Formation of fast-spreading lower oceanic crust as revealed by a new Mg–REE coupled geospeedometer

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A B S T R A C T

A new geospeedometer is developed based on the differential closures of Mg and rare earth element (REE) bulk-diffusion between coexisting plagioclase and clinopyroxene. By coupling the two elements with distinct bulk closure temperatures, this speedometer can numerically solve the initial temperatures and cooling rates for individual rock samples. As the existing Mg-exchange thermometer was calibrated for a narrow temperature range and strongly relies on model-dependent silica activities, a new thermometer is developed using literature experimental data. When the bulk closure temperatures of Mg and REE are determined, respectively, using this new Mg-exchange thermometer and the existing REE-exchange thermometer, this speedometer can be implemented for a wide range of compositions, mineral modes, and grain sizes.

Applications of this new geospeedometer to oceanic gabbros from the fast-spreading East Pacific Rise at Hess Deep reveal that the lower oceanic crust crystallized at temperatures of 998–1353 °C with cooling rates of 0.003–10.2 °C/yr. Stratigraphic variations of the cooling rates and crystallization temperatures support deep hydrothermal circulations and in situ solidification of various replenished magma bodies. Together with existing petrological, geochemical and geophysical evidence, results from this new speedometry suggest that the lower crust formation at fast-spreading mid-ocean ridges involves emplacement of primary mantle melts in the deep section of the crystal mush zone coupled with efficient heat removal by crustal-scale hydrothermal circulations. The replenished melts become chemically and thermally evolved, accumulate as small magma bodies at various depths, feed the shallow axial magma chamber, and may also escape from the mush zone to generate off-axial magma lenses.

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1. Introduction

Earth's lower oceanic crust is mainly composed of mafic cumulate rocks (e.g., gabbros and gabbronorites), solidifying from mantle-derived melts beneath the spreading mid-ocean ridges. This cumulate section thus records styles of igneous accretion and crustal cooling. Many crustal formation models have been proposed based on petrological observations, deformation structures, and geodynamic simulations at various ocean ridge settings and ophiolites (e.g., Nicolas et al., 1988; Phipps Morgan and Chen, 1993; Quick and Denlinger, 1993; Kelemen et al., 1997; Dick et al., 2008). Among these, two end-member models for fast spreading mid-ocean ridges are actively debating whether cumulates of

the lower oceanic crust crystalize mainly in a shallow melt lens (e.g., Phipps Morgan and Chen, 1993; Quick and Denlinger, 1993; Coogan et al., 2007; Faak et al., 2015) or *in situ* solidify largely from magma sills at various depths (e.g., Nicolas et al., 1988; Kelemen et al., 1997; Lissenberg et al., 2004; Maclennan et al., 2005; VanTongeren et al., 2008, 2015; Natland and Dick, 2009). The former postulates much slower cooling in the deeper crust (i.e., near-conductive cooling), whereas the latter necessitates efficient heat removal by hydrothermal circulations throughout the entire crust. Thus, a key to distinguishing these two models is the cooling history of the lower crust at fast-spreading mid-ocean ridges.

Geospeedometers have the ability to extract cooling information of natural rocks from mineral compositions using analytical or numerical models (e.g., Dodson, 1973; Eiler et al., 1992; Ganguly and Tirone, 1999; Costa et al., 2003; Müller et al., 2013; Watson and Cherniak, 2015; Liang, 2017). Applying the closure temperature equation of Dodson (1973) to Ca in olivine, two research groups estimated cooling rates of oceanic gabbros from the

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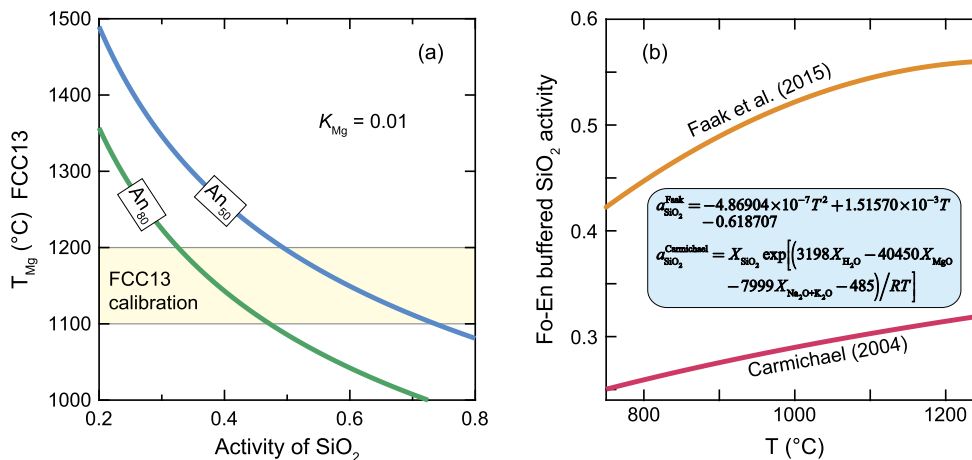
Fig. 1. Plots showing (a) the variations of temperatures (T_{Mg}) calculated using the plagioclase–clinopyroxene Mg-exchange thermometer of Faak et al. (2013) as a function of silica activity and (b) the differences of two existing silica activity models for a basaltic system. Light yellow region in (a) indicates the temperature calibration range for the thermometer of Faak et al. (2013). A fixed Mg partition coefficient ($K_{Mg} = 0.01$) and two plagioclase compositions (An$_{50}$ and An$_{80}$; An$_{50}$ denotes 50 mol% anorthite in plagioclase) were used in (a). Inset in (b) shows the silica activity model expressions of Faak et al. (2015) and Carmichael (2004), in which T is temperature in K, R is the gas constant, and X denotes the oxide molar fraction. The melt in (b) used for Carmichael's model has a typical basaltic composition (i.e., 022005-1522 used in Faak et al., 2013). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Oman ophiolite, an analogue of fast-spreading mid-ocean ridges, but obtained highly controversial results: one showed slower cooling rates consistent with near-conductive cooling (e.g., Coogan et al., 2007), whereas the other found higher cooling rates supporting deep hydrothermal cooling (VanTongeren et al., 2008). The reasons for their discrepancies remain unclear, but their approaches may involve uncertainties arising from the Dodson-type assumptions: (1) negligible influences of initial temperatures and (2) surrounding clinopyroxene acting as an infinite reservoir.

Using their newly developed Mg-in-plagioclase geospeedometer, Faak et al. (2015) argued that cooling rates derived from their 1-D grain-scale diffusion modeling support near-conductive cooling of the lower crust at the East Pacific Rise (EPR). However, in addition to the Dodson-type assumptions, results of Faak et al. (2015) are also likely subject to uncertainties from their Mg-exchange thermometer (Faak et al., 2013) and 1-D plane sheet approximation. Particularly, Faak et al.'s thermometer has a strong dependence upon silica activities that can only be calculated using existing activity models (Fig. 1a–b). Silica activities in a typical basaltic system buffered by olivine and orthopyroxene appear to differ by a factor of two between the models of Faak et al. (2015) and Carmichael (2004) (Fig. 1b), corresponding to 100–200 °C differences in Faak et al.'s thermometer (cf. Fig. 1a). Because Faak et al.'s thermometer was calibrated only at 1100–1200 °C for plagioclase with 50–80 mol% anorthite, it is unclear how accurately their thermometer can be extrapolated to lower temperatures (e.g., 700–900 °C; Faak et al., 2015), at which Mg in gabbros has been extensively reset by diffusion. Although the 1-D plane sheet diffusion model is easy to implement, it is likely inadequate for 3-D shaped crystals with substantial diffusive resetting (e.g., Ganguly and Tirone, 1999; Costa et al., 2003).

In this study, we present a new Mg–REE coupled speedometer for plagioclase- and clinopyroxene-bearing rocks that could overcome the aforementioned limitations regarding the Dodson-type assumptions, silica activities, applicable temperatures and 1-D geometry. Using the bulk closure temperatures of REE and Mg, this speedometer can simultaneously determine the initial temperatures and cooling rates of individual samples. The bulk closure temperatures of REE can be calculated using the REE-exchange thermometer of Sun and Liang (2017), while those of Mg can be determined using a new Mg-exchange thermometer calibrated at 800–1430 °C. Applying this speedometer to oceanic gabbros from the Hess Deep rift valley (Lissenberg et al., 2013), we show that

the lower crust of EPR at Hess Deep formed by *in situ* solidification of axial and off-axial magma intrusions at various depths with efficient heat removal through crustal-scale hydrothermal circulations.

2. Developing a Mg–REE coupled speedometer

2.1. Basic concept

The basis of geospeedometry using bulk closure temperatures was initially defined by Dodson (1973) for diffusion in a single crystal and has recently been extended to polycrystalline petrological systems (e.g., Eiler et al., 1992; Ehlers and Powell, 1994; Yao and Liang, 2015; Liang, 2017). In general, the bulk closure temperature (T_c) of an element of interest (j) in two coexisting minerals (α and β) can be described as,

$$T_c^j = f\left(T_0, dT/dt, G_{\alpha/\beta}^j\right), \tag{1a}$$

$$G_{\alpha/\beta}^j = \left\{D_{\alpha}^j, D_{\beta}^j, K_{\alpha/\beta}^j, \phi_{\alpha}, \phi_{\beta}, L_{\alpha}, L_{\beta}\right\}, \tag{1b}$$

where f denotes an unspecified expression; T_0 and dT/dt are the initial temperature and cooling rate, respectively; and G is a set of variables, including diffusion coefficients (D), partitioning coefficients (K), mineral proportions (ϕ), and grain radii (L) of the two minerals. Notably, initial temperatures of cumulate rocks can be regarded as the mean temperatures of cumulus crystallization because of their simple monotonic cooling histories subsequent to crystallization. As two elements with different diffusivities have distinct closure temperatures, when considered together the two elements could uniquely constrain both the cooling rate and initial temperature. The initial concept was briefly discussed in Sun and Liang (2017) for understanding the different temperatures derived from their REE-exchange thermometer and the Mg-exchange thermometer of Faak et al. (2013). A similar concept has also been used in Watson and Cherniak (2015) with a focus on diffusive relaxation of stepwise concentration profiles in single crystals. Here we further pursue this idea to develop a new speedometer by coupling the bulk closure temperatures of slowly diffusing REE and fast diffusing Mg in coexisting plagioclase and clinopyroxene.

In oceanic gabbros, plagioclase and clinopyroxene are the two main rock-forming minerals, co-crystallizing from the relatively dry basaltic magmas that characterize mid-ocean ridges over an extended temperature interval (e.g., Grove et al., 1992). According to