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Letter

Hybrid troctolites from mid-ocean ridges: inherited mantle in the lower crust

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ABSTRACT

Studies on olivine-rich troctolites from oceanic ridges propose that hybridized mantle rocks may locally constitute small portions of the lower oceanic crust. The exact reaction process by which they originate is still debated and their hybrid nature is controversial. We show that textural and chemical inheritances of the pre-existing mantle are preserved in olivine-rich troctolites recently sampled at the Central Indian Ridge. The occurrence of a large orthopyroxene of a probable mantle origin suggests that these rocks formed through the reactive overprint of a mantle peridotite. Combining our data with those of olivine-rich troctolites worldwide, we show that the clinopyroxenes from these rocks follow chemical trends slightly distinct to those of the oceanic gabbros. These chemical trends can be ascribed to crystallization from melts assimilating mantle peridotites, suggesting that a "mantle flavor" can be locally retained in these hybrid rocks. The present distribution of Ol-rich troctolites suggests that melt-mantle reaction processes by which these rocks originate is likely to be more diffuse at slower spreading environments, where extensive melt-rock reactions within a thick thermal boundary layer enhances the conversion of the shallow oceanic mantle into hybrid crustal rocks.

1. Introduction

Troctolites have been recovered in nearly all the plutonic sample suites from mid-ocean ridges (e.g. Blackman et al., 2006; Dick and Natland, 1996; Dick et al., 2000; 2010; Elthon, 1987; Perk et al., 2007). These rocks constitute the lowermost crustal sector of Hess Deep in the Pacific Ocean (Gillis et al., 2014) and occur in association with more evolved gabbros in a variety of sites at oceanic core complexes (OCC) from Atlantic (Blackman et al., 2006) and Indian oceans (Dick et al., 2000). Although the majority of these rocks are interpreted to be olivine and plagioclase cumulates crystallized from primitive MORB (see also Lissenberg and Dick, 2008; Godard et al., 2009), the origin of the olivine (Ol)-rich troctolites (Ol > 60 vol%) has been recently related to interaction between the pre-existing mantle and migrating melts, through a multistage process entailing dunitization, dissolution and crystallization of magmatic phases (Drouin et al., 2009; Renna and Tribuzio, 2011; Suhr et al., 2008). The apparent lack of inheritances of the pre-existing mantle (Sanfilippo et al., 2014) and the large amounts of melt required during this multistage process (Von der Handt and Hellebrand, 2012) strongly questioned this idea, making the hybrid nature of these rocks highly debated (Dick et al., 2010; Drouin et al., 2010; Sanfilippo et al., 2014).

Recent bulk estimates of the fast-spreading oceanic crust at Hess Deep indicate that the oceanic crust composition approximates those of experimentally derived primitive MORB (Gillis et al., 2014). In contrast, the bulk composition of Hole U1309D at Atlantis Massif (Atlantic) furnishes values coherent with primitive MORB only if the contribution of Ol-rich troctolites is excluded from the bulk estimates (Godard et al., 2009). Hence, deciphering the hybrid nature of Ol-rich troctolites is important to define to what extent hybridized mantle material can be a contributor to the lower crust, calling into question the assumptions that the oceanic crust reflects the composition of the melt extracted from the mantle.

This study shows that textural and chemical inheritances of the pre-existing mantle are preserved in the Ol-rich troctolites recently sampled at the intermediate-spreading Central Indian Ridge (CIR). We use this inference to examine the significance of Ol-rich troctolites to the global ridge system, suggesting that hybrid crustal rocks likely characterize the crust-mantle boundary at slower spreading environments, where a thick thermal boundary layer allows extensive interaction between the shallow mantle and the melt migrating through it.

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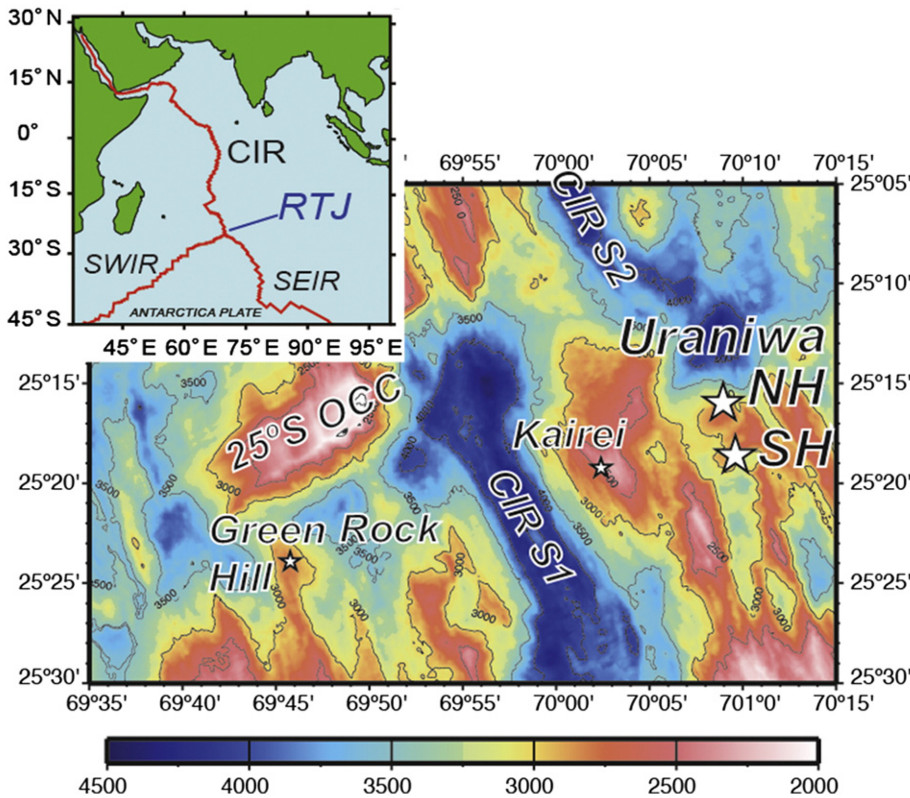

Fig. 1. Geology of the 25°S area at Central Indian Ridge and the location of the Uraniwa Hills; SH and NH indicate the North and South Hill, respectively. Details of the Shinkai 6500 Dives 922 and 925 and of the Uraniwa morphology are reported in Nakamura et al. (2009). Gabbros and peridotites were also collected at the 25°S oceanic core complex, the Green Rock Hill and the Kairei hydrothermal field (Hellebrand et al., 2002; Morishita et al., 2009; 2014).

2. Olivine-rich troctolites from the Central Indian Ridge

The Ol-rich troctolites have been collected during Shinkai dives 922 and 925 at the Uraniwa Hills, two core complex-like reliefs in the proximity of the Rodrigues Triple Junction (Fig. 1). Similar to the Oceanic Core Complexes (OCC) from slow spreading ridges, two corrugation structures perpendicular to the ridge-axis characterize the Uraniwa Hills, suggesting that the lower crust in this area has been exposed through detachment faulting (Nakamura et al., 2009). Ol-rich troctolites occur along the slopes of the hills, where they show magmatic layering towards Pl-rich (Pl-rich troctolites; Pl up to 90 vol%), Pl-poor (Pl-dunites; Pl <5 vol%) and Cpx-rich (Pl-wehrlites; Cpx ~25 vol%) end members. Gabbros are also found in association with the Ol-troctolites. They consist of chemically primitive Ol-gabbros (Ol 10 to 5 vol%) and constitute <20% of the collected samples. Basalts and rare diabases have been collected at the top of the two hills. Details of the samples petrography, the analytical methods and the major and trace elements compositions of the mineral phases are reported as supplementary material.

CIR Ol-rich troctolites have textural features similar to those described for Ol-rich troctolites worldwide (Dick et al., 2010; Drouin

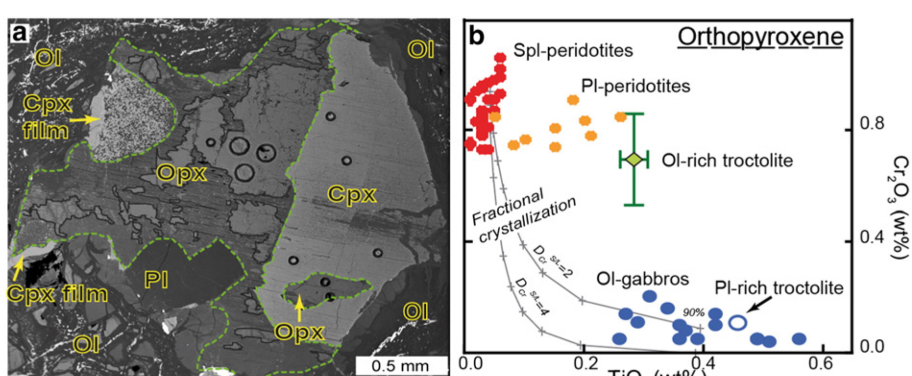

Fig. 2. a) Back scattered image of the relict orthopyroxene (Opx) in CIR Ol-rich troctolite 925R03. The original Opx (green dashed lines) is widely replaced by low-temperature alteration (black lines), mainly consisting of bastite. Plagioclase (Pl) is almost totally altered by fine-grained epidote ± chlorite ± albite assemblages; Olivine (Ol) shows the typical serpentine + magnetite mesh texture; Clinopyroxene (Cpx) is mostly fresh. An irregular portion of the Opx is included into the associated Cpx. The laser ablation spots (50 to 100 diameters) are also visible. b) TiO_2 versus Cr_2O_3 contents (wt%) of the relict Opx in CIR Ol-rich troctolite 925R03 compared to the intergranular Opx in Pl-rich troctolites and Ol-gabbros (this study; Morishita et al., 2014). The compositions of mantle Opx from CIR Spl-peridotites (Hellebrand et al., 2002) and MAR Pl-peridotites (Tartarotti et al., 2002; Dick et al., 2010) are also shown. The grey lines represent the composition of Opx in equilibrium with melt evolving through fractionation of a mineral assemblage similar to the Pl-rich troctolite 925R15 (Table SM1). Starting melt is in equilibrium with the mean composition of Opx from CIR Spl-peridotites (Ti = 2400 ppm; Cr = 1500 ppm). Each step corresponds to 10% of crystallization. Opx/melt partition coefficients are 0.1 for Ti and 4 for Cr (Adam and Green, 2006). The trends are calculated with bulk $D_{Cr}^{\text{solid/liquid}}$ ranging between 2 and 4.

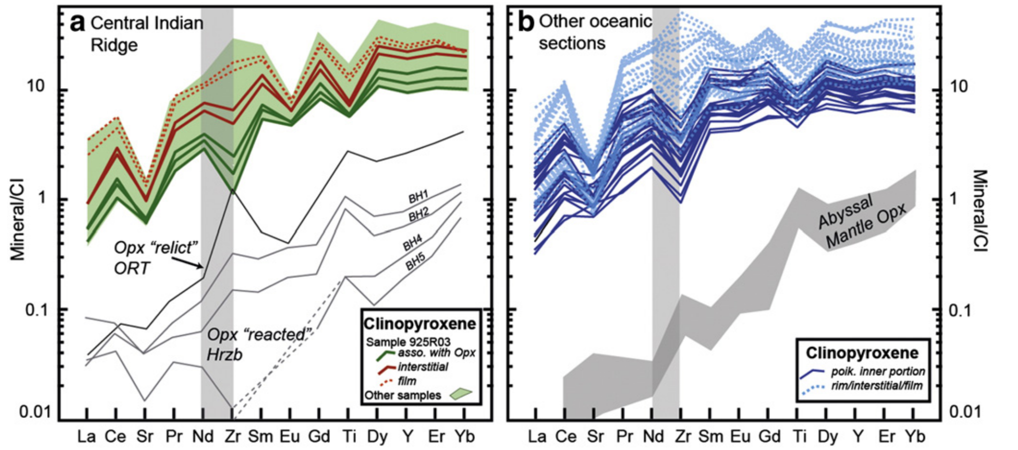

Fig. 3. a) Incompatible element compositions normalized to CI chondrite composition (Anders and Ebihara, 1982) of the clinopyroxenes from the Ol-rich troctolites 925R03 (lines) and other CIR Ol-rich troctolites (field). The patterns of the orthopyroxene in CIR Ol-rich troctolite (Fig. 2a) and of the orthopyroxenes from MORB-reacted harzburgites (Tamura et al., 2008) are also depicted. Samples BH1 and BH2 are collected within 20 cm from the contact with gabbro, BH4 and BH5 are collected far from the contact. b) Incompatible element compositions of the clinopyroxene (poik., poikilitic) of Ol-rich troctolites from other oceanic sections (Hess Deep: Dick and Natland, 1996; Atlantis Massif: Drouin et al., 2009; Alpine ophiolites: Borghini and Rampone, 2007; Renna and Tribuzio, 2011; Godzilla Megamullion: Sanfilippo, unpublished data). The grey field indicates the composition of orthopyroxene from Gakkel Ridge abyssal harzburgites and lherzolites (Hellebrand et al., 2005).

et al., 2010; Renna and Tribuzio, 2011; Sanfilippo et al., 2013). They commonly consist of rounded to polygonal olivine (Ol, 72–54 vol%), anhedral to poikilitic plagioclase (Pl, 45–24 vol%) and trace amounts of clinopyroxene (Cpx) and spinel (Spl). CIR Ol-rich troctolites have high forsterite Ol (Fo, 89.4 to 88.0 mol%) and anorthite Pl (An, 88.6 to 83.6 mol%). High-Mg# Cpx [100*Mg/(Mg + Fe), 90.9–89.0] mostly occur in small (<0.2 mm) discrete grains showing interstitial to film-like habits. These Cpx are rarely interconnected to form up to 20 mm-wide poikilitic grains. One large orthopyroxene (Opx) (~2 mm in size) has been found in one CIR Ol-rich troctolite (925R03). This Opx shows an irregular shape and embayed grain boundaries against the adjacent phases (Fig. 2a). This Opx has Mg#, Al_2O_3 and Cr_2O_3 contents slightly lower than the Opx from CIR Spl-peridotites (Fig. 1 in data repository), but relatively high TiO_2 and HREE contents and a deep Eu anomaly

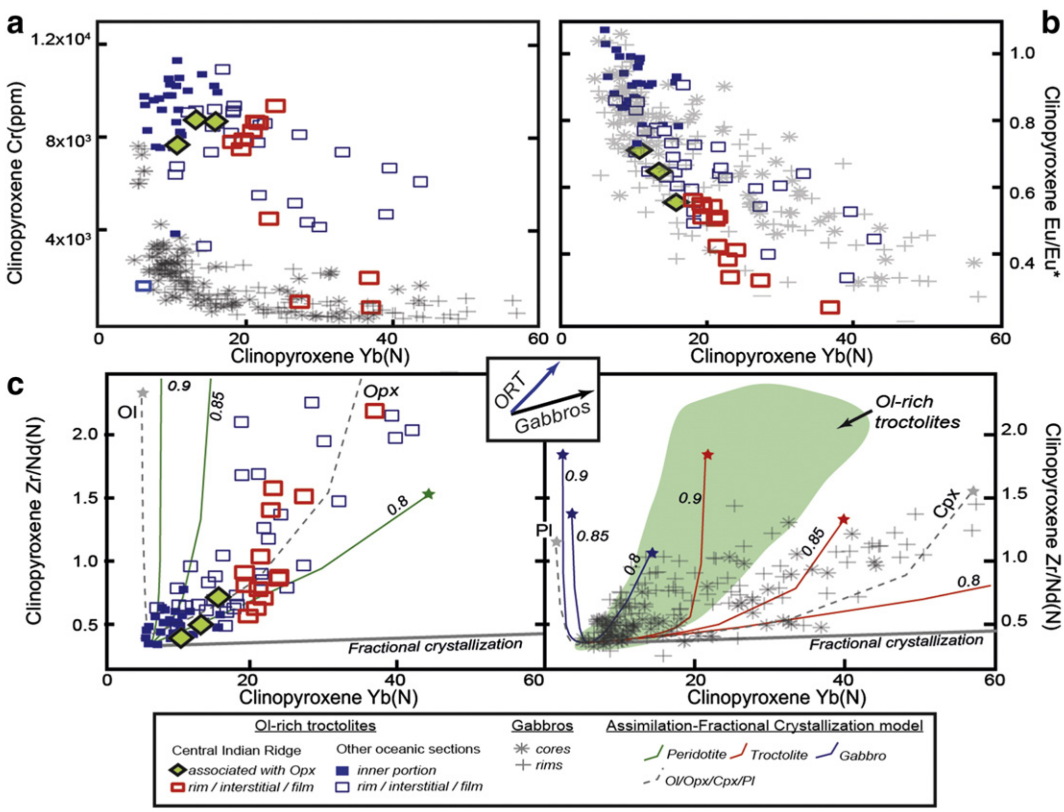

Fig. 4. Variation of Yb_N versus a) Cr ppm; b) $Eu/Eu^* = [Eu_N/\sqrt{(Sm_N \times Gd_N)}]$ and (c) Zr_N/Nd_N ratios of the clinopyroxenes from the Ol-rich troctolites and oceanic gabbros (N, values in ppm normalized to CI chondrite of Anders and Ebihara, 1982). Data of clinopyroxenes from the Ol-rich troctolites are same as in Fig. 3c; data of the clinopyroxene from oceanic gabbros are from Coogan et al. (2000); Gao et al. (2007) and Lissenberg et al. (2013). The chemical trends of the clinopyroxenes in equilibrium with melt produced during assimilation-fractional crystallization processes (AFC) are depicted in Fig. 4c (see text for details). Italic numbers on each trend indicate mass assimilated/mass crystallized ratios (Ma/Mc). For simplicity, the trends produced by assimilation of single mineral (Ol, Opx, Cpx and Pl) are reported only for Ma/Mc = 0.85. Stars indicate >99% of crystallization of the initial melt mass. The compositional trends of Cpx in equilibrium with melt evolving through fractional crystallization are also reported (same parameters of the AFC model).

(Figs. 2b, 3a). Chemical maps by electron probe microanalysis show that this Opx is homogeneous in major element composition (Fig. 2 supplementary material). Interstitial to film-like Opx are also found in the associated Pl-rich troctolites and Ol-gabbros, but they have lower Mg#, Al_3O_3 and Cr_2O_3 contents than the Opx in Ol-rich troctolites (Fig. 1 in data repository).

The Cpx associated with this Opx is chemically distinct by the interstitial and film-like Cpx in the same sample. In particular, from the Cpx associated with Opx, to the interstitial and film-like Cpx in the same sample the REE abundances increase and the Eu anomaly becomes gradually deeper (Fig. 3, 4). The Cpx associated with the Opx is chemically similar to the inner portions of the Cpx oikocrysts in the Ol-rich troctolites worldwide, which also show a decrease in Eu anomaly with increasing REE abundances towards the rim/film-like grains (Fig. 3b) (Borghini and Rampone, 2007; Drouin et al., 2009).

3. Orthopyroxene in olivine-rich troctolites: inheritance of the pre-existing mantle

The Opx included in the CIR Ol-rich troctolite 925R03 is texturally and chemically different from the Opx found in the associated Pl-rich troctolites and Ol-gabbros (Fig. 2; Fig. 1 in data repository). Interstitial to film-like Opx is common in oceanic troctolites and moderately evolved gabbros, where it is attributed to the crystallization of chemically evolved melts either produced by extensive fractionation or partial melting of pre-existing phases (see discussion in Koepke et al., 2007). The high TiO_2 and low Cr_2O_3 contents of the Opx in Pl-rich troctolites and Ol-gabbros from Uraniwa can be attributed to crystallization from chemically evolved melts, starting from primitive melt in chemical equilibrium with the CIR mantle peridotites (see fractional crystallization model Fig. 2b). On the other hand, the large Opx in the Ol-rich troctolite has TiO_2 contents approaching those of the Opx in gabbros, but Mg#, Cr_2O_3 and Al_2O_3 contents slightly lower than the Opx in the associated peridotites (Fig. 2b; Fig. 1 supplementary material). These Mg#, Cr_2O_3 and Al_2O_3 compositions are too high to be related to crystallization from chemically evolved melts, and clearly indicate a different origin. Cumulus Opx grains have been recently documented in primitive cumulates from Hess Deep (Gillis et al., 2014). In this case, Opx is a common euhedral to subhedral phase and is interpreted as a product of crystallization from chemically primitive, Opx-saturated melts, either produced by equilibration with the shallow mantle or by low pressures mantle melting (see discussion in Gillis et al., 2014). Although a similar origin would account for the high Mg#, Cr and Al contents in the Opx from Ol-rich troctolite 925R03, this is difficult to reconcile with its high incompatible element contents (Figs. 2b, 3a). Furthermore, a direct crystallization from primitive, Opx-saturated melts cannot explain both the irregular habitus, and the unique occurrence of this Opx in one sample. A magmatic origin for the Opx in Ol-rich troctolite 925R03 is thereby unlikely.

Relatively high TiO_2 contents are typically documented in the mantle Opx from abyssal Pl-peridotites and ascribed to a gradual equilibration of a mantle Opx with impregnating melts (Tartarotti et al., 2002; Dick et al., 2010). Tamura et al. (2008) characterized the trace element compositions of the Opx from the mantle harzburgite slices collected within the crustal sequence of the Atlantis Massif. These authors showed that toward the contact with the host gabbros the mantle Opx gradually increases in incompatible element concentrations (Fig. 3b), despite the Mg#, Cr and Al contents remain relatively constant or, eventually, slightly decrease (see also Tartarotti et al., 2002). Hence, the incompatible element concentrations of the large Opx in Ol-rich troctolite 925R03, coupled with relatively high Mg#, Cr_2O_3 and Al_2O_3 contents (Figs. 2b; 3a; Fig. 1 supplementary material) can be ascribed to a partial equilibration of a mantle Opx with a reacting melt.

We calculated the equilibration temperature of this Opx with the spatially associated Cpx (Fig. 2a) using the REE-in-two-pyroxene thermometer (Liang et al., 2013). This thermometer furnishes extremely high temperatures (~1800 °C), much higher than those furnished by the Brey and Kohler (1990) calibration based on Opx-Cpx Fe-Mg exchange (~1100 °C) (see details in supplementary materials). This discrepancy typically characterizes Opx–Cpx pairs from abyssal peridotites that suffered high degrees of melt percolation (Liang et al., 2013) and indicates that the REE in the coexisting Opx-Cpx of Ol-rich troctolite 925R03 preserve an original chemical disequilibrium, whereas Fe and Mg (and Mg#) re-equilibrated at nearly magmatic temperature due to their fast diffusion in pyroxenes (Cherniak and Dimanov, 2010). We thereby propose that the Opx in Ol-rich troctolite 925R03 is a relict of a pre-existing mantle peridotite, partly survived from dissolution in a migrating melt. This origin is well reconcilable with both the irregular habitus and the occurrence of an irregular, optically continuous portion of Opx in the associated Cpx (Fig. 3a).

At odds with models of formation of Ol-rich troctolites through a multistage interaction between the mantle peridotites and melts (peridotite➔dunite➔troctolite), the occurrence of this inherited mantle Opx suggests that these rocks formed through a one-stage process, which directly converted a mantle peridotite into a hybrid crustal rock. Henceforth, we show that the assimilation of an Opx-bearing peridotite can account for the composition of the Cpx in the Ol-rich troctolites worldwide.

4. Trace element compositions Of clinopyroxene: evidence for a “mantle flavor”?

Fig. 4 shows a comparison between the Cpx from the Ol-rich troctolites and those in oceanic (olivine- to oxide) gabbros. To focus our comparison with the gabbros formed far from the crust mantle transition (Coogan et al., 2000; Gao et al., 2007; Lissenberg et al., 2013), we excluded abyssal gabbros spatially associated with peridotites or dunites (i.e., Dick and Natland, 1996; Dick et al., 2010; Sanfilippo et al., 2013).

The first notable difference between the Cpx in the Ol-rich troctolites and those in the gabbros is represented by their high Cr contents (Fig. 4a). In particular, the Cr contents of the Ol-rich troctolites Cpx approach those of Cpx in mantle peridotites (up to 10000 ppm; e.g., Hellebrand et al., 2005), although they show a wide range of incompatible element abundances (Yb from 5 up to 40 times chondrites) (Fig. 4a). Several authors pointed out that these Cpx could not have been produced by simple fractionation of a Cr-rich parental MORB (e.g.; Coogan et al., 2000; Drouin et al., 2009; Lissenberg and Dick, 2008; Renna and Tribuzio, 2011; Suhr et al., 2008), but likely derived from melts constantly buffered by (or mixed with) melts residual from interactions with a Cr-rich ultramafic matrix (Arai et al., 1997; Dick and Natland, 1996). This hypothesis is supported by experimental studies (e.g. Saper and Liang, 2014), which showed that the magmatic Cpx with Cr contents up to 12000 ppm and relatively high incompatible element compositions (i.e., TiO_2) may crystallize by melt interacting with mantle peridotites. In addition, this idea is in agreement with the occurrence of Spl locally having multiphase hydrous-silicate inclusions (Ti-pargasite, Na-phlogopite) and ilmenite (Table SM7), commonly interpreted to be crystallized from melts enriched in Cr and incompatible elements (Renna and Tribuzio, 2011) by melts interacting with the mantle at decreasing temperature and pressure conditions (Arai et al., 1997; Tamura et al., 2014).

Compared to those in Ol-rich troctolites, the Cpx in gabbros commonly have low Cr contents (<4000 ppm), although few primitive grains (Yb_N <10) with Cr up to 8000 ppm also occur. These Cpx mostly form large poikilitic grains in Ol-gabbros (Coogan et al., 2000), and have been also ascribed to crystallization from melts dissolving a pre-existing crystal assemblage (i.e., Lissenberg and Dick, 2008). Hence, the high and almost constant Cr contents of the Ol-rich troctolites Cpx (Cr up to 12000 ppm) is in agreement with the idea that melts interacting with an ultramafic assemblage constrained the formation of these rocks at or close to the crust-mantle transition. In contrast, the infrequent occurrence of high-Cr Cpx within the gabbros (Cr < 8000 ppm) suggests that similar melts are rare in the shallower portion of the lower crust.

Another interesting deviation of the Cpx in Ol-rich troctolites from those in the gabbros can be seen in Fig. 4c. The Cpx cores of Ol-rich troctolites are relatively homogeneous in Ti, Zr and REE abundances (Figs. 3, 4), suggesting that they might have crystallized from the chemically similar parental MORB. In contrast, the Cpx rims and film-like grains show large enrichments in Ti, Zr and REE concentrations (Fig. 3). These chemical variations have been previously related to the crystallization from melts enriched in incompatible elements due to melt-mass reduction (Drouin et al., 2009) and synchronous crystallization of late stage phases (i.e., amphibole; Borghini and Rampone, 2007) at the closure of the magmatic system. However, a similar process cannot explain the sharp increase in the Zr_N/Nd_N ratio at increasing Yb concentrations (Fig. 4c), nor the high and constant Cr contents of the Ol-rich troctolite Cpx. Systematic studies showed that fractionation of Zr from Nd (more to less incompatible elements) also typically characterize the Cpx rims from many gabbro suites (Fig. 4c). This chemical feature has been generally attributed to the effect of reactive melt migration in a crystal mush (e.g., Coogan et al., 2000; Gao et al., 2007; Coogan 2007). This hypothesis has been validated by assimilation-fractional crystallization models (AFC; DePaolo, 1981), which suggested that the assimilation of Ol, Pl and Cpx at various proportion might reproduce the chemical variations observed in most oceanic gabbros Cpx (see also Lissenberg et al., 2013).

The Cpx in the Ol-rich troctolites depict a steep Zr_N/Nd_N ratios vs. Yb_N correlation, extended toward higher Zr_N/Nd_N ratios (up to 2.2) than Cpx in gabbros (Zr_N/Nd_N ratios <1.5) (Fig. 4c). The occurrence of an Opx most likely inherited from the mantle led us to propose that an Opx-bearing peridotite was dissolved during the crystallization of the Ol-rich troctolites. Hence, we can suppose that the different Zr, Nd and Yb variations in the Ol-rich troctolites Cpx with respect to those in the gabbros are expression of different melt-rock reaction scenarios. To test our hypothesis, we calculated the AFC trends produced by the assimilation of single minerals (Ol, Opx, Cpx and Pl) (Figs. 4c, d), then combined in various proportions to simulate whether melt-rock reaction processes in a mantle (assimilating an Opx-bearing mantle peridotite) and crustal (assimilating a troctolite to gabbro) scenario can reproduce the Cpx from the Ol-rich troctolites and the gabbro, respectively. The aim of our simulation is to discuss the role of the assimilated minerals, hence, we fixed the composition of the initial melts and the modal proportions of the crystallizing phases (details in supplementary material).

In agreement with previous studies (see Lissenberg et al., 2013 and references therein), our model shows that AFC processes in a Opx-free gabbroic system (i.e. dissolving gabbro to troctolite) can reproduce the Zr, Nd and Yb variations of gabbros Cpx. On the other hand, the dissolution of an Opx-free dunite (mass assimilated 100% Ol) and synchronous crystallization of an Ol-Pl-Cpx assemblage cannot account for the steep Zr_N/Nd_N versus Yb correlation of the Cpx in Ol-rich troctolites. Opx is enriched in Zr relative to Nd and has Yb contents one order of magnitude higher than Ol (0.2–0.4 and 0.02–0.05, respectively; Hellebrand et al., 2005; Sanfilippo et al., 2014). The occurrence of this mineral in the assimilated material is thereby able to increase the reacting melt in Yb and, at the same time, to fractionate Zr from Nd, following the correlation displayed by the Cpx in Ol-rich troctolites. In particular, our model shows that the Zr, Nd and Yb contents of the Cpx in Ol-rich troctolites can be reproduced by assimilation of an Opx-bearing peridotite until the last phases of the AFC processes (remaining melt mass <1%). This is in agreement with the evidence that the extreme Zr/Nd fractionations are documented exclusively in the rim/interstitial/film-like Cpx grains, which likely crystallized at the final stages of the interaction process (Drouin et al., 2009). Given the number of variables arbitrarily fixed in this calculation (e.g. compositions of the initial melt and of the assimilated phases), we cannot demonstrate that this AFC process is the only contributor to the incompatible element budget of the Cpx from the Ol-rich troctolites. However, our calculation supports the idea that the different Zr, Nd and Yb variations of the Cpx in Ol-rich troctolites and those in gabbros may be related to different melt-rock reaction scenarios, respectively in mantle and lower crustal environments.

In agreement with the occurrence of a relict mantle Opx, the chemistry of the Cpx from Ol-rich troctolites worldwide suggest that these rocks most likely formed by melts buffered by the dissolution of a preexisting Opx-bearing mantle peridotite. The melt-rock reaction scenario we propose in this study confirms observations on highly reacted harzburgites (i.e. Von der Handt and Hellebrand, 2012), which suggest that the replacement of mantle Opx by magmatic Cpx typically occur during melt–peridotite interactions. The assimilation of the mantle material produced chemical trends distinguishable to those of the oceanic gabbros, suggesting that a “mantle flavor” is likely retained in these hybrid rocks.

5. Significance of hybrid troctolites in the oceanic lithosphere

The migration of the primitive melts in the upwelling mantle enhances the dissolution of the mantle Opx and the crystallization of Ol, which at increasing melt rock ratio causes the formation of replacive dunite channels (e.g. Kelemen, 1990). When the melts cross the thermal boundary layer (i.e. decreasing temperature and pressure), the migration mechanism changes from channelized to diffuse porous flow with consequent decreases in permeability and melt velocity, conditions that enhance the assimilation of the host mantle (Kelemen and Aharonov, 1998). Petrological experiments and numerical calculations agreed that at these conditions melt–peridotite interactions trigger the early crystallization of Cpx (Collier and Kelemen, 2010; Saper and Liang, 2014), contrary to what is expected during low-pressure fractional crystallization processes (e.g., Grove et al., 1992). In particular, a recent experiment showed that during the *in-situ* dissolution of a mantle peridotite, high-Mg# Cpx can nucleate around the original mantle Ol, leaving a partly dissolved Ol physically isolated from the melt (Saper and Liang, 2014). This process produces large Cpx oikocrysts including sub-rounded Ol chadacrysts, a texture typically shown by the Ol-rich troctolites worldwide (Drouin et al., 2010; Renna and Tribuzio, 2011; Sanfilippo et al., 2013; Suhr et al., 2008). The low incompatible element compositions (Fig. 3) and the almost absent Eu anomaly (Fig. 4b) of the Cpx cores in Ol-rich troctolites indicate that some portion of Cpx from these rocks crystallized from chemically primitive melts (Drouin et al., 2009) during the early stages of the melt–mantle interaction process. Furthermore, the same experiments showed that the magmatic Ol also crystallizes around the original mantle Ol (Saper and Liang, 2014), in agreement with the idea that the Ol in Ol-rich troctolites mostly records dissolution-recrystallization processes (Sanfilippo et al., 2013; 2014). Hence, melt–mantle interactions at decreasing temperature and pressure conditions are able to convert an Opx-bearing peridotite into an Opx-free lithology, exhibiting the same textural and chemical features of an Ol-rich troctolite. Hybrid troctolites can represent a natural product of the reactive migration of parental melt through the shallow mantle, converted into hybrid crustal rocks by extensive interaction within the thermal boundary layer.

The idea that the lower crust at Uraniwa Hills might have experienced exhumation through detachment faulting (Nakamura et al., 2009) is in agreement with the common occurrence of Ol-rich troctolites at OCC from slow spreading ridges (Kelemen et al., 2007; Blackman et al., 2006; Dick et al., 2010), back arc basins (Sanfilippo et al., 2013) and fossil OCC analogues (Renna and Tribuzio, 2011; Sanfilippo and Tribuzio, 2013). In contrast, Ol-rich troctolites are rare amongst the plutonic sample suites formed at fast spreading ridges (Gillis et al., 2014; Perk et al., 2007), where Pl-bearing lithologies exclusively constitute a minimal part (<5 wt%) of the dunitic crust-mantle transition (Abily and Ceuleneer, 2013; Dick and Natland, 1996). The direct sampling of the oceanic lithosphere is now too limited to consider the present distribution of the Ol-rich troctolites as accurate. However, if our idea is correct, we should expect hybrid troctolites to be more diffused at the crust-mantle transition in slower spreading environments. Here extensive interaction within a thick thermal boundary layer (Collier and Kelemen, 2010; Niu, 2004) may facilitate the conversion of the shallow oceanic mantle into hybrid crustal rocks. A detailed characteriation of the lower crustal architecture is thereby necessary to understand at what extent mantle material can contribute to the composition of the oceanic crust, and whether melt-mantle reaction processes can shape the chemistry of the basalts erupted on the seafloor.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.lithos.2015.06.025.

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