



Spatial variations in cooling rate in the mantle section of the Samail ophiolite in Oman: Implications for formation of lithosphere at mid-ocean ridges



Nick Dygert^{a,*}, Peter B. Kelemen^b, Yan Liang^c

^a Department of Geological Sciences, University of Texas at Austin, Austin, TX 78712, United States

^b Department of Earth and Environmental Sciences, Columbia University, Lamont Doherty Earth Observatory, Palisades, NY 10964, United States

^c Department of Earth, Environmental and Planetary Sciences, Brown University, Providence, RI 02912, United States

ARTICLE INFO

Article history:

Received 12 July 2016

Received in revised form 20 February 2017

Accepted 22 February 2017

Available online 10 March 2017

Editor: M. Bickle

Keywords:

Mantle

REE

thermometry

Oman ophiolite

closure temperature

geospeedometry

ABSTRACT

To understand how the mantle cools beneath mid-ocean ridge spreading centers, we applied a REE-in-two-pyroxene thermometer and major element thermometers to peridotites from the Wadi Tayin massif in the southern part of the Samail ophiolite in the Sultanate of Oman, which represent more than 10 km of structural depth beneath the paleo-Moho. Closure temperatures for REEs in pyroxenes deduced from the REE-in-two-pyroxene thermometer (T_{REE}) decrease smoothly and systematically with depth in the section, from $>1300^{\circ}\text{C}$ near the crust to $<1100^{\circ}\text{C}$ near the metamorphic sole, consistent with previously observed, similar variations in mineral thermometers with lower cooling temperatures. Estimated cooling rates decrease from $\sim 0.3^{\circ}\text{C}/\text{y}$ just below the crust–mantle transition zone (MTZ) to $\sim 10^{-3}^{\circ}\text{C}/\text{y}$ at a depth of six km below the MTZ. Cooling rates derived from Ca-in-olivine thermometry also decrease moving deeper into the section. These variations in cooling rate are most consistent with conductive cooling of the mantle beneath a cold overlying crust. In turn, this suggests that hydrothermal circulation extended to the MTZ near the axis of the fast-spreading ridge where the igneous crust of the Samail ophiolite formed. These observations are consistent with the Sheeted Sills model for accretion of lower oceanic crust, and with previous work demonstrating very rapid cooling rates in the crust of the Wadi Tayin massif. Our observations, combined with previous results, suggest that efficient hydrothermal circulation beneath fast spreading centers cools the uppermost mantle from magmatic temperatures to $<1000^{\circ}\text{C}$ as quickly as tectonic exhumation at magmatic spreading centers. In contrast, thermometers sensitive to cooling over lower temperature intervals indicate that the Wadi Tayin peridotites cooled more slowly than tectonically exhumed peridotites sampled near the seafloor along mid-ocean ridges. Hydrothermal cooling of the crust may have waned, so that the crust–mantle package cooled more slowly, whereas rapid cooling of abyssal peridotites during tectonic exhumation continued to seafloor temperatures.

© 2017 Elsevier B.V. All rights reserved.

1. Introduction

Geothermometers are widely used to investigate the thermal history of mafic and ultramafic rocks. They utilize the temperature dependent solubility or partitioning of a component among phases in a mineral assemblage, allowing temperatures to be calculated from measured mineral compositions. Geothermometers are calibrated experimentally or with well-equilibrated natural samples, and depending on the thermometer, take advantage of temperature dependent major element (e.g., Boyd, 1973; Brey and Köhler, 1990;

Nickel and Green, 1985; Putirka, 2008; Wells, 1977; Witt-Eickschen and Seck, 1991; Wood and Banno, 1973) and/or trace element exchange reactions (Eggins et al., 1998; Lee et al., 2007; Liang et al., 2013; Seitz et al., 1999; Sun and Liang, 2015; Witt-Eickschen and O'Neill, 2005).

The physical meaning of a temperature derived from the application of a geothermometer to a natural sample depends on its thermal history. In cases where the sample is maintained at constant pressure and temperate conditions and then rapidly exhumed or erupted, any well calibrated geothermometer should give a temperature reflecting the condition of equilibration in agreement with other thermometers (e.g., Liang et al., 2013; Smith, 2013; Witt-Eickschen and Seck, 1991). No kinetic information is preserved in such samples. In contrast, if the sample cools sufficiently

* Corresponding author at: Jackson School of Geosciences, University of Texas at Austin, 2275 Speedway Stop C9000, Austin, TX 78712.

E-mail address: ndygert@jsg.utexas.edu (N. Dygert).

slowly to allow appreciable diffusive reequilibration to occur during cooling, geothermometers will give a range of temperatures. All will record higher temperatures for faster cooling rates, providing the basis for “geospeedometry” (e.g., Dodson, 1973; Lasaga, 1983; Ozawa, 1984), a powerful tool that has been widely used to study the thermal history of crust and mantle formed at oceanic spreading ridges (e.g., Coogan et al., 2002, 2005a, 2007a, 2007b; Dygert and Liang, 2015; Faak et al., 2015; Faak and Gillis, 2016; VanTongeren et al., 2008). In addition, the temperature recorded by a given thermometer will depend on the effective diffusion rates of the components used to calibrate the thermometer. Thermometers based on slowly diffusing elements record higher temperatures than those based on faster diffusing elements (e.g., for peridotites, Dygert and Liang, 2015; Hanghøj et al., 2010; Liang et al., 2013; Müntener et al., 2010; Yao and Liang, 2015).

In this work we will discuss temperatures from three types of thermometers. (1) The REE-in-two-pyroxene thermometer of Liang et al. (2013), which utilizes the composition-dependent temperature sensitivity of exchange of trivalent REEs + Y between orthopyroxene (opx) and clinopyroxene (cpx). (2) Two-pyroxene solvus thermometers (e.g., Brey and Köhler, 1990; Lindsley, 1983; Lindsley and Anderson, 1983; Wells, 1977), which parameterize temperature sensitive “transfer of the enstatite component between coexisting ortho- and clinopyroxene” around the solvus (Brey and Köhler, 1990). In reality, this exchange reaction is more complicated as unmixing of solid solutions during cooling involves coupled diffusion of several major elements (e.g., Ca, Mg and Si), and net growth of one phase at the expense of another. (3) Cation exchange thermometers, which parameterize the temperature sensitivity of exchange of major elements between two phases (e.g., Fabriès, 1979; Köhler and Brey, 1990). For samples that cooled slowly, thermometers based on exchange of trivalent elements (e.g., REEs, Al) give temperatures tens to hundreds of degrees higher than two-pyroxene solvus thermometers, which in turn give higher temperatures than divalent cation exchange thermometers (e.g., D’Errico et al., 2016; Dygert and Liang, 2015; Liang et al., 2013; Marchesi et al., 2016; Müntener et al., 2010; Sun and Liang, 2015; Wang et al., 2015; Witt-Eickschen and Seck, 1991). These differences in temperature can be attributed to slower diffusion of trivalent elements compared to divalent elements (e.g., Chakraborty, 2010; Cherniak and Dimanov, 2010 and references therein), and the slower diffusion of multivalent mineral components compared to interdiffusion of isoivalent cations.

As a general rule, the larger the difference between the temperatures given by thermometers based on trivalent elements and solvus or cation exchange thermometers, the slower the average cooling rate for the sample. Thermometers based on trivalent cation exchange may reflect cooling rates in high temperature intervals along the cooling path; solvus thermometers may reflect cooling rates in intermediate temperature intervals along the cooling path. Divalent cation exchange thermometers are sensitive to lower temperature cooling intervals, and among themselves, are sensitive to cooling at different temperatures, with thermometers based on the fastest diffusing cations reflecting cooling over the lowest temperature intervals.

In a recent study, Dygert and Liang (2015) applied the REE-in-two-pyroxene thermometer of Liang et al. (2013) and several solvus thermometers to abyssal peridotites and peridotites sampled from the mantle section of ophiolites. Some ophiolites cooled more slowly than abyssal peridotites. This was expected, as abyssal peridotites are dredged from mantle exposures that were tectonically exhumed along transform faults and detachment faults in less than a million years, while ophiolites have crustal sections that generally act as insulating barriers for underlying mantle peridotites for many millions of years. In contrast, peridotites from the northern Samail ophiolite appear to have cooled as quickly as the

abyssal peridotites based on REE thermometry. This is surprising as the Samail ophiolite has a thick (5–7 km) crustal section and probably formed at a fast-spreading center (e.g., Nicolas, 1989; Rioux et al., 2012, 2013, 2016; Tilton et al., 1981), suggesting that cooling of the mantle beneath mid-ocean ridges is independent of spreading rate and the presence or absence of crust, at least in the temperature interval from ~1300 to 1000 °C.

To investigate the thermal history of mantle peridotites beneath thick crustal sections, as compared to mantle peridotites that are tectonically exhumed along faults near mid-ocean ridges, we applied the REE-in-two-pyroxene thermometer (Liang et al., 2013) and conventional major element-based pyroxene solvus, olivine-cpx and olivine-spinel cation exchange thermometers (Brey and Köhler, 1990; Fabriès, 1979; Köhler and Brey, 1990; Putirka, 2008; Wells, 1977; Witt-Eickschen and Seck, 1991) to a suite of samples from the Wadi Tayin massif in the southern Samail ophiolite (Fig. 1), previously studied by Hanghøj et al. (2010). Corrected for structural depth beneath the paleo-Moho, assuming that there is a constant dip parallel to the crust–mantle transition, and that there are no faults that repeat or omit section, these samples represent more than 10 km of paleo-depth below the Moho, with continuous outcrop. Samples from this section can thus be used to investigate the dependence of cooling rate on depth beneath the crust.

Our focus on the Wadi Tayin massif was motivated by the observation of large gradients in major element thermometer temperatures across the mantle section, with higher temperatures in mantle samples near the base of the crust and lower temperatures deeper in the section (Fig. 2, also see Fig. 7 in Hanghøj et al., 2010). In addition, interpretation of closure temperatures for olivine-cpx Ca–Mg exchange indicates that the entire crustal section in the Wadi Tayin massif cooled very rapidly, with no systematic gradient in cooling rate with depth in the crust (VanTongeren et al., 2008).

The southern massifs of the Samail ophiolite show some geochemical characteristics indicative of a “subduction component” (e.g., Pearce et al., 1981 and recent reviews in MacLeod et al., 2013 and Rioux et al., 2016), but also record a fast rate of submarine, sea-floor spreading (Rioux et al., 2012, 2013; Tilton et al., 1981). The massifs have a well-developed, gabbroic lower crust underlying sheeted dikes and pillow basalts, with mid-ocean ridge basalt (MORB)-like parental magmas and trace element chemistry, and they have mantle composition similar to abyssal peridotites (e.g., Braun, 2004; Garrido et al., 2001; Godard et al., 2000; Hanghøj et al., 2010; Kelemen et al., 1995, 1997a, 1997b; Nicolas, 1989; Pallister and Knight, 1981). Thus, the southern massifs of the Samail ophiolite in Oman represent the ophiolites with the greatest affinities to crust formed at fast-spreading mid-ocean ridges. As a result, our study provides new insight into the processes that cool the mantle beneath present-day, fast-spreading mid-ocean ridges such as the East Pacific Rise.

2. Samples and mineral compositions

Here we report major element compositions from analyses of opx, cpx and olivine and trace element compositions of opx and cpx in eight peridotites from the OM94 traverse originally studied by Hanghøj et al. (2010) (Fig. 3, Supplementary Tables S1 and S2, Supplementary Figs. S2–S5). Analytical methods are described in the Electronic Supplement. The samples are depleted, plagioclase-free harzburgites. Pyroxene minor element concentrations plot at the depleted ends of the ophiolitic and abyssal peridotite fields (Figs. 3a, 3b, Supplementary Figs. S2, S3). Consistent with the depleted pyroxene compositions, bulk rock REE and other incompatible trace element characteristics in Wadi Tayin peridotites overlap the low end of the compositional range for abyssal peridotites (Fig. 3a in Hanghøj et al., 2010). Similarly, spinel Cr#s in

Download English Version:

<https://daneshyari.com/en/article/5779986>

Download Persian Version:

<https://daneshyari.com/article/5779986>

[Daneshyari.com](https://daneshyari.com)