Asthenospheric metasomatism beneath the mid-ocean ridge: Evidence from depleted abyssal peridotites

Monique Seyler* Laboratoire de Géosciences Marines, Centre National de la Recherche Scientifique UMR 7097, Institut de Physique du Globe de Paris (IPGP), case 89, 4 place Jussieu, 75252 Paris cedex 05, France
Jean-Pierre Lorand* Laboratoire de Minéralogie, Centre National de la Recherche Scientifique FRE 2456, Muséum National d'Histoire Naturelle (MNHN), 61 rue Buffon, 75005 Paris, France
Michael J. Toplis* Centre de Recherches Pétrographiques et Géochimiques (CRPG), Centre National de la Recherche Scientifique UPR 2300, 15, rue Notre-Dame-des-Pauvres, BP 20, 54501 Vandœuvre-Les-Nancy, France
Gaston Godard* Laboratoire de Géosciences Marines, Centre National de la Recherche Scientifique UMR 7097, Institut de Physique du Globe de Paris (IPGP), case 89, 4 place Jussieu, 75252 Paris cedex 05, France

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 (Meyzen 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, albite, and sulfides. Surprisingly, these metasomatic minerals do not occur within the other mineral phases (olivine, spinel) or as interstitial phases or veinlets. 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 basalt 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 and is unusually deep (Cannat et al., 1999). Furthermore, the basaltic crust is very thin (Debayle and Lévêque, 1997; Muller et al., 1997), and erupted basalts are highly enriched in Na (Robinson et al., 2001; Meyzen 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 dm^3 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 serpentinized olivine (Ol; Fo [forsterite] = 90.5 ± 0.2 wt%) and orthopyroxene (Opx; Al_2O_3 = 4.19 ± 0.17 wt%), characterized by curved grain boundaries, and a few millimeter-sized, holly leaf–shaped spinels [Cr/(Cr + Al) = 0.26 ± 0.04, TiO_2 = 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 10–1000-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 Al_2O_3 (5–7 wt%) and low to moderate TiO_2 contents (0.4–0.6 wt%) (Table DR1[1]). These assemblages are, in decreasing order of abundance, (1) Cpx + Ol ± spinel ± apatite; (2) Cpx ± spinel ± apatite; (3) Cpx + pargasite ± 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

*E-mails: seyler@ipgp.jussieu.fr; lorand@mnhn.fr; mtoplis@crpg.cnrs-nancy.fr; gg@ccr.jussieu.fr.

[1]GSA Data Repository item 2004051, Table DR1, electron-microprobe analyses of Cpx, amphiboles, phlogopites, and albite in inclusions and Opx host, and Table DR2, ion-microprobe analyses of inclusion Cpx and amphibole, is available online at www.geosociety.org/pubs/ft2004.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

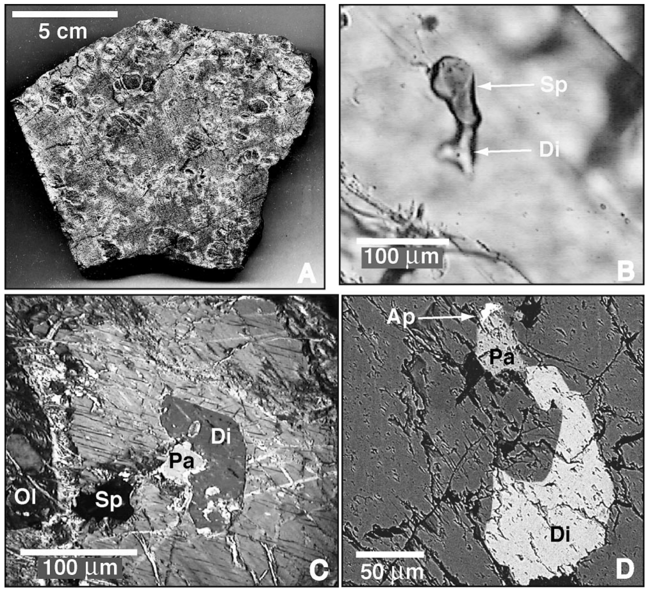

Figure 1. A: EDUL Site 23 harzburgite sample showing coarse-grained texture (serpentinized olivine [Ol] and orthopyroxene [Opx]). Average modal composition of this block (in volume percent): Ol, 66.3 ± 3.8; Opx, 31.8 ± 3.3; spinel (Sp), 1.17 ± 0.4; clinopyroxene (Cpx) + hydrous phases, 0.5–1. B: Cpx (Cr diopside, Di) and Sp-filled cavity in Opx of EDUL 23-2-1L harzburgite, representative of assemblage 2 inclusions. C: Photomicrograph of Sp and Cpx (Cr diopside, Di) and amphibole (pargasite, Pa) assemblage enclosed in very coarse Opx of EDUL 23-2-1B harzburgite, representative of assemblage 3 inclusions. Mica (phlogopite) is also present. D: Backscattered-electron image of polymineral inclusion of Cr diopside (Di), Pa, and apatite (Ap) in very coarse Opx of EDUL 23-2-1N harzburgite.

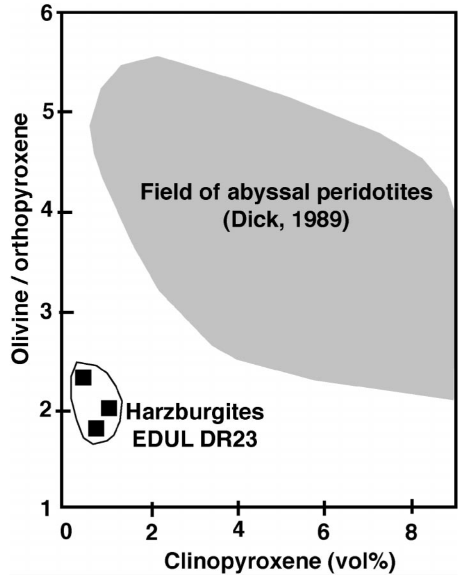

Figure 2. Modal olivine/orthopyroxene vs. clinopyroxene contents (in vol%) of three EDUL 23-2 harzburgites compared to compositions of abyssal peridotites of Dick (1989). Modal compositions have been estimated by combining image analysis of 10 decimeter-sized slabs and point counting of 10 standard-sized thin sections.

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_2O_3 and NiO contents and, for pargasite, high Al_2O_3 and Na_2O 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 ($[Fe,Ni]_9S_8$) 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_2O 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 unveined abyssal peridotite. Surprisingly, these high Na_2O contents are associated with high concentrations of Cr_2O_3 (1.0–2.4 wt%) (Fig. 3). In contrast, TiO_2 is not as strongly enriched as Na_2O, 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 C1-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-Eickeisen 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

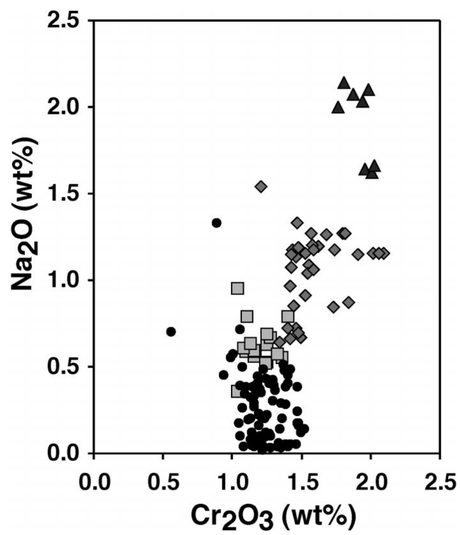

Figure 3. Average Na_2O vs. Cr_2O_3 compositions of 34 clinopyroxene grains occurring as mineral inclusions within orthopyroxene crystals of EDUL Site 23 harzburgites (gray diamonds), compared to residual-mantle clinopyroxenes from peridotites sampled from same region of Southwest Indian Ridge (light gray squares; Seyler et al., 2003) and from Mid-Atlantic Ridge peridotites (black dots; Bonatti et al., 1992; Cannat et al., 1992; Cannat and Casey, 1995; Ghose et al., 1996; Juteau et al., 1990; Komor et al., 1990; Michael and Bonatti, 1985; Niida, 1997; Seyler and Bonatti, 1997; Stephens, 1997) and to metasomatic clinopyroxenes from Kerguelen spinel harzburgite xenoliths in basalt (triangles; Grégoire et al., 2000).

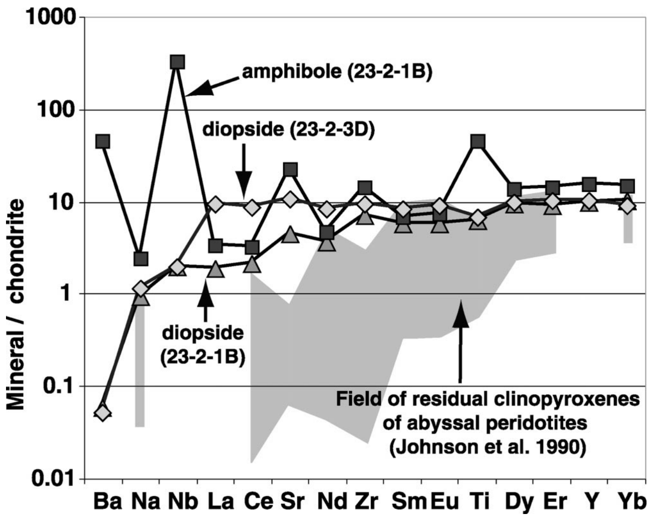

Figure 4. Trace element concentrations in clinopyroxene (Cr diopside) and amphibole (pargasite) grains enclosed in orthopyroxene crystals from two different samples of EDUL Site 23 harzburgite. Sample 23-2-1B, coexisting clinopyroxene (triangles) and pargasite (squares) of assemblage 3 inclusion. Sample 23-2-3D, clinopyroxene (diamonds) coexisting with albite in assemblage 4 inclusion. See text for inclusion assemblage definitions. Values normalized to C1 chondrites (Anders and Grevesse, 1989). Gray is field of residual clinopyroxenes of abyssal peridotites analyzed by Johnson et al. (1990); these peridotites are same as those defining field of abyssal peridotites in Figure 2.

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_2O_3 and Na_2O. Whereas the high Cr in diopside, pargasite, and phlogopite reflects high bulk Cr contents, the high Na is correlated with high ^{VI}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 basalt-borne harzburgitic xenoliths is of indisputable metasomatic origin (Fig. 3). In our samples, liquid was clearly introduced after the creation of the harzburgite matrix, and the inclusions probably formed during the grain-coarsening process of Opx. The fact that Al-rich Cr-spinel (rather than plagioclase) coexists with the Al-, Cr-, Na-rich Cpx in these inclusions implies that they last equilibrated in the spinel stability field at pressures of >0.9 GPa, arguing against late-stage percolation at high levels in the subaxial lithosphere. The coarse, undeformed nature of the Opx grains and the fact that the mineral inclusions commonly have a partially annealed texture further suggest a long residence time at these pressures.

Concerning the timing of liquid addition, we note that despite intensive study using the scanning electron microscope combined with energy-dispersive spectrometer analyses, no metasomatic minerals (or their alteration products) were identified as inclusions within olivines, or as interstitial phases, reaction rims, or veins, in contrast to characteristic observations in metasomatized lithospheric mantle peridotites. Furthermore, the major elements and REE chemistry of erupted basalts from the same region of the Southwest Indian Ridge have been interpreted to suggest both depletion of their source by a prior melting event and the presence of an enriched component in their source mantle (Meyzen et al., 2003). Not only does this concordance of interpretation provide strong indirect evidence for a genetic link between abyssal peridotites and basaltic glasses in this region, but, more important in the present context, it further strengthens our interpretation that the metasomatic component was introduced before present-day partial melting, i.e., in the asthenosphere rather than in the lithosphere.

We believe that olivine-hosted and intergranular equivalents of the metasomatic inclusions may have been present, but were eliminated during subsequent partial melting, thus explaining both their absence in the rocks studied here and the presence of this geochemical component in the basalts (Meyzen et al., 2003). However, the Opx grains are robust enough to have escaped deformation and recrystallization in the very low melting regime beneath this ridge (Nicolas and Poirier, 1976). As a consequence, although the Opx-hosted inclusions partially or totally melted during the last melting episode, the Opx grains retained this metasomatic material, which (re)crystallized at the lower pressure and temperature conditions of the subaxial lithosphere. The present mineral inclusions in the Opx grains thus represent traces of this fertile hydrous component.

Concerning the composition and origin of the metasomatic liquid, the following points can be noted. First, the trace element abundances in the Cpx of the inclusions exclude crystallization from carbonatitic to alkali-basaltic melts. Second, harzburgitic mantle containing nearly pure albite has been shown to be in equilibrium with highly silicic melt containing 12% Na_2O at 1 GPa (Falloon et al., 1997), and assemblage 4 likely crystallized from such a liquid. The major element compositions and flat to slightly LREE-depleted patterns of the Cpx of the inclusions (Figs. 3 and 4) suggest that they crystallized from liquids analogous to silica- and alumina-rich, alkaline glass inclusions found in spinel harzburgite xenoliths, but never before described in silicate hosts in abyssal peridotites. We note that such inclusions in mantle xenoliths have been interpreted as the product of alkali basaltic melt modified by wall-rock interaction and fractional crystallization (Wulff-Pedersen et al., 1999). The original metasomatic liquid that formed the inclusions in the rocks of the present study was probably a low-degree partial melt of a more fertile ''normal'' mantle or a partial melt of an enriched lithology such as pyroxenite, although we cannot distinguish between these hypotheses at the present time.

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).

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