation calculations estimate anhydrite deposition rates. Applied to vent endmembers observed at the fast spreading ridge at the East Pacific Rise, our results suggest that sealing times due to anhydrite formation are longer than the typical time between tectonic and magmatic events. The chemical composition of the neighboring low temperature flow indicates relatively uniform energetically favorable conditions for commonly inferred microbial processes such as methanogenesis, sulfate reduction and numerous oxidation reactions, suggesting that factors other than energy availability may control subsurface microbial biomass distribution. Thus, these model simulations complement fluid-sample datasets from surface venting and help infer the chemical distribution and transformations in subsurface flow.

1. Introduction

Deep sea hydrothermal activity is manifest by the iconic black smoker, but measurements at a number of vent fields suggest that discharge of warm fluid ("diffuse flow") is at least as significant, if not more so, than focused high temperature venting in terms of heat flux to the ocean (Bemis et al., 1993; Veirs, 2003; Ramondenc et al., 2006) and microbial activity in the subsurface (Sogin et al., 2006; Von Damm and Lilley, 2004). The mixing between the hot, reducing venting fluid with cold, oxidizing seawater creates temperature and chemical gradients that can enhance rates of chemical transformations and support rich microbial life adapted to catalyzing thermodynamically favorable reduction–oxidation reactions (Butterfield et al., 2004). These processes are reflected in the composition of diffuse fluids (<120 °C, but typically less than about 40 °C) seeping from the seafloor, with microbial activity clearly evidenced by the expulsion of large amounts of biomass in the wake of magmatic or tectonic events (Embley and Chadwick, 1994; Haymon et al., 1993).

High temperature and associated diffuse hydrothermal activity have been observed in a range of mid-ocean ridge environments from Lucky Strike on the slow spreading Mid-Atlantic Ridge (Mittelstaedt et al., 2012) to Axial Volcano (Rona and Trivett, 1992), the Endeavour segment (Schultz et al., 1992) on the intermediate spreading Juan du Fuca ridge and 9°N on the fast spreading East Pacific Rise (Ramondenc et al., 2006). Lacking direct samples of subsurface pore fluids, the assessment of subsurface processes largely relies on the interpretation of the observed composition of the venting fluid, which reflects the entire history of a water parcel, including mixing and abiotic and microbial transformations. These multiple processes can be quantified and integrated using mathematical models. Comparison of predicted diffuse fluid compositions arising from, e.g., conductive heating or cooling of seawater, or mixing between vent fluid and seawater, with field

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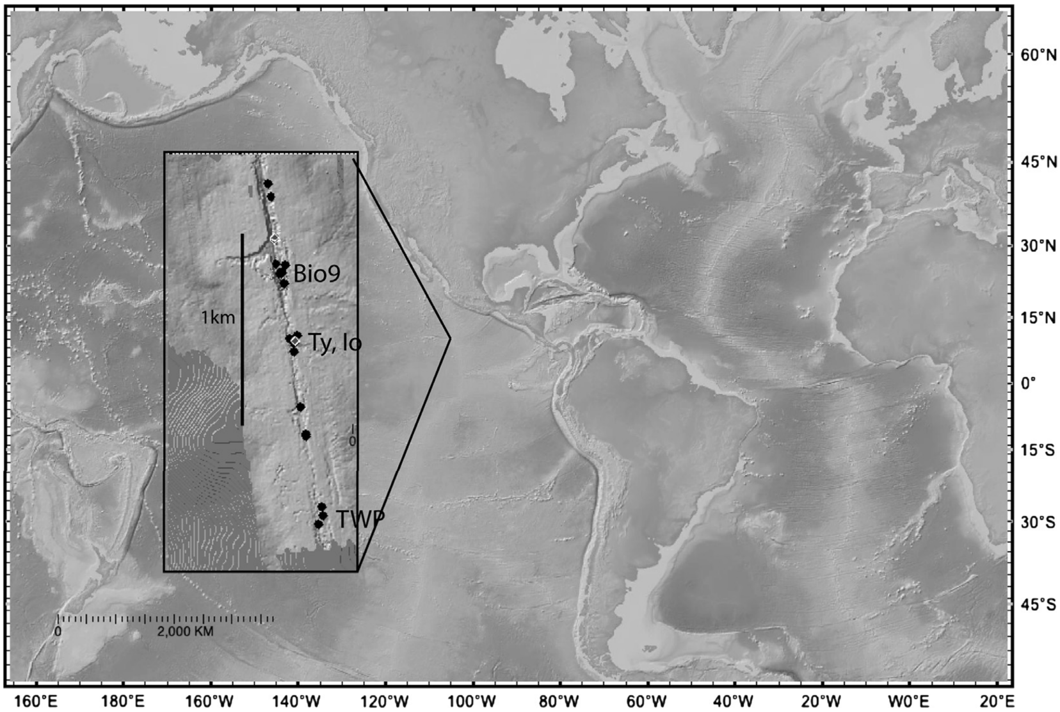

Fig. 1. Location of 9° N EPR with inset of expanded view of vent field. Dots indicate individual vent sites. The map was created with GeoMapApp (http://www.geomapapp.org; Ryan et al., 2009).

observations allows identification of the dominant mechanisms (Butterfield et al., 2004).

Here we quantify inferred subsurface processes and their role in shaping the subsurface environment at the Biogeotransect on the fast-spreading East Pacific Rise (EPR) where magmatism is robust and two separate eruptions have been observed separated by roughly 14 years (Haymon et al., 1993; Tolstoy et al., 2006). We use geochemical models to estimate diffuse fluid compositions by calculating and speciating mixtures of measured vent fluid and seawater compositions. We also consider variable temperature in the seawater endmember and variable composition in the high temperature endmember, as manifested in data from the study site (Von Damm and Lilley, 2004). A thermal model is used to predict the subsurface temperature field, and the temperature–composition (T–C) relationships from the geochemical mixing model are then superimposed on the modeled temperature distribution to estimate the spatial distribution of fluid composition in the subsurface. From that, free energies of reactions are computed, which for temperatures below the thermal limit for life (on the order of 120 °C; Kashefi and Lovley, 2003) show regions of potential microbial metabolism. Where temperatures exceed the limit for life and where relatively rapid equilibration dominates chemical dynamics, we focus our discussion on prediction of anhydrite deposition rates.

2. Study site: Biogeotransect (9° N), East Pacific Rise

The EPR is a fast spreading mid-ocean ridge (Sinton and Detrick, 1992) with a relatively high inferred rate of magmatic resupply (Fornari et al., 2012; Liu and Lowell, 2009; Lowell et al., 2012), giving rise to vigorous hydrothermal venting at several spots along the ridge (Von Damm et al., 2003, 1997; Von Damm, 2000). It is one of the best-studied mid-ocean ridge systems and copious time series datasets of chemistry, biology, and seismology exist (Tolstoy et al., 2006; Von Damm and Lilley, 2004; Shank et al., 1998). The Biogeotransect segment of the EPR (9° N) extends from 9° 49.5′ N to 9° 50.5′ N (Fig. 1) along a widened section of the axial summit collapse trough and is characterized by vigorous and long-lived high temperature (>290 °C) venting and associated low temperature (<40 °C) diffuse flow (Von Damm, 2000). Heat flux for a 2 km ridge segment along the Biogeotransect is estimated to be 325 ± 160 MW, with a little over 10% directly attributed to focused flow based on feature tracking in video footage of focused and diffuse flow combined with estimates of the aerial extent of each type of flow (Ramondenc et al., 2006).

Despite the disruptive effects of volcanism along the Biogeotransect, venting style has maintained a characteristic pattern through time in which low temperature diffuse fluids emanate as unfocused flow directly from basalt through cracks and broken lava pillars in close proximity to long-lived high temperature vents (Scheirer et al., 2006). Furthermore, previous observations of evolving phase separation within a single high temperature vent at EPR suggest that source fluids at depth flow along the same conduits over time (Von Damm et al., 1997; Von Damm and Lilley, 2004). Seismically-driven perturbations and co-registered variability in diffuse flow suggest a connection between diffuse and focused flow (Sohn et al., 1998), possibly via a warm subsurface reservoir created by mixing of endmember fluid with seawater, and tapped by sites of diffuse venting (e.g., near the Rusty and Bio9 sites) but with varying degrees of additional seawater entrainment during ascent from the reservoir (Scheirer et al., 2006; Germanovich et al., 2011; Lowell et al., 2013).

In a comprehensive review of EPR diffuse fluids by Von Damm and Lilley (2004), differences between the diffuse fluid and adjacent high temperature endmember fluid were best explained by nearly conservative mixing with a minor component of conductive heating of seawater. Thus, we build on this work and model diffuse fluid as a result of mixing heated seawater with vent fluid, undergoing reactions in the subsurface.