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The role of sedimentation history and lithology on fluid flow and reactions in off-axis hydrothermal systems: A perspective from the Troodos ophiolite

K.M. Gillis *, L.A. Coogan, C. Brant

School of Earth and Ocean Sciences, University of Victoria, Victoria, BC, Canada

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ABSTRACT

Off-axis hydrothermal systems are thought to carry globally significant chemical fluxes but different ocean crust sections show widely differing extents of alteration making the quantification of these fluxes complex. With the aim of better understanding the origin of this diversity in alteration extent we have studied two sections of the lava pile in the Troodos ophiolite with distinct sedimentation history and volcanic architecture. The Akaki section is dominated by pillow lavas and the oldest sediments overlying the crust are ~20 Myr younger than the ophiolite. Here there is a 300 m thick zone at the top of the lavas that is enriched in CO_2 and alkali elements, and has high $^{87}Sr/^{86}Sr$ and δ^7Li. These features indicate extensive chemical exchange with seawater. In contrast to the Akaki area, the Onophrious section is dominated by sheet flows and the oldest sediments are of the same age as the ophiolite. Here the CO_2 and alkali element enriched zone is much thinner (<100 m), is less enriched in these elements (e.g. by a factor of three for CO_2), and has lower $^{87}Sr/^{86}Sr$ and δ^7Li. The O-isotopic compositions of calcites from these CO_2- and alkali-enriched zones were precipitated from fluids with bottom water temperatures (~10 °C). Maintaining such low temperatures to 300 m depth in the crust in the Akaki area suggests that this was a region of recharge. Below these CO_2- and alkali-enriched zones temperatures increase with depth such that calcite precipitation in the Onophrious area occurred at ~10 °C higher temperature, at any given depth, than in the Akaki area. The increase in precipitation temperature with depth indicates poor thermal mixing within the crustal aquifer, likely due to laterally continuous sheet flows restricting the permeability. The chemical and thermal constraints suggest that both timing of the onset of sedimentation and volcanic architecture play important roles in controlling fluid and chemical fluxes. The same signal can be seen in drill core data from the modern ocean basins, with higher sedimentation rates leading to lower fluid fluxes and higher temperatures in the crustal aquifer.

1. Introduction

Low-temperature (10's of Celsius) hydrothermal circulation through the upper oceanic crust, away from the ridge axis, leads to globally significant fluxes of solutes into and out of the ocean (Mottl and Wheat, 1994; Staudigel, 2014). These off-axis hydrothermal systems carry about 25% of the global heat flow (Stein and Stein, 1994) and have fluid fluxes of the same order of magnitude as those from rivers (e.g. Fisher and Wheat, 2010). Changes in the alkalinity flux associated with rock alteration within ridge flank hydrothermal systems have been suggested to play an important, and maybe dominant, role in the long-term carbon cycle (Francois and Walker, 1992; Brady and Gislason, 1997; Gillis and Coogan, 2011; Coogan and Gillis, 2013). Additionally, changing bottom water temperature feeding off-axis systems and hence reaction rates within the crust, has been suggested to play a major role in controlling the secular variation in the Mg- and Sr-isotopic composition of seawater (Higgins and Schrag, 2015; Coogan and Dosso, 2015).

Fluid flow within the off-axis crustal aquifer (i.e. the lava pile) is driven by changes in fluid temperature, and hence density, due to extraction of lithospheric heat into the fluid. Since the heat budget is globally near uniform, and relatively well understood, the main unknown in modelling fluid flow comes from the distribution of permeability within the upper crust (e.g. Fisher and Becker, 2000). Two controls on permeability need to be considered: sediment cover and lava lithology.

Sediment deposited on top of the crust acts as an impermeable layer impeding the ingress of seawater into the crustal aquifer (e.g. Spinelli et al., 2004). Today, abyssal sedimentation rates vary globally so the ability of fluid to enter and exit the crust is expected to be quite variable. Over time a crustal section likely passes through three general stages of sediment cover. At very young ages, sediment is generally thin

* Corresponding author.
E-mail address: kgillis@uvic.ca (K.M. Gillis).

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enough that fluid flow is not inhibited substantially. At intermediate ages, sediment fills topographic lows and fluids will enter and leave the crust through isolated outcrops (e.g. Fisher and Becker, 2000; Anderson et al., 2012). At older ages sediment forms a near impermeable blanket vastly decreasing fluid exchange between the lavas and ocean.

The accretion of the lava pile leads to large spatial variations in permeability on a range of scales (Fisher, 1998). Lavas are commonly described as sheet (or massive) flows, pillow flows and breccias (or hyaloclastites) with large differences in permeability (Gillis and Sapp, 1997; Bach et al., 2004). Faults are also likely to play an important, but poorly understood, role in crustal permeability, both producing local high permeability pathways and offsetting high permeability layers, hence decreasing large-scale permeability (Fisher, 1998). Different crustal sections will have different permeability structures reflective of their particular lithologic stratigraphy and tectonic disruption.

Here we present a comparison of the compositions of two crustal sections of the Troodos ophiolite with differing sedimentation history and lava stratigraphy. The Troodos ophiolite was selected for this work as it has the best preservation of the low-temperature, off-axis hydrothermal alteration of any ophiolite and because the exposure and preservation of the upper crustal sequences is exquisite. The Troodos ophiolite formed in the Cretaceous (91.6 ± 1.4 Myr; Mukasa and Ludden, 1987) above a subduction zone (e.g. Miyashiro, 1973) but has an off-axis hydrothermal alteration history very similar to that of modern oceanic crust (e.g. Bednarz and Schmincke, 1989; Gillis and Robinson, 1988). We show that the bulk-rock geochemistry, including Sr- and Li-isotopic compositions, of the two studied crustal sections differ substantially as does the temperature of calcite precipitation. These differences are interpreted as recording the importance of crustal permeability on off-axis hydrothermal fluxes. Comparison with data from a global suite of drill cores from the modern ocean basins suggests the same controls in the modern ocean basins, as well as demonstrating the importance of the history of sedimentation.

2. Materials and methods

2.1. Field relationships

Two well-exposed lava sections in the Troodos ophiolite were selected for study based on differing sedimentation history and lava stratigraphy. The two study areas are ~7.5 km apart along the northern flank of the ophiolite (Fig. 1). The Akaki section was the location of extensive study in the 1980s (e.g. Rautenschlein et al., 1985; Gillis and Robinson, 1990) and was the location of the International Crustal Research Drilling Group (ICRDG) drill holes CY1 and CY1A. These holes were offset from one another (Fig. 1a) with the aim of stacking them to produce a complete section through the lavas and upper sheeted dikes (Gibson, 1991). Samples from these drill cores were largely used in this study because previous work on these cores provides context for this study. The Onophrious section, to the east of Akaki, is well-exposed along the Onophrious river and surface samples were collected here (Fig. 1b).

In the Akaki area, mapping along the lava–sediment interface shows that the lava section is overlain by chalky limestones of the Late Cretaceous to Tertiary Lefkara formation (Bear, 1960) and the contact is very planar dipping about 7°N with only very subdued (probably <10 m) paleoseafloor topography over >1 km along strike (Fig. 1a). The average dip of the sediments is somewhat steeper than that of the lava–sediment interface, 20° towards 355. This difference is most simply explained by deposition of the sediments onto an initially gently south sloping seafloor (in the modern reference frame). Subsequent northward rotation of this portion of the ophiolite, about a horizontal east–west axis, would be consistent with the data. We take the average sediment dip (20°) to reflect the average dip of the crust in this area when determining depths within the crust both for the surface and drill core samples; using dips between 10 and 30° would lead to <8% change in sample depths. Both surface geology and the drill cores show that the upper 300 m of the lava section at Akaki is dominated by pillows and breccias, with an increasing abundance of sheet flows

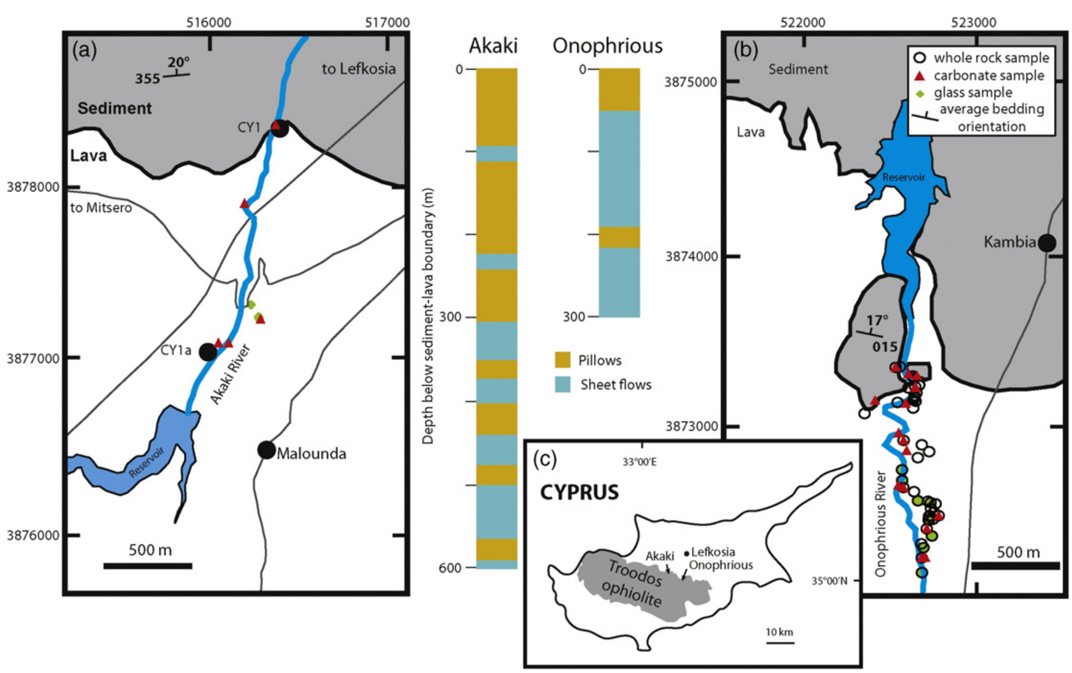

Fig. 1. Simplified geological maps and lithological columns for the (a) Akaki and (b) Onophrious River sections (both rivers flow to the north). Depth distribution of lithologies for Akaki is based on the CY1/1a drillcore (Gibson et al., 1991), which is very similar to surface outcrops (e.g. Rautenschlein et al., 1985). (c) Map of Cyprus showing the locations of Troodos ophiolite (grey) and Akaki and Onophrious River sections.