Evidence from depleted abyssal peridotites

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ABSTRACT

The Southwest Indian Ridge, between 61° and 68°E, is one of the deepest, slowest, and coldest sections of the global mid-ocean ridge system, and the composition of the basaltic crust suggests an extremely low degree of melting (Meuzen et al., 2003). In contrast to normal expectations, the subaxial mantle contains peridotites highly depleted in clinopyroxene (< 2%), the lowest-melting mineral phase, but anomalously enriched in orthopyroxene (modal olivine/orthopyroxene = 2). Furthermore, orthopyroxene grains host mineral inclusions enriched in OH, Na, K, P, S, and light rare earth elements never previously reported in residual mineral assemblages of abyssal peridotites; these inclusions are primarily Na-, Cr-rich diopside variably associated with apatite, amphibole, mica, albitite, and sulfides. Surprisingly, these metasomatic minerals do not occur within the other mineral phases (olivine, spinel) or as interstitial phases or veins. We conclude that the metasomatic mineral inclusions represent traces of a fertile mantle component that locally escaped extraction during decompression beneath the ridge. Our observations (1) imply interactions of the suboceanic asthenosphere with incompatible element–rich melts, and (2) provide evidence for refractory mantle blobs in the suboceanic mantle that have compositional similarities to continental lithosphere.

Keywords: metasomatism, asthenosphere, abyssal peridotite, mid-ocean ridge, Indian Ocean.

INTRODUCTION

Volcanism at mid-ocean ridges is commonly understood to result from partial melting of the underlying oceanic mantle (e.g., Dick et al., 1984). However, interpretation of the geochemistry of basaltic glasses—often ambiguous as to the potential role of compositional variations of the source mantle both on a local and a global scale—is highly controversial (Sleep, 1984; Allègre and Turcotte, 1986; Hirschmann and Stolper, 1996; Salters and Dick, 2002). In this respect, study of abyssal peridotites, interpreted as solid residues of the partial-melting process, can provide alternative and direct information concerning the composition and homogeneity of the suboceanic mantle. Here we describe abyssal peridotites dredged near the eastern extremity of the Southwest Indian Ridge. This region of the Southwest Indian Ridge, extending from the Rodrigues triple junction to the Melville Fracture Zone, is characterized by one of the slowest spreading rates of the global ridge system (full rate, < 1.6 mm/yr; Shu and Gordon, 1999). The ridge axis shows extremely rough topography

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and is unusually deep (Cannat et al., 1999). Furthermore, the basaltic crust is very thin (Debayle and Lévéque, 1997; Muller et al., 1997), and erupted basalts are highly enriched in Na (Robinson et al., 2001; Meuzen et al., 2003). All these features imply that the current extent of melting in the region is extremely low. In such a context, abyssal peridotites are expected to be lherzolites, only weakly depleted in basalt-forming elements compared to unmelted mantle, making this ridge an ideal place to look for preservation of fertile geochemical components that may be usually eliminated completely from the mantle during more extensive melting (e.g., Salters and Dick, 2002).

Instead of being fertile, however, the peridotites dredged in this region (EDUL cruise, Mével et al., 1997) have only moderate modal abundance (< 6%) of clinopyroxene (Cpx), and their mineral compositions are depleted (i.e., the pyroxenes have higher Mg and Cr but lower Al and Ti contents than pyroxenes in fertile peridotite) (Seyler et al., 2003). At EDUL Site 23 at 63°16′ E on the northern wall of the axial valley, we have further identified 3, 15–35 dm³ blocks of harzburgite (i.e., spinel peridotite highly depleted in Cpx) that are described here.

MINERALOGY AND GEOCHEMICAL DATA

EDUL Site 23 harzburgites contain no residual Cpx. Their texture is coarsely granular; the grains are of serpentinitized olivine (Ol; Fo [forsterite] = 90.5 ± 0.2 wt%) and orthopyroxene (Opx; Al₂O₃ = 4.19 ± 0.17 wt%), characterized by curved grain boundaries, and a few millimeter-sized, holly leaf–shaped spinel [Cr/(Cr + Al) = 0.26 ± 0.04, TiO₂ = 0.13 ± 0.07 wt%]. This harzburgite is especially rich in Opx (Fig. 1A); it has a modal Ol/Opx ratio of ~ 2, significantly lower than common abyssal harzburgites (typical modal Ol/Opx ratios are 4–5; Fig. 2) (Dick, 1989; Niu, 1997). In addition, some Opx crystals are very large, to 2 cm across, and show almost no deformation or recrystallization features (Fig. 1A).

Another distinctive feature of the Opx is the widespread occurrence of 10–100-μm-sized solid inclusions. Although many inclusions are, in two dimensions, isolated blebs of Cpx, a significant number consist of mineral assemblages never before described in abyssal peridotite. Four different assemblages were recognized, all containing Cr- and Na-rich diopside with high Al₂O₃ (5–7 wt%) and low to moderate TiO₂ contents (0.4–0.6 wt%) (Table DR1). These assemblages are, in decreasing order of abundance, (1) Cpx + Ol ± spinel ± apatite; (2) Cpx ± spinel ± apatite; (3) Cpx + garnet ± phlogopite ± spinel ± apatite; (4) Cpx + spinel + albite. In assemblage 1, Cpx mantles euhedral Ol and may locally occur as euhedral crystals, to 1 mm in

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Geology; April 2004; v. 32; no. 4; p. 301–304; doi: 10.1130/G20191.1; 4 figures; Data Repository item 2004051.
size. In assemblage 2, Cpx ranges in shape from subhedral to oval. Cleavage planes and exsolution lamellae of the enclosed Cpx and host Opx intersect at a high angle. Spinel adheres to the Cpx as small anhedral grains (Fig. 1B) or occurs as larger, subhedral crystals. These are invariably poorer in chromium [Cr/(Cr + Al) = 0.10–0.17] and poorer in TiO$_2$ (0.03 ± 0.02 wt%) than intergranular matrix spinel. In assemblage 3 inclusions, pargasite and phlogopite have typical mantle compositions (high Mg/Fe ratios and Cr$_2$O$_3$ and NiO contents and, for pargasite, high Al$_2$O$_3$ and Na$_2$O contents), but do not display replacement relationships with the Cpx. Instead, they form interlocked crystals, suggesting a primary magmatic origin for all three minerals (Fig. 1C). However, in other inclusions, a grain-boundary adjustment produced a granular texture (Fig. 1D). In assemblage 4, Cpx and spinel occur as euhedral grains cemented by almost pure albite (Ab$_{97}$ An$_3$). Small grains of hydroxylapatite and pentlandite ([Fe,Ni]$_9$S$_8$) are also observed in assemblages 1–3.

The major and trace element chemistry of the Cpx grains is unusual for mid-ocean ridge peridotites. For example, Cpx shows high Na$_2$O contents, increasing from 0.65–1.28 wt% in assemblages 1 and 2, through 1.16–1.34 wt% in assemblage 3, to 1.35–1.65 wt% in assemblage 4. This latter value is the highest ever reported for Cpx from unevolved abyssal peridotite. Surprisingly, these high Na$_2$O contents are associated with high concentrations of Cr$_2$O$_3$ (1.0–2.4 wt%) (Fig. 3). In contrast, TiO$_2$ is not as strongly enriched as Na$_2$O, as reflected by high Na/Ti ratios compared to Mid-Atlantic Ridge residual Cpx (4.6–7.2 vs. ≤ 2.5). Ion-microprobe analyses (Table DR2; see footnote 1) confirm the incompatible element–rich nature of the inclusions, in particular the assemblage 4 inclusions that contain albite (Fig. 4). For example, the Cpx from assemblage 4 has an almost flat C1-chondrite–normalized REE (rare earth element) pattern that contrasts with the light (L) REE depleted pattern usually reported for residual Cpx from abyssal peridotites (Johnson et al., 1990). High field strength elements such as Nb and Zr are also enriched, but are not significantly fractionated from the REEs (Fig. 4). Amphibole, analyzed along with the Cpx in one assemblage 3 inclusion, displays a CI-chondrite–normalized REE pattern almost identical to that of the associated Cpx (Fig. 4), indicating that these two minerals crystallized in equilibrium. Cpx/amphibole partition coefficients for other trace elements (Ba, Nb, Sr, Zr, Y) are also in good agreement with those calculated from mineral pairs in peridotites from continental lithospheric mantle (Witt-Eickeren and Harte, 1994; Chazot et al., 1996).

**DISCUSSION**

Although dredged at the ridge axis, EDUL Site 23 harzburgites clearly cannot be interpreted by conventional partial-melting models of a typical mantle composition. The lack of residual Cpx argues for degrees of melting (>20%) far in excess of the degree implied by the geophysical characteristics of this section of the Southwest Indian Ridge. Furthermore, their low Ol/Opx ratios are inconsistent with trends expected for low-pressure partial melting.
melting or low-pressure melt-rock interaction (Kinzler and Grove, 1992; Kelemen et al., 1995). In this respect we note that the low Ol/Opx ratios, coarse grain sizes (>1 cm), and Mg-rich compositions make the EDUL Site 23 Opx-rich peridotites akin to harzburgite xenoliths that sample old continental lithospheric mantle (Kelemen et al., 1998). All these considerations lead to the conclusion that EDUL Site 23 harzburgites are residues of melting event(s) predating the current mantle upwelling, pointing to an origin in a buoyant, refractory blob floating in the fertile asthenosphere underlying the Southwest Indian Ridge.

The Opx-hosted inclusions, however, are clearly at odds with the refractory nature of the harzburgite. Their mineralogy, chemistry, and textures all point to precipitation from a “fertile” liquid (i.e., rich in Ti, Al, Na, K, P, OH, S, and incompatible trace elements). Neither partial melting nor any crystal fractionation processes can explain the enrichment in both Cr$_2$O$_3$ and Na$_2$O. Whereas the high Cr in diopside, pargasite, and phlogopite reflects high bulk Cr contents, the high Na is correlated with high V/Al contents compared with common abyssal Cpx. The Cpx is thus enriched in jadeite, the abundance of which is controlled both by melt composition and pressure. Similarly enriched Cpx in basaltic xenoliths of the Indian Ocean that the source mantle below that ocean may be variable (Salters and Dick, 2002; Dupré and Allègre, 1983; LeRoex et al., 1992; Meyzen et al., 2003), and our results may have direct bearing on interpretation of those data. Furthermore, on a global scale, the discovery of refractory lithospheric blobs in the Southwest Indian Ridge provides further clues to understanding the old osmium model ages reported for abyssal peridotites, which are inconsistent with current partial melting in the global ridge system of the modern Earth (Brandon et al., 2000).

**CONCLUSION**

On a regional scale, there is considerable evidence from mid-oceanic-ridge basalts of the Indian Ocean that the source mantle below that ocean may be variable (Salters and Dick, 2002; Dupré and Allègre, 1983; LeRoex et al., 1992; Meyzen et al., 2003), and our results may have direct bearing on interpretation of those data. Furthermore, on a global scale, the discovery of refractory lithospheric blobs in the Southwest Indian Ridge provides further clues to understanding the old osmium model ages reported for abyssal peridotites, which are inconsistent with current partial melting in the global ridge system of the modern Earth (Brandon et al., 2000).

**ACKNOWLEDGMENTS**

Financial support was provided by Centre National de la Recherche Scientifique—Institut National des Sciences de l’Univers (Programme Intérieur de la Terre). We thank C. Mével, L. Reisberg, E. Humler, and A. Luguet for fruitful discussions, and H. Dick and P. Michael for their constructive reviews.
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