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Chemical interactions in the subduction factory: New insights from an in situ trace element and hydrogen study of the Ichinomegata and Oki-Dogo mantle xenoliths (Japan)

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Abstract

The uppermost mantle in back arc regions is the site of complex interactions between partial melting, melt percolation, and fluid migration. To constrain these interactions and evaluate their consequences on geochemical cycles, we carried out an in situ trace element and water study of a suite of spinel peridotite xenoliths from two regions of the Japan back arc system, Ichinomegata (NE Japan) and Oki-Dogo (SW Japan), using LA-ICPMS and FTIR spectrometry, respectively. This study provides the first full dataset of trace element and hydrogen compositions in peridotites including analyses of all their main constitutive silicate minerals: olivine, orthopyroxene and clinopyroxene. The Ichinomegata peridotites sample a LREE-depleted refractory mantle (Mg# olivine = 0.90; Cr# spinel = 0.07–0.23; Yb clinopyroxene = 7.8–13.3 × C1-chondrite, and La/Yb clinopyroxene = 0.003–0.086 × C1-chondrite), characterized by Th-U positive anomalies and constant values of Nb/Ta. The composition of the studied Ichinomegata samples is consistent with that of an oceanic mantle lithosphere affected by cryptic metasomatic interactions with hydrous/aqueous fluids (crypto-hydrous metasomatism). In contrast, the Oki-Dogo peridotites have low Mg# olivine (0.86–0.93) and a broad range of compositions with clinopyroxene showing "spoon-shaped" to flat, and LREE-enriched patterns. They are also characterized by their homogeneous compositions in the most incompatible LILE (e.g., Rb clinopyroxene = 0.01–0.05 × primitive mantle) and HFSE (e.g., Nb clinopyroxene = 0.01–2.16 × primitive mantle). This characteristic is interpreted as resulting from various degrees of melting and extensive melt-rock interactions. FTIR spectroscopy shows that olivine in both Ichinomegata and Oki-Dogo samples has low water contents ranging from 2 to 7 ppm wt. H_2O. In contrast, the water contents of pyroxenes from Ichinomegata peridotites (113–271 ppm wt. H_2O for orthopyroxene, and 292–347 ppm wt. H_2O for clinopyroxene) are significantly higher than in Oki-Dogo peridotites (9–35 ppm wt. H_2O for orthopyroxene, and 15–98 ppm wt. H_2O for clinopyroxene). This indicates a relationship between melt-rock interaction and water concentrations in pyroxenes. Our study suggests that the water content of the Japan mantle wedge is controlled by the late melt/fluid/rock interactions evidenced by trace element geochemistry: a

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mechanism triggered by magma-rock interactions may have acted as an efficient dehydrating process in the Oki-Dogo region while the Ichinomegata mantle water content is controlled by slab-derived crypto-hydrous metasomatism.

Keywords: Peridotite; Trace element geochemistry; Olivine; Pyroxene; Metasomatism; Melt; Water; Mantle wedge

1. INTRODUCTION

In the sampled Earth's uppermost mantle, water is present in the form of minor hydrous minerals and as impurities of hydrogen atoms (H) in the crystalline structure of nominally anhydrous minerals (NAMs e.g., olivine, pyroxenes and garnet; see Miller et al., 1987; Bell and Rossman, 1992; Ingrin and Skogby, 2000; Demouchy and Bolfan-Casanova, 2016). The estimated concentrations of water in NAMs are at most a few hundred ppm H_2O by weight (e.g., Rossman, 1996); yet, NAMs may represent one of the main water reservoirs in Earth because they dominate mantle lithology. Also, small amounts of H in NAMs are expected to induce disproportionate effects on the chemical and physical properties of mantle rocks, such as melting temperature, deformation, ionic diffusion, heat transfer, electrical conductivity and seismic wave propagation, which in turn control the Earth's dynamics (e.g., Green, 1973; Mackwell et al., 1985; Karato et al., 1986; Karato, 1990; Hirose and Kawamoto, 1995; Hirth and Kohlstedt, 1996; Gaetani and Grove, 1998; Jung and Karato, 2001; Hofmeister, 2004; Hier-Majumder et al., 2005; Wang et al., 2006, 2008; Yoshino et al., 2006; Demouchy et al., 2012). Therefore, measuring precisely the past and present water distribution within the Earth's mantle and exchanges between the Earth's interior and its outer envelopes is critical to understand the mechanisms controlling modern deep water cycle (Smyth, 1987; Wood, 1995; Regenauer-Lieb et al., 2001; Regenauer-Lieb and Kohl, 2003; Peslier and Luhr, 2006; Karato et al., 2013).

The deep Earth water cycle is strongly coupled to plate tectonics: water is introduced into the oceanic crust by hydrothermal alteration at mid-oceanic ridges and during the aging of the lithosphere (e.g., Staudigel et al., 1995, 1996; Alt, 1995; Alt and Teagle, 2003; Früh-Green et al., 2004), and the serpentinization of lithospheric mantle via bent-related faulting prior to subduction (Ranero et al., 2003; Van Avendonk et al., 2011). Then it is brought into the mantle by subducting altered oceanic lithosphere and associated sediments (e.g., Staudigel et al., 1996; Plank and Langmuir, 1998; Scambelluri et al., 2004; Bebout, 2013). As a consequence, subduction zones are characterized by a complex suite of petrological processes triggered by the dehydration of hydrous minerals present in the subducted slab (e.g., Schmidt and Poli, 2014 and references therein). These processes include hydrous partial melting, metasomatism and, even, secondary serpentinization of the mantle wedge, and thus they affect the dynamics of subduction environments (e.g., recent reviews by Grove et al., 2012; Alt et al., 2013; Deschamps et al., 2013; Reynard, 2013; Spandler and Pirard, 2013 and references therein). Active arc volcanism and the building of island arcs are the most prominent demonstration of the immediate impact of these deep fluid-rock interactions on the Earth's outer envelopes and lithosphere dynamics; these processes have also been considered as the possible trigger for the formation of continental lithosphere (e.g., Tatsumi et al., 1997; Kelemen et al., 2014 and references therein). Yet, in spite of the many recent studies focused on the abundance and role of water and fluid mobile elements in subduction related environments (e.g., Van Keken et al., 2002; Manning, 2004 and above cited review articles), the actual water content of the mantle wedge as well as the magmatic and metasomatic processes controlling its distribution in mantle rocks in this geodynamic system remains poorly constrained because of two main difficulties. First, mantle xenolith suites preserving their deep magmatic features (no evidence of late alteration and serpentinization, no secondary hydrous phases) are rare. Yet these characteristics are essential to carry out both the detailed geochemical study and the precise water measurements required to decipher deep water-melt-rock processes. Second, the most powerful tool to identify and track magmatic and metasomatic processes is trace element geochemistry, but until recently, the measurements of the geochemical composition of depleted mantle minerals required the complete destruction of the sample. The recent developments of LA-ICPMS techniques now allows in situ trace element analyses of highly depleted silicate minerals (e.g., olivine: Pettke, 2006; Drouin et al., 2009) and measuring hydrogen and trace element chemistry on the same mantle mineral is finally possible.

In this study, we combine for the first time these two approaches in order to better characterize the processes controlling the deep water distribution in back arc settings. The subduction zone along Japan Island arcs was chosen as a field laboratory. Two well characterized suites of Sp (spinel)-peridotite xenoliths interpreted as sampling the mantle wedge were selected for this study (Arai et al., 2007): Ichinomegata (NE Japan) where the Pacific plate is subducting under the North American plate and Oki-Dogo (SW Japan) where the Philippine Sea plate is subducting under the Eurasia plate. A detailed petrographic and geochemical study was carried out to decipher their petrogenetic history; the distribution of trace lithophile elements between the constitutive silicate phases of mantle peridotites (Ol: olivine, Opx: orthopyroxene and Cpx: clinopyroxene) was analyzed to characterize the type and extent of melt-fluid-rock interactions that affected the Ichinomegata and Oki-Dogo mantle xenolith suites. The water content of Ol, Opx and Cpx was analyzed in the same samples. This study allows to quantify the fraction of water (i.e., hydroxyls group detected by infrared spectrometry) embedded as hydrogen impurity in point defects in