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ORIGIN OF OLIVINE-RICH TROCTOLITES FROM THE OCEANIC LITHOSPHERE: A COMPARISON BETWEEN THE ALPINE JURASSIC OPHIOLITES AND MODERN SLOW SPREADING RIDGES

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ABSTRACT

Olivine-rich troctolite bodies occur within lower crust and mantle sections of the Jurassic oceanic lithosphere exposed along the Alpine-Apennine belt. These rocks bear structural and compositional resemblances to the olivine-rich troctolites from slow spreading ridges. The olivine-rich troctolites from the Alpine-Apennine belt contain olivines (Fo = 89-87 mol%) with rounded to embayed morphology and clinopyroxene oikocrysts with high Mg# (90-88). The clinopyroxene oikocrysts have higher Cr_2O_3 (1.6-1.3 wt%) and lower Ti/Yb than clinopyroxenes in equilibrium typical MORB-type melts. These chemical characteristics were most likely acquired by reaction between an olivine-rich matrix and migrating melts crystallizing clinopyroxene and plagioclase. The plagioclases from the olivine-rich troctolites of the Alpine-Apennine belt are commonly poorer in anorthite component (71-61 mol%) than the plagioclases from slow spreading ridge olivine-rich troctolites. The migrating melts involved in the formation of the olivine-rich troctolites from the Alpine-Apennine belt were most likely slightly enriched in Na_2O with respect to the basalts normally produced at slow spreading ridges. We attribute this Na_2O enrichment to a low degree of melting of asthenospheric sources. The olivine-rich troctolites from fossil and modern oceanic lithosphere probably formed at the mantle-crust transition. The occurrence of olivine-rich troctolite bodies within gabbroic sequences is reconciled with a process of dissection and entrapment of the mantle-crust transition during the growth of the lower crust.

INTRODUCTION

There is a general consensus that reactions between the sub-oceanic mantle and MORB may diffusely occur during the early phases of formation of the lower oceanic crust. For instance, olivine-rich troctolites are locally found in close association with mantle harzburgites at Kane Megamullion, Mid Atlantic Ridge 23°N (Dick et al., 2008; 2010) and at Godzilla Megamullion, Parece Vela Basin of Philippine Sea (Sanfilippo et al., 2013), and could form by multi-stage melt-peridotite interactions at the mantle-crust transition. Olivine-rich troctolite bodies were also found within the gabbroic section of Atlantis Massif oceanic core complex, Mid Atlantic Ridge 30°N (Blackman et al., 2006), thereby leading to the hypothesis that a substantial amount of mantle olivine is incorporated into the lower oceanic crust (Suhr et al., 2008; Drouin et al., 2009; 2010).

Olivine-rich troctolites in fossil sections of oceanic lithosphere have been documented since the early 1970s (Bezzi and Piccardo, 1970; 1971) in the Jurassic ophiolites from eastern Liguria (Fig. 1). These rocks form bodies reaching up to few hundreds of meters in size within large-scale gabbroic sequences (Cortesogno et al., 1987). These gabbroic sequences show close structural and compositional similarities to lower crust sections from slow and ultra-slow spreading ridges (Hebert et al., 1989; Tribuzio et al., 1995; Tiepolo et al., 1997; Rampone et al., 1998). In the pioneering studies of Bezzi and Piccardo (1970; 1971), the olivine-rich troctolites were considered to be cumulates formed by primitive basalts under closed system conditions. A similar origin was proposed (Borghini and Rampone, 2007) for the olivine-rich troctolites associated with the mantle peridotites from the Erro-Tobbio ophiolite (western Liguria). The olivine-rich troctolites from eastern Liguria were re-interpreted as reaction products between an olivine-rich matrix and migrating MORB-type melts (Renna and Tribuzio, 2011), in agreement with the petrogenetic hypotheses reported for the olivine-rich troctolites from slow spreading ridges (Suhr et al., 2008; Drouin et al., 2009; 2010). Olivine-rich troctolite bodies were also found within the km-scale lower crust section of Pineto (ophiolites from central Corsica) and inferred to have formed by melt-dunite interactions (Sanfilippo and Tribuzio, 2013).

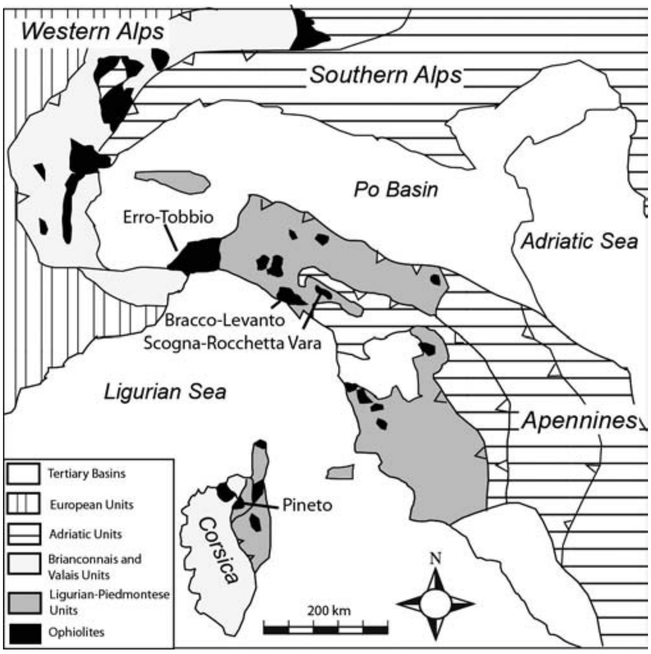

Fig. 1 - Geological sketch map showing the locations of the Erro-Tobbio ophiolite (western Liguria), the Bracco and the Scogna-Rocchetta Vara ophiolites from Internal Ligurian units (eastern Liguria) and the Pineto gabbroic sequence (central Corsica).

This work presents a review of the structural, petrological and geochemical data reported in the literature for the olivine-rich troctolites from the ophiolites from the Alpine-Apennine-Corsica system (hereafter referred to as Alpine Jurassic ophiolites). New whole-rock analyses were also carried out to compile a complete dataset for these rocks. The comparison with the olivine-rich troctolites from the modern oceanic slow spreading lithosphere allowed us to yield a comprehensive overview of the petrogenetic hypotheses proposed for these rocks. New information about the building of the lower oceanic crust was thus acquired.

THE GABBRO-PERIDOTITE ASSOCIATION FROM THE ALPINE JURASSIC OPHIOLITES

The Alpine Jurassic ophiolites are lithospheric remnants of the Middle to Late Jurassic Ligurian-Piedmontese basin. This basin developed in conjunction with the opening of the Central Atlantic Ocean and separated the Europe-Iberia plate to the northwest from the Africa-Adria plate to the southeast (Schettino and Turco, 2011). The Alpine Jurassic ophiolites include different successions that were interpreted to have formed at magma-poor ocean-continent transitions (e.g., Marroni et al., 1998; Manatschal and Müntener, 2009) and/or within an embryonic (ultra-)slow spreading ocean (e.g., Piccardo et al., 2009). These ideas are consistent with the mantle sections frequently retaining a subcontinental lithospheric origin (Rampone et al., 1995; Müntener et al., 2004; Montanini et al., 2006; 2012). However, some of the mantle sequences mostly consist of depleted mantle peridotites that do not show structural and chemical characteristics indicating a subcontinental origin (Beccaluva et al. 1984; Lagabrielle and Cannat, 1990; Tribuzio et al., 2004). These mantle sequences represent either asthenospheric material that ascended in response to oceanic spreading (Rampone et al., 2008; 2009; Sanfilippo and Tribuzio, 2011), or exhumed subcontinental mantle that experienced thermochemical erosion by upwelling asthenosphere during rifting (Piccardo and Vissers, 2007; Piccardo et al., 2007). In the ophiolites from eastern Liguria (Internal Ligurian units) and central Corsica, the depleted mantle peridotites are associated with large-scale MOR-type gabbroic sequences (Menna, 2009; Sanfilippo and Tribuzio, 2011; 2013). These gabbro-peridotite associations were correlated with paleomorphological highs similar to the oceanic core complexes from Mid Atlantic Ridge (see also Principi et al., 2004; Alt et al., 2012).

THE OLIVINE-RICH TROCTOLITES FROM THE ALPINE JURASSIC OPHIOLITES

Field relationships

Olivine-rich troctolite bodies occur within the large-scale gabbroic sections (Fig. 1) of Bracco and Scogna-Rocchetta Vara (Internal Ligurian ophiolites), and of Pineto (central Corsica). The Bracco and the Scogna-Rocchetta Vara gabbroic sequences mostly consist of clinopyroxene-rich gabbros associated with minor amounts of olivine gabbros to troctolites (Cortesogno et al., 1987; Sanfilippo and Tribuzio, 2011). The Pineto gabbroic section is mainly made up of clinopyroxene-rich gabbros to gabbronorites near its stratigraphic top and of troctolites and minor olivine gabbros in its deeper sector (Sanfilippo and Tribuzio, 2013). The olivine-rich troctolites constitute sill-like lenses that are up to tens of meters thick and few hundreds of meters long in the Bracco and the Scogna-Rocchetta Vara sequence. In the Pineto gabbroic section, the olivine-rich troctolites form up to 5 m thick bodies within the troctolites. The gabbroic sequences of Bracco, Scogna-Rocchetta Vara and Pineto also enclose up to 50 m thick mantle peridotite bodies at different stratigraphic heights.

In the Erro-Tobbio ophiolite (Fig. 1), a hectometer-scale olivine-rich troctolite body is associated with mantle peridotites (Borghini et al., 2007). The Erro-Tobbio mantle section here consists of clinopyroxene-poor lherzolites showing evidence for plagioclase facies melt impregnation. The contacts between the olivine-rich troctolites and the mantle peridotites are diffuse and characterized by the occurrence of plagioclase-bearing wehrlites.

The olivine-rich troctolite bodies are commonly characterized by randomly distributed internal compositional heterogeneities. In the Bracco and Scogna-Rocchetta Vara sequences, the olivine-rich troctolites locally enclose irregular clots (up to few tens of centimeters in scale) made up of spinel-bearing dunite (Renna and Tribuzio, 2011). These olivine-rich troctolite bodies also contain sparse plagioclase-rich gabbroic veins (up to 0.1 m in thickness) showing fuzzy contacts with respect to the host rock and anastomosed morphology. Lenses displaying "harrisitic" pegmatoid structure are locally included within the olivine-rich troctolite bodies of Bracco and Erro-Tobbio (Bezzi and Piccardo, 1970; 1971). These lenses display sinuous contacts with respect to the host-rock and have up to 30 cm long olivine grains intergrown with plagioclase and minor clinopyroxene.

The olivine-rich troctolite bodies locally include layers (up to few meters thick) displaying planar contacts with respect the host rock and ranging in composition from troctolite to clinopyroxene-rich gabbro. In the Bracco gabbroic sequence, the troctolite layers exhibit in places wide variations in the relative proportion of olivine and plagioclase, thereby grading from troctolite to anorthosite (Bezzi and Piccardo, 1970; 1971). In the Scogna-Rocchetta Vara section, the olivine-rich troctolite bodies include gabbroic layers that are sub-parallel to the gabbroic sills intruding the associated mantle sequence (Sanfilippo and Tribuzio, 2011). In the Erro-Tobbio ophiolite, the gabbroic layers within the olivine-rich troctolites locally show grain-size decreasing towards the host rock (Borghini et al., 2007). Finally, spinel- and plagioclase-rich layers ("chromitites") displaying diffuse to planar contacts with respect to the host rock are locally enclosed within the Bracco and Scogna-Rocchetta Vara bodies (Renna and Tribuzio, 2011). The chromitite layers are up to few tens of cm thick and show in places modal layering to anorthosite compositions.

Micro-structural, petrological and geochemical characteristics

The olivine-rich troctolites mostly consist of euhedral to subhedral olivine (grain size ranging from 10 mm to 0.2 mm) and minor anhedral to poikilitic plagioclase (Bezzi and Piccardo, 1970; 1971; Cortesogno et al., 1987). Accessory amounts of clinopyroxene, spinel and, locally, titanian pargasite are also present. The olivine locally shows rounded morphology and embayed shape against clinopyroxene and plagioclase (Borghini and Rampone, 2007; Renna and Tribuzio, 2011). The olivine (Fig. 2a) has high forsterite component ranging from 89 to 87 mol% and 0.30-0.27 wt% NiO (see also Sanfilippo and Tribuzio, 2013). The plagioclase from the olivine-rich troctolites of the Erro-Tobbio ophiolite and the Pineto gabbroic sequence has anorthite component of 71-69 mol% and 65-61 mol%, respectively (Fig. 2b). In the olivine-rich troctolites from the Internal Ligurian ophiolites, the plagioclase is altered into fine-grained aggregates made up of prehnite ± epidote ± hydrogrossular.

Accessory clinopyroxene commonly occurs as large oikocrysts (up to 5 cm) including olivine and spinel. The clinopyroxene oikocrysts have film-like apophyses interstitial to olivine and plagioclase. In addition, small clinopyroxene grains (up to 0.2 mm) interstitial to olivine and plagioclase are also locally present. The inner portions of the clinopyroxene oikocrysts have high Mg# [Mg/(Mg + Fe^{2+}_{tot}) × 100, in atoms per formula unit] that positively correlates with the forsterite proportion of the coexisting olivine (Fig. 3). The clinopyroxene-olivine pairs plot within the field indicating magmatic equilibrium on the basis of the Mg# partition coefficients of Roeder and Emslie (1970) and Obata et al. (1974). The inner portions of the clinopyroxene grains have high contents of Cr_2O_3 (1.6-1.3 wt%) and Na_2O (0.7-0.5 wt%), and TiO_2 ranging from 1.2 to 0.4 wt%. The rims of the clinopyroxene oikocrysts and the interstitial clinopyroxenes have lower Cr_2O_3 and higher TiO_2 than the inner portions of the clinopyroxene oikocrysts.

The inner portions of the clinopyroxene oikocrysts display chondrite-normalized patterns (Fig. 4) characterized by LREE depletion (La_N/Sm_N = 0.19-0.10) with respect to the MREE and HREE, which are nearly flat at 17 to 9 times CI (Rampone et al., 1998; Borghini et al., 2007; Borghini and Rampone, 2007; Renna and Tribuzio, 2011). The REE patterns of the clinopyroxene oikocrysts are characterized by negative Eu anomaly, which increases with increasing REE, Y and Zr concentrations (Fig. 5). The rims of the clinopyroxene oikocrysts and the interstitial clinopyroxenes have the highest abundances of REE, Y and Zr (Borghini and Rampone, 2007).

Accessory spinel commonly occurs within the plagioclase; it is locally also included within olivine and clinopyroxene. The spinels have low Mg#, relatively high Cr# [Cr/(Cr + Al) × 100] and TiO_2 ranging from 2.3 to 1.0 wt% (Fig. 6). Mineral inclusions are frequently present within the spinels from the olivine-rich troctolites (Renna and Tribuzio, 2011). These inclusions are monophase to multiphase and commonly consist of kaersutite to titanian pargasite, phlogopite to Na-phlogopite (aspidolite) and/or orthopyroxene (see also Sanfilippo and Tribuzio, 2013). Accessory titanian pargasite locally occurs outside the spinels, mainly in association with the rims of the clinopyroxene oikocrysts and as coronas around the spinels.

The whole-rock chemical compositions of the olivine-rich troctolites (Tiepolo et al., 1997; Rampone et al., 1998; Borghini et al., 2007; this work) are characterized by high Mg# [molar Mg/(Mg + Fe^{2+}_{tot}) × 100] and low contents of Al_2O_3, CaO and Na_2O (Fig. 7, Table 1). In particular, the samples selected for the present study have high loss on ignition values (11.4-6.7 wt%), which reflect different extents of olivine and plagioclase alteration. Taken as a whole, the olivine-rich troctolites are also distinct in the high concentrations of Cr, Ni and Co (4060-550 ppm, 2000-1280 ppm and 133-81 ppm, respectively). On the basis of whole-rock and mineral core major element compositions, we estimated an olivine modal amount of 82 to 68 vol% for the olivine-rich troctolites (Table 1, see also Borghini and Rampone, 2007). Calculated modes of plagioclase and clinopyroxene are 28-18 vol% and ≤ 5 vol%, respectively.

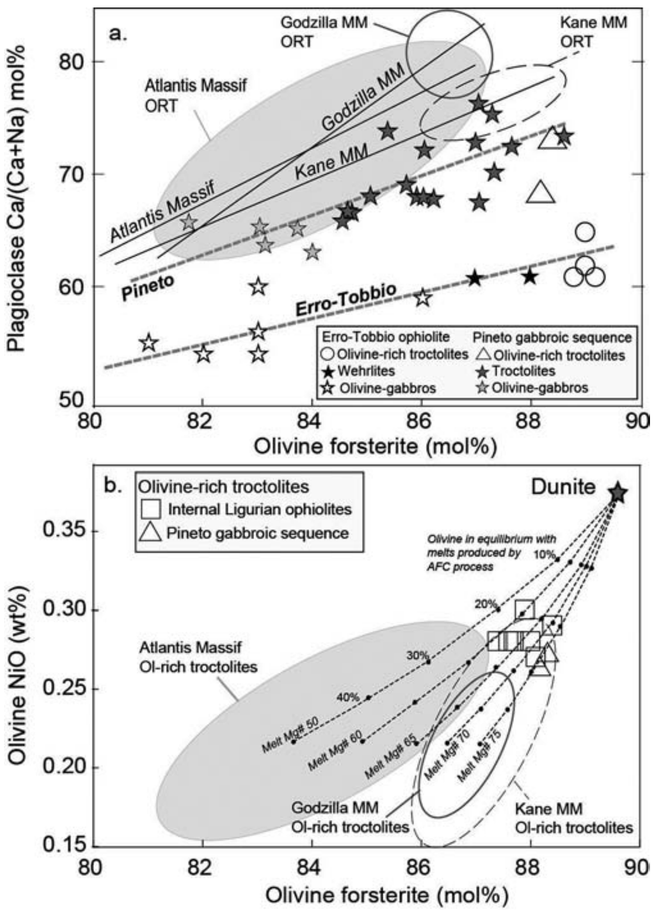

Fig. 2 - a) Forsterite proportion of olivine versus anorthite proportion of coexisting plagioclase (mol%) for the olivine-rich troctolites from the Erro-Tobbio ophiolite (Borghini et al., 2007; Borghini and Rampone, 2007) and the Pineto gabbroic sequence (Sanfilippo and Tribuzio, 2013). The compositions of wehrlites, troctolites and olivine gabbros associated with these olivine-rich troctolites are also reported. Dashed gray lines display the crystal-line of descents (calculated by best fitting) for the Pineto and Erro-Tobbio rock suites. The compositional fields defined by the olivine-rich troctolites from Atlantis Massif (Suhr et al., 2008; Drouin et al., 2009), Kane Megamullion (Dick et al., 2010) and Godzilla Megamullion (Sanfilippo et al., 2013) are shown. The crystal-line of descents for Atlantis Massif, Kane Megamullion and Godzilla Megamullion rock suites are depicted with solid gray lines. b) Forsterite proportion (mol%) versus NiO (wt%) for the olivines from the olivine-rich troctolites of the Internal Ligurian ophiolites (Renna and Tribuzio, 2011) and the Pineto gabbroic sequence (Sanfilippo and Tribuzio, 2013). The compositions of the olivine-rich troctolites from Atlantis Massif (Suhr et al., 2008; Drouin et al., 2009), Kane Megamullion (Dick et al., 2010) and Godzilla Megamullion (Sanfilippo et al., 2013) are also reported. The olivine dissolution/re-equilibration model from Sanfilippo et al. (2013) is also shown. This model reproduces the composition of olivine produced by assimilation of dunite olivine (black star in the figure) and crystallization of new olivine, clinopyroxene and plagioclase for seven reacting melt compositions (see Appendix 1 and Table 6 in Sanfilippo et al., 2013 for further details).

COMPARISON WITH THE OLIVINE-RICH TROCTOLITES FROM SLOW SPREADING RIDGES

Similar to the olivine-rich troctolites from the Alpine Jurassic ophiolites, those from slow spreading ridges have plagioclase and clinopyroxene with anhedral to oikocrystic morphology and olivine with euhedral to rounded and embayed morphology (Suhr et al., 2008; Drouin et al., 2009; 2010; Dick et al., 2010; Sanfilippo et al., 2013). Taken as a whole, the olivine-rich troctolites also have similar modal

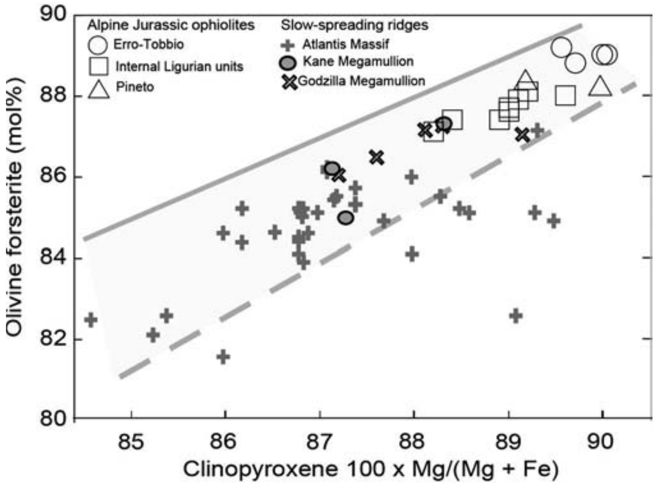

Fig. 3 - Forsterite proportion of olivine versus Mg# of coexisting clinopyroxene for the olivine-rich troctolites from the Erro-Tobbio ophiolite (Borghini et al., 2007; Borghini and Rampone, 2007), the Bracco and the Scogna-Rocchetta Vara ophiolites from Internal Ligurian units (Renna and Tribuzio, 2011) and the Pineto gabbroic sequence (Sanfilippo and Tribuzio, 2013). Solid and dashed lines contour the compositions of olivine-clinopyroxene pairs expected for magmatic equilibrium conditions, assuming: (i) 1:1 Fe-Mg partitioning between olivine and clinopyroxene (Obata et al., 1974), and (ii) mineral-melt Fe-Mg partition coefficients of 0.30 for olivine and 0.23 for clinopyroxene (Roeder and Emslie, 1970). The compositions of the olivine-clinopyroxene pairs from the olivine-rich troctolites of Atlantis Massif (Suhr et al., 2008; Drouin et al., 2009), Kane Megamullion (Dick et al., 2010) and Godzilla Megamullion (Sanfilippo et al., 2013) are also reported.

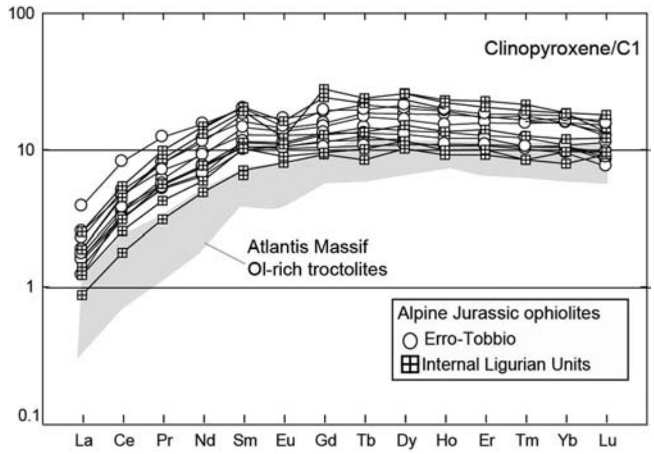

Fig. 4 - REE element compositions of the clinopyroxene oikocrysts (inner portions) from the olivine-rich troctolites of the Erro-Tobbio ophiolite (Borghini et al., 2007; Borghini and Rampone, 2007) and the Bracco and the Scogna-Rocchetta Vara ophiolites from Internal Ligurian units (Renna and Tribuzio, 2011) normalized to CI chondrite (Anders and Ebihara, 1982). The compositions of the clinopyroxene oikocrysts (cores) from the olivine-rich troctolites of Atlantis Massif (Suhr et al., 2008; Drouin et al., 2009) are also reported.

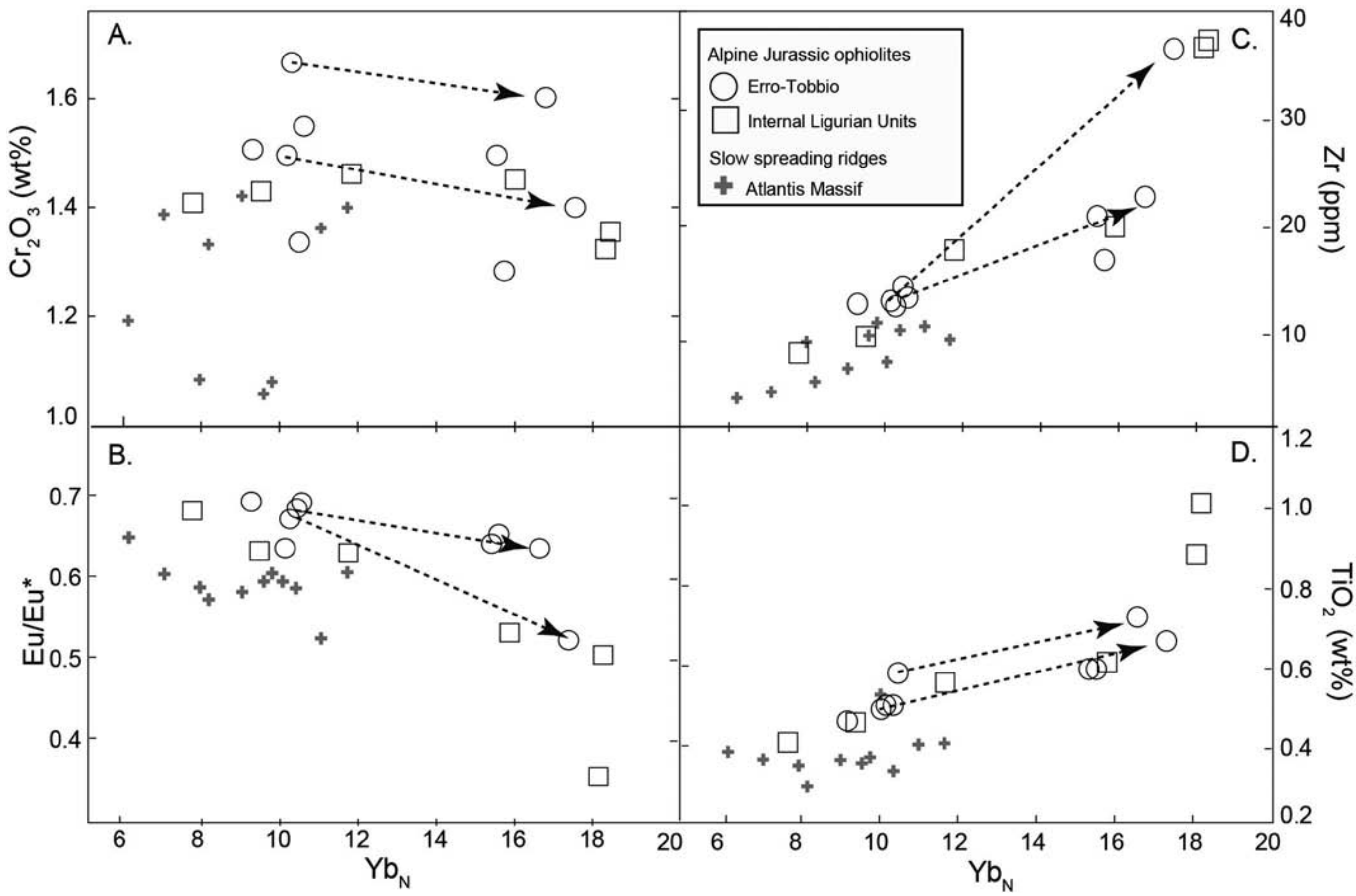

Fig. 5 - Variation of Yb_N (Yb ppm normalized to CI chondrite of Anders and Ebihara, 1982) versus Cr_2O_3 (wt%), Eu/Eu* [$Eu/\sqrt{(Sm^2 + Gd^2)}$], Zr (ppm) and TiO_2 (wt%) for the clinopyroxene oikocrysts (inner portions) from the olivine-rich troctolites of the Erro-Tobbio ophiolite (Borghini et al., 2007; Borghini and Rampone, 2007) and the Bracco and the Scogna-Rocchetta Vara ophiolites from Internal Ligurian units (Renna and Tribuzio, 2011). Analyses carried out on the same clinopyroxene grains (cores to intermediate portions) for the olivine-rich troctolites from the Erro-Tobbio ophiolites are linked by black arrows. The compositions of the clinopyroxene oikocrysts (cores) from the olivine-rich troctolites of Atlantis Massif (Suhr et al., 2008; Drouin et al., 2009) are also reported.

Table 1 - Whole-rock compositions of the olivine-rich troctolites.

		Pineto gabbroic sequence			Internal Ligurian ophiolites		
sample		PI85*	PI41*	PI 80°	MA 5°	SC 7°	ST 3°
SiO_2	(wt %)	37.4	39.2	38.3	38.3	37.4	37.3
TiO_2		0.07	0.03	0.07	0.05	0.04	0.03
Al_2O_3		6.03	3.67	4.60	5.40	5.13	4.32
Fe_2O_3		9.24	10.3	10.0	8.36	8.79	8.17
MnO		0.12	0.14	0.13	0.11	0.12	0.11
MgO		34.2	36.4	38.5	36.6	36.1	38.3
CaO		2.83	1.69	1.98	2.32	3.17	1.16
Na_2O		0.40	0.26	0.05	0.03	b.d.l.	b.d.l.
K_2O		b.d.l.	b.d.l.	0.01	0.01	0.00	0.00
LOI		9.33	6.67	7.35	9.70	10.2	11.4
Total		99.6	98.3	101.0	100.8	100.9	100.8
Mg#		88.0	87.5	88.4	89.7	89.1	90.3
V	(ppm)	37.0	13.0	25.1	26.5	28.4	21.3
Cr		3320	550	1640	3010	4060	2710
Co		102	133	123	110	114	128
Ni		1330	1680	1690	1680	1710	2000
Cu		60.0	90.0	70.6	92.2	86.5	59.8
Zn		50.0	50.0	45.0	43.3	41.2	43.1
Sr		46.0	28.0	44.6	59.1	17.3	15.6
mineral	Pl	23	15		22	23	18
modes	Ol	76	82		75	72	82
(vol%)	Cpx	1	3		3	5	<1

Mg# = molar Mg/(Mg+Fe^{2+}_{tot})*100; b.d.l. = below detection limit.
* Chemical analyses were carried out by inductively coupled plasma atomic emission spectroscopy at Activation Laboratories (Ancaster, Ontario). Accuracy is estimated to be better than 5% and 10% for major and trace elements, respectively.
° Chemical analyses were carried out by X-ray fluorescence (XRF) at the Dipartimento di Fisica e Scienze della Terra, Università degli Studi di Ferrara (Italy). Accuracy is estimated to be better than 5% for SiO_2, Fe_2O_3 and MgO, and better than 10% for the other elements analyzed.
The mineral modes are estimated on the basis of the whole-rock and mineral compositions using MODAN software (Pactunk, 1997) and the following mineral densities: olivine 3.32; plagioclase 2.68; clinopyroxene 3.40. Mineral compositions of Pineto gabbroic sequence and Internal Ligurian ophiolites are given in Sanfilippo and Tribuzio (2012) and Renna and Tribuzio (2011), respectively. Plagioclase with An = 70 mol% was assumed in the calculations for the olivine-rich troctolites from the Internal Ligurian ophiolites. The lack of mineral compositions for sample PI80 prevented the determination of the mineral modes.

compositions, although those from Atlantis Massif occasionally have higher clinopyroxene amounts (up to 30 vol%).

The olivines from the olivine-rich troctolites of the Alpine Jurassic ophiolites, Kane Megamullion and Godzilla Megamullion have similar compositions (Fig. 2a). The olivines from Atlantis Massif olivine-rich troctolites are frequently distinct in the relatively low proportion of forsterite component. The plagioclases from the olivine-rich troctolites of the Alpine Jurassic ophiolites generally display lower anorthite component than the plagioclases from slow spreading ridge counterparts (Fig. 2b).

The inner portions of the clinopyroxene oikocrysts are chemically similar for the different olivine-rich troctolite occurrences (Figs. 3, 4, 5). Note, however, that the clinopyroxene oikocrysts from slow spreading ridge olivine-rich troctolites commonly have slightly lower Na_2O (0.5-0.3 wt%) than their fossil counterparts from the Alpine Jurassic ophiolites. In addition, the clinopyroxene oikocrysts from Atlantis Massif frequently have slightly lower Mg# and Cr_2O_3 than those from the olivine-rich troctolites of the Alpine Jurassic ophiolites, Kane Megamullion and Godzilla Megamullion. The clinopyroxene oikocrysts from the olivine-rich troctolites of the Alpine Jurassic ophiolites and Atlantis Massif have akin LREE depletion, although the former have generally slightly lower REE concentrations. Similar to the olivine-rich troctolites from the Alpine Jurassic ophiolites, the rims of the clinopyroxene oikocrysts from slow spreading ridge rocks are slightly depleted in Mg# and Cr_2O_3, and slightly enriched in TiO_2, REE, Y and Zr with respect to the cores.

The spinels from the olivine-rich troctolites of the Alpine Jurassic ophiolites, Kane Megamulion and Godzilla Megamullion have similar compositions (Fig. 6). The spinels from Atlantis Massif olivine-rich troctolites are frequently distinct in the slightly lower Mg# and higher Cr# and TiO_2. Inclusions of amphibole, phlogopite and orthopyroxene were documented for the spinels from the olivine-rich troctolites of Atlantis Massif (Suhr et al., 2008), similar to the spinels from the olivine-rich troctolites of the Alpine Jurassic ophiolites.

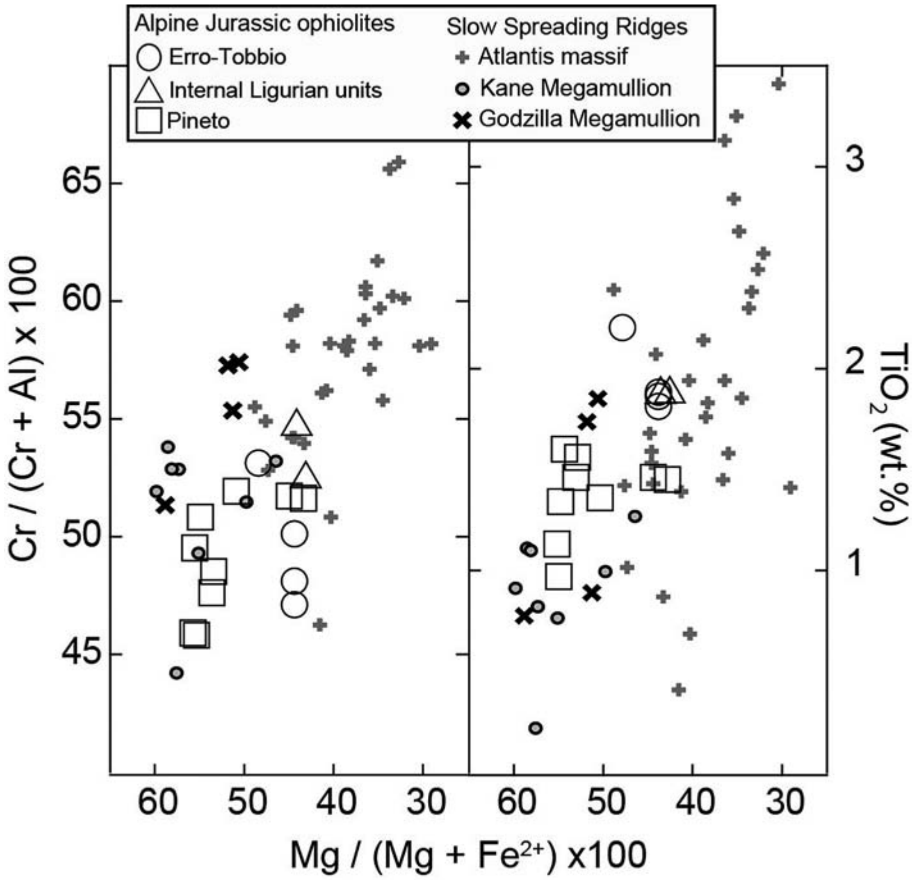

Fig. 6 - Mg# [100*Mg/(Mg + Fe^{2+})] versus Cr# [100*Cr/(Cr + Al)] and TiO_2 for the spinels from the olivine-rich troctolites of the Erro-Tobbio ophiolite (Borghini et al., 2007; Borghini and Rampone, 2007), the Bracco and the Scogna-Rocchetta Vara ophiolites from Internal Ligurian units (Renna and Tribuzio, 2011) and the Pineto gabbroic sequence (Sanfilippo and Tribuzio, 2013). The compositions of the spinels from the olivine-rich troctolites of Atlantis Massif (Suhr et al., 2008; Drouin et al., 2009), Kane Megamullion (Dick et al., 2010) and Godzilla Megamullion (Sanfilippo et al., 2013) are also reported.

The whole-rock compositions show that the olivine-rich troctolites from Atlantis Massif (Godard et al., 2009) and the Alpine Jurassic ophiolites similarly contain low amounts of Al_2O_3 and CaO (Fig. 7). The Atlantis Massif olivine-rich troctolites are commonly characterized by slightly lower Mg# than those from the Alpine Jurassic ophiolites, in agreement with the chemical variations displayed by the olivines, the clinopyroxenes and the spinels.

DISCUSSION

Evidence for formation by melt-dunite reactions

Bezzi and Piccardo (1970; 1971) proposed that the olivine-rich troctolites from the Alpine Jurassic ophiolites are cumulates formed by precipitation of olivine and accessory spinel from primitive basalts. The anhedral morphology of plagioclase and clinopyroxene was attributed to post-cumulus crystallization of the interstitial melts (see also Cortesogno et al., 1987; Hebert et al., 1989). In this section, we show that several arguments argue against this petrogenetic model, thereby leading to the idea that these rocks formed by melt-rock reactions.

Most clinopyroxene oikocrysts from the olivine-troctolites of the Alpine Jurassic ophiolites and slow spreading ridges have higher Mg# than clinopyroxenes crystallized from primitive MORB under low-pressure experimental conditions (Mg# ~ 87; Grove and Bryan, 1983; Tormey et al., 1987; Grove et al., 1992; Yang et al., 1996). The high Mg# of the clinopyroxene oikocrysts may reflect high MgO contents of the melts acquired during the partial dissolution of forsterite-rich olivine (see also Lissenberg and Dick, 2008). This interpretation was suggested by the local finding of olivines with embayed morphology and is consistent with the correlation between Mg# of the clinopyroxene and forsterite component of the coexisting olivine (Fig. 4) indicating conditions of magmatic equilibrium (Suhr et al., 2008; Drouin et al., 2009; Renna and Tribuzio, 2011; Sanfilippo et al., 2013).

The chondrite-normalized REE patterns of the clinopyroxene oikocrysts have negative Eu anomalies increasing with absolute REE concentrations (Fig. 5). This correlation documents the coeval crystallization of clinopyroxene and plagioclase, in agreement with the equilibrium structures between these two phases. The olivine-rich troctolites may have thus formed by reaction between an olivine-rich matrix and migrating melts crystallizing plagioclase and clinopyroxene. Following this hypothesis, the sparse dunitic clots from the olivine-rich troctolite bodies of the Internal Ligurian ophiolites were interpreted to be remnants of the olivine-rich matrix (Renna and Tribuzio, 2011). In addition, the plagioclase-rich gabbroic veins from these olivine-rich troctolite bodies may represent crystallization products of the migrating reacting melts.

Calculated Ti and Yb compositions of the melts in equilibrium with the clinopyroxenes from the olivine-rich troctolites of the Alpine Jurassic ophiolites and Atlantis Massif are reported in Fig. 8. Computed melt compositions depict trends with lower Ti/Yb than expected by fractional crystallization of MORB under low-pressure conditions. Calculated equilibrium melts are also characterized by lower Ti/Yb values than MORB-derived glasses from Mid Atlantic Ridge. Notably, the clinopyroxene-olivine partition coefficient for Ti is higher than the clinopyroxene-olivine parti-

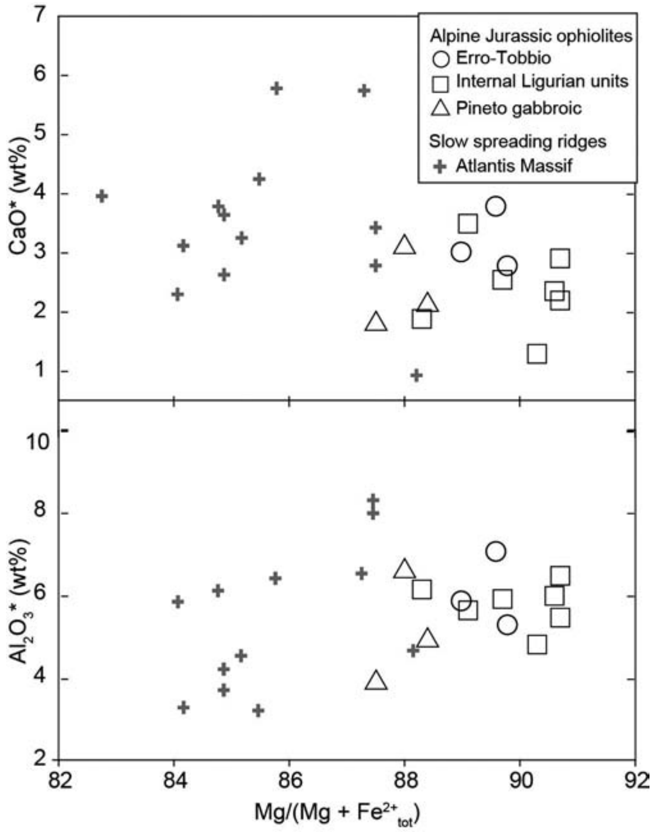

Fig. 7 - Mg/(Mg + Fe^{2+}_{tot}) versus CaO* and Al_2O_3* (calculated on anhydrous basis) for the olivine-rich troctolites from Erro-Tobbio ophiolite (Borghini et al., 2007; Borghini and Rampone, 2007), the Bracco and the Scogna-Rocchetta Vara ophiolites from Internal Ligurian units (Tiepolo et al., 1997; Rampone et al., 1998; this work) and the Pineto gabbroic sequence (this work). The compositions of the olivine-rich troctolites from Atlantis Massif (Godard et al., 2009) are also reported.

tion coefficient for Yb ($D^{Cpx/Ol}$ ~ 35 and ~ 8, respectively; Witt-Eickschen and O'Neill, 2005). This implies that the reactive crystallization of clinopyroxene + plagioclase at the expenses of olivine may produce residual melts with lower Ti/Yb ratios than those related to a typical MORB-type Rayleigh fractional crystallization.

The clinopyroxene oikocrysts from the olivine-rich troctolites of the Alpine Jurassic ophiolites have high Cr_2O_3 contents (Fig. 5), which are difficult to reconcile with crystallization from MORB-type melts. Using a clinopyroxene/basalt partition coefficient of 3.8 (Hart and Dunn, 1993), we evaluated Cr amounts of 3000-1900 ppm for the melts in equilibrium with these clinopyroxenes. These Cr concentrations are dramatically higher than those of primitive MORB (520-330 ppm, Roeder and Reynolds, 1991). In addition, the Cr_2O_3 contents in the clinopyroxene oikocrysts do not decrease with increasing concentrations of incompatible elements (Fig. 5). High Cr_2O_3 contents and lack of correlation between Cr_2O_3 and incompatible elements are similarly documented for the clinopyroxenes from the olivine-rich troctolites of Atlantis Massif (Suhr et al., 2008; Drouin et al., 2009). We thus propose that the clinopyroxenes from the different olivine-rich troctolite occurrences formed by migrating melts variably enriched in Cr. This Cr enrichment may be related to partial dissolution of pre-existing spinel grains (i.e., from the precursor olivine-rich matrix), which may release significant Cr amounts to the melts (Suhr et al., 2008; Lissenberg and Dick, 2008; Renna and Tribuzio, 2011). The Cr enrichment in the migrating melts may be alternatively acquired by preferred dissolution of pyroxene from mantle peridotites during the formation of the precursor olivine-rich matrix (Sanfilippo et al., 2013).

A further argument in agreement with a formation of the olivine-rich troctolites under open system conditions is the occurrence of mineral inclusions within the spinels (Renna and Tribuzio, 2011; Sanfilippo and Tribuzio, 2013).

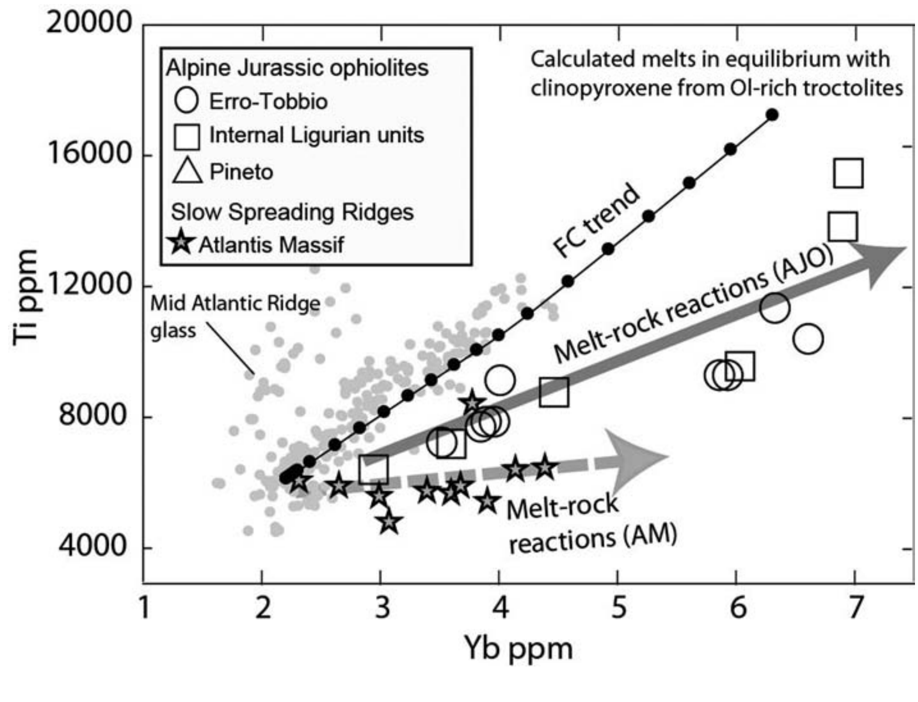

Fig. 8 - Calculated Yb versus Ti compositions of the melts in equilibrium with the clinopyroxene oikocrysts (inner portions) from the olivine-rich troctolites of the Alpine Jurassic ophiolites (AJO) and Atlantis Massif (AM). Computations were carried out on the basis of the clinopyroxene/basalt partition coefficients of Hart and Dunn (1993). The compositions of the melts tracing the fractional crystallization (FC) trend were calculated using the PELE potential minimization program based on the algorithms and databases of Ghiorso (1985) and Ghiorso and Sack (1995), and programmed by A.E. Boudreau (http:// www. nicholas.duke.edu/people/faculty/boudreau/DownLoads.html). In the FC trend, each step corresponds to a decrease of 5 °C in temperature at a fixed pressure of 0.2 GPa. Mid Atlantic Ridge glass data were achieved from the Petrological Database of the Ocean Floor (http://petdb.ldeo.columbia.edu). The concentrations of Yb and Ti in the initial melt are 2.2 and 6000 ppm, respectively.

These inclusions commonly consist of hydrous silicate phases (kaersutite to titanian pargasite and phlogopite to aspidolite) locally associated with orthopyroxene, which were considered to be crystallization products of melts enriched in incompatible elements (e.g., volatiles, Na_2O, K_2O and TiO_2) with respect to primitive basalts and trapped during spinel growth. Notably, inclusions of Ti-rich amphibole, dark mica and orthopyroxene were also reported for spinels from dunites of oceanic mantle sections (Arai et al., 1997; Morishita et al., 2011). In this case, the inclusion-bearing spinels were interpreted to have formed by hybrid melts oversaturated in spinel (± olivine), which were produced by interaction of melts evolved through melt-peridotite reactions with new injections of primitive olivine-saturated melts. The evolved melts were inferred to be relatively rich in SiO_2 and Cr_2O_3 because of pyroxene dissolution in the mantle harzburgite/lherzolite, and incompatible elements in response to olivine crystallization under lowering temperature conditions (see also Arai and Matsukage, 1998).

We wish finally to emphasize that the local occurrence of layers compositionally ranging from troctolite to anorthosite and chromitite, and of lenses displaying harrisitic pegmatoid structure in the Alpine Jurassic ophiolites (Bezzi and Piccardo, 1970; 1971) does not argue against formation of the olivine-rich troctolites by melt-rock reactions. Taken as a whole, these internal compositional heterogeneities may have derived from late melt injections, before and after complete solidification of the olivine-rich troctolites. Intrusions unambiguously post-dating the crystallization of the olivine-rich troctolites are shown by the layers consisting of clinopyroxene-rich gabbro (Borghini et al., 2007; Sanfilippo and Tribuzio, 2011).

Origin of the precursor olivine-rich matrix

The olivine-rich matrix precursor of the olivine-rich troctolites may represent remnants of replacive dunites formed at the expenses of mantle harzburgites/lherzolites in response to reactive infiltration of olivine-saturated melts (Dick, 1977; Quick, 1981; Kelemen et al., 1990; 1995; Suhr, 1999). When the melts decrease in mass because of reactions with the host peridotites and/or to conductive heat loss, the replacive dunites may be transformed into olivine-rich troctolites by further melt-rock interactions (Suhr et al., 2008). The replacive origin of the precursor dunite was substantiated by mineral trace element compositions. In particular, Drouin et al. (2009) documented that the olivines from Atlantis Massif olivine-rich troctolites are too depleted in LREE and MREE to be in equilibrium with MORB, and are geochemically similar to olivines from residual harzburgites of Oman ophiolite. In addition, the lattice preferred orientation of the olivines from Atlantis Massif olivine-rich troctolites are consistent with a mantle fabric disrupted by melt impregnation (Drouin et al., 2010). Notably, the Kane Megamullion exposes an association of mantle residual harzburgites, dunites, olivine-rich troctolites and troctolites, which was interpreted to represent a mantle-crust transition (Dick et al., 2008; 2010). An association of olivine-rich troctolites and mantle peridotites is also present in Godzilla Megamullion (Sanfilippo et al., 2013) and the Erro-Tobbio ophiolite (Borghini and Rampone, 2007). These olivine-rich troctolite occurrences are thus consistent with the idea that the precursor olivine-rich matrix was a replacive dunite formed by reaction between mantle peridotites and migrating melts at the mantle-crust transition.

In an alternative petrogenetic hypothesis, the precursor olivine-rich matrix of the olivine-rich troctolites corresponds to material produced by fractional crystallization of primitive melts, in agreement with experimental studies (Tormey et al., 1987; Grove et al., 1992) showing that the early cooling evolution of primary MORB is characterized by olivine crystallization. Note that MORB-related replacive dunites and dunites formed by fractional crystallization of MORB are expected to have similar olivine and spinel compositions (cf. Tormey et al., 1987, and Kelemen et al., 1995). We cannot thus exclude that the precursor olivine-rich matrix of the olivine-rich troctolites formed by fractional crystallization. To unravel the origin of the olivine-rich matrix, further detailed investigations are required. In both the petrogenetic scenarios, however, the precursor olivine-rich matrix of the olivine-rich troctolites may have formed at the mantle-crust transition.

Formation of the olivine-rich troctolites within lower crust gabbroic sections

The olivine-rich troctolites are not only associated with mantle peridotites, but also occur at different stratigraphic heights within the lower crust gabbroic sequences from the Alpine Jurassic ophiolites (Cortesogno et al., 1987; Sanfilippo and Tribuzio, 2013) and Atlantis Massif (Blackman et al., 2006). The architecture of these gabbroic sequences is characterized by a somewhat random distribution of chemically primitive and evolved rocks (see also Suhr et al., 2008; Godard et al., 2009; Sanfilippo and Tribuzio, 2011). Cooling evaluations based on Ca in olivine geospeedometry (Coogan et al., 2007; Sanfilippo and Tribuzio, 2013) and U-Pb zircon geochronological investigations (Schwartz et al., 2005; Grimes et al., 2008; 2011) document that the lower crust gabbroic sections from slow spreading settings form by multiple intrusions derived from variably evolved melts and related to different magmatic episodes. Hence, the mantle peridotite bodies within the lower crust gabbroic sequences from the Alpine Jurassic ophiolites (Sanfilippo and Tribuzio, 2011; 2013) and Atlantis Massif (Tamura et al., 2008; Godard et al., 2009) are interpreted to represent mantle remnants dissected by multiple gabbroic intrusions. A similar process may also account for the occurrence of the olivine-rich troctolite bodies within the gabbroic sequences, if we assume that the olivine-rich troctolites formed at the mantle-crust transition. Portions of the mantle-crust transition may be dismembered by the gabbroic intrusions and incorporated within the growing lower crust.

The olivine-rich troctolite chemical variations: the role of the reacting melts

The olivine from the Atlantis Massif olivine-rich troctolites are commonly distinct in the relatively low proportion of forsterite component (Fig. 2b). In addition, the coexisting plagioclases have anorthite component ranging from ~ 80 to ~ 65 mol%, with the lowermost values matching those of associated evolved gabbros to gabbronorites. Models for formation of the olivine-rich troctolites showed that both the forsterite proportion and the NiO contents of olivine are controlled by the fraction of dissolved olivine and by the MgO content of the melt (Suhr et al., 2008). In particular, the compositions of the Atlantis Massif olivines were reproduced by interaction of a primitive olivine-rich matrix with moderately evolved melts (Mg# = 65-50; Sanfilippo et al., 2013). The Atlantis Massif olivine-rich troctolites retain evidence for interaction with moderately evolved melts similar to those crystallizing the associated gabbros to gabbronorites. The olivine-rich matrix may have repeatedly experienced interactions with migrating melts, from its formation at the mantle-crust transition to its entrapment within the gabbroic sequences.

The plagioclases from the olivine-rich troctolites of the Alpine Jurassic ophiolites (Borghini et al., 2007; Borghini and Rampone, 2007; Sanfilippo and Tribuzio, 2013) are relatively poor in anorthite component (71-61 mol%). In addition, the clinopyroxene oikocrysts from these rocks commonly contain relatively high amounts of Na_2O (0.7-0.5 wt%, see also Renna and Tribuzio, 2011). Notably, the plagioclases from the gabbroic rocks associated with the olivine-rich troctolites from the Alpine Jurassic ophiolites are also relatively poor in anorthite component (see also Tiepolo et al., 1997; Rampone et al., 1998; Sanfilippo and Tribuzio, 2011). In particular, the co-variations between forsterite proportion of olivine versus anorthite proportion of coexisting plagioclase delineate low-anorthite crystal-line of descents that are sub-parallel to those produced by the olivine-plagioclase pairs from slow spreading ridge gabbroic sequences (Fig. 2a).

The low-anorthite trends of the gabbroic sequences from the Alpine Jurassic ophiolites may reflect moderate pressure conditions of crystallization (0.5-0.3 GPa, Borghini et al., 2007), similar to what was inferred for Mid Cayman Rise gabbros (Elthon et al., 1992; Ross and Elthon, 1997). Another hypothesis implies that the primitive melts forming these gabbroic sequences were slightly enriched in Na_2O with respect to the basalts normally produced at slow spreading ridges (Sanfilippo and Tribuzio, 2011; 2013). This Na_2O enrichment may be related to a low degree of melting of asthenospheric sources, in agreement with experimental investigations (Kinzler and Grove, 1993) and geochemical studies of MORB (Klein and Langmuir, 1987). This interpretation is consistent with the whole-rock compositions of the basalts from the Alpine Jurassic ophiolites, which are slightly LREE- and Zr-enriched with respect to typical N-MORB (e.g., Rampone et al., 1998; Desmurs et al., 2002; Montanini et al., 2008). This incompatible element signature is also locally reported for basalts erupted along asymmetrical segments of Mid Atlantic Ridge and attributed to low degree melting of asthenospheric sources (Kempton and Casey, 1997; Escartin et al., 2008). Some of the Alpine Jurassic ophiolites could thus represent remnants of slow spreading centres characterized by a low magma supply and an elevated lithospheric thickness (see also Sanfilippo and Tribuzio, 2011).

CONCLUSIONS

Olivine-rich troctolites occur within the mantle and lower crust sections from the Alpine Jurassic ophiolites and slow spreading ridges. These rocks are interpreted to form by interaction between an olivine-rich matrix and migrating melts crystallizing plagioclase and clinopyroxene. The primitive melts involved in the formation of the olivine-rich troctolites from the Alpine Jurassic ophiolites were most likely slightly enriched in Na_2O with respect to the basalts normally produced at slow spreading ridges. We attribute this enrichment to a low degree of melting of asthenospheric sources.

The olivine-rich matrix precursor of the olivine-rich troctolites may have formed by melt-peridotite reactions at the mantle-crust transition. The occurrence of olivine-rich troctolite bodies within the gabbroic sequences is reconciled with a process by which the mantle-crust transition is dissected by gabbroic intrusions eventually leading to entrapment within the growing lower crust. This process was associated with interactions between the olivine-rich matrix and the melts forming the gabbros.

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