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An experimental study of pyroxenite partial melts at 1 and 1.5 GPa: Implications for the major-element composition of Mid-Ocean Ridge Basalts

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ABSTRACT

To better assess the potential role of pyroxenites in basalt generation at mid-ocean ridges, we performed partial melting experiments on two natural websterites and one clinopyroxenite representative of worldwide pyroxenites. The experiments were conducted at 1 and 1.5 GPa in a piston-cylinder apparatus; the microdike technique was used to separate the liquid from the solid phases and to obtain reliable glass analyses even at low degrees of melting. Contrasted melting behaviors were observed depending on the phase proportions at the solidus, especially the abundance of orthopyroxene. (1) If orthopyroxene is abundant, the main melting reaction is similar to the melting reaction in peridotites (clinopyroxene + orthopyroxene ± spinel = liquid + olivine), and the liquids are similar to peridotite-derived melts for most major elements. (2) In the absence of orthopyroxene, the main melting reaction is clinopyroxene + spinel = liquid + olivine, yielding liquids that are strongly depleted in SiO_2 in comparison to peridotite-derived melts. This low-SiO_2 content can be associated with a high FeO content, a combination usually ascribed to a high average pressure of melting (of a peridotitic source).
Because of their higher melt productivities and lower solidus temperatures, 5 wt.% of pyroxenites in a heterogeneous mantle may contribute up to 40 wt.% of the total melt production. (1) In some cases, pyroxenite-derived melts differ strongly from peridotite partial melts, leading to a distinct pyroxenite signature in the average melt (lower alkali and TiO_2 contents, lower SiO_2, higher FeO and/or lower Mg#). The classical criteria used to select primitive mantle-derived magmas (melt inclusions hosted into high Mg# olivine or MORB glasses with Mg# ≥67) or to track down enriched mantle sources (MORB glasses with high incompatible element contents) must be considered with caution, otherwise melts carrying a pyroxenite signature may be eliminated. (2) In general, however, the major-element signature of pyroxenites should be hardly detectable in the average melt because of the similarity of most pyroxenite-derived melts with peridotite partial melts. This similarity may explain why MORB have relatively uniform major-element compositions, but may have variable trace element and/or isotopic compositions.

1. Introduction

The main mechanism involved in the generation of Mid-Ocean Ridge Basalt (MORB), the most voluminous rock type on the Earth's surface, is polybaric partial melting of the lherzolitic mantle ascending beneath mid-ocean spreading centers. Assuming a homogeneous mantle, the major-element variability of MORB is generally explained in terms of variations of the potential temperature of the ascending mantle (Klein and Langmuir, 1987; McKenzie and Bickle, 1988; Langmuir et al., 1992) and low-pressure fractionation (Grove et al., 1992). There are, however, several aspects of MORB composition, including variations in abundance of trace elements (e.g., Allègre et al., 1995; Niu and Batiza, 1997), in volatile and halogen contents (e.g., Michael and Schilling, 1989; Michael, 1995) and in isotope ratios (e.g., Dupré and Allègre, 1983; Blichert-Toft et al., 1999; Eiler et al., 2000) that cannot easily be explained in the case of a homogeneous source. Moreover several lines of evidence indicate that the mantle contains a significant fraction of pyroxenites (Schulze, 1989), which present a large spectrum of bulk-rock composition (Fig. 1) and modal proportions, and which may play an important role in controlling the chemical variability of mantle-derived melts (Sleep, 1984; Allègre and Turcotte, 1986; Sobolev et al., 2007). At last models based on trace elements and isotopic systematics (e.g., Hirschmann and Stolper, 1996) have emphasized the role of pyroxenites in MORB generation. Accordingly, one may wonder why pyroxenites would control isotopic and trace element systematics of MORB without significantly affecting their major-element compositions.

High-pressure experiments on a range of pyroxenite bulk compositions have allowed us to better constrain the melting relations of these rocks at pressure *P* higher than 2 GPa, and their role in the generation of oceanic island basalts (e.g., Yasuda et al.,

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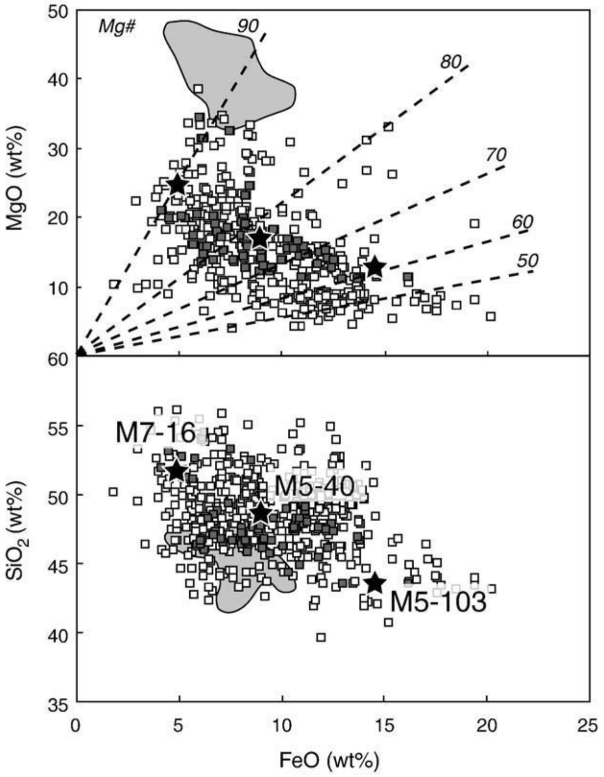

Fig. 1. Plots of MgO and SiO_2 vs. FeO for natural pyroxenites (small squares; pyroxenites from the Beni Bousera ultramafic massif are shown by the small grey squares); the stars are starting materials M5–103, M5–40 and M7–16. The grey area is the mantle peridotite field from GEOROC database (http://georoc.mpch-mainz.gwdg.de). The pyroxenite data come from compilation of Hirschmann and Stolper (1996) completed with analyses from Becker (1996), Bodinier et al. (2008), Dessai et al. (2004), Dickey (1970), Ducea (2002), Garrido and Bodinier (1999), Ghent et al. (1980), Jahn et al. (2003), Kornprobst (1970), Kumar et al. (1996), Kuno and Aoki (1970), Lee et al. (2006), Liu et al. (2005), Melcher et al. (2002), Porreca et al. (2006), Santos et al. (2002), Schmickler et al. (2004), Tang et al. (2007), Volkova et al. (2004), and Xu (2002).

1994; Kogiso et al., 1998; Hirschmann et al., 2003; Pertermann and Hirschmann, 2003b; Keshav et al., 2004; Kogiso and Hirschmann, 2006). Assuming a normal oceanic crust thickness (7 ± 1 km), most petrologic models (e.g., Langmuir et al., 1992; Kinzler and Grove, 1992) predict a mean pressure of melting less than 1.5 GPa (for peridotitic mantle). To constrain the role of pyroxenites on the major-element compositions of primitive MORB, it is therefore necessary to compare melt compositions and degrees of melting in peridotites and pyroxenites at $P<2$ GPa. At present, very little is known about the melting behavior of pyroxenites at $P<2$ GPa. Ito and Kennedy (1974) realized melting experiments on a pyroxenite between 1 atm and 2.5 GPa. However, they used Pt capsules without inner graphite container and so their charges may have suffered iron loss. Adam et al. (1992) investigated partial melting of two garnet pyroxenites at 1.3–2 GPa, but the presence of some water in their experiments led to the crystallization of amphibole.

We have selected three natural pyroxenites that cover the composition ranges of natural pyroxenites (Fig. 1), and we have determined experimentally their melting relations and phase compositions at 1 and 1.5 GPa. Although this contribution is primarily focused on intermediate to large degrees of melting, we also analysed liquid compositions at low degrees of melting, down to 2.6%. Comparing our data with previous studies on the peridotitic system (Hirose and Kushiro, 1993; Baker and Stolper, 1994; Baker et al., 1995; Kushiro, 1996; Robinson et al., 1998; Falloon and Danyushevsky, 2000; Wasylenki et al., 2003; Laporte et al., 2004), (1) we try to find discriminating features between pyroxenite-derived and peridotite-derived melts, and (2) we discuss the relative contributions of pyroxenites and peridotites to basalt generation and the influence of pyroxenite-derived melts on the major-element composition of MORB. This work provides the first experimental study of the influence of pyroxenite on the major-element compositions of MORB. Moreover, it extends the database of pyroxenite partial melts from the literature, in which compositions at low degrees of melting were almost completely lacking up to now.

2. Experimental and analytical procedure

2.1. Selection of starting materials

In order to select representative compositions of pyroxenites, a principal component analysis was first performed on normalized major-element compositions of a worldwide pyroxenite dataset from the literature (see references in Fig. 1 caption). This technique gives the principal directions of the data cloud, expressed mathematically by the eigenvectors of the variance–covariance matrix of the data, and the associated principal variances, which are the corresponding eigenvalues. Three natural pyroxenites from the Beni Bousera ultramafic massif were selected to account for the dispersion of the data (Fig. 1). Sample M5–40 is a garnet websterite, which plots very close to the mean of the pyroxenite population. It contains 16.6 wt.% MgO, and its Mg# [that is, the molar ratio $100\times Mg^{2+}/(Mg^{2+}+Fe^{2+})$] is equal to 76.7 (Table 1). The two other samples plot on the opposite sides of the first principal component axis, which expresses the largest linear dispersion of the data. Sample M5–103 is an olivine websterite with 24.6 wt.% MgO and Mg# = 89.8; compared with M5–40, it is enriched in SiO_2, and depleted in Al_2O_3, FeO, TiO_2, and Na_2O. Sample M7–16 is a garnet–olivine clinopyroxenite, with 12.5 wt.% MgO and a low Mg# (60.6); compared with M5–40, it is depleted in SiO_2 and Na_2O, and enriched in FeO, CaO, and TiO_2. The three pyroxenites are olivine (Ol) normative, but show different degrees of silica undersaturation: M7–16 is nepheline (Ne) normative (2.3%), M5–40 is hypersthene (Hy) normative (8.3%), and M5–103 is strongly Hy-normative (31.3%).

2.2. Experimental and analytical techniques

Pyroxenites were crushed in an agate mortar, and ground under ethanol to 2–4 µm using an agate micronizing mill. They were then fired for 6 h at 900 °C in a CO_2/H_2 atmosphere with an oxygen fugacity between the magnetite–wüstite and the iron–wüstite buffers ($f_{O2}=10^{-15.91}$ bar). All powders were stored under vacuum to minimize the adsorption of water. The experiments were made in a non-end-loaded, 3/4-inch piston-cylinder apparatus, using double containers made of graphite and platinum; containers, assemblages, and experimental techniques are similar to those described in Lambart et al. (2009).

To analyse the composition of liquids in equilibrium with mineral phases, we used the "microdike" technique (Laporte et al., 2004). In all the experiments, we observed a few microdikes (Fig. 2), both at the top and at the bottom of the graphite sample chamber, which vary from tens to hundreds of microns in length and from a few microns to hundreds of microns in width. Degrees of melting (from 2.6 to 95.0 wt.%) and run durations in our study (Table 2) are such that the liquid in the microdikes is in equilibrium with neighboring mineral phases (Laporte et al., 2004). Moreover, Lambart et al. (2009) showed that the average glass compositions measured at the top and at the bottom of the sample chamber are equal within error in a given experiment, indicating thus a small temperature gradient (~5 °C) in the sample chamber.

At the end of an experiment, the capsule was enclosed in epoxy, sectioned lengthwise, polished and carbon-coated. Textures, phase assemblages (Table 2) and compositions (Table 1) were characterized using a JEOL JSM-5910 LV scanning electron microscope and a Cameca SX100 electron microprobe. A 15-kV accelerating voltage, a 15-nA