

# Rapid magma ascent recorded by water diffusion profiles in mantle olivine

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## ABSTRACT

**Mechanisms and rates of magma ascent play a critical role in eruption dynamics but remain poorly constrained phenomena. Water, dissolved in mantle minerals as hydrogen and partitioned into the magma during ascent, may provide clues to quantifying magma ascent rates prior to eruption. We determined the dehydration profiles in olivine crystals from peridotite mantle xenoliths within the Pali-Aike alkali basalt from Patagonia, Chile. The results demonstrate that the amount of water stored in the uppermost mantle has likely been underestimated due to water loss during transport. Using experimental diffusion data for hydrogen, we estimate that the xenoliths reached the surface from 60–70 km depth in several hours, a surprisingly rapid rise comparable to ascent rates for kimberlite magmas.**

**Keywords:** Earth's upper mantle, mantle xenolith, hydrogen, diffusion, olivine, magma ascent rate.

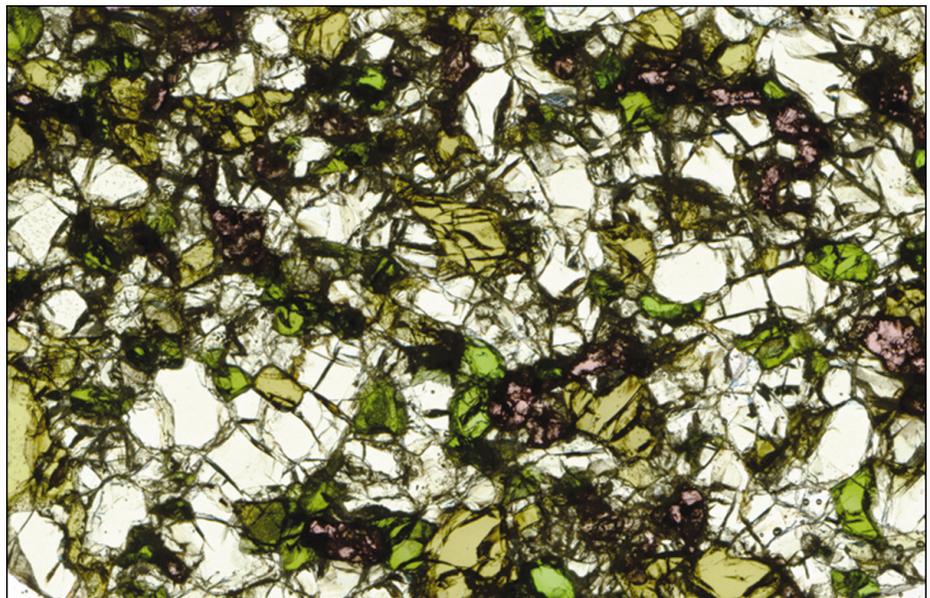
## INTRODUCTION

A small amount of water embedded within mantle minerals has major effects on the physical and chemical processes of Earth's mantle (e.g., Karato, 1990; Hirth and Kohlstedt, 1996; Smyth and Frost, 2002) and potentially acts as a critical component in the development of plate tectonics (Regenauer-Lieb et al., 2001). Emerging theories on Earth's deep-water cycle (e.g., Bercovici and Karato, 2003; Ohtani et al., 2004) require observational and experimental constraints on the storage capacity and mobility of water inside Earth's mantle. Previous studies (e.g., Miller et al., 1987; Bell and Rossman, 1992) have characterized the water contents in a range of upper-mantle minerals from mantle-derived peridotite. However, from experimental studies, it is expected that water in mantle minerals is partially lost during transport (Kohlstedt and Mackwell, 1999; Ingrin and Skogby, 2000). While it is often assumed that the major-element composition of mantle-equilibrated xenoliths is representative of Earth's upper mantle, changes during entrainment and transport may overprint the chemical signatures of the source region, especially for volatile ele-

ments. Some mantle rocks may rise rapidly to the surface within the magma (i.e., 4 m/s; Kelley and Wartho, 2000), while others may reside in magma chambers for extended periods,

allowing partial or complete reequilibration (Shaw, 2004).

Nominally anhydrous minerals of the upper mantle (olivine, pyroxene, garnet) usually contain trace amounts of hydrogen, as protons bound to structural oxygen atoms, which is detectable as hydroxyl using Fourier transform infrared (FTIR) spectroscopy in the region of O-H stretching ( $3000\text{--}4000\text{ cm}^{-1}$ ). Experimental studies (Kohlstedt et al., 1996; Mierdel and Keppeler, 2004; Withers et al., 1998; Zhao et al., 2004) have demonstrated that the hydrogen storage capacity of these minerals increases with increasing water fugacity and temperature and is sensitive to chemical composition. Hydration is mainly accommodated by ionic substitution for major elements and/or by association with other defects for electrical charge balance. However,



**Figure 1.** Pali-Aike garnet-lherzolite xenolith derived from Earth's uppermost mantle. Transmitted light photomicrograph with mineral assemblage: olivine (transparent-pale green), diopside (bright green), orthopyroxene (brown-green), and garnet (pink). Horizontal field of view is 20 mm. Olivine grains in this xenolith exhibit hydroxyl-depleted rims, which are indicative of natural dehydration processes during ascent in host magma.

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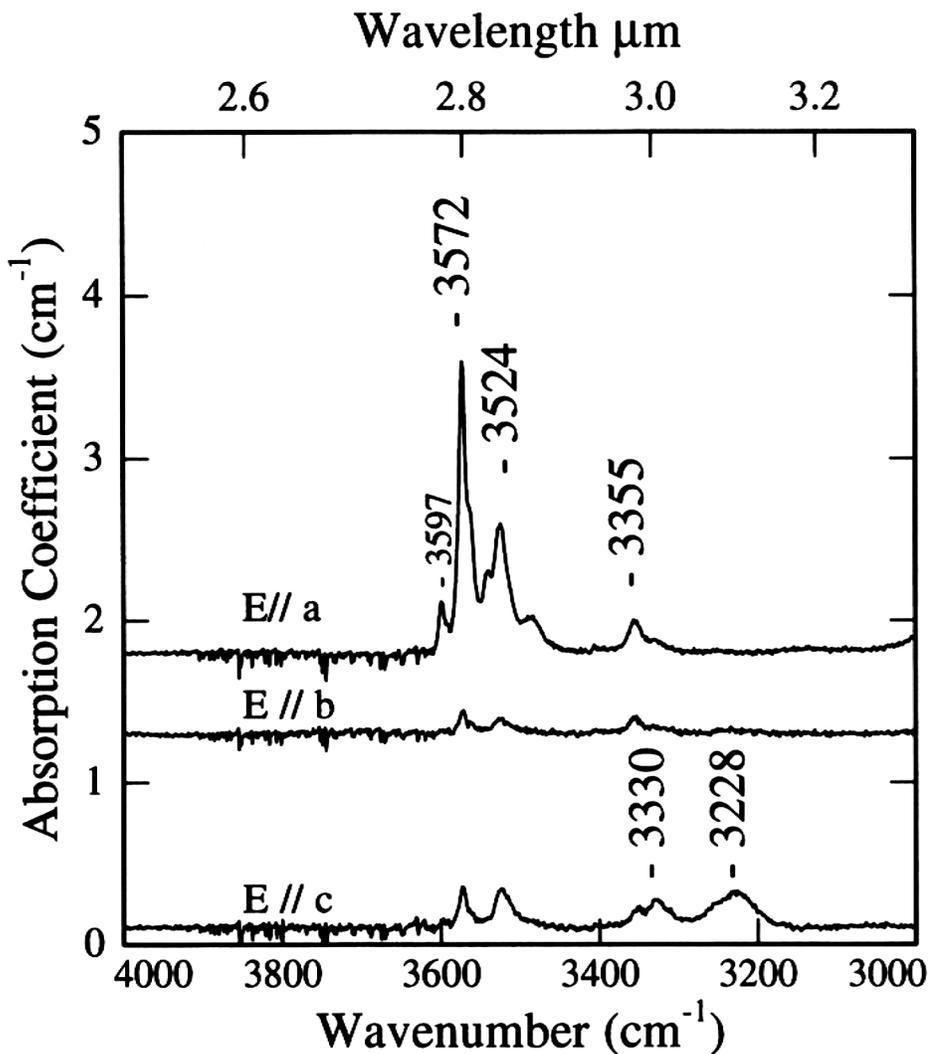


Figure 2. Polarized infrared spectra for olivine PA-3. Spectra were taken with different orientations of electric vector E.

the water concentrations in olivine from peridotite xenoliths always yield hydrogen contents lower than expected from the solubility laws determined experimentally (Kohlstedt et al., 1996; Zhao et al., 2004). Only olivine from kimberlites (Miller et al., 1987; Bell et al., 2003), a rapidly rising volatile-rich magma, shows high water concentrations ( $\sim 200$  ppm H<sub>2</sub>O by weight; Bell et al., 2003). It is known from experimental studies on the kinetics of hydration in olivine (Mackwell and Kohlstedt, 1990; Kohlstedt and Mackwell, 1999) and forsterite (Demouchy and Mackwell, 2003) that hydrogen could be lost in just a few hours during ascent from depths at temperatures over 800 °C. Such a process has not previously been recognized for natural samples. We present evidence for water diffusion in mantle olivine based upon FTIR analyses of hydroxyl distribution in olivines in xenolithic garnet-bearing peridotite within alkali olivine basalt from the Pali-Aike volcanic field. These diffusion profiles were used to

constrain ascent rates using experimentally determined hydrogen diffusion rates for olivine.

#### SAMPLES AND ANALYSIS

The studied samples are olivine crystals from garnet-bearing lherzolite xenoliths within Quaternary alkali olivine basalts from Pali-Aike, Patagonia, Chile (Skewes and Stern, 1979; Stern et al., 1999). Their mineral assemblage consists of olivine, orthopyroxene, Cr-diopside, and Cr-pyrope garnet (Fig. 1; the chemical compositions of the mineral phases are given in Table DR1 of the GSA Data Repository<sup>1</sup>). The pyrope garnet contains hydrous and brownish glassy inclusions and secondary spinel-rich kelyphytic rims. The

<sup>1</sup>GSA Data Repository item 2006084, Table DR1, sample descriptions, analytical methods and diffusion analysis, Table DR2, and Figure DR1, is available online at [www.geosociety.org/pubs/ft2006.htm](http://www.geosociety.org/pubs/ft2006.htm), or on request from [editing@geosociety.org](mailto:editing@geosociety.org) or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

lherzolites show no evidence of weathering, secondary recrystallization, or massive melt infiltration by the host basalt. There is no evidence for deformation-induced fabric development (Douglas et al., 1987). The major-element composition of xenoliths is representative of Ringwood's pyrolite (Ringwood, 1962), and trace-element and isotopic compositions are similar to the global asthenospheric source of mid-ocean-ridge basalt (Stern et al., 1999), without any indication of subducted components. Additionally, core compositions of lherzolite minerals indicate equilibrium temperatures between 970 °C and 1160 °C and a pressure range of 1.9–2.4 GPa, corresponding to 60–80 km depth (Stern et al., 1999). No magma chamber has been clearly identified geophysically in which the xenoliths could have reequilibrated before transport.

The alkali basalt erupted with a temperature estimated to be between 1200 °C and 1290 °C based on phenocryst olivine liquid distribution coefficients for divalent elements (D'Orazio et al., 2000). Furthermore, FTIR measurements of basaltic clinopyroxene phenocrysts show no evidence of hydroxyl, which, together with the absence of amphibole in the basalt, indicates that the alkali basalt was undersaturated in water (loss on ignition range [LOI] 0.44–1.37 wt%; D'Orazio et al., 2000), making the host magma an effective sink for hydrogen (incompatible element) and providing an environment for dehydration of the lherzolite.

To compare the amount of water in each mineral phase, the water contents were initially determined using an identical method based on unpolarized FTIR spectroscopy (Table DR2, see footnote one). Enstatite and diopside were richer in water than olivine, with concentrations of  $310 \pm 105$  wt ppm H<sub>2</sub>O and  $416 \pm 150$  wt ppm H<sub>2</sub>O, respectively (Table DR2, see footnote one). Profiles of unpolarized FTIR measurements across individual grains reveal that the water distribution in pyroxenes is homogeneous, in contrast to olivine where rims are hydroxyl-depleted (Fig. DR1, in see footnote one). In total, we studied 30 olivine grains from two different xenoliths (LS33 and palix-1), and all olivines larger than 0.8 mm show hydroxyl-depleted rims. Two selected grains were oriented for polarized FTIR for further investigation because hydrogen diffusion in olivine is anisotropic (Kohlstedt and Mackwell, 1999). Therefore profile measurements were repeated on crystallographically oriented single grains of olivine. In this case, another infrared calibration, specific for iron-bearing olivine, requiring polarized FTIR was used (Bell et al., 2003; Table DR2, see footnote one). In the polarized FTIR spectra of an olivine grain (PA-3), shown in Figure 2, the major hydroxyl absorption band

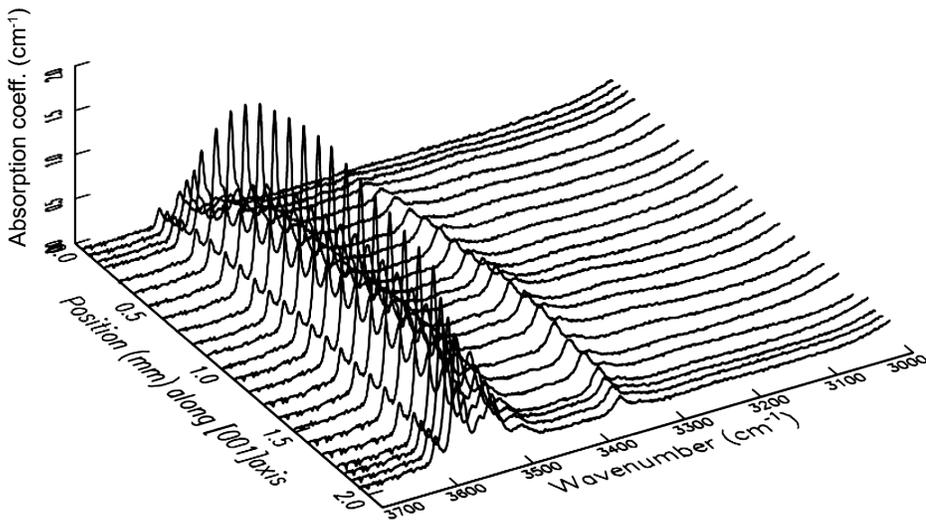


Figure 3. Series of polarized infrared spectra for olivine PA-7. Spectra were taken with E parallel to [100] and are presented as a function of lateral position (in mm) parallel to [001] axis.

is located at  $3572\text{ cm}^{-1}$  when the electric vector (E) is parallel to [100]. Weak bands are visible near  $3572\text{ cm}^{-1}$  and  $3525\text{ cm}^{-1}$  with E parallel to [010] and [001]. The FTIR spec-

tra also contain strongly polarized bands at  $3330\text{ cm}^{-1}$  and  $3228\text{ cm}^{-1}$  with E parallel to [001]. These FTIR features are common for mantle-derived olivine (Miller et al., 1987; In-

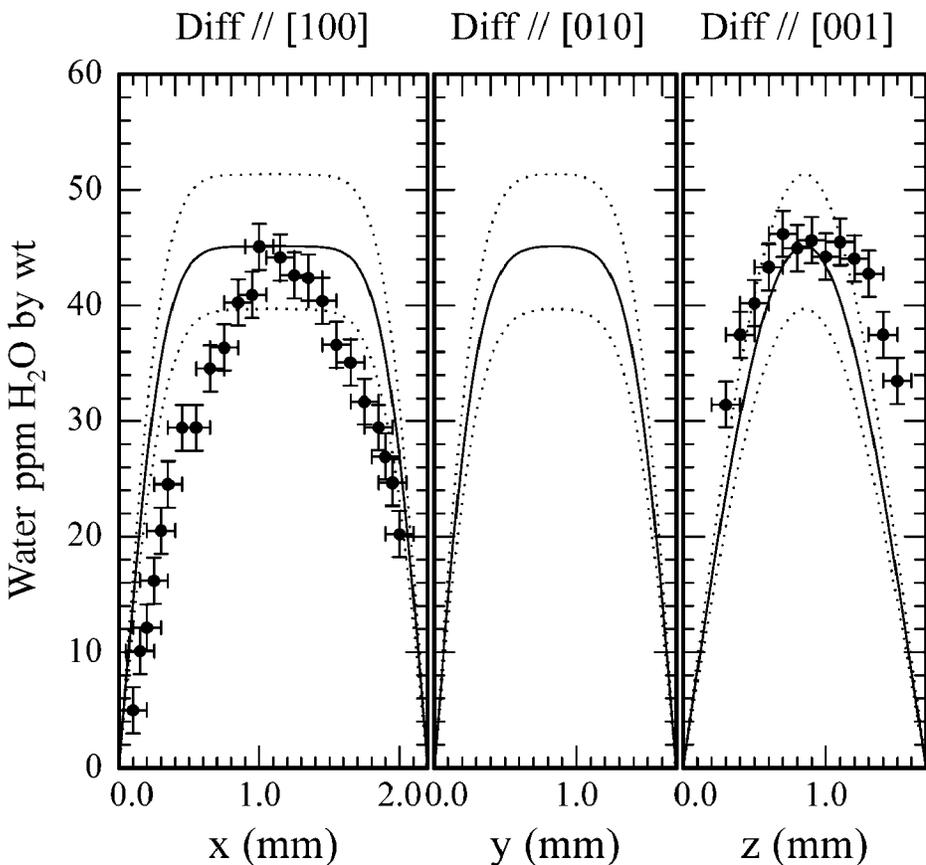


Figure 4. Water content (in ppm  $\text{H}_2\text{O}$  by weight) as a function of position parallel to each axis using calibration of Bell et al. (2003). Polarized infrared profiles are across olivine PA-7. Solid lines are not a fit but represent calculated diffusion profiles based on previous experimental work. As a function of temperature, different durations for dehydration are extracted and yield a global ascent rate of  $6 \pm 3\text{ m/s}$  (see text and GSA Data Repository [see text footnote 1] for details). Dotted lines give  $\pm 5\%$  on ascent time.

grin and Skogby, 2000). The water content obtained with the calibration specifically for olivine using polarized radiation (Bell et al., 2003) has a maximum value of  $45 \pm 4\text{ wt ppm H}_2\text{O}$  within the core of olivine PA-7. A series of polarized FTIR spectra (Fig. 3) was collected at  $50\text{ }\mu\text{m}$  (near edges) and  $100\text{ }\mu\text{m}$  intervals from a *b*-plate of olivine PA-7 in order to obtain profiles in the [100] and [001] directions. The mineral section was  $\sim 500\text{ }\mu\text{m}$  thick and was taken from the central part of the  $\sim 4\text{ mm}$  grain after its orientation was obtained with X-ray diffraction. These measurements confirm that the olivine rims are hydroxyl-depleted, indicating that the olivine was dehydrating in the water-undersaturated host magma during entrainment and transportation. The total water contents for olivine PA-7 are plotted as a function of position along the [100] and [001] axes in Figure 4.

#### IMPLICATIONS FOR WATER IN THE MANTLE

The observations from Pali-Aike lherzolite xenoliths suggest that garnet is dehydrated, olivine was quenched in the process of dehydrating, and pyroxene has not been dehydrated yet. These observations are fairly consistent with laboratory investigations, which have suggested that diffusion of hydrogen at  $1245\text{ }^\circ\text{C}$  is faster in garnet (Blanchard and Ingrin, 2004) than in olivine (Kohlstedt and Mackwell, 1999; Demouchy and Mackwell, 2003), which is faster than in pyroxene (Carpenter Woods et al., 2000; Hercule and Ingrin, 1999; Ingrin and Skogby, 2000). We have also assumed that hydrogen diffusion in pyroxenes is limited by metal vacancy diffusion at high temperature, as for olivine. In addition, chemical composition may influence hydrogen incorporation and diffusion rate in pyroxene (Stalder, 2004).

The dehydration profiles in olivine reported here imply that the water concentration before entrainment and ascent of mantle olivine must have been notably higher than the observed concentration level. The re-estimation of the water content in olivine prior to ascent suggests that the bulk uppermost mantle, at least beneath Patagonia, contains  $\sim 170\text{ wt ppm H}_2\text{O}$  (i.e., using the calibration of Paterson, 1992) at  $60\text{--}70\text{ km}$  depth for a garnet peridotite.

#### ESTIMATING ASCENT RATE

Using experimentally determined diffusion coefficients for hydration of olivine (Kohlstedt and Mackwell, 1999; Demouchy 2004), we calculated water diffusion profiles for all three crystallographic axes in an olivine grain at a temperature of  $1245 \pm 45\text{ }^\circ\text{C}$ , for various durations, an initial water content of  $\sim 312\text{ wt}$

ppm H<sub>2</sub>O, and a final water content of 0 wt ppm H<sub>2</sub>O at the rims (see GSA Data Repository for the details on the calculation [see footnote one]). Thus, we were able to approximate the ascent rate of the peridotite xenolith and, by extension, its host basalt (assuming a nearly adiabatic ascent). Calculated profiles are shown by the solid lines in Figure 4, yielding ascent rates of 1.9 h at 1290 °C, 3.4 h at 1245 °C, and 6.3 h at 1200 °C. For the same water content observed in the middle of the olivine, an overestimation of the initial water content in the calculation would yield to an underestimation of the ascent rate. In addition, FTIR analyses across intergranular cracks in the olivine grains did not exhibit perturbations of the hydrogen profile, indicating that hydrogen diffusion occurred predominantly prior to cracking near the surface or after eruption. Therefore, in a matter of only several hours, the xenoliths must have reached the surface. Assuming a depth of origin for the xenoliths of 60–70 km (Stern et al., 1999), the corresponding ascent rate is  $6 \pm 3$  m/s. Because the xenoliths are denser than the host magma, this estimate gives a minimum ascent rate for the host alkali basaltic magma. Such rapid ascent toward the surface is consistent with the fresh aspect of the various xenoliths, but it is faster than the ~1 m/s rate estimated for granulite xenoliths from Pali-Aike (Selverstone and Stern, 1983) and calculations based on mantle nodule settling velocities of ~10<sup>-1</sup> m/s (Spera, 1980). Interestingly, such rapid ascent rates are similar to the 4 m/s rate previously reported for ascent of volatile-rich kimberlitic magmas based on Ar diffusion profiles in phlogopite-bearing ultramafic xenoliths (Kelley and Wartho, 2000), which suggests that alkali basaltic magmas may rise as rapidly as kimberlitic magmas.

#### ACKNOWLEDGMENTS

We thank H. Schulze for sample preparation and F. Langenhorst for transmission electron microscopy observations. We are grateful to S.J. Mackwell and D.L. Kohlstedt for direction and valuable discussions. Demouchy is supported by grants from the European Community through the Human Potential Programme HydroSpec, the German Science Foundation, and by the U.S. National Science Foundation (NSF). Jacobsen is supported by the NSF (Geophysics) grant EAR-0440112 and by a Carnegie Fellowship. This paper is Lunar and Planetary Institute (LPI) contribution number 1262.

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Manuscript received 1 November 2005

Revised manuscript received 9 January 2006

Manuscript accepted 12 January 2006

Printed in USA