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Continental smokers couple mantle degassing and distinctive microbiology within continents

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ABSTRACT

The discovery of oceanic black (and white) smokers revolutionized our understanding of mid-ocean ridges and led to the recognition of new organisms and ecosystems. Continental smokers, defined here to include a broad range of carbonic springs, hot springs, and fumaroles that vent mantle-derived fluids in continental settings, exhibit many of the same processes of heat and mass transfer and ecosystem niche differentiation. Helium isotope ($^3He/^4He$) analyses indicate that widespread mantle degassing is taking place in the western U.S.A., and that variations in mantle helium values correlate best with low seismic-velocity domains in the mantle and lateral contrasts in mantle velocity rather than crustal parameters such as GPS, proximity to volcanoes, crustal velocity, or composition. Microbial community analyses indicate that these springs can host novel microorganisms. A targeted analysis of four springs in New Mexico yield the first published occurrence of chemolithoautotrophic Zetaproteobacteria in a continental setting. These observations lead to two linked hypotheses: that mantle-derived volatiles transit through conduits in extending continental lithosphere preferentially above and at the edges of mantle low velocity domains. High CO_2 and other constituents ultimately derived from mantle volatiles drive water–rock interactions and heterogeneous fluid mixing that help structure diverse and distinctive microbial communities.

1. Introduction

Black and white smokers in oceanic settings are well-established as strongly coupled systems of mantle degassing, hydrologic mixing, and distinctive biologic communities (Lowell et al., 2008). Geochemical analyses of geothermal and carbonic springs across the western U.S.A. reveal high $^3He/^4He$ ratios indicating pervasive degassing of mantle volatiles also occurs in continental extensional regions (Welhan et al., 1988; Newell et al., 2005). Microbial community analyses of continental springs indicate a role for mantle-derived fluids in structuring microbial diversity within them (Colman et al., 2014). However, such springs with mantle constituents have not yet been considered as systems with coupled processes directly analogous to oceanic smokers. This paper shows that mantle-derived gases in springs correlate spatially with geophysical signals of partial melts in the underlying mantle, and that some of these springs that are rich with mantle-derived volatiles host organisms similar to chemolithoautotrophic organisms that are largely associated with low-temperature marine vent ecosystems. Based on strong similarity to coupled tectonic, hydrologic and biotic systems in oceans, we define continental smokers as carbonic springs, hot springs, and fumaroles that vent mantle-derived fluids in continental extensional settings.

Mantle volatiles degas through conduits and vents in both oceanic and continental extensional settings. In oceanic settings, upwelling of melts derived from geochemically depleted astheno-

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spheric mantle produces mid-ocean ridge basalt (MORB), builds new oceanic lithosphere, and helps drive plate tectonics. Upward transfer of volatiles (e.g. H_2O, CO_2, H_2, He, CH_4) accompanies upward transfer of magma through thin oceanic lithosphere with profound hydrochemical and diagenetic effects on oceans. Seismic and magmatic activity, concentrated at ridge crests, facilitates episodic degassing into the oceans. The transport of volatiles is locally focused into gas vents and hot springs emanations (smokers) that take on unique compositions driven by differences in local hydrochemical settings including sulfide-rich black smokers and carbonate-rich white smokers.

Continental extensional environments have many similarities to oceanic ridges but both the structural expression of extension and the associated melt and volatile transfer between asthenosphere and lithosphere are more diffuse and varied due to the greater thickness and heterogeneity of continental crust, and variations in the composition of crustal fluids (e.g. Chiodini et al., 2004; Karlstrom et al., 2013). The conduit systems, transit times, and drivers for transfer of melts and volatiles through continental lithosphere are less well understood. In this paper we use the term continental smokers to include not only volcanic fumaroles and hot springs, but also a wide range of cool to hot carbonic travertine-depositing springs. These carbonic springs are locations of heterogeneous mixing between endogenic (deeply derived) fluids, groundwater, and surface water systems (Crossey et al., 2006, 2009). Similar mantle inputs and mixing and fractionation of fluids and volatiles also take place in continental gas fields (Poreda et al., 1986; Gilfillan et al., 2008, 2009).

Oceanic smokers have fundamentally advanced our understanding of Earth's biosphere, life in extreme environments, and connections to early Earth (Baross and Hoffman, 1985; Nakagawa and Takai, 2008). Similarly, microbial research in Yellowstone geothermal systems has revealed a diverse, yet phylogenetically distinct, terrestrial thermophilic biota leading to extraordinary insights into microbial diversity and biogeography, biogeochemistry, and the evolution of life (e.g. Barns et al., 1994; Hugenholtz et al., 1998; Reysenbach and Shock, 2002; Whitaker et al., 2003; Shock et al., 2010; Inskeep et al., 2013). Recent research in low-temperature, alkaline, serpentinite-hosted continental systems has indicated that underexplored continental systems hold great promise for understanding the interaction of deeply derived fluids, rich in reduced substrates (e.g. H_2), and the microbial communities associated with them (Suzuki et al., 2013; Crespo-Medina et al., 2014; Meyer-Dombard et al., 2015; Morrill et al., 2014). Moreover, microbial phylogenetic analysis of 28 of the carbonic springs described here (Table S1) suggested that some of the springs with highest deep-fluid input contain organisms closely related to chemolithoautotrophs present at marine vent sites and iron-oxidizing biofilms (Colman et al., 2014). Thus, microbiological studies from a wider range of lower-temperature terrestrial springs of the type presented here have rich potential to expand our understanding of subsurface geobiological processes and a fuller spectrum of microbial biodiversity.

Research into transport of mantle volatiles including CO_2 to the surface through continental smokers has been underway for some time (e.g., Matthews et al., 1987; Greisshaber et al., 1992; Hilton, 1996), but understanding fluid conduits, the influence of endogenic fluids on near-surface water quality (Earman et al., 2008) and microbial diversity are less well developed. We compile hydrochemical data from springs across the tectonically active western U.S.A., from the western margin of the North American tectonic plate to the Great Plains stable continental interior. To understand fluid conduits better, we seek to quantify and understand the relationships of $^3He/^4He$ values observed in near-surface hydrologic systems to possible controlling factors such as mantle seismic velocity structure (Schmandt and Humphreys, 2010), contemporary crustal stain rate (Kennedy and van Soest, 2007), proximity to Quaternary volcanoes, and lithology of the crust as inferred from ν_P/ν_S seismic velocity ratios (Lowry and Gussinve, 2011).

The noble gases have widespread utility as geochemical tracers (Porcelli et al., 2002) due to chemically inert behavior, relatively low abundance in the solid Earth, and large and diagnostic isotope variations among various reservoirs. Helium consists of two isotopes: ^3He (dominantly of primordial origin) and ^4He (from radioactive decay). The fluid circulation systems in mid-ocean ridge settings carry a uniform $^3He/^4He$ ratio of $8 \pm 1R_A$ (Graham, 2002) where R_A = atmospheric $^3He/^4He$ ratio of 1.4×10^{-6}. Deep mantle plume settings (e.g. Hawaii, Iceland, Samoa) can have $^3He/^4He$ $>30R_A$ consistent with tapping less degassed lower mantle reservoirs (Graham, 2002). These observations suggest that primordial helium (enriched in ^3He) has been retained by the mantle throughout Earth history, making it a unique tracer of juvenile volatiles (Clarke et al., 1969). In stark contrast, ancient continental cratons are characterized by low $^3He/^4He$ ratios ($0.02R_A$) indicating that mantle keels insulate cratonic crust from asthenospheric volatiles, so radiogenic ^4He accumulates in crustal rocks and fluids over long periods (Andrews, 1985). Helium isotope values $>0.1R_A$ in fluids found in continental settings – assuming correction for the presence of any air-derived He, are considered to provide unambiguous evidence for a mantle He input (Ballentine et al., 2002) and hence this tracer is valuable for evaluating the influence of endogenic inputs to the hydrochemistry and microbiology of fluids.

2. Methods

2.1. Mantle tomography methods

Body-wave tomography models (Schmandt and Humphreys, 2010) and surface wave tomography models (Shen et al., 2013; Yuan and Romanowicz, 2010) were used for comparison with $^3He/^4He$ values. For the higher resolution tomography models using data from EarthScope's Transportable Array $^3He/^4He$ values were compared with upper mantle velocity variations and local relief in upper mantle velocities. Relief was measured as the difference between the minimum and maximum velocity within a radius of 70 km, which is the nominal spacing of the Transportable Array.

2.2. Regression of wedge plots

The correlations between the $^3He/^4He$ values of springs and the properties of the underlying crust and mantle were determined by linear (least squares) regression through the maximum $^3He/^4He$ values (least mixed/diluted values) over a range of the mantle/crustal values. The regressed points are the maximum $^3He/^4He$ values plotted at the midpoint of the associated bins. The effect of varied bin sizes on the regressions was examined along with the exclusion of bins with less than a critical number of data points ("#bin" in the wedge-plots). These sensitivity tests showed that the slope of the regressed line was not strongly controlled by choice of bin size and minimum number of points in a bin in the cases of the regressions of $^3He/^4He$ value with ν_P, ν_S, $d\nu_P$.

2.3. Strain/GPS map methods

A GPS-derived estimate of the second invariant of crustal strain rate in southwestern U.S. was used to assess the importance of regional-scale contemporary crustal strain (Kreemer et al., 2012). Farther into the continental interior strain rates are near or below the limits of detection with existing GPS constraints (Berglund et al., 2012), so our analysis of the correlation between $^3He/^4He$ value