Helium distribution in a mantle shear zone from the Josephine Peridotite

A. Recanati [a,b,*], M.D. Kurz [b], J.M. Warren [c], J. Curtice [b]

[a] Laboratoire de Geologie, Ecole Normale Superieure, UMR 8538, 24 rue Lhomond, 75231 Paris Cedex 5, France
[b] Marine Chemistry and Geochemistry, Clark Lab 421, Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA
[c] Geological and Environmental Sciences, Stanford University, 450 Serra Mall, Stanford CA 94305-2115, USA

ABSTRACT

A previous study of oceanic mylonites suggested that peridotite helium concentrations are correlated with the degree of high-temperature ductile deformation in the mantle. In order to test this result, this study combines helium measurements with characterization of the deformation state of harzburgite samples in a small (6 m width) ductile mantle shear zone from the Josephine Peridotite, Oregon, USA. All measurements were made by coupled in vacuo crushing and melting, demonstrating that most of the helium (> 80%) resides within the solid phases rather than fluid or melt inclusions. The present study confirms the influence of deformation on helium contents, but only at the highest shear strain ($\gamma > 20$) are helium contents significantly higher. The highest helium concentration, by roughly a factor of two, is found in the center-most sample, which also has grain size reduction by a factor of ~ 4. Dislocations and sub-grain boundaries are present in all samples and do not correlate with helium concentrations. Mineralogy also appears to have a negligible influence in this shear zone, as modal mineralogy is relatively homogeneous, with all samples being harzburgites. These observations suggest that the increase in helium concentration is related to grain size reduction, with grain boundaries proposed as an additional storage site for helium in the mantle.

The present data also characterize the isotopic composition of the Josephine Peridotite: $^3He/^4He = 6.7 \pm 0.2$ Ra ($n = 33$, between 6.3 and 7.1 Ra). The presence of cosmogenic ^3He in the matrix is indicated by the helium isotopic composition released by melting: $^3He/^4He = 8.5 \pm 0.3$ Ra ($n = 10$; from 7.9 to 10.9). This corresponds to an exposure age of 10 Kyr, which is approximately concordant with the end of the last glacial maximum. Very little radiogenic helium is present in the samples, suggesting extremely low uranium and thorium contents ($[U] < 0.3$ ppb). Helium isotope measurements in four samples outside the shear zone suggest that mineralogy and melt infiltration are also important factors for understanding helium storage in the mantle.

1. Introduction

Helium isotopes have been extensively used as tracers of mantle fluxes and heterogeneity. However, mantle geochemistry is restricted by the availability of appropriate/representative mantle samples. Most previous studies of helium have focused on zero-age basalts from mid-ocean ridges and ocean islands, particularly in submarine glasses that trap substantial quantities of mantle helium (e.g., Kurz and Jenkins, 1981; Graham, 2002). Peridotites are more difficult to analyze, because they are the depleted residues of melting and therefore contain lower concentrations of helium and other incompatible elements. There

have been studies of continental peridotite xenoliths, which are generally thought to represent lithospheric sources (e.g., Gautheron et al., 2002, 2005), and some studies of seafloor peridotites (Kumagai et al., 2003, 2008; Kurz et al., 2009). Ophiolites and orogenic peridotites represent easily accessible portions of exhumed mantle, but there have been very few helium studies, with the single exception of the Beimarang ophiolite, in Tibet (Ye et al., 2007).

A previous study of mylonites from oceanic transform faults suggested that mantle deformation might increase the helium concentration in peridotites (Kurz et al., 2009). The high helium concentrations in oceanic mylonites were interpreted as evidence for noble gas storage on crystal defect sites or on grain boundaries. Hiraga et al. (2003, 2004, 2007) suggested that grain boundaries constitute significant reservoirs of incompatible elements (e.g. Ca, Al), based on analysis of natural and synthetic aggregates of olivine and other mineral assemblages. They also presented thermodynamic models to predict element enrichment at interfaces. Baxter et al. (2007) developed an experimental

* Corresponding author at: Laboratoire de Geologie, Ecole Normale Superieure, UMR 8538, 24 rue Lhomond, 75231 Paris Cedex 5, France.
E-mail addresses: alice.recanati@gmail.com, arecanati@mnhn.fr (A. Recanati), mkurz@whoi.edu (M.D. Kurz), warrenj@stanford.edu (J.M. Warren), jcurtice@whoi.edu (J. Curtice).

samples are moderately deformed, and the foliation and lineation are almost perpendicular to the shear plane/shear direction. Close to the shear zone center ($|Z| < 1$), the foliation and lineation are parallel to the shear plane/shear direction.

In addition to systematic sampling across the shear zone, this study includes several coarse-grained, undeformed samples that were collected within ~50 m of shear zone A. These samples represent the different mineralogies found within the Josephine Peridotite, and are included here to provide a broader context for the shear zone samples. Sample JP10M01 is a chromitite vein in a dunite pod within harzburgite. Sample JP10M02 is a pyroxenite sample from a 10–20 cm wide vein inside a clinopyroxene-bearing harzburgite (JP10M04). These two samples are within 0.5 m of each other in the field. The harzburgite has a relatively high abundance of clinopyroxene (~4–5%) for the Josephine Peridotite, which may be due to melt percolation related to the pyroxenite vein. JP10M05 is a separate 6 cm wide clinopyroxenite vein in harzburgite. These samples and veins are related to melt transport in the peridotite, which is interpreted to have occurred before, during, and after deformation at Fresno Bench (Kelemen and Dick, 1995).

3. Methods

This study combines helium measurements with deformation analysis of samples from shear zone A, including shear strain calculation, grain size measurement and textural analysis. The methodology used to characterize deformation in the samples follows that of previous studies of the Fresno Bench shear zones (Warren et al., 2008; Skemer et al., 2010), as well as sample oxidation to study olivine dislocation populations. The helium measurements were performed following the experimental procedure and mass spectrometry techniques previously reported by Kurz et al. (1990, 2004, 2009).

Assuming that volume change did not occur, displacements within the shear zone are only due to deformation by simple shear (Ramsay and Graham, 1970; Warren et al., 2008). The deflection of the orthopyroxene foliation was used as a marker for shear strain, γ (Fig. 1), assuming $\gamma=0$ for the sample furthest from the shear zone center (JP10M15). Samples were reoriented in the laboratory, and thin sections were cut in the X–Z plane (315/50) perpendicular to the shear plane. Grain size measurements were performed by the mean line intercept technique on 300 grains per sample for seven samples, applying a stereographic correction factor of 1.5 (Underwood, 1970; Drury, 2005; Warren et al., 2008). Four thin sections were decorated using the Kohlstedt et al. (1976) method in order to examine olivine dislocation structure. This method results in the selective oxidation of lattice dislocations, which can be imaged using either a petrographic microscope or a scanning electron microscope. In this study, it was used in an attempt to determine if dislocation abundance correlates with helium content in the peridotites.

For noble gas analysis, samples were lightly crushed in a stainless steel mortar and pestle, and three fractions were hand-picked using a binocular microscope. Chips of > 2 mm size were used for whole rock measurements and, whenever possible, olivine and orthopyroxene from the 1–2 mm size fraction were separated. The orthopyroxene fraction is composed of non-altered orthopyroxene macroscopic crystals. The olivine fraction is composed of multiple olivine grains, avoiding major oxidation and larger chromite or magnetite inclusions (i.e. > 100 μm). In the most deformed sample, JP10M08, it was impossible to make an orthopyroxene separate due to the small grain size. Mineral separates were prepared from the 0.5–1 mm size fraction for three samples, using a Frantz magnetic separator, in order to

eliminate separation technique and grain size as influences on the helium measurements. Mineral separates were also prepared from harzburgite sample JP10M04 (olivine, orthopyroxene, clinopyroxene), because clinopyroxene was more abundant than in the shear zone samples.

All samples were analyzed by coupled in vacuo crushing and melting, to document the distribution of helium within the rocks and minerals. Numerous blanks and standards were run along with the samples, with at least 10 air standards and blanks typically run over the course of a single day. Concentrations and isotopic compositions are reported relative to air standards. The error in ^{3}He/^{4}He was computed as a function of the error in the blanks and standards, and is generally 1–2%. The analytical error in ^{4}He is ~1%, i.e. the quadrature sum of the uncertainty in the blank (~2.8×10^{-12} ccSTP/g) and the reproducibility of standards (< 1%). Repeat measurements of several samples yielded larger variability (~7% for sample JP10M08, $n=3$). This variability was included in the estimate of the ^{4}He uncertainties, yielding ~7%, which is a conservative estimate because it combines both analytical uncertainties with an estimate of reproducibility of individual samples. These conservative uncertainties are included in Table 1 and represented as ^{4}He error bars in all figures. The experimental procedure and helium mass spectrometry have been previously documented (Kurz et al., 2004, 2009).

4. Results

4.1. Microstructural evolution of shear zone A

The angle between the foliation plane and the shear plane decreases from 70° at the edge of the shear zone to 1° at the center. This corresponds to a variation in calculated shear strain from $\gamma=0$ to $\gamma=64$ (Fig. 2A, Table 1), assuming that the sample the furthest from the shear plane (JP10M15) represents zero shear strain. The main uncertainty in this calculation is the choice of the reference "unstrained" sample. However, taking either JP10M13, 14, or 15 as the unstrained sample results in < 1% difference in the calculated strain for the most deformed sample. The center-most sample has a significantly higher shear strain than all the other samples, due to shear localization in the central 1 m wide portion of the shear zone (Fig. 1).

Samples from the edge of the shear zone are coarse-grained harzburgite, mostly composed of 1–3 mm round orthopyroxene

Table 1
Background information: Results from grain size measurements, shear strain calculation, and trace element analyses, where "nd" and "na" respectively denote not determined and not applicable. Uranium and thorium concentrations were determined from whole rock inductively-coupled plasma mass spectrometer measurements, analyzed at WSU Geoanalytical Lab. DST-1 is an analytical dunite standard, referenced by Govindaraju (1994).

	Z (m)	Grain size (μm)	Shear strain	U (ppm)	Th (ppm)
JP10M15	7.0	838	0	nd	nd
JP10M14	4.7	797	0	0.0118	0.04
JP10M13	3.6	1022	0	nd	nd
JP10M12	2.6	780	0	0.0105	0.05
JP10M11	2.2	nd	1	nd	nd
JP10M10	1.7	nd	2	nd	nd
JP10M09	0.8	642	8	nd	nd
JP10M08	0	289	64	0.0101	0.04
JP10M07	-0.6	nd	17	nd	nd
JP10M06	-0.8	482	11	0.0081	0.03
JP10M05	na	nd	na	0.0130	0.04
DTS 1	na	na	na	0.0175	0.04
DTS 1-Govindaraju	na	na	na	0.0036	0.01