

Origin and emplacement of ultramafic–mafic intrusions in the Erro-Tobbio mantle peridotite (Ligurian Alps, Italy)

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Abstract

The Erro-Tobbio peridotites (Voltri Massif, Ligurian Alps) represent subcontinental lithospheric mantle tectonically exhumed during Permo–Mesozoic extension of the Europe–Adria lithosphere. Previous studies have shown that exhumation started during Permian times, and occurred along kilometer-scale lithospheric shear zones which enhanced progressive deformation and recrystallization from spinel- to plagioclase-facies conditions. Ongoing field and petrologic investigations have revealed that the peridotites experienced, during uplift, a composite history of diffuse melt migration and multiple episodes of ultramafic–mafic intrusions. In this paper we present the results of field, structural and petrologic–geochemical investigations into a sector of the Erro-Tobbio peridotite unit that preserves well this multiple intrusion history. Melt impregnation in the peridotites is evidenced by significant plagioclase enrichment and crystallization of unstrained orthopyroxene replacing kinked mantle olivine and clinopyroxene; impregnating melts were thus opx-saturated. Melt–rock interaction caused chemical changes in mantle minerals (e.g. Al decrease and REE increase in cpx; Ti and Cr# enrichment in spinel). Nevertheless, clinopyroxenes still exhibit LREE depletion ($Ce_N/Sm_N=0.006–0.011$), indicating a depleted signature for the percolating melts. Melt impregnation was thus related to diffuse porous flow migration of depleted MORB-type melt fractions that modified their compositions towards opx saturation by mantle–melt interaction during ascent. The impregnated peridotites are intruded by a hectometer-scale stratified cumulate body, mostly consisting of troctolites and plagioclase wehrlites, showing gradational, interfingering contacts with the host mantle rocks. Subsequent intrusion events are revealed by the occurrence of olivine gabbros as decameter-wide lenses, variably thick (centimeter- to meter-scale) dykes and thin dykelets, which crosscut both the peridotite foliation and the magmatic layering in the cumulates. Overall, major and trace element compositions of minerals in the intrusives indicate that they represent variably differentiated cumulus products crystallized from rather primitive N-MORB-type aggregated melts. Slightly more evolved compositions are shown by olivine gabbros, relative to the troctolites and plagioclase wehrlites of the cumulate body. Mineral chemistry features (e.g. the Fo–An correlation and high Na, Ti, Mg# in cpx) indicate that the studied intrusive rocks crystallized at moderate pressure conditions (3–5 kbar, i.e. 9–15 km depth). Our study thus points to a progressive transition from porous flow melt migration to emplacement of magmas in fractures, presumably related to progressive change of lithospheric mantle rheology during extension-related uplift and cooling.

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Keywords: Gabbroic rocks; Olivine cumulates; MORB-type intrusion; Mantle peridotite; Melt impregnation

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1. Introduction

Recent petrologic and isotope studies on the Ligurian ophiolites (Northern Apennines and Ligurian Alps), which are lithosphere remnants of the Jurassic Ligurian Tethys ocean, have indicated that they do not represent mature oceanic lithosphere formed at a mid-ocean ridge setting because they consist of a peculiar gabbro–peridotite association, in which older (Proterozoic and Permian) subcontinental lithospheric mantle was intruded by younger (Jurassic) MORB-type magmas (Piccardo et al., 1994; Rampone et al., 1995, 1998; Rampone and Piccardo, 2000; Rampone et al., 2005). Thus, it has been inferred that the Ligurian ophiolites represent the structure and composition of oceanic lithosphere that floors embryonic oceans developed through passive continental rifting and slow-spreading oceanization (Rampone and Piccardo, 2000; Tribuzio et al., 2000a,b; Piccardo et al., 2002). This interpretation has been further supported by petrologic and radiometric studies on the Northern Apennine and Tuscan ophiolitic gabbroic rocks, which mostly occur as discrete intrusions within mantle peridotites. These studies have provided evidence that the gabbroic rocks were intruded under low- to moderate-pressure conditions (2–5 kbar), similar to some gabbroic suites from modern slow-spreading ridges. Moreover, the ages of magmatic crystallization of some gabbroic rocks (EL and Tuscany; Tribuzio et al., 2004) are older than the oldest pelagic sediments (radiolarites) of the Ligurian Tethys ocean (Bill et al., 2001).

In spite of a rather large number of petrologic and isotope studies devoted to both mantle peridotites and gabbroic rocks from the Northern Apennine ophiolites (Rampone et al., 1993, 1995, 1997, 1998; Tribuzio et al., 2000a,b, 2004) and to mantle peridotites from the Erro-Tobbio (ET) (Voltri Massif, Ligurian Alps) ophiolitic unit (Piccardo et al., 1992; Hoogerduijn Strating et al., 1990, 1993; Rampone et al., 2004, 2005), very few studies have yet been made on the mafic rocks associated with the Erro-Tobbio peridotites. Available studies mostly refer to late gabbroic and basaltic dykes which crosscut all mantle structures and show MORB-type affinity (Piccardo et al., 2001). Ongoing field and petrologic investigations (Borghini et al., 2004; De Ferrari et al., 2004; Piccardo et al., 2004a) have revealed that during uplift the ET peridotites experienced a composite history of diffuse melt migration and multiple episodes of gabbroic injections forming discrete intrusive bodies and decameter-scale dykes. In this paper we present an insight into a sector of the ET peridotite unit that well preserves this multiple intrusion history, by results of field, structural and petrologic–geochemical investigations. Our major aim is to provide

structural and petrologic constraints on the impregnation–intrusion steps of the exhumation-related evolution of the ET mantle. Samples studied are plagioclase-bearing wehrlites, clinopyroxene-bearing troctolites and olivine gabbros, representative of the intrusion events. A few mantle peridotite samples, constituting the country rocks, have been also included in this study, in order to define the relationships, if any, between the diffuse melt impregnation and discrete melt intrusion events. Specific aims of this study are (i) to define the magmatic affinity of parental melts, and (ii) to provide an estimate of the conditions of intrusion of the gabbroic rocks.

2. Petrologic and structural background on the Erro-Tobbio mantle

Peridotites from the ET unit (Voltri Massif, Ligurian Alps) (Fig. 1) have long been thought to be the Alpine equivalents to the Northern Apennine ophiolites, except that they were involved in the Alpine orogeny (Bezzi and Piccardo, 1971; Scambelluri et al., 1991; Piccardo et al., 1992). In spite of the Alpine overprint, the ET unit preserves kilometer-scale volumes of unaltered peridotites that retain mantle textures and mineral assemblages, thus allowing the study of their pre-Alpine mantle evolution (Bezzi and Piccardo, 1971; Ernst and Piccardo, 1979; Ottonello et al., 1979; Piccardo et al., 1990; Hoogerduijn Strating et al., 1990; Vissers et al., 1991; Piccardo et al., 1992; Hoogerduijn Strating et al., 1993; Capponi et al., 1999; Borsi et al., 1996; Piccardo et al., 2004a; Rampone et al., 2004, 2005).

The ET mantle peridotites consist mostly of partly serpentinized clinopyroxene-poor lherzolites and harzburgites, which commonly display spinel-bearing assemblages. Petrologic and structural investigations have documented that they record a composite tectono-metamorphic subsolidus decompressional evolution, testified by progressive reequilibration from spinel- to plagioclase- to amphibole-facies conditions, and deformation from granular to tectonite to mylonite fabrics, developed along kilometer-scale shear zones interpreted as fragments of an extensional detachment system (Hoogerduijn Strating et al., 1990; Vissers et al., 1991; Hoogerduijn Strating et al., 1993; Rampone et al., 2005). On this basis, it has been inferred (Hoogerduijn Strating et al., 1993) that the ET peridotites represent subcontinental lithospheric mantle which was tectonically denuded during rifting and opening of the Jurassic Ligurian Tethys ocean, similar to the Northern Apennine (External Ligurides) ophiolitic peridotites. However, Sm/Nd radiometric dating on plagioclase peridotites, representative of the plagioclase-bearing mylonitic extensional shear zone, have yielded ages of 273 ± 16 Ma and

313±16 Ma, for the plagioclase-facies recrystallization stage, thus suggesting that the onset of exhumation of the ET mantle occurred at a much earlier time than the inferred Triassic–Jurassic age of rifting and opening of the Ligurian Tethys ocean (Rampone et al., 2005). Geochemical investigations have revealed that the ET mantle protoliths record a composite history of partial melting and melt migration by reactive porous flow, which presumably preceded exhumation (Rampone et al., 2004, 2005).

Ongoing field and petrologic investigations on the ET peridotites (Hoogerduijn Strating et al., 1993; Piccardo et al., 2004a; Borghini et al., 2004; De Ferrari et al., 2004; and this study) have revealed evidence of diffuse melt percolation/impregnation and multiple episodes of gabbroic intrusions. Melt impregnation is evidenced by the occurrence of plagioclase-rich peridotites, cut by a network of dunite channels and gabbro-noritic dykelets which, in turn, crosscut

the tectonite and mylonite spinel peridotite foliation; this suggests that melt impregnation and dunite formation postdates the spinel-facies lithospheric deformation (Piccardo et al., 2004a). In the studied area, plagioclase-rich peridotites are intruded by hectometer-scale body of ultramafic–mafic rocks. Mantle peridotites and the ultramafic–mafic body are then intruded by olivine–gabbro dykes and lens-shaped bodies, thus indicating a composite history of diffuse melt impregnation and multiple episodes of discrete gabbroic intrusions.

3. Field occurrence

The area investigated in this paper is situated in the southern sector of the ET unit (Fig. 1) and exposes an about 0.5 km wide body of mantle peridotites and ultramafic–mafic associated intrusions, mostly recording

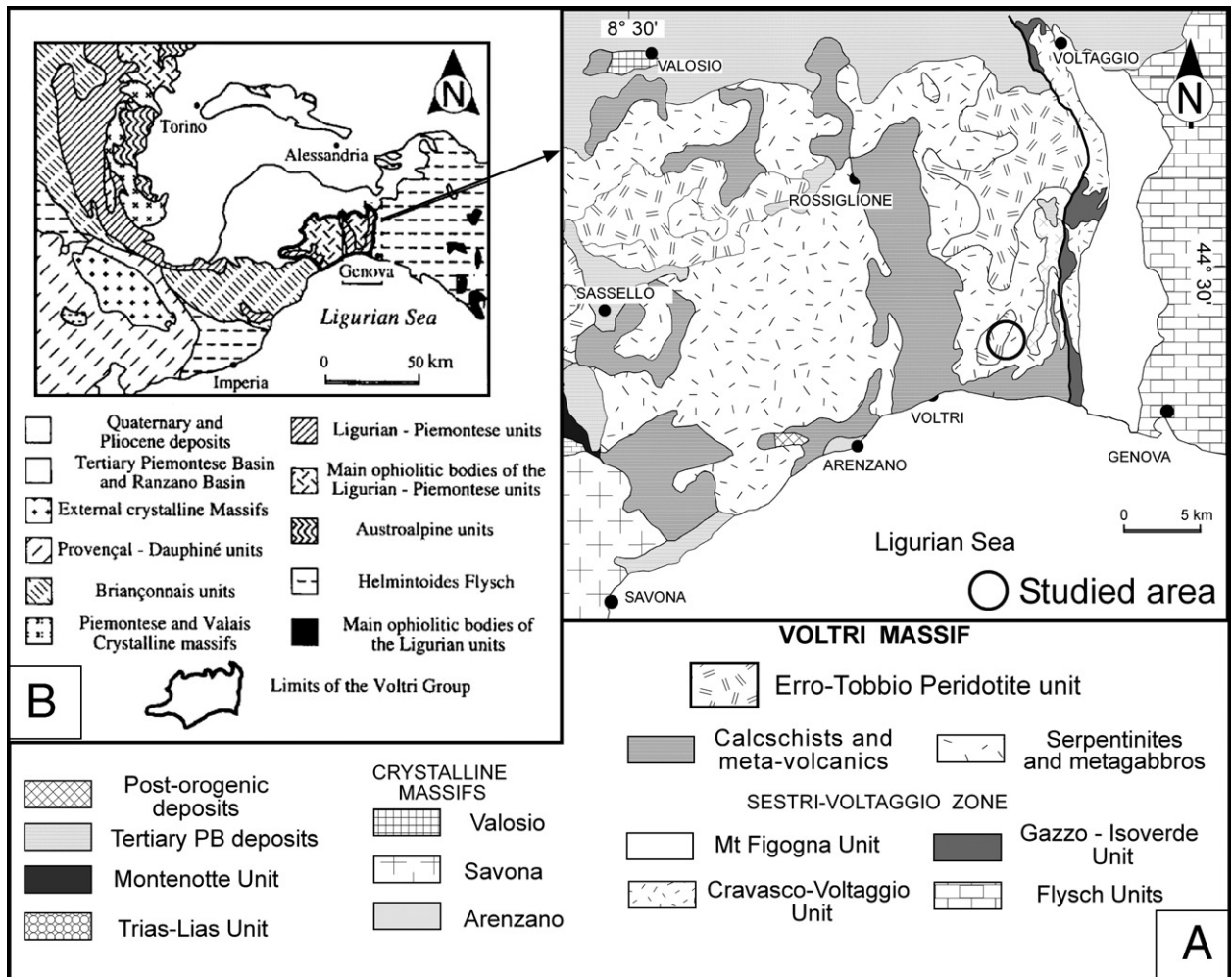


Fig. 1. (A) Sketch map of the Voltri Massif, showing the Erro-Tobbio peridotite and surrounding units (redrawn after Federico et al., 2004). Open circle is the studied area. Inset (B) shows the location of the Ligurian ophiolites in the framework of the Northern Apennines and Western Alps.

a pre-Alpine mantle history (Fig. 2). Preserved mantle peridotites are bounded by serpentinites, with minor metarodngites, strongly overprinted by Alpine metamorphism and deformations. Mantle peridotites are strongly

serpentinized and show a low-strain tectonite foliation defined by pyroxene shape-preferred orientation (Fig. 3A). They display a significant enrichment in plagioclase, this latter mostly occurring as interstitial

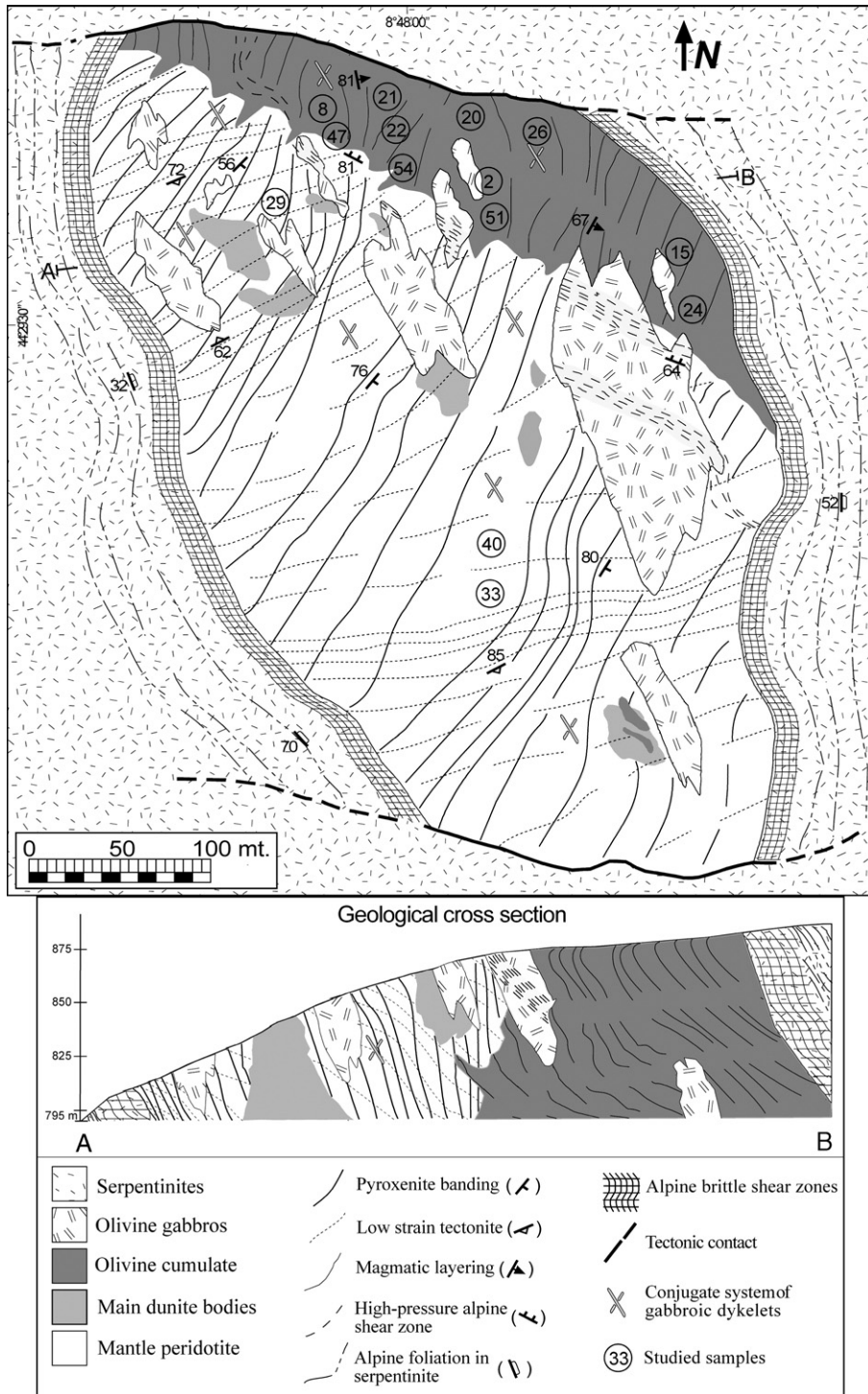


Fig. 2. Structural map of the studied area.

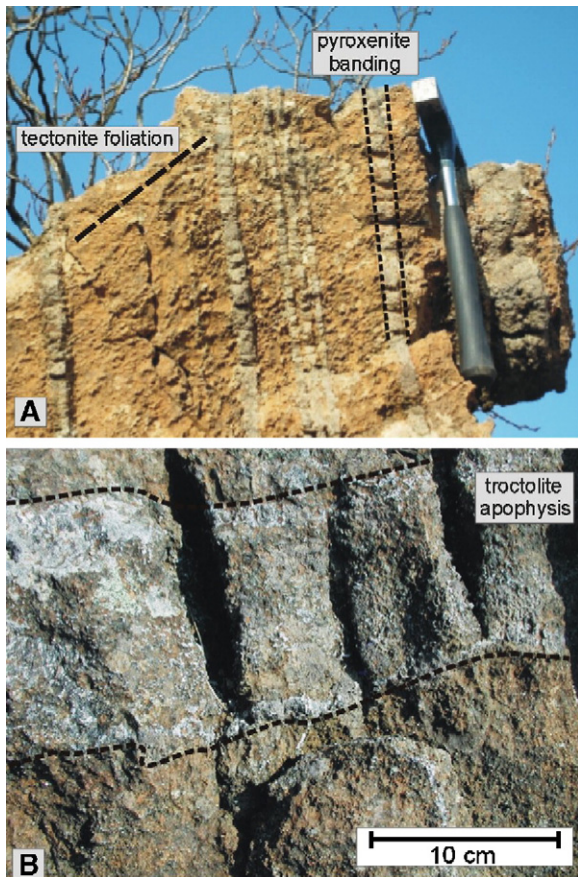


Fig. 3. (A) Pyroxenite banding crosscut by low-strain mantle tectonite foliation; (B) cumulate body apophysis (troctolite MF51) within the host mantle peridotites.

blebs and veins between mantle minerals. Diffuse pyroxenite bands and meter-scale dunite bodies occur within the peridotites. Pyroxenites occur in a sub-parallel centimeter-scale banding which is crosscut at medium-high angle by the tectonite mantle foliation (Fig. 3A).

In the northern part of the studied area, the plagioclase-rich peridotites are intruded by hectometer-scale olivine cumulate body, showing variable modal composition, ranging from dunites with interstitial plagioclase and clinopyroxene, to clinopyroxene-bearing troctolites to plagioclase-bearing wehrlites. In places, this compositional variability defines a magmatic layering. In the outcrop, olivine frequently displays skeletal texture. The contact between the cumulate body and the host mantle peridotites is irregular and defined by decameter-scale plagioclase wehrlite–troctolite apophyses crosscutting the pyroxenite banding and tectonite mantle foliation at low angle (Fig. 3B.). At the map scale, the contact strikes NW–SE and dips towards the west. To the east, the body is in contact with serpentinites along brittle Alpine shear zones.

Gabbroic intrusions occur within both peridotites and olivine cumulates. They mostly consist of nearly isotropic medium- to coarse-grained (pegmatitic) olivine gabbros. They show a well-preserved magmatic granular texture and mineralogy which is, in places, overprinted by a high-pressure metamorphic recrystallization. This recrystallization occurs in coronitic textures or in heterogeneously developed high-strain mylonitic shear zones. Alpine structures and metamorphic overprint of olivine gabbros from the ET unit have been previously described (Capponi and Crespini, 1990; Messiga et al., 1995).

Olivine gabbros occur as decameter lens-shaped bodies, dykes of variable thickness (decimeter- to meter-scale) and thin (centimeter-scale) dykelets, which show clear crosscutting relationships with respect to both tectonite foliation in the peridotites and magmatic layering in the cumulates. Gabbroic dykes and dykelets display rather sharp contacts with the host peridotites and olivine cumulate, and often exhibit a grain-size variability, with finer grain size toward the margins. Lenses of gabbros are elongated in a NNW–SSE direction, steeply dipping towards the E, and are arranged in “en echelon” geometry (Fig. 2). Dykes mainly strike NNW–SSE, as well. Dykelets often occur in conjugate pairs; they show a prevailing NNW–SSE strike (with minor N–S orientation) and dip 40° – 50° , mainly to the east and subordinately to the west (Fig. 2).

4. Sample description

4.1. Mantle peridotites

The studied peridotites (samples MF33 and MF40) consist of partly serpentinized cpx-poor lherzolites ($<10\%$ modal clinopyroxene) showing a complete equilibration in the spinel-facies stability field. They have porphyroclastic texture and exhibit a low-strain tectonite deformation, mostly defined by undulatory extinction of tabular-shaped olivine and pyroxenes.

The peridotites are characterized by the diffuse occurrence of plagioclase, in variable modal amounts (up to 10% by vol.), which is almost completely replaced by low-grade alteration products. Plagioclase occurs in peculiar microstructures clearly indicating impregnation and interaction of the peridotite matrix with percolating melt: (i) plagioclase blebs and veins between tectonite mantle olivine, (ii) unstrained orthopyroxene and plagioclase intergrowths which partially replace deformed and exsolved mantle clinopyroxene (Fig. 4A). Melt impregnation is also indicated by the presence of large undeformed “poikilitic” orthopyroxene grains, which display irregular, lobate contacts towards tectonite mantle

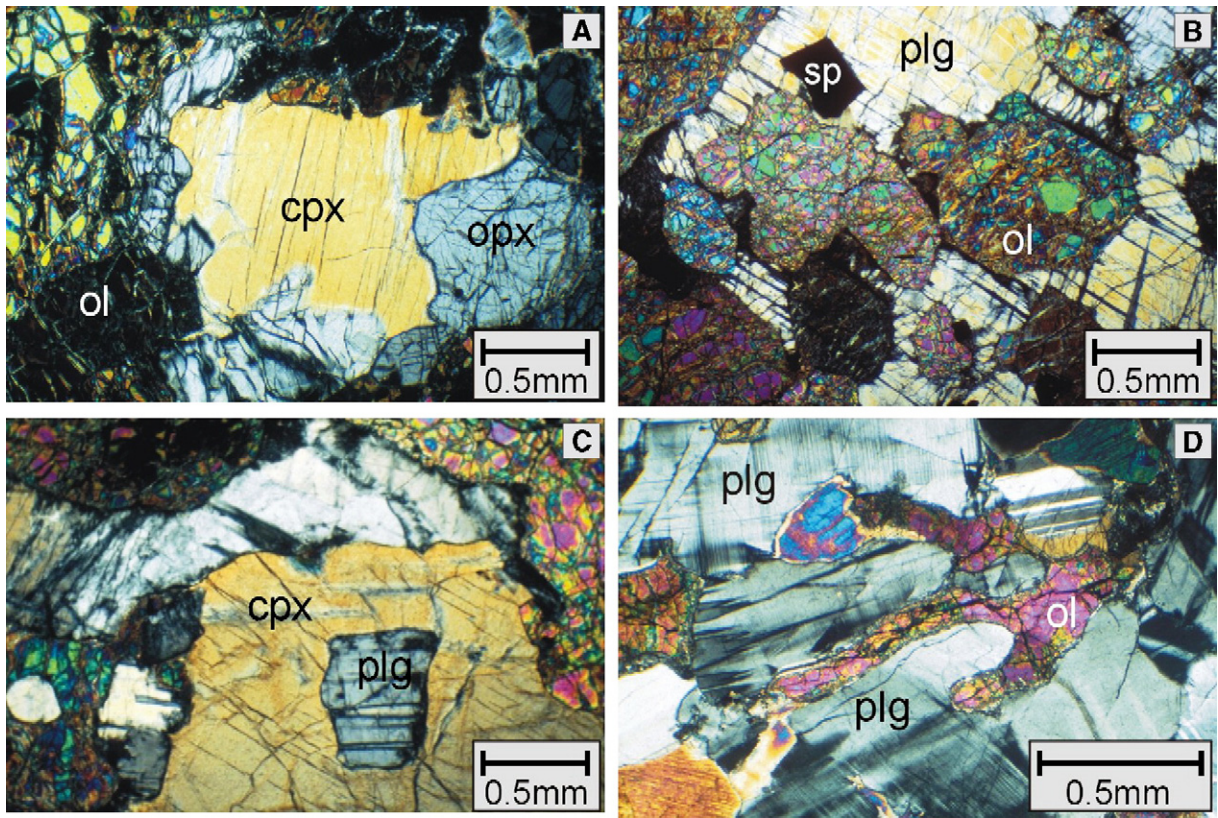


Fig. 4. Mantle peridotite. (A) Orthopyroxene rim replacing clinopyroxene porphyroclast. Troctolite. (B) Euhedral olivine and chromite crystals associated with interstitial plagioclase. Plagioclase wehrlite. (C) Subhedral clinopyroxene grain including euhedral plagioclase. Group B olivine gabbro. (D) Anhedral olivine crystals associated with plagioclase.

olivine; the poikilitic orthopyroxene often constitutes a single crystal in continuity with the orthopyroxene rim crystallized around mantle clinopyroxene. Such textural features indicate that the impregnating melts crystallized both plagioclase and orthopyroxene, the latter partly replacing mantle olivine and clinopyroxene.

4.2. Olivine cumulates

The cumulate body exhibits variable modal composition (from plagioclase–clinopyroxene-bearing dunite to clinopyroxene-bearing troctolite, to plagioclase-bearing wehrlite) and is mostly constituted by troctolites. Samples MF8, MF15 and MF21 have been collected from the inner part of the ultramafic body, whereas sample MF51 represents an apophysis at the contact with the host mantle peridotites (see Fig. 3B). Troctolites are characterized by hypidiomorphic texture and medium- to coarse-grain size. They consist of euhedral cumulus olivine, interstitial plagioclase and subordinate poikilitic clinopyroxene (Fig. 4B). Small euhedral chromite crystals are commonly found within

plagioclase and orthopyroxene occurs as discontinuous rims around olivine. Clinopyroxene also occurs as thin interstitial “vermicular” crystals between olivine and plagioclase. A similar texture has been observed in gabbroic rocks from oceanic (Hekinian et al., 1993; Ross and Elthon, 1997) and ophiolitic (Tribuzio et al., 1995) settings, and has been interpreted as resulting from post-cumulus crystallization of intercumulus melt. Rare pargasitic-amphibole rims are also observed, mostly confined around chromite grains. In the troctolites all minerals are unstrained, whereas in sample MF51 olivine occurs both in euhedral undeformed crystals and in large grains showing kinkbands. Based on textural features, we can reconstruct the following crystallization order: (i) olivine+chromite, (ii) plagioclase+clinopyroxene, (iii) clinopyroxene (vermicular grains) and pargasitic amphibole.

The plagioclase wehrlites (samples MF47 and MF54) have been collected from apophyses within the host mantle peridotites. They are coarse-grained rocks showing hypidiomorphic texture, and consist of olivine, clinopyroxene, plagioclase and rare Cr-spinel. Olivine is

partially serpentinized and is present both as small rounded crystals and as larger grains often showing undulatory extinction and spaced kinkbands. Clinopyroxene occurs either in subidiomorphic coarse crystals (Fig. 4C) or in interstitial and poikilitic grains. Thin interstitial “vermicular” clinopyroxenes between olivine and plagioclase are also observed. Plagioclase mostly occurs in anhedral interstitial grains, but small subhedral plagioclase crystals are also found within poikilitic clinopyroxene (Fig. 4C). Cr-spinel consists of small subhedral crystals mostly confined between olivine grains. The crystallization order in the plagioclase wehrlites is therefore similar to that recognized in the troctolites: (1) olivine+Cr-spinel, (2) plagioclase+clinopyroxene, (3) clinopyroxene (vermicular grains).

4.3. Olivine gabbros

The gabbroic lenses (MF2, MF22, MF24), dykes (MF20, MF29) and dykelets (MF26) display hypidiomorphic texture and mostly consist of nearly isotropic coarse- to medium-grained olivine-bearing gabbros. In most gabbroic rocks (samples MF2, MF22 and MF26, group A) olivine (modal amount 10–15% by vol.) occurs both in euhedral grains included in clinopyroxene and/or plagioclase, and in anhedral crystals in plagioclase+clinopyroxene+olivine aggregates indicative of eutectic crystallization. Plagioclase is the most abundant mineral phase (up to 60–65% by vol.) and occurs in euhedral to subhedral crystals. Clinopyroxene (20–25% by vol.) mostly crystallizes in large anhedral grains including euhedral plagioclase. In a few gabbro samples (MF20, MF24 and MF29, group B), olivine is present in lower modal amounts (8–10% by vol.) and mostly crystallizes as anhedral crystals associated with plagioclase (Fig. 4D). In these samples, clinopyroxene occurs in poikilitic crystals which include both olivine and plagioclase. In all the studied gabbros, olivine often displays discontinuous reaction rims made by orthopyroxene, and Ti-rich pargasitic amphibole frequently occurs as a thin rim between clinopyroxene and plagioclase, or partially replacing clinopyroxene. Textural features in the gabbroic lenses, dykes and dykelets indicate a similar crystallization sequence, i.e. olivine–plagioclase–clinopyroxene.

5. Analytical methods

Major element chemistry data of minerals in the selected samples were obtained both: (i) at the Dipartimento di Scienze della Terra, University of Genova, by means of a Philips SEM 515 electron

microscope equipped with an X-ray dispersive analyzer (EDS) (accelerating potential 15 kV; sample current 20 nA), and (ii) at the C.N.R. — Centro di studio per la Minerogenesi e la Geochimica applicata of Firenze by means of a JEOL JXA-8600 electron microscope, equipped with four wavelength dispersive spectrometers (WDS) and one energy dispersive spectrometer (EDS) (accelerating potential 15 kV; sample current 10 nA) (Vaggelli et al., 1999).

In situ trace element mineral analyses were obtained by LAM-ICP-MS techniques at IGG-CNR (Istituto di Geoscienze e Georisorse) in Pavia. A detailed description of this analytical procedure is reported in Tiepolo et al. (1997). Mineral REE abundances have been normalized to the average C1 chondrite composition (Anders and Ebihara, 1982).

Whole rock trace element data were determined on a quadrupole VG-PG2 Inductively Coupled Plasma-Mass Spectrometer (ICP-MS) at ISTEEM (Université de Montpellier 2, France) following the procedure described by Ionov et al. (1992). REE, Sr, Zr, Hf, Rb and Ba concentrations were determined by external calibration. Detailed description of the method and detection limits can be found in Godard et al. (2000).

6. Major element mineral chemistry

Major element representative compositions of minerals from the studied peridotites, olivine cumulates and olivine-gabbros are reported in Tables 1–5.

6.1. Mantle peridotites

In all samples, olivine shows uniform compositions and rather low forsterite contents (Fo_{88} – Fo_{89}) and spinels exhibit rather high Cr values [$Cr/(Cr+Al)=0.46$ – 0.49] coupled with high TiO_2 contents ($TiO_2=0.76$ – 0.94) (Fig. 5A). Such Ti contents are much higher (at similar Cr values) compared to the compositions of spinels in the ET plagioclase-reequilibrated peridotites from Rampone et al. (2005), in which plagioclase undergoes a subsolidus reaction product (Fig. 5A). Plagioclase is completely replaced by low-grade alteration products. Orthopyroxene compositions are quite homogeneous in spite of different microstructural sites (mantle porphyroclasts vs. magmatic poikilitic crystals), with Mg values [$Mg/(Mg+Fe^{2+})$] mostly in the range 0.89–0.90. Clinopyroxenes do not display significant compositional variations from cores to rims; they are characterized by rather high Ti ($TiO_2=0.42$ – 0.52 wt.%) and low Al ($Al_2O_3=2.88$ – 4.52 wt.%) concentrations (Fig. 5B) and Mg values in the range 0.89–0.90 (see Table 1). In Fig. 5B, the compositions of clinopyroxene cores in the studied peridotites are

Table 1
Representative major element mineral compositions of peridotites

Sample	MF33						MF40			
	cpx		cpx		opx		opx		ol	
	p.c.	p.r.	p.c.	p.r.	p.c.	p.r.	p.c.	p.r.	p.c.	p.r.
SiO ₂	51.29	52.12	55.68	55.76	40.60	40.60	51.94	55.49	41.35	41.35
TiO ₂	0.47	0.45	0.30	0.28	0.01	0.01	0.52	0.24	0.05	0.05
Cr ₂ O ₃	1.31	1.40	0.80	0.73	0.03	0.03	1.14	0.73	0.00	0.00
Al ₂ O ₃	4.11	2.88	2.75	2.31	0.03	0.03	4.52	2.68	0.00	0.00
Fe ₂ O ₃	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FeO	3.42	2.94	6.96	7.09	10.43	10.43	3.42	6.45	10.05	10.05
MnO	0.13	0.12	0.18	0.15	0.15	0.15	0.12	0.16	0.12	0.12
MgO	17.04	16.92	32.40	32.55	48.38	48.38	17.08	32.54	48.92	48.92
CaO	21.22	23.24	1.49	1.30	0.04	0.04	20.44	1.46	0.05	0.05
Na ₂ O	0.37	0.31	0.00	0.00	0.00	0.00	0.37	0.10	0.00	0.00
Total	99.36	100.38	100.56	100.17	99.67	100.51	99.55	99.85	100.54	99.60
Mg#	0.90	0.91	0.89	0.89	0.89	0.48	0.90	0.90	0.89	0.53

p.c.=porphyroclast core; p.r.=porphyroclast rim; rim=magmatic orthopyroxene rim around mantle clinopyroxene; poikil.=poikilitic crystal.

compared with those of clinopyroxene porphyroclast cores in spinel and plagioclase-bearing peridotites, representative of the exhumation-related decompressional evolution of the ET mantle (Hoogerduijn Strating et al., 1993; Rampone et al., 2005). Clinopyroxene cores in the studied peridotites display systematically lower Al contents, compared to previously published data (Rampone et al., 2005).

6.2. Olivine cumulates

In the troctolites, olivine compositions are quite homogeneous, mostly ranging Fo₈₈–Fo₈₉. No compositional differences are observed in sample MF51 between

euhedral and kinked olivines. Spinels display rather uniform Cr and Al concentrations (Cr# = 0.51–0.60), whereas the Ti contents are variable (TiO₂ = 0.80–2.46 wt.%).

Plagioclase is characterized by variable anorthite contents in the An₅₉–An₆₉ range, without core to rim systematic variation. According to the Leake (1997) classification, amphibole rims around spinels are pargasites and pargasitic hornblendes: they display high Mg values (Mg# = 0.86–0.89) and high Na and Ti content (Na₂O = 2.00–3.12 wt.%; TiO₂ = 3.11–4.06 wt. %). Clinopyroxenes exhibit high Mg values (Mg# = 0.89–0.91), coupled with high Al₂O₃, Cr₂O₃, TiO₂ and

Table 2
Representative major element mineral compositions of troctolites

Sample	MF8					MF15				MF21				MF51			
	cpx	plag	ol	sp	sp	cpx	plag	ol	sp	cpx	cpx	plag	ol	cpx	plag	ol	ol
	core	core	euhed.	core	core	core	core	euhed.	core	core	verm.	core	euhed.	verm.	core	euhed.	kinked
SiO ₂	51.60	51.66	40.79	0.00	0.00	52.51	52.01	40.74	0.00	51.35	51.44	51.98	40.47	51.08	51.93	40.98	40.77
TiO ₂	0.59	0.02	0.00	1.95	1.46	0.60	0.07	0.00	1.06	0.50	1.29	0.04	0.00	1.38	0.08	0.00	0.00
Cr ₂ O ₃	1.48	0.02	0.03	39.43	40.40	1.29	0.00	0.03	39.53	1.49	1.24	0.00	0.02	0.82	0.00	0.00	0.00
Al ₂ O ₃	3.28	30.96	0.00	20.69	21.01	3.28	30.75	0.00	22.56	3.47	3.57	29.41	0.00	3.78	31.20	0.00	0.00
Fe ₂ O ₃	0.00	0.00	0.00	7.20	7.24	0.00	0.00	0.00	6.27	0.00	0.00	0.20	0.00	0.00	0.00	0.00	0.00
FeO	3.25	0.14	10.79	19.73	19.79	3.43	0.18	10.66	19.65	3.20	3.20	0.00	10.61	3.84	0.11	10.61	10.76
MnO	0.12	0.00	0.20	0.04	0.01	0.13	0.00	0.17	0.12	0.14	0.17	0.04	0.17	0.08	0.00	0.15	0.16
MgO	16.19	0.03	47.90	10.94	11.03	17.32	0.04	48.32	10.67	16.25	16.02	0.03	49.00	16.08	0.03	48.09	47.83
CaO	22.27	13.36	0.02	0.12	0.01	20.45	12.79	0.06	0.20	22.68	22.15	12.70	0.07	22.22	12.97	0.03	0.03
Na ₂ O	0.44	3.84	0.00	0.00	0.00	0.51	4.01	0.00	0.00	0.62	0.66	4.56	0.00	0.54	4.36	0.00	0.00
Total	99.22	100.03	99.73	100.10	100.95	99.53	99.85	99.98	100.06	99.70	99.74	98.96	100.34	99.82	100.68	99.86	99.55
An	—	0.66	—	—	—	—	0.64	—	—	—	—	0.61	—	—	0.62	—	—
Mg#	0.90	—	0.88	0.47	0.48	0.90	—	0.88	0.47	0.90	0.90	—	0.89	0.88	—	0.89	0.89

core=core of rather large crystal; verm.=vermicular, interstitial clinopyroxene; euhed.=euhedral undeformed olivine; kinked=deformed olivine with kinkbands.

Table 3

Representative major element mineral compositions of plagioclase wehrlites

Sample	MF47				MF54			
	cpx	plag	ol	ol	cpx	plag	ol	ol
	core	core	euhed.	kinked	core	core	euhed.	kinked
SiO ₂	52.04	52.13	40.51	40.50	52.40	52.65	40.82	40.52
TiO ₂	0.48	0.03	0.00	0.00	0.35	0.07	0.00	0.00
Cr ₂ O ₃	1.03	0.00	0.00	0.00	1.25	0.02	0.00	0.00
Al ₂ O ₃	3.58	30.22	0.00	0.00	3.76	30.29	0.00	0.00
FeO	3.55	0.15	11.30	11.14	3.36	0.16	12.00	11.91
MnO	0.08	0.00	0.13	0.13	0.19	0.07	0.16	0.16
MgO	16.53	0.07	47.64	47.82	16.43	0.08	46.77	46.76
CaO	22.05	12.46	0.03	0.00	21.90	12.68	0.04	0.03
Na ₂ O	0.52	4.15	0.00	0.00	0.55	4.37	0.00	0.00
Total	99.85	99.21	99.61	99.59	100.19	100.39	99.79	99.38
An	–	0.62	–	–	–	0.62	–	–
Mg#	0.89	–	0.88	0.88	0.90	–	0.87	0.87

core = core of rather large crystal; euhed. = euheidal undeformed olivine; kinked = deformed olivine with kinkbands.

Na₂O concentrations, consistent with the compositions of clinopyroxenes in the most primitive cumulate from oceanic and ophiolitic (e.g. Northern Apennine) settings (Fig. 6). Clinopyroxenes also show remarkable compositional variations, systematically correlated with their microstructural occurrence, i.e. TiO₂ increase and Cr₂O₃ decrease from cores to rims of poikilitic crystals, to thin interstitial vermicular grains (Fig. 6). These compositional changes are most likely related to post-cumulus crystallization of interstitial trapped melt.

Mineral compositions in the plagioclase wehrlites are similar to those described in the troctolites. Olivine displays high forsterite contents (Fo₈₇–Fo₈₈) in both idiomorphic and kinked grains. Plagioclases are moderately anorthitic (An₆₀–An₆₂) and clinopyroxenes display high Mg values (Mg# = 0.88–0.90). As in the

troctolites, their Al₂O₃, Cr₂O₃, TiO₂ and Na₂O contents are similar to those of clinopyroxenes in the most primitive cumulates from oceanic and ophiolitic (e.g. Northern Apennine) settings (Fig. 6).

6.3. Olivine gabbros

In the olivine gabbros, clinopyroxene cores show a progressive decrease in the Mg value from group A to group B (group A: Mg# = 0.90–0.87, group B: Mg# = 0.87–0.84) coupled with Cr and Al content decrease and Ti content increase. Overall, they display high Na concentrations (group A: Na₂O = 0.44–0.57 wt.%, group B: Na₂O = 0.42–0.55 wt.%). As shown in Fig. 6, the compositional variations in clinopyroxenes from the olivine gabbros are consistent with chemical trends defined by

Table 4

Representative major element mineral compositions of olivine gabbros (group A)

Sample	MF2			MF22			MF26		
	cpx	plag	ol	cpx	plag	ol	cpx	plag	ol
	core	core	euhed.	core	core	euhed.	core	core	euhed.
SiO ₂	51.73	55.60	39.28	53.00	52.89	40.17	51.68	53.22	40.50
TiO ₂	0.41	0.19	0.00	0.35	0.03	0.15	0.50	0.04	0.10
Cr ₂ O ₃	0.98	0.12	0.00	0.79	0.00	0.18	1.41	0.00	0.04
Al ₂ O ₃	3.17	27.87	0.00	2.84	30.15	0.00	3.71	29.96	0.00
FeO	3.81	0.33	15.89	3.49	0.00	15.86	3.72	0.16	13.03
MnO	0.12	0.00	0.28	0.01	0.00	0.37	0.13	0.00	0.26
MgO	18.21	0.00	43.98	16.31	0.04	45.48	16.93	0.01	46.43
CaO	20.86	11.58	0.04	22.95	12.60	0.10	21.32	11.84	0.11
Na ₂ O	0.58	4.63	0.05	0.45	4.60	0.00	0.47	4.55	0.00
Total	99.87	100.32	99.52	100.20	100.31	102.31	99.87	99.78	100.47
An	–	0.56	–	–	0.60	–	–	0.59	–
Mg#	0.89	–	0.83	0.89	–	0.83	0.89	–	0.86

core = core of rather large crystal; euhed. = euheidal undeformed olivine.

Table 5
Representative major element mineral compositions of olivine gabbros (group B)

Sample	MF20			MF24			MF29		
	cpx	plag	ol	cpx	plag	ol	cpx	plag	ol
	core	core	anhed.	core	core	anhed.	core	core	anhed.
SiO ₂	52.58	54.48	39.66	54.14	54.07	39.15	53.20	54.85	38.90
TiO ₂	0.58	0.09	0.03	0.61	0.06	0.16	0.46	0.04	0.15
Cr ₂ O ₃	0.16	0.02	0.00	0.30	0.00	0.05	0.32	0.00	0.17
Al ₂ O ₃	2.56	29.15	0.00	2.78	29.32	0.00	2.65	28.83	0.00
FeO	4.75	0.25	15.93	4.65	0.00	17.17	4.70	0.24	16.67
MnO	0.15	0.00	0.26	0.18	0.00	0.24	0.11	0.00	0.26
MgO	16.65	0.03	43.96	15.89	0.02	42.59	16.12	0.01	44.11
CaO	22.01	10.99	0.02	21.48	11.39	0.15	21.74	10.56	0.12
Na ₂ O	0.47	5.22	0.00	0.41	5.09	0.00	0.44	5.24	0.00
Total	99.91	100.23	99.86	100.44	99.95	99.51	99.74	99.77	100.38
An	—	0.54	—	—	0.55	—	—	0.54	—
Mg#	0.86	—	0.83	0.86	—	0.81	0.86	—	0.82

core=core of rather large crystal; anhed.=anhedral olivine.

oceanic gabbroic rocks from slow spreading settings (Elthon et al., 1992) which are considered to represent cumulate products of progressive magmatic differentiation. Similar compositional variations are documented in clinopyroxenes from the most primitive olivine cumulates of Northern Apennine (Tiepolo et al., 1997; Rampone et al., 1998). Plagioclase displays a progressive decrease of the anorthite content from group A (An₆₀–An₅₃) to group B (An₅₆–An₅₁); consistently, the forsterite content in olivine gradually decreases from group A (Fo₈₇–Fo₈₂) to group B (Fo₈₃–Fo₈₀). Such compositional trends are shown in Fig. 7, where the gabbroic rocks, together with the olivine cumulates (troctolites and plagioclase wehrlites) define positive (forsterite–anorthite) and (anorthite–Mg# in clinopyroxene) correlations. Amphibole compositions are mostly pargasites to pargasitic hornblendes (according to Leake classification, 1997) with relatively high Mg values (Mg#=0.86–0.89), Na and Ti content (Na₂O=2.04–3.05 wt.%; TiO₂=2.58–3.70 wt.%).

7. Trace element mineral chemistry

Representative clinopyroxene and plagioclase trace element compositions of the studied samples are reported in Tables 6 and 7. Clinopyroxenes in the impregnated peridotites exhibit rather homogeneous trace element concentrations and do not display any significant core to rim variation. Their compositions are strongly modified when compared to already published data for clinopyroxenes in the ET spinel peridotites (Rampone et al., 2005; see Fig. 8A). They show low Sr (0.36–1.50 ppm) and high Ti, REE, Zr, Y, Sc and V concentrations. The REE spectra are characterized by significant LREE depletion ($L_{AN}/Y_{bN}=0.007–0.013$),

nearly flat M-to H-REE (at about $20–30\times C1$) and weakly negative Eu anomalies ($Eu_N/Eu_N^*=0.68–1.04$) (Fig. 8A). In spite of overall high REE absolute

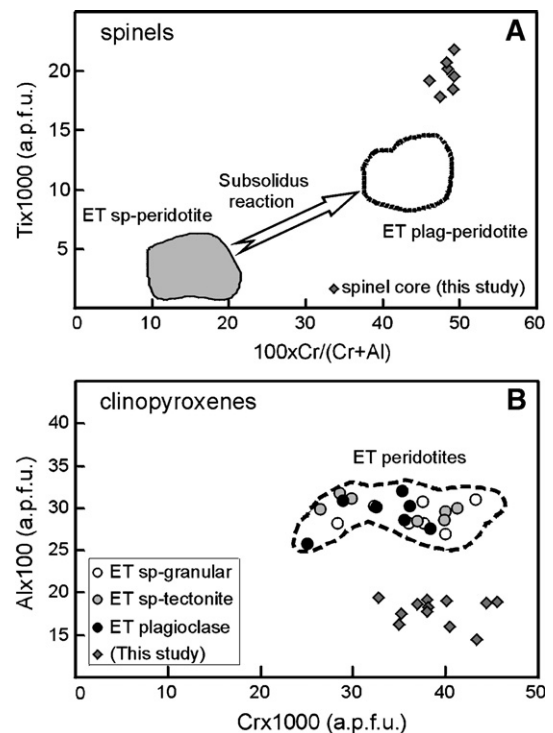


Fig. 5. (A) $Ti \times 1000$ (atoms per formula units) vs. $100 \times Cr / (Cr + Al)$ of spinels from the studied peridotites; also shown are compositional field of spinels in the ET spinel and plagioclase-reequilibrated peridotites (data from Rampone et al., 2005). (B) $Al \times 100$ (a.p.f.u.) vs. $Cr \times 1000$ (a.p.f.u.) of clinopyroxene cores from the studied peridotites; also shown are the compositions of clinopyroxenes from spinel and plagioclase ET peridotites (data from Rampone et al., 2005).

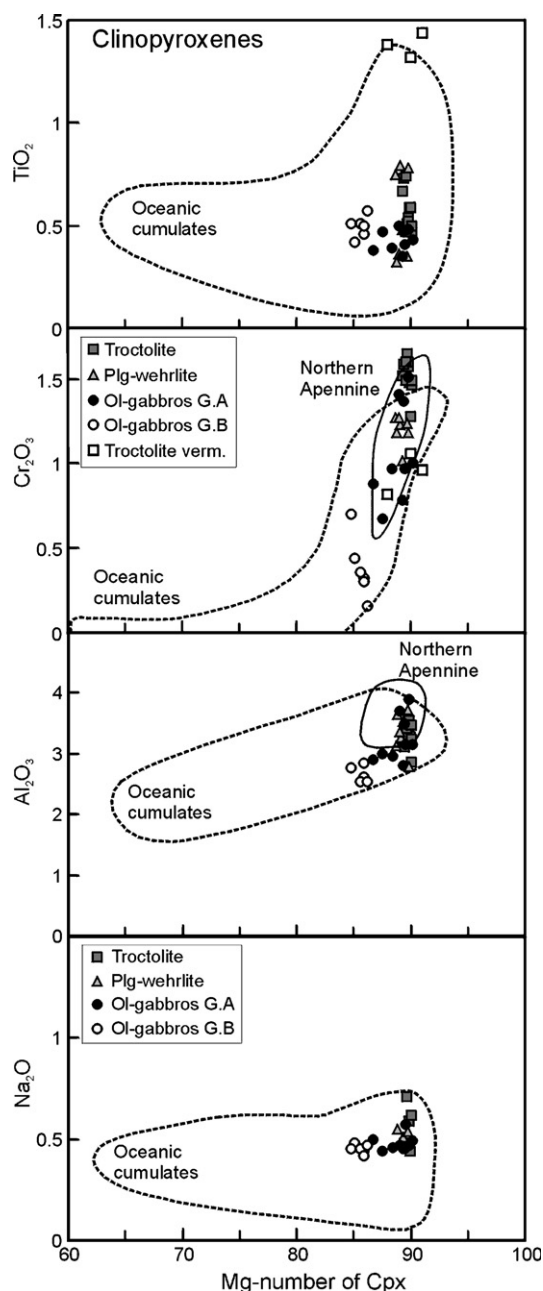


Fig. 6. TiO_2 , Cr_2O_3 , Al_2O_3 and Na_2O contents vs. $\text{Mg}\#$ values [$100 \times \text{Mg}/(\text{Mg} + \text{Fe})$] of clinopyroxenes in the ultramafic–mafic rocks. The fields refer to the composition of clinopyroxenes from: (i) oceanic cumulates (data from Elthon et al., 1992) and (ii) primitive cumulates from the Northern Apennine ophiolites (data from Tiepolo et al., 1997; Rampone et al., 1998).

concentrations, clinopyroxenes in the impregnated peridotites still exhibit similar LREE depletion relative to clinopyroxenes in the ET spinel peridotites (Rampone et al., 2005), which can be considered representative of the mantle protoliths before the impregnation event (Fig. 8A).

Chondrite-normalized REE patterns of clinopyroxene cores from troctolites are characterized by LREE depletion ($\text{La}_\text{N}/\text{Sm}_\text{N}=0.10\text{--}0.17$) and rather high M- to H-REE concentrations (at about $10\text{--}15 \times \text{C1}$; Fig. 9A). Clinopyroxenes also contain moderate amounts of other incompatible elements like Zr (13–21 ppm) and Y (17–26 ppm). Fig. 9A also shows the REE composition of an vermicular clinopyroxene from troctolite MF21, in order to illustrate the chemical changes related to post-cumulus crystallization. The vermicular clinopyroxene exhibits high M- to H-REE concentrations (up to $30\text{--}40 \times \text{C1}$), as well as high Zr (81 ppm) and Y (39 ppm) contents, although maintaining the same LREE fractionation ($\text{La}_\text{N}/\text{Sm}_\text{N}=0.16$). REE spectra of clinopyroxenes in the plagioclase wehrlites are similar to those in the troctolites ($\text{La}_\text{N}/\text{Sm}_\text{N}=0.19\text{--}0.22$), although displaying lower REE absolute concentrations (MREE at about $10 \times \text{C1}$). In both troctolites and plagioclase wehrlites, plagioclases show LREE-enriched patterns ($\text{La}_\text{N}/\text{Sm}_\text{N}=1.38\text{--}2.64$), strong positive Eu

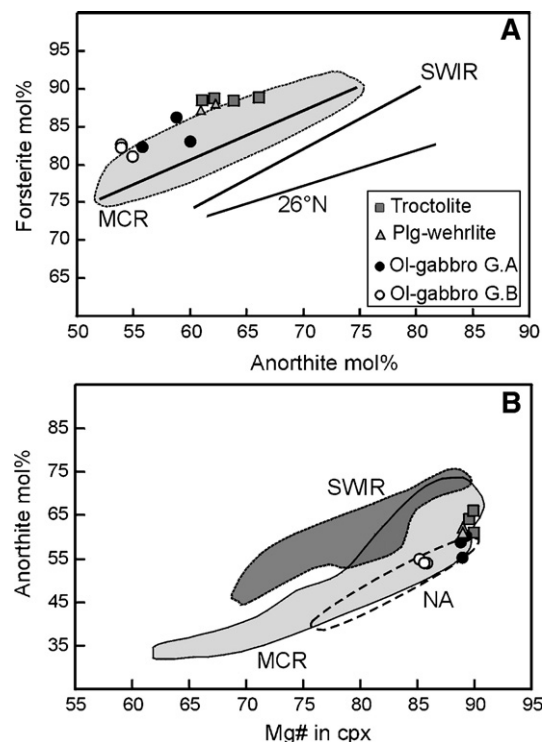


Fig. 7. (A) Fo [$100 \times \text{Mg}/(\text{Mg} + \text{Fe})$] in olivine versus An [$100 \times \text{Ca}/(\text{Ca} + \text{Na})$] in plagioclase from the studied intrusives; the sloping lines for the Mid-Cayman Rise (MCR), SW Indian Ridge (SWIR), and 26°N on the Mid-Atlantic Ridge (MAR) are approximate trends for these oceanic cumulates suites (data from Elthon et al., 1992); the grey field refers to MCR cumulates (Elthon, 1987). (B) Anorthite in plagioclase vs. Mg value in clinopyroxene from the studied intrusives, compared to different suites of oceanic (MCR, SWIR; Ross and Elthon, 1997) and ophiolitic (Northern Apennine; Tribuzio et al., 2000a) cumulates.

Table 6

Representative trace element mineral compositions (ppm) of peridotites and ol-cumulates

Sample	Peridotite MF33		Peridotite MF40		Troctolite MF8		Troctolite MF15		Troctolite MF21			Plag-wehrlite MF47		
	cpx		cpx		cpx		cpx		cpx		plag	cpx		plag
	p.c.	p.r.	p.c.	p.r.	core	core	core	core	core	verm.	core	core	core	core
Sc	62.9	71.2	61.1	66.0	86.6	1.91	92.1	2.12	86.5	108	1.40	79.7	76.9	2.10
Ti	2647	2986	3011	3275	3896	300	3417	539	2697	7253	300	2727	2856	401
V	371	377	369	398	390	2.02	358	0.91	306	448	0.60	411	387	3.68
Sr	0.36	0.25	0.78	0.50	13.3	274	14.1	314	15.9	13.6	318	14.8	12.9	267
Y	23.5	20.9	29.1	25.6	17.3	0.48	20.1	0.70	16.9	38.7	0.23	14.8	14.9	0.19
Zr	9.59	9.72	16.0	14.7	13.3	–	16.8	–	12.7	80.7	–	11.9	15.3	–
La	0.03	0.03	0.02	0.04	0.37	0.43	0.58	0.74	0.38	1.17	0.60	0.40	0.57	0.45
Ce	0.51	0.55	0.70	0.68	2.11	1.48	2.78	2.31	1.90	6.01	1.67	2.10	2.80	1.13
Pr	0.28	0.28	0.32	0.32	0.51	0.21	0.62	0.37	0.45	1.44	0.29	0.42	0.53	0.15
Nd	2.86	2.80	3.37	3.30	3.59	0.88	4.04	1.86	2.85	10.9	1.22	2.83	3.41	0.61
Sm	2.03	2.01	2.39	2.20	1.85	0.20	2.10	0.22	1.44	4.52	0.14	1.28	1.60	0.14
Eu	0.64	0.56	0.84	0.77	0.70	0.46	0.75	0.52	0.58	1.04	0.41	0.56	0.60	0.39
Gd	3.12	3.06	3.75	3.46	2.51	0.13	2.85	0.26	2.19	5.37	0.10	1.88	2.12	0.08
Tb	0.61	0.60	0.79	0.70	0.52	0.02	0.62	0.03	0.45	1.02	0.01	0.41	0.45	0.01
Dy	4.01	4.05	4.74	4.62	3.28	0.09	3.95	0.12	2.70	6.35	0.06	2.68	2.63	0.05
Ho	0.95	0.91	1.00	1.02	0.73	0.02	0.83	0.01	0.58	1.48	–	0.63	0.62	0.01
Er	2.10	2.09	2.69	2.72	1.98	0.05	2.45	0.03	1.67	3.82	–	1.66	1.58	0.03
Tm	0.32	0.33	0.41	0.38	0.29	–	0.37	–	0.24	0.55	–	0.23	0.23	0.01
Yb	1.93	2.02	2.46	2.36	1.72	0.03	2.54	–	1.51	3.53	0.05	1.55	1.65	0.03
Lu	0.29	0.30	0.34	0.35	0.27	–	0.30	0.01	0.18	0.49	–	0.23	0.22	–
Hf	0.76	0.70	1.07	0.93	0.61	0.01	0.53	–	0.43	2.42	–	0.47	0.50	–

p.c.=porphyroclast core; p.r.=porphyroclast rim; core=core of rather large crystal; verm.=vermicular, interstitial clinopyroxene; (–)=not determined.

anomalies ($\text{Eu}_\text{N}/\text{Eu}_\text{N}^*=6.61\text{--}10.16$), very low HREE concentrations and rather high Sr contents ($\text{Sr}=267\text{--}318$ ppm).

The REE spectra of clinopyroxenes in the olivine gabbros are similar to those described for clinopyroxenes in the olivine cumulates: they display analogous LREE depletion ($\text{La}_\text{N}/\text{Sm}_\text{N}=0.09\text{--}0.17$) and almost flat M- to H-REE in the range $8\text{--}15\times\text{C1}$ and are consistent with REE spectra of clinopyroxenes from the most primitive olivine cumulates of Northern Apennine (Fig. 9B). Slightly higher incompatible trace element abundances are systematically shown by clinopyroxenes in group B gabbros (HREE ranging $10\text{--}15\times\text{C1}$, $\text{Zr}=16\text{--}25$ ppm; $\text{Y}=21\text{--}23$ ppm), relative to clinopyroxenes in group A samples (HREE at about $8\text{--}10\times\text{C1}$, $\text{Zr}=7\text{--}10$ ppm; $\text{Y}=11\text{--}15$ ppm). Plagioclases from both groups A and B gabbros exhibit similar LREE enrichment ($\text{La}_\text{N}/\text{Sm}_\text{N}=1.04\text{--}3.11$) and REE concentrations (LREE at about $0.8\text{--}1.5\times\text{C1}$). Overall, it is remarkable that the highest LREE concentrations (up to $2\text{--}3\times\text{C1}$) in plagioclase are recorded by the troctolites, where plagioclase occurs as an intercumulus mineral.

8. Whole-rock trace element chemistry

The trace element bulk-rock compositions of selected olivine cumulates and gabbros are reported in Table 8. Overall, they are ruled by the relative modal proportions of

the cumulus minerals. Olivine cumulates display very low contents in incompatible elements like Y ($1.69\text{--}3.79$ ppm), Zr ($3.13\text{--}5.73$ ppm) and Sr ($52.5\text{--}76.6$ ppm). They also exhibit low REE concentrations, variably flat to LREE-depleted patterns ($\text{Ce}_\text{N}/\text{Sm}_\text{N}=0.35\text{--}0.47$) and positive Eu anomalies ($\text{Eu}_\text{N}/\text{Eu}_\text{N}^*=1.22\text{--}1.75$). Higher M- to H-REE contents are shown by plagioclase wehrlites ($2\text{--}3\times\text{C1}$) due to their higher clinopyroxene modal amounts, relative to troctolites ($<2\times\text{C1}$) mostly consisting of olivine and plagioclase (Fig. 10).

Gabbroic rocks, due to higher clinopyroxene and plagioclase modal amounts, show slightly higher Zr ($6.66\text{--}10.7$ ppm) and Y ($5.21\text{--}8.35$ ppm) contents and significantly higher Sr concentrations ($163\text{--}174$ ppm). The REE patterns are characterized by LREE depletion ($\text{Ce}_\text{N}/\text{Sm}_\text{N}=0.48\text{--}0.56$), marked Eu positive anomalies ($\text{Eu}/\text{Eu}^*=3.88\text{--}5.97$) and M- to H-REE concentrations in the range $3\text{--}6\times\text{C1}$. Slightly higher REE abundances are shown by group B gabbros, relative to group A, consistent with their lower modal amounts of olivine (Fig. 10).

9. Discussion

9.1. Melt impregnation in the host mantle peridotites

A thorough discussion of the origin and significance of the melt impregnation event is beyond the aim of this

paper. Rather, we will briefly summarize the main microstructural and chemical features recorded by the studied peridotites, which indicate that melt impregnation most likely was a separate (earlier) and unrelated event relative to the olivine cumulate and gabbro intrusions.

Field evidence indicates that mantle peridotites in the investigated area are significantly enriched in plagioclase. It mostly occurs in veins and blebs interstitial to tectonite mantle olivine or crosscutting single olivine grains, thus suggesting that its crystallization was related to melt impregnation rather than to the subsolidus spinel- to plagioclase-facies recrystallization. Peculiar microtextures like (i) the crystallization of orthopyroxene (+plagioclase) intergrowth partially replacing mantle clinopyroxene, and (ii) the occurrence of large undeformed poikilitic orthopyroxenes substituting kinked mantle olivine, indicate that the impregnation event occurred after the development of the tectonite foliation, and that the impregnating melts were in disequilibrium with the peridotite minerals. Also, they had an orthopyroxene-(silica)-saturated and clinopyroxene-undersaturated composition. Similar textural features have been ubiquitously documented in the impregnated plagioclase-rich peridotites from the Northern Apennine, Lanzo, Western Alps and Mt. Maggiore (Alpine Corsica)

ophiolites (Rampone et al., 1997; Muntener and Piccardo, 2003; Rampone et al., 2004; Piccardo et al., 2004a,b; Rampone et al., 2005) and it has been inferred that such orthopyroxene-saturated impregnating melts originated at deeper mantle levels and reached orthopyroxene saturation during percolation through the overlying mantle by diffuse reactive porous flow.

Mineral compositions in the peridotites have been significantly modified by interaction with the impregnating melts. When compared to published data for ET spinel peridotites which can be reasonably considered representative of the mantle protoliths before impregnation (Rampone et al., 2004, 2005), clinopyroxenes exhibit strong enrichment in Ti, M- to H-REE (Fig. 8A), Zr, Y, Sc, V, coupled to depletion in Al and Sr (see Fig. 5B). Moreover, spinels in the studied peridotites are significantly enriched in Ti, compared to available data on spinels in the ET spinel and plagioclase-reequilibrated peridotites (Fig. 5A; data from Rampone et al., 2005). It is clear however that clinopyroxenes, in spite of the observed trace element enrichment, preserve a marked LREE-depletion ($La_N/Yb_N=0.007–0.013$), analogous to that of clinopyroxenes in the inferred spinel peridotite protoliths.

Similar mineral chemistry modifications have been documented in the impregnated peridotites from the

Table 7
Representative trace element mineral compositions (ppm) of olivine gabbros

Sample	Ol-gabbros (group A)					Ol-gabbros (group B)					
	MF2		MF22		MF26	MF20		MF24		MF29	
	cpx		cpx	plag		cpx	plag	cpx	plag	cpx	plag
	core		core	core	core	core	core	core	core	core	core
Sc	88.9		74.9	1.35	82.2	111	1.51	109	1.99	124	2.82
Ti	2562		2015	272	2997	3149	461	4871	275	4419	402
V	311		329	3.09	314	341	4.33	454	0.68	436	4.14
Sr	15.3		14.0	323	13.7	12.6	282	13.7	329	18.3	259
Y	14.8		10.5	0.24	13.3	20.6	0.16	23.4	0.09	21.3	0.45
Zr	10.3		6.78	–	10.5	16.1	0.02	20.1	–	24.8	–
La	0.22		0.14	0.17	0.24	0.38	0.35	0.69	0.39	0.61	0.40
Ce	1.42		1.15	0.47	1.45	2.14	0.96	3.23	1.07	2.75	1.13
Pr	0.37		0.29	0.07	0.34	0.59	0.09	0.74	0.12	0.66	0.15
Nd	2.46		2.20	0.33	2.42	4.35	0.52	5.40	0.54	4.84	0.72
Sm	1.19		0.99	0.06	1.24	1.85	0.11	2.18	0.08	2.25	0.24
Eu	0.48		0.43	0.45	0.52	0.80	0.38	0.81	0.44	0.79	0.60
Gd	2.07		1.57	0.05	1.73	2.52	0.08	3.50	0.07	3.14	0.14
Tb	0.37		0.31	0.02	0.36	0.51	0.01	0.71	0.01	0.62	0.02
Dy	2.62		1.85	0.03	2.44	3.88	0.07	4.52	0.03	4.11	0.08
Ho	0.55		0.42	0.02	0.54	0.80	0.01	1.00	–	0.88	0.01
Er	1.54		1.14	0.04	1.35	2.16	–	2.82	–	2.48	–
Tm	0.22		0.17	–	0.22	0.31	0.00	0.42	–	0.35	–
Yb	1.54		1.03	–	1.46	2.19	0.05	2.82	0.04	2.15	–
Lu	0.20		0.13	0.00	0.20	0.28	–	0.39	0.01	0.30	0.05
Hf	0.42		0.27	–	0.50	0.53	–	0.80	0.00	0.84	–

core=core of rather large crystal; (–) not determined.

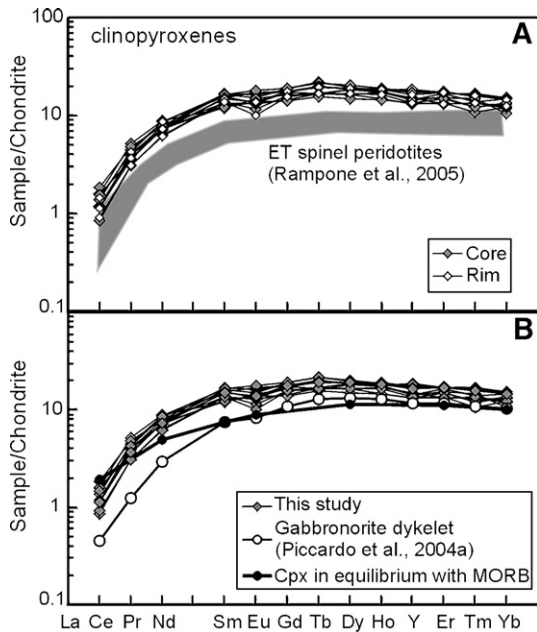


Fig. 8. (A) Chondrite-normalized REE abundances of clinopyroxenes from the studied peridotites; the grey field refers to the composition of clinopyroxenes in ET spinel peridotites (from Rampone et al., 2005), which can be considered representative of the mantle protoliths before the impregnation event. (B) Chondrite-normalized REE abundances of clinopyroxenes from: (1) studied peridotites, (2) gabbro dykelets (data from Piccardo et al., 2004a). Computed REE abundances of clinopyroxene in equilibrium with average N-MORB (from Hofmann, 1988) are also shown. Normalization factors from Anders and Ebihara (1982).

Alpine–Apennine system (Rampone et al., 1997, 2004; Piccardo et al., 2004a,b). The trace element enrichment recorded by “reacted” (partially dissolved and replaced by orthopyroxene + plagioclase) mantle clinopyroxenes has been variably interpreted to reflect (i) equilibration with migrating melts which acquired a trace element enriched signature during upwelling via melt/peridotite interaction (i.e. pyroxene dissolution and olivine precipitation with decreasing melt volume) (Piccardo et al., 2004a,b), (ii) crystallization, within the peridotites, of trapped interstitial melts (Rampone et al., 1997) or (iii) a combination of the two processes described above (Rampone et al., 2003). In spite of such discrepancies, available studies agree that preserved LREE-depletion in mantle clinopyroxene (as observed in the studied peridotites) indicates that the impregnating melts had most likely LREE-depleted compositions, and they originated as single depleted melt fractions, rather than as aggregated MORB-type melts. Similar LREE-depleted compositions have been documented in impregnated peridotite and gabbro dykelets (related to the impregnation) from other

areas of the Erro-Tobbio Unit (Piccardo et al., 2004a; see data reported in Fig. 8B).

In summary, the studied peridotites were most likely impregnated by orthopyroxene-saturated depleted melts, which originated as single depleted melt increments (produced by near-fractional melting of a MORB-type asthenospheric mantle source), and modified their composition (towards SiO₂ saturation) by upward migration via diffuse reactive porous flow. Field evidence in other sectors of the ET mantle unit (Piccardo et al., 2004a) indicate that melt impregnation postdated the

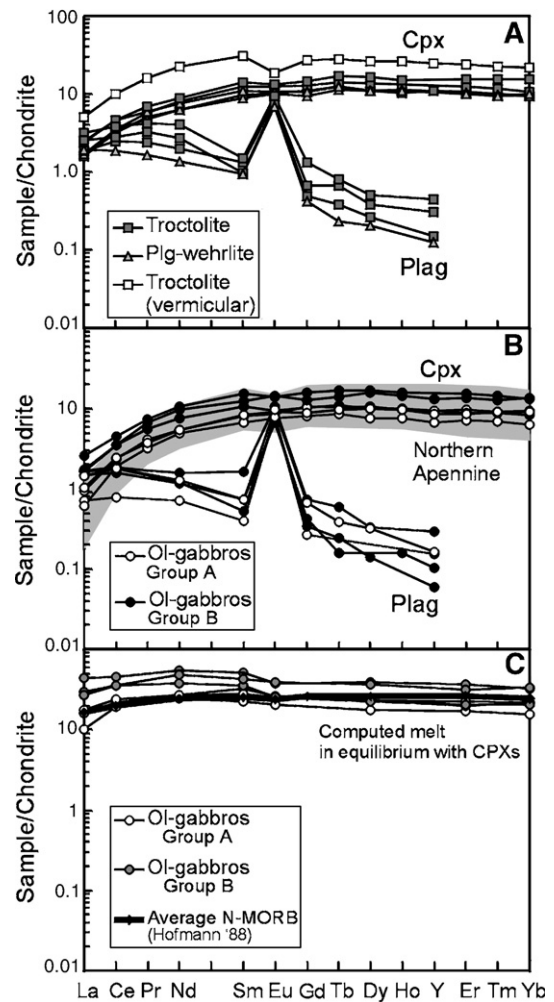


Fig. 9. Chondrite-normalized REE abundances of: (A) clinopyroxenes and plagioclases in the troctolites and plagioclase wehrlites, (B) clinopyroxenes and plagioclases in the olivine gabbros compared with the compositional field defined by clinopyroxenes from the most primitive Northern Apennine cumulates (data from Tribuzio et al., 2000a), (C) melts computed in equilibrium with clinopyroxenes from olivine gabbros (using cpx/liquid partition coefficients from Suhr et al., 1998), and the average N-MORB (from Hofmann, 1988). Normalization factors as in Fig. 8.

Table 8

Whole rock trace element compositions (ppm) of troctolites, plag-wehrlites and olivine gabbros

Sample	Troctolite	Plag-wehrlites		Ol-gabbros (group A)		Ol-gabbros (group B)	
	MF21	MF47	MF54	MF2	MF22	MF20	MF29
Rb	0.243	0.339	0.373	0.525	0.344	0.281	0.387
Sr	76.6	67.6	52.5	170	163	174	159
Y	1.65	3.79	2.80	6.14	5.21	7.69	8.35
Zr	4.29	5.73	3.13	7.56	6.66	7.83	10.7
Nb	0.042	0.038	0.013	0.037	0.044	0.034	0.072
Ba	17.9	6.79	5.97	20.2	21.0	27.6	28.6
La	0.194	0.193	0.092	0.408	0.366	0.438	0.486
Ce	0.632	0.706	0.368	1.37	1.22	1.47	1.59
Pr	0.112	0.145	0.083	0.271	0.233	0.300	0.329
Nd	0.602	0.892	0.564	1.61	1.37	1.82	1.96
Sm	0.189	0.366	0.253	0.632	0.530	0.745	0.812
Eu	0.131	0.197	0.133	0.433	0.401	0.497	0.492
Gd	0.275	0.591	0.428	0.960	0.817	1.15	1.26
Tb	0.048	0.110	0.078	0.173	0.141	0.205	0.227
Dy	0.339	0.796	0.570	1.22	1.01	1.46	1.64
Ho	0.073	0.171	0.123	0.256	0.216	0.307	0.350
Er	0.205	0.476	0.347	0.750	0.621	0.875	1.02
Tm	0.032	0.071	0.050	0.101	0.085	0.121	0.138
Yb	0.218	0.442	0.321	0.619	0.516	0.732	0.844
Lu	0.039	0.073	0.053	0.097	0.083	0.118	0.136
Hf	0.110	0.178	0.111	0.258	0.219	0.279	0.336

spinel-facies tectonite and mylonite deformation, thus presumably occurring at rather shallow lithospheric levels, during progressive exhumation of the ET mantle. However, no clear constraints are available yet on this aspect. In terms of melt dynamics, melt impregnation in the peridotites represents a stage in which single melt increments escaped aggregation and migrated, reacted, and finally crystallized in the overlying lithospheric mantle as unmixed and isolated melt fractions. In the following, we will show that petrologic and chemical features of parental melts to the olivine cumulates and gabbros point to an unrelated, most likely subsequent, melt migration and intrusion event.

9.2. Magmatic affinity of parental melts to the intrusive rocks

Overall, major element compositions of minerals in the studied intrusive rocks define narrow variations, consistent with those of rather primitive cumulates from slow-spreading mid-ocean ridge settings (Elthon, 1987; Elthon et al., 1992; Ross and Elthon, 1997) (Figs. 6 and 7). Similar compositions have been also documented in gabbroic rocks intruding the Northern Apennine ophiolitic peridotites (Tiepolo et al., 1997; Rampone et al., 1998; Tribuzio et al., 2000a). The most “primitive” compositions are shown by troctolites and plagioclase wehrlites from the cumulate body. In these rocks, the high forsterite content in olivine (Fo₈₈–Fo₈₉) and high Mg

values in clinopyroxene (Mg# = 89–91) indicate that they crystallized from rather undifferentiated melts (see Fig. 7 and Tables 2 and 3).

In the olivine gabbros, slight but systematic compositional changes are shown by minerals from group A to group B samples, e.g. progressive decrease of the Mg values in olivine (Fo₈₇–Fo₈₀) and clinopyroxene (Mg# = 90–84) coupled to decrease of the anorthite content in plagioclase (An₆₀–An₅₁), thus indicating that the group B gabbros crystallized from relatively more evolved magmas. This is consistent with the textural observation that in group B gabbros olivine is present in

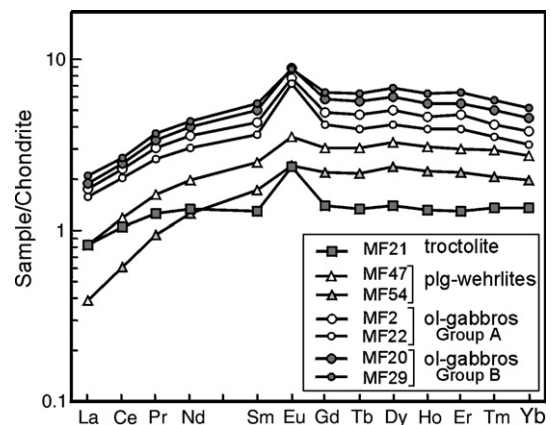


Fig. 10. Chondrite-normalized whole-rock REE abundances of intrusive rocks. Normalization factors as in Fig. 8.

lower modal amounts (8–10% by vol.) relative to group A gabbros, and it mostly crystallized as anhedral crystals associated with plagioclase (Fig. 4D). Textural and mineral chemistry features of the ultramafic and gabbroic intrusives thus indicate that they are consistent with variably differentiated cumulus rocks produced by fractional crystallization of a rather primitive melt.

In principle, further insights on the magmatic affinity and extent of differentiation of parental melts can be obtained by clinopyroxene trace element chemistry because, using appropriate mineral–liquid distribution coefficients, we can calculate the trace element composition of equilibrium liquids. This procedure, however, assumes that minerals retain the composition of crystals formed in equilibrium with a melt, and that they were not affected by late postcumulus crystallization. It is worth noting that, in all the studied rocks, clinopyroxene does not represent an early cumulus mineral phase, and mostly occurs in poikilitic crystals suggestive of postcumulus crystallization. This is particularly evident in the troctolites, where both plagioclase and clinopyroxene crystallize as anhedral intercumulus mineral phases. As already mentioned, a strong correlation has been observed in these rocks between the textural occurrence of clinopyroxene (cores vs. rims of large crystals, vs. thin vermicular grains) and its trace element chemistry, with significant overall trace element (e.g. REE) enrichment in the most interstitial grains (vermicular cpx in Fig. 9). This indicates that trapped melt crystallization can dramatically affect the trace element composition of postcumulus minerals, as already documented in ophiolitic and oceanic gabbroic rocks (Ross and Elthon, 1997; Tribuzio et al., 1999, 2000b).

In this study we have only considered the REE abundances measured in cores of large clinopyroxene in order to minimize the effects of postcumulus crystallization (Fig. 9). Overall, clinopyroxenes in all the studied rocks display a similar LREE depletion (La_N/Sm_N in the range 0.10–0.22), indicative of a MORB-type affinity of parental melts ($La_N/Sm_N=0.13$: clinopyroxene in equilibrium with average MORB from Hofmann, 1988). In spite of their almost constant LREE fractionation, the REE content variability of clinopyroxene in the troctolites, even considering the cores of large crystals, results from the postcumulus process described above. This is highlighted in Fig. 11, where Mg values vs. Yb_N variation in clinopyroxenes from all the studied intrusives is compared with postcumulus and differentiation trends (this latter specifically refers to the variational range defined by the Oman layered gabbros, Kelemen et al., 1997). It is evident that poikilitic clinopyroxenes in the troctolites exhibit a large Yb_N

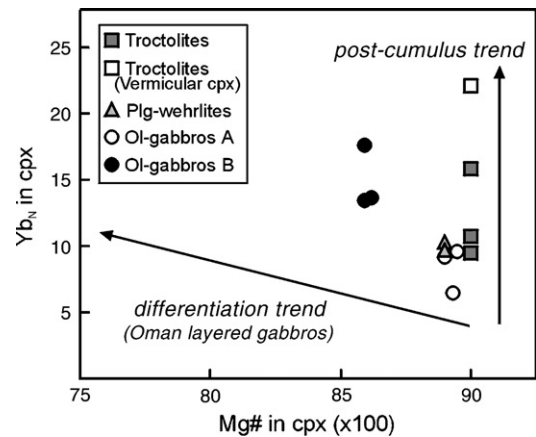


Fig. 11. Yb_N vs. $Mg\# (\times 100)$ variation in clinopyroxenes from the studied ultramafic and gabbroic rocks. The “differentiation trend” refers to compositional variation recorded by the Oman layered gabbros (Kelemen et al., 1997). The post cumulus trend is defined by the compositional variation correlated to microstructural occurrence (cores vs. rims of large crystals, vs. thin vermicular grains) recorded by clinopyroxenes from the troctolites.

variation at constant Mg values, consistent with a postcumulus trend (Rampone et al., 1997; Tribuzio et al., 1999, 2000a,b). This effect is less marked in the plagioclase wehrlites, where clinopyroxene is more abundant and mostly crystallized in subidiomorphic grains. The lowest Yb_N contents, at high Mg values, are shown by clinopyroxenes in group A olivine gabbros (Fig. 11), their REE abundances thus being the most reliable to estimate the compositions of equilibrium melts. Fig. 11 also shows that the Yb_N increase in clinopyroxenes from group A to group B gabbros is correlated with decrease of their Mg values, as expected in a differentiation trend. However, the Yb_N values in group B clinopyroxenes are rather high compared to the trend defined by the Oman MORB-type gabbros at similar Mg values (i.e. degree of differentiation). This could reflect both (i) compositional differences of the parental melts between the Oman and the studied gabbros, (ii) slight REE increase in the group B clinopyroxenes due to postcumulus effect.

The REE concentrations of clinopyroxenes in the olivine gabbros have been used to calculate the compositions of equilibrium melts (using cpx/liquid partition coefficients from Suhr et al., 1998; Fig. 9C). Overall, computed melts display almost flat REE patterns, similar to the REE abundances of average N-MORB (Fig. 9C) and variable concentrations in the range 20–40 $\times C_1$ values.

To summarize, major and trace element compositions of minerals in the studied intrusives indicate that they represent variably differentiated cumulus products crystallized by rather primitive N-MORB-type aggregated

melts. Slightly more evolved compositions are shown by olivine gabbros, especially group B, relative to troctolites and plagioclase wehrlites of the cumulate body. A similar N-MORB magmatic affinity has been documented for gabbroic rocks from the Northern Apennine ophiolites (Rampone et al., 1998; Tribuzio et al., 2000a,b). Chemical and petrologic features of ultramafic–mafic rocks thus point to fundamental compositional differences between their parental melts (olivine-saturated, N-MORB-type aggregated melts) and melts which impregnated the host peridotites (orthopyroxene-saturated single depleted melt increments). Impregnation and ultramafic–mafic intrusions thus represent two unrelated events.

9.3. Conditions of intrusion

Textural and compositional features of the ET intrusive rocks can be used to infer their depth of intrusion. A first order constraint derives from the observed sequence of crystallization in all the studied rocks, i.e. olivine–plagioclase–clinopyroxene. According to experimental studies on MORB-type tholeiitic melts, such crystallization order indicates pressure conditions <7 kbar (Bender et al., 1978).

Previous studies of various suites of oceanic cumulates (Elthon, 1987; Elthon et al., 1992; Ross and Elthon, 1997) have inferred that, given the same crystallization order ol–plag–cpx, some chemical parameters in minerals can vary significantly depending on the pressure of crystallization. Specifically, Elthon et al. (1992) have documented peculiar mineral chemistry features, e.g. high Mg#, TiO₂, Na₂O content in clinopyroxene, low An content in plagioclase, in rather primitive oceanic gabbros from the Mid-Cayman Rise (MCR), and inferred that they represent high-pressure cumulate crystallization products (Elthon et al., 1992; Ross and Elthon, 1997).

Meyer et al. (1989), however, have argued that some of the peculiar compositional features described above, namely the high TiO₂ content in clinopyroxene at high Mg#, are most likely related to postcumulus trapped melt crystallization rather than to crystallization at elevated pressure. At this purpose, the results of this study have shown that detailed and combined textural–chemical investigations allow to discriminate the effect of postcumulus crystallization. Specifically we have shown that the compositions of clinopyroxene cores, except for troctolites, can be considered reliable in terms of “primary crystallization features” (e.g. P of crystallization).

Further constraints on this topic come from experimental work and numerical modelling on high-P (up to 7 kbar) fractional crystallization of MORBs (Langmuir, 1989; Weaver and Langmuir, 1990; Langmuir et al., 1992).

These studies have shown that, given the same crystallization sequence olivine–plagioclase–clinopyroxene, and at similarly high forsterite content of olivine, the solubility of the albite component in plagioclase increases with pressure. Therefore, at increasing P plagioclase tends to be progressively poorer in anorthite. Also, clinopyroxenes crystallizing at higher P are richer in Na₂O and TiO₂, and display high Mg# (up to 90). This is due to the increase, at increasing P, of the temperature of appearance of clinopyroxene relative to olivine and plagioclase. At high pressure, clinopyroxene thus begins to crystallize from a liquid which is still MgO-rich and poorly fractionated (Bender et al., 1978). By contrast, clinopyroxene crystallizing from MORBs at 1 atm typically displays Mg# <82 (Elthon et al., 1992).

Available petrologic studies on oceanic cumulates from slow-spreading mid-ocean ridge settings (Elthon et al., 1992) have documented that different gabbroic suites (e.g. Mid-Cayman Rise MCR, South West Indian Ridge SWIR, etc.) define distinct trends in terms of specific mineral chemistry parameters, i.e. forsterite vs. anorthite and anorthite vs. Mg# in clinopyroxene (Fig. 7). Such trends, according to the above experimental evidence, have been interpreted as a consequence of varying depth of crystallization of the different gabbroic suites (Elthon et al., 1992; Ross and Elthon, 1997). In more detail, the MCR gabbroic rocks, whose primitive terms define trends at high Mg# in clinopyroxene coupled to rather low An content in plagioclase, have been interpreted as cumulate products of moderate-P crystallization (3–5 kbar; Elthon et al., 1992; Ross and Elthon, 1997).

As shown in Fig. 6, clinopyroxenes in the ET intrusives, even only considering the group A olivine gabbros (i.e. the least affected by postcumulus crystallization) display fairly high TiO₂ (0.35–0.50 wt.%) and Na₂O (0.44–0.57 wt.%) contents, coupled to high Mg# (0.87–0.90). Furthermore, overall ultramafic and gabbroic rocks define mineral chemistry trends which fall within the compositional ranges defined by the most primitive MCR cumulates (see Fig. 7), i.e. at rather high Mg# in cpx and low anorthite values. It is noteworthy that troctolites display variable An contents at constant Fo value (see Fig. 7A). This variability, in particular the occurrence of low An contents, could be due to postcumulus effects, as plagioclase in the troctolites is an intercumulus phase. This observation agrees with the rather high REE concentrations in plagioclase (see Fig. 9). As discussed by Meyer et al. (1989), interstitial plagioclase crystallizing in an olivine matrix can be more sodic than expected from the equilibrium olivine composition, because the plagioclase composition is controlled by the intercumulus liquid which evolves upon cooling, and can be partially trapped

within the cumulus matrix. Nevertheless, if we consider only the gabbros, in which plagioclase is a cumulus phase, the investigated intrusive rocks still define a Fo–An trend at rather low An contents, similar to the MCR cumulates.

In summary, we infer that the studied cumulate rocks were intruded and crystallized in the host mantle peridotites at moderate P (3–5 kbar, i.e. 9–15 km depth). Similar pressure estimates have been obtained using the Nimis and Ulmer (1998) geobarometer, based on the compositions of clinopyroxene crystallized from anhydrous basalts and applicable to Mg-rich cumulate rocks. Results on clinopyroxenes from the group A olivine gabbros mostly fall within 2.9–4.5 kbar range.

10. Conclusions

Field and petrologic evidence on the studied peridotite–cumulate association point to a composite history of melt migration, melt–peridotite interaction and melt intrusion which occurred at lithospheric depths, during progressive exhumation and cooling of the ET mantle.

Structural and geochemical features of melt impregnation and melt intrusion products point to a progressive change in melt composition and dynamics. In the peridotites, the evidence of unstrained poikilitic orthopyroxene crystallizing at the expense of deformed kinked mantle olivine indicates that melt impregnation occurred after deformation, when the ET peridotites were already incorporated into the lithospheric environment. This event was related to the diffuse porous flow migration of depleted MORB-type melt fractions that modified their compositions towards opx saturation by mantle–melt interaction (olivine precipitation and pyroxene dissolution reactions) during their ascent. These melts finally crystallized by cooling and impregnated the peridotites, presumably at rather shallow lithospheric levels.

The subsequent intrusion events originated by MORB-type aggregated magmas which did not experience significant compositional modifications during ascent. Gradational, interfingering contacts between the cumulate body and the host peridotites indicate that the intruding melts were still moving by porous flow and presumably reached a low-permeability, low-porosity mantle level (i.e. the host impregnated peridotites) which formed a barrier for further migration. Melts thus pooled and crystallized the cumulate body. Meso- and micro-structural features in the cumulates, i.e. the compositional layering and frequent skeletal olivine texture, indicate their predominant magmatic origin. However, the occurrence of both kinked (mantle-derived) and undeformed euhedral (magmatic) olivine in the plagioclase wehrlite and troctolite apophyses and the irregular contacts between the cumulate apophyses

and the host mantle peridotites, suggest that at least the marginal part of the ultramafic intrusion could be constituted by “hybrid” rocks.

Subsequent intrusion by slightly more evolved MORB melts is testified by the emplacement within the peridotite–cumulate association of olivine–gabbro lenses, dykes and dykelets. This stage indicates the progressive transition from porous flow melt migration to emplacement of magmas in fractures, presumably related to progressive change of the lithospheric mantle rheology, across the ductile to brittle transition, during extension-related uplift and cooling of the ET mantle. This is testified by the geometric en echelon arrangement of gabbroic bodies, suggesting a semi-brittle or brittle–ductile shear deformation of the country rocks, during their emplacement. Final intrusion of gabbroic dykelets in conjugate fracture systems indicate a transition to brittle deformation regime.

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