



Invited review article

Markers of the pyroxenite contribution in the major-element compositions of oceanic basalts: Review of the experimental constraints

Sarah Lambart ^{a,*}, Didier Laporte ^{b,c}, Pierre Schiano ^{b,c}

^a Division of Geological and Planetary Sciences 170-25, California Institute of Technology, Pasadena, CA 91125, USA

^b Laboratoire Magmas et Volcans, Clermont Université, Université Blaise Pascal, BP 10448, 63000 Clermont-Ferrand, France

^c CNRS, UMR 6524, IRD, R 163, 5 rue Kessler, F-63038 Clermont-Ferrand Cedex, France

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ABSTRACT

Based on previous and new results on partial melting experiments of pyroxenites at high pressure, we attempt to identify the major element signature of pyroxenite partial melts and to evaluate to what extent this signature can be transmitted to the basalts erupted at oceanic islands and mid-ocean ridges. Although peridotite is the dominant source lithology in the Earth's upper mantle, the ubiquity of pyroxenites in mantle xenoliths and in ultramafic massifs, and the isotopic and trace elements variability of oceanic basalts suggest that these lithologies could significantly contribute to the generation of basaltic magmas. The question is how and to what degree the melting of pyroxenites can impact the major-element composition of oceanic basalts. The review of experimental phase equilibria of pyroxenites shows that the thermal divide, defined by the aluminous pyroxene plane, separates silica-excess pyroxenites (SE pyroxenites) on the right side and silica-deficient pyroxenites (SD pyroxenites) on the left side. It therefore controls the melting phase relations of pyroxenites at high pressure but, the pressure at which the thermal divide becomes effective, depends on the bulk composition; partial melt compositions of pyroxenites are strongly influenced by non-CMAS elements (especially FeO, TiO₂, Na₂O and K₂O) and show a progressive transition from the liquids derived from the most silica-deficient compositions to those derived from the most silica-excess compositions. Another important aspect for the identification of source lithology is that, at identical pressure and temperature conditions, many pyroxenites produce melts that are quite similar to peridotite-derived melts, making the determination of the presence of pyroxenite in the source regions of oceanic basalts difficult; only pyroxenites able to produce melts with low SiO₂ and high FeO contents can be identified on the basis of the major-element compositions of basalts. In the case of oceanic island basalts, high CaO/Al₂O₃ ratios can also reveal the presence of pyroxenite in the source-regions. Experimental and thermodynamical observations also suggest that the interactions between pyroxenite-derived melts and host peridotites play a crucial role in the genesis of oceanic basalts by generating a wide range of pyroxenites in the upper mantle: partial melting of such secondary pyroxenites is able to reproduce the features of primitive basalts, especially their high MgO contents, and to impart, at least in some cases, the major-element signature of the original pyroxenite melt to the oceanic basalts. Finally, we highlight that the fact the very silica depleted compositions (SiO₂ < 42 wt.%) and high TiO₂ contents of some oceanic island basalts seem to require the contribution of fluids (CO₂ or H₂O) through melting of either carbonated lithologies (peridotite or pyroxenite) or amphibole-rich veins.

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Contents

1. Introduction	15
2. Garnet–pyroxene thermal divide and compositional variability of pyroxenite melts	15
2.1. Constraints on the effective pressure of the garnet–pyroxene thermal divide	16
2.1.1. The CMAS (CaO–MgO–Al ₂ O ₃ –SiO ₂) system	16
2.1.2. From CMAS to natural systems: modeling the effects of FeO, Na ₂ O, K ₂ O and TiO ₂	17

* Corresponding author at: California Institute of Technology, MC 170-25, Pasadena, CA 91125, USA. Tel.: +1 626 240 9705; fax: +1 626 568 0935.
E-mail address: slambart@caltech.edu (S. Lambart).

2.2.	Melt composition variability	21
2.2.1.	Melts compositions and thermal divide	21
2.2.2.	Melts compositions at pressures <2 GPa	22
2.2.3.	The effect of fluids	22
3.	Pyroxenites in oceanic basalt genesis	23
3.1.	Pyroxenites in MORB source-regions	25
3.1.1.	SiO ₂ and FeO: barometers and/or markers of the pyroxenite contribution?	25
3.1.2.	Quantification of the role of pyroxenites	26
3.2.	Pyroxenites in OIB source-regions	27
3.2.1.	Pyroxenite versus peridotite major-element signatures	27
3.2.2.	Implications for mantle melting beneath Hawaii during the post-shield phase	28
3.3.	Preservation of the pyroxenite signal during melt extraction and transport	30
3.4.	Importance of pyroxenite–peridotite interactions in the genesis of oceanic basalts	31
3.4.1.	Direct interaction model	31
3.4.2.	Indirect interaction model: formation of stage 2 pyroxenites from SE and SD pyroxenite-derived melts	31
3.5.	Nature of pyroxenites in the source of oceanic basalts and the origin of SD pyroxenites	32
4.	Summary points	33
	Acknowledgements	33
	References	34

1. Introduction

The petrogenesis and differentiation processes of mantle-derived magmas have been the subject of numerous studies both direct (i.e., experimental melting of ultramafic rocks) and indirect via the study of lavas, and are now reasonably well characterized. Accordingly, partial melting of a peridotitic-type mantle, melt extraction and ascent, fractional crystallization, and potentially crustal contamination are thought to be responsible for the genesis of various types of mafic magmas, such as mid-ocean ridge basalts (MORB), ocean island basalts (OIB), and volcanic arc basalts (e.g., McKenzie and Bickle, 1988). Understanding of these processes has reached a reasonably mature state, thanks to numerous experiments (e.g., Baker et al., 1995; Davis et al., 2011; Falloon et al., 2008; Green and Ringwood, 1967; Kushiro, 1969; O'Hara, 1968; Presnall et al., 1978; Presnall et al., 2002; Stolper, 1980; Takahashi and Kushiro, 1983; Walker et al., 1979; Yoder and Tilley, 1962) and theoretical studies (e.g., Asimow et al., 2001; Grove et al., 1992; Kinzler and Grove, 1992a,b; Klein and Langmuir, 1987; Langmuir et al., 1992; Niu and Batiza, 1997; Niu et al., 2011; Plank and Langmuir, 1992; Stolper and Asimow, 2007).

However, the compositional variability of oceanic lavas cannot be generated by varying the melting degree of peridotite, and thus suggests strong lithological heterogeneities in the source of these magmas (e.g., Hanson, 1977; Wood, 1979; Zindler et al., 1984), which are corroborated by the observed isotopic variations (e.g., Allègre and Turcotte, 1986; White, 1985; Zindler and Hart, 1986). Therefore, several authors have proposed that olivine-poor lithologies such as pyroxenites and eclogites contribute significantly to the generation of basaltic magmas (e.g., Chase, 1981; Helffrich and Wood, 2001; Hirschmann and Stolper, 1996; Hofmann, 1997; Hofmann and White, 1982; Salters and Dick, 2002; Schiano et al., 1997). The source of basalts is therefore now envisioned as a heterogeneous mantle that comprises a range of lithological heterogeneities, especially pyroxenites, introduced into peridotites by various geodynamic and magmatic processes. Consequently, many experimental studies in the last two decades have sought to constrain the melting relations and partial melt compositions of pyroxenites, and to discuss their role in basalt genesis. The starting compositions used in these studies are compared to natural pyroxenite compositions in Figs. 1 and 2 (the compositions of starting materials used in experimental studies of pyroxenite partial melting are summarized in Table S1 in the supplementary material).

The significance of pyroxenitic rocks in basalt source regions is still widely debated. Geochemical evidence has been used to argue

for, or against, an important role of pyroxenites in various localities (e.g., Day et al., 2009; Hékinian et al., 2000; Herzberg, 2006, 2011; Michael et al., 2003; Salters and Dick, 2002; Sobolev et al., 2005, 2007; Stracke and Bourdon, 2009; Stracke et al., 1999), and the potential effect of these lithologies on the major-element variability of oceanic basalts remains unclear (Hauri, 1996; Humphreys and Niu, 2009; Korenaga and Kelemen, 2000; Le Roux et al., 2002; Niu et al., 2011; Shorttle and MacLennan, 2011). This work aims to identify potential markers of pyroxenite contribution in the major-element compositions of oceanic basalts. With this objective in mind, we start by reviewing experimental phase equilibria of pyroxenites, both in simple systems and in natural compositions, to provide strong constraints on the relationships between bulk compositions, melt compositions, and the pressure (P)–temperature (T) conditions of magma formation (beneath oceanic islands and mid-ocean ridges). We then evaluate to what extent the characteristic major-element features of pyroxenite-derived melts are reflected in the basalts erupted at the Earth's surface.

2. Garnet–pyroxene thermal divide and compositional variability of pyroxenite melts

Kogiso et al. (2004a) provided a detailed review of the phase relations of pyroxenites at high pressures. In particular, they emphasized the potential influence of the thermal barrier defined by the aluminous-pyroxene plane, on melt compositions (Fig. 2a). In the pseudoternary diagram forsterite (Fo)–Ca-Tschermak's pyroxene (CaTs)–quartz (Qz) projected from diopside (Di), the thermal divide is defined by the enstatite (En)–CaTs join (Fig. 2b). Because all stoichiometric garnets and pyroxenes project along the En–CaTs join, when these two minerals are the major phases in the residue, the divide is stable and separates two fundamental types of pyroxenites (Kogiso et al., 2004a; Schiano et al., 2000): silica-excess pyroxenites on the right side and silica-deficient pyroxenites on the left side (termed respectively SE and SD pyroxenites hereafter) and thus, melting and crystallization paths of compositions on opposite sides of this join diverge.

Despite the critical influence of this thermal divide on the melting relations of pyroxenites, the significance of its influence, in terms of pressure and composition, has not been precisely determined and its effects on melt compositions, especially at low fractions, are not well established. Consequently, based on previous and new experimental data, we start by constraining the extent of this thermal divide and its influence on melt compositions.

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