



Melt/rock reaction at oceanic peridotite/gabbro transition as revealed by trace element chemistry of olivine

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Abstract

Several recent studies have documented that reactions between melt and crystal mush in primitive gabbroic rocks (via reactive porous flow) have an important control in the formation of the lower oceanic crust and the evolution of MORBs. In this context, olivine-rich rocks can form either by fractional crystallization of primitive melts or by open system reactive percolation of pre-existing (possibly mantle-derived) olivine matrix. To address this question, we performed in-situ trace element analyses (by LA-ICP-MS) of olivine from the Erro-Tobbio ophiolite Unit (Ligurian Alps), where mantle peridotites show gradational contacts with an hectometer-scale body of troctolites and plagioclase wehrlites, and both are cut by later decameter-wide lenses and dykes of olivine gabbros. Previous studies inferred that troctolites and olivine gabbros represent variably differentiated crystallization products from primitive MORB-type melts. Olivines in the three rock types (mantle peridotites, troctolites, olivine gabbros) exhibit distinct geochemical signature and well-defined elemental correlations. As expected, compatible elements (e.g. Ni) show the highest concentrations in peridotites (2580–2730 ppm), intermediate in troctolites (2050–2230 ppm) and lowest in gabbros (1355–1420 ppm), whereas moderate incompatible elements (e.g. Mn, Zn) show the opposite behaviour. By contrast, highly incompatible elements like Zr, Hf, Ti, HREE are variably enriched in olivines of troctolites, and the enrichment in absolute concentrations is coupled to development of significant HFSE/REE fractionation (Zr_N/Nd_N up to 80). AFC modelling shows that such large Zr_N/Nd_N ratios in olivines are consistent with a process of olivine assimilation and plagioclase crystallization at decreasing melt mass, in agreement with textural observations. In-situ trace element geochemistry of olivine, combined with microstructural investigations, thus appears a powerful tool to investigate reactive percolation and the origin of olivine-rich rocks in the lower oceanic crust.

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1. INTRODUCTION

Several lines of evidence have stressed that melt/rock reactions acting at the oceanic mantle-crust boundary play an important role in the chemical evolution of MORBs and the formation of the primitive (olivine-rich) lower oceanic crust (Bédard et al., 2000; Coogan et al., 2000; Drouin et al., 2009, 2010; Gao et al., 2007; Dick et al., 2008;

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Lissenberg and Dick, 2008; Kvassnes and Grove, 2008; Eason and Sinton, 2009; Godard et al., 2009; Collier and Kelemen, 2010; Renna and Tribuzio, 2011; Sanfilippo and Tribuzio, 2011, 2013a,b; Lissenberg et al., 2013; Sanfilippo et al., 2013, 2014, 2015a,b; Saper and Liang, 2014). Specific chemical features in MORBs, such as the spread in MgO contents at given CaO values, cannot be easily reconciled with processes of fractional crystallization of heterogeneous parental melts occurring at variable pressure. Based on this observation, a series of papers inferred that the composition of MORBs can be modified by melt/rock reactions taking place either in the primitive lower oceanic crust, or in the uppermost lithospheric mantle (e.g. Lissenberg and Dick, 2008; Collier and Kelemen, 2010; Lissenberg et al., 2013). Collier and Kelemen (2010) described this process as reactive crystallization, linking the peculiar chemical signatures of MORBs to the diffuse evidence of melt percolation and impregnation in the oceanic mantle (e.g. Dick, 1989; Cannat et al., 1990; Rampone et al., 1997, 2008; Godard et al., 2000; Tartarotti et al., 2002; Dijkstra et al., 2003; Niu, 2004; Chazot et al., 2005; Piccardo et al., 2007; Kelemen et al., 2007; Muntener et al., 2010).

Parallel chemical and microstructural studies on olivine-rich intrusive rocks (troctolites, wehrlites, olivine gabbros) from modern ridge settings and ophiolites (Lissenberg and Dick, 2008; Drouin et al., 2009, 2010; Renna and Tribuzio, 2011; Sanfilippo and Tribuzio, 2011; Lissenberg et al., 2013; Sanfilippo et al., 2013, 2014, 2015a,b) have suggested a composite “hybrid” origin of these rocks, likely related to open-system melt impregnation of an olivine crystal framework. An open issue thus concerns the origin of oceanic troctolites, whether they formed by fractional crystallization of primitive melts or by reactive percolation of pre-existing (possibly mantle-derived) olivine matrix.

Olivine is an ubiquitous mineral in both mantle and primitive lower crustal rocks, and largely involved in melt/rock reaction processes. Consequently, it has become increasingly important to improve knowledge about its trace element composition, and to test the existence of geochemical signatures to distinguish a magmatic versus a mantle origin. Foley et al. (2013) proposed a large compilation of trace element data in olivine from mantle peridotites and Mediterranean volcanics. They outlined the great potential of olivine as a petrogenetic tracer of mantle melting and early igneous crystallization, and the need of further studies on natural olivines, in order to improve the current database, lacking many promising elements.

Many studies have been devoted to determining diffusion and partition coefficients for minor and trace elements in olivine (e.g. Irving, 1978; Shimizu et al., 1982; Kinzler et al., 1990; Beattie (1994); Dunn and Sen, 1994; Eggins et al., 1998; Taura et al., 1998; Gregoire et al., 2000; Petry et al., 2004; Zanetti et al., 2004; Bédard, 2005; Coogan et al., 2005; Witt-Eickschen and O'Neill, 2005; Holzapfel et al., 2007; Lee et al., 2007; Spandler et al., 2007; Brady and Cherniak, 2010; Chakraborty, 2010; Cherniak, 2010; Dohmen et al., 2010; Spandler and O'Neill, 2010; Cherniak and Watson, 2012; Burgess and Cooper, 2013; Girona and Costa, 2013; Cherniak and

Liang, 2014; Cherniak and Van Orman, 2014; Jollands et al., 2014; Kennedy et al., 1993; Zhukova et al., 2014), and a very robust data set exists on selected minor element abundances (e.g. Ni, Co, Mn, Cr) of olivine phenocrysts in basalts from different tectonic environments (Sobolev et al., 2005, 2007; Foley et al., 2013). Other studies have determined selected minor, trace elements concentrations in mantle olivines (e.g. O'Reilly et al., 1997; Normann, 1998; see also the data compilations in De Hoog et al., 2010; Foley et al., 2013). However, only a few studies provide a complete set of trace element compositions measured in olivine from mantle peridotite (Sun and Kerrich, 1995; Eggins et al., 1998; Bedini and Bodinier, 1999; Garrido et al., 2000; Gregoire et al., 2000; De Hoog et al., 2010) and gabbroic rocks (Drouin et al., 2009; Sanfilippo et al., 2014). This is mostly due to the difficulty to get reliable analyses, due to the extremely low abundances of many trace elements (e.g. REE, Ti, Zr, Hf) in this mineral.

We have selected peridotite, troctolite and gabbro samples from the ophiolitic Erro-Tobbio Unit (Ligurian Alps, Italy; Borghini et al., 2007; Borghini and Rampone, 2007), and performed a set of in-situ trace element analyses (by LA-ICP-MS) on olivine in both mantle and crustal rocks, with the objective to provide a first “baseline” dataset on olivine trace element chemistry in associated rocks of different origins (mantle and magmatic), and to exploit the potential of olivine geochemistry to get insights into processes of reactive melt percolation at the oceanic peridotite/gabbro transition. A major outcome of this work is that olivine in most of the troctolites has unexpected trace element compositions, indicative of melt/rock reactions likely involving concomitant olivine dissolution and plagioclase crystallization. Furthermore, discrepancies between the compositions of melts in equilibrium with olivine and coexisting minerals, in both mantle and gabbroic rocks, point to the need for a better understanding of the mechanisms of incorporation and diffusion of trace elements in olivine.

2. FIELD RELATIONS AND SAMPLES

The Erro-Tobbio Unit (ET, Voltri Massif, Ligurian Alps, Italy, Fig. 1) consists of predominant mantle peridotites, intruded by discrete gabbroic bodies and dykes, and represent remnants of the Jurassic Ligurian Tethys oceanic lithosphere. These rocks, in spite of the Alpine overprint, preserve kilometre-scale structural and chemical records of their pre-Alpine evolution (Bezzi and Piccardo, 1971; Chiesa et al., 1975; Ernst and Piccardo, 1979; Ottonello et al., 1979; Piccardo et al., 1990, 1992, 2004; Hoogerdujin Strating et al., 1990, 1993; Vissers et al., 1991; Borsi et al., 1996; Capponi et al., 1999; Rampone et al., 2004, 2005).

The extension-related exhumation of the Erro-Tobbio mantle from deep lithospheric depths ($P > 15\text{--}20$ kbar) to a shallow level ($P < 5$ kbar) was accompanied by a composite history of melt migration and intrusion marked by (i) open-system melt migration and reactive porous flow at spinel-facies depths, (ii) melt/rock reaction at shallower and colder lithospheric level, leading to the formation of

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