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THE PLAGIOGRANITE - FeTi-OXIDE GABBRO ASSOCIATION OF VERNE (MONVISO METAMORPHIC OPHIOLITE, WESTERN ALPS)

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ABSTRACT

The Verné plagiogranite-FeTi-oxide gabbro association is exposed in the southern Basal Serpentinite Unit of the Monviso meta-ophiolite and consists of a tabular body (about 400 x 250 m wide and 70 m thick) of jadeite - quartz - bearing massive metaplagiogranite in primary contact with omphacite - garnet - rutile ± glaucophane eclogite (recrystallized FeTi-oxide gabbro). Albite - quartz - bearing leucocratic layers within the metaplagiogranite body are interpreted as late-magmatic dikes.

Despite Alpine re-crystallization under eclogite-facies conditions, both the FeTi-oxide gabbros and the plagiogranites retain most of their primary geochemical features. Composition of the Verné FeTi-oxide gabbros (average Mg# = 31.8) is very similar to those of FeTi-oxide metagabbros from other units of the Monviso meta-ophiolite. Their REE chondrite-normalized patterns are characterized by the typical MORB depletion in LREE; two samples are between 10 and 13 times chondrite and display rather flat patterns; one sample (also having the highest contents in Ce and Zr) is about 100 times chondrite and displays a negative Eu anomaly. The plagiogranites ($64.20 < SiO_2 < 65.90$ wt%, $7.23 < Na_2O < 8.28$, average Mg# = 19.1) are leucocratic, Fe-rich quartz diorites; the plagiogranite dikes ($SiO_2 = 70.85$ wt%, $FeO_{tot} = 3.37$ wt% and average Mg# = 17.3) are more differentiated trondhjemite varieties. All plagiogranites are Zr-enriched rocks lying along a typical MORB differentiation trend. Their REE chondrite-normalized patterns are also typical of MORB, ranging between 20 and 500 times chondrite. All samples display a negative Eu anomaly, ranging from weak to strong.

The Verné association represents late stages of the plutonic activity within ultramafic oceanic crust and its occurrence can be modelled by fractional crystallization of an evolved tholeiitic magma, possibly of oceanic andesite composition. After fractional crystallization of the FeTi-oxide gabbros, the remaining liquid has a composition similar to those of the plagiogranites, suggesting that these formed essentially from direct crystallization of such a residual liquid. The trondhjemite dikes, being the most differentiated liquids, were probably emplaced through deformation-controlled, late-stage melt migration in the near-solidified crystal mush of the plagiogranite.

INTRODUCTION

Oceanic plagiogranites are low-K, leucocratic rocks commonly found as minor bodies, pods and dikes in the ophiolite suites (e.g. Coleman and Peterman, 1975; Coleman and Donato, 1979; Koepke et al., 2007). Though there is little agreement over the term "plagiogranite" (e.g., Dick et al., 2002), the term oceanic plagiogranite is used here in a very broad sense to include the whole suite of evolved, SiO_2-enriched plutonic rocks within the lower oceanic crust, diorites and quartz diorites included (Le Maitre, 1989). These rocks are believed to be generated by magmatic processes similar to those active in present-day mid-oceanic ridges (e.g. Casey et al., 2007) and supra-subduction zone oceanic basins (e.g. Shervais, 2001).

Metamorphosed plagiogranites, trondhjemites and other leucocratic rocks, ranging from (leuco-)ferrodiorite to albite granite and albitite, form pods, dikes and veinlets in the eclogite-facies ophiolites of the internal Piedmont Zone and in the blueschist-facies ophiolites of the external Piedmont Zone and Corsica (e.g. Ohnenstetter and Ohnenstetter, 1980; Pognante et al., 1982; Borsi et al., 1996; Castelli et al., 2002) (Fig. 1). Pods and dikes of unmetamorphosed plagiogranites and trondhjemites are widespread in the Northern Apennines ophiolites (e.g. Serri, 1980; Tiepolo et al., 1997; Montanini et al., 2006) and also occur in the Montgenèvre ophiolite of the Western Alps (Bertrand et al., 1987; Costa and Caby, 2001). Their genesis by fractional crystallization has been supported by several papers on Alpine and Apennine ophiolites (e.g. Borsi et al., 1998; Montanini et al., 2006).

A body of jadeite-quartz-bearing metaplagiogranite, retaining magmatic contacts with Omp-Grt-Rt ± Gln metagabbro (and of very large size relative to other metaplagiogranites from the Western Alps and Northern Apennines), was recently described by Castelli et al. (2002) in the southern portion of the Monviso meta-ophiolite. Its 152±2 Ma crystallization age (SHRIMP II U-Pb zircon age: Lombardo et al., 2002), compared to the 163±2 U-Pb age of an eclogitized FeTi-oxide gabbro (Rubatto and Hermann, 2003), indicates that the formation of plagiogranite likely represents a late stage of plutonic activity within this portion of the Piedmont oceanic crust.

In this paper new petrological and geochemical data on the metaplagiogranite - FeTi-oxide metagabbro association found in the southern Monviso meta-ophiolite are presented to integrate the preliminary data of Castelli et al. (2002). The petrogenesis of this suite is discussed in the frame of igneous differentiation processes recorded in the Monviso ophiolite and presently operating at low-spreading ridges (e.g., Niu et al., 2002).

GEOLOGICAL AND PETROLOGICAL SETTING

The Monviso metamorphic ophiolite is a north-trending body, 35 km long and up to 8 km wide, structurally sandwiched between the underlying Dora-Maira thrust units and the dominantly metasedimentary units of the ocean-derived Piedmont Zone (Fig. 1). It is one of the best preserved relics of oceanic crust in the Western Alps that formed during opening of the Mesozoic Western Alpine Tethys and under-

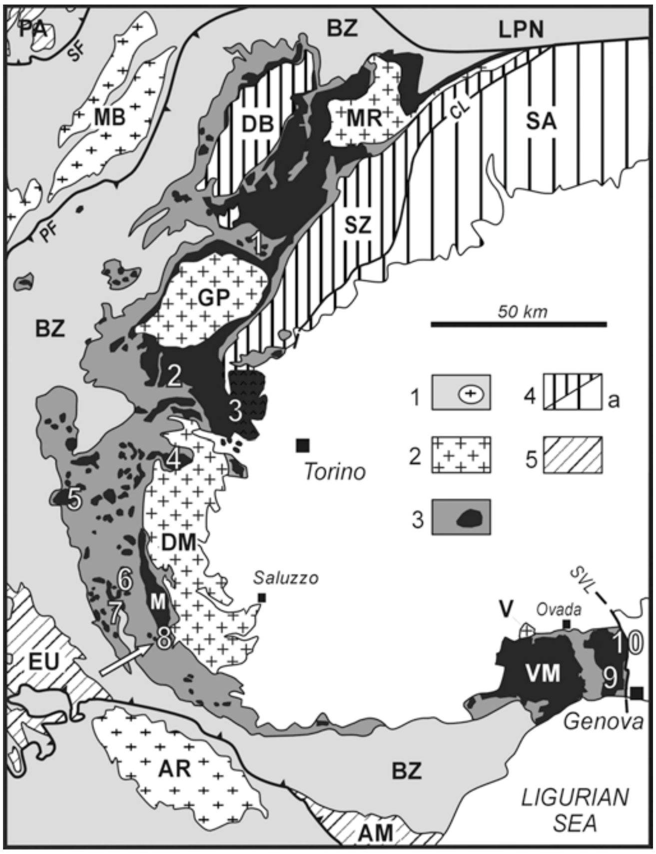

Fig. 1 - Structural sketch map of the Western Alps with locations of the metaplagiogranite-metagabbro association at Verné (white arrow) and of other metaplagiogranite occurrences (from Castelli et al., 2002). 1: Helvetic and External Penninic Units, and External Crystalline Massifs (AR: Argentera; MB: Mont Blanc - Aiguilles Rouges). BZ: Briançonnais Zone; LPN: Lower Penninic Nappes; 2: Internal Crystalline Massifs (MR: Monte Rosa; GP: Gran Paradiso; DM: Dora-Maira; V: Valosio); 3: Piedmont Zone, with ophiolite bodies shown in black (VM: Voltri Massif; M: Monviso); 4: Austroalpine Units (DB: Dent Blanche Nappe; SZ: Sesia-Lanzo Zone) and Southern Alps (a); 5: Helminthoid Flysch nappes (PA: Préalpes; EU: Embrunais-Ubaye; AM: Alpi Marittime). CL: Canavese Line; SF: Subalpine Frontal Thrust; PF: Penninic Frontal Thrust. Numbers referring to location of metaplagiogranites from the Western and Ligurian Alps are: 1) Monte Nero (Novo et al., 1989); 2) Val d'Ala di Lanzo (Leardi et al., 1984; Sandrone et al., 1986); 3) Lanzo peridotite body (Pognante et al., 1982; 1985; Pognante, 1989; Kaczmarek and Müntener, 2005); 4) Fonte Neiretto, Orsiera-Rocciavré (Lombardo and Pognante, 1982; Pognante et al., 1982); 5) Montgenèvre (Bertrand et al., 1987; Costa and Caby, 2001, with refs.); 6) Queyras (Steen, 1975; Lemoine, 1980; Lagabrielle, 1981); 7) Tour Real (Lombardo and Pognante, 1982); 8) Monviso (Castelli et al., 2002); 9) Voltri Group (Borsi et al., 1996, with refs.); 10) Sestri-Voltaggio Zone (Serri, 1980; Borsi et al., 1996; 1998; Tiepolo et al., 1997; with refs.). Layers of jadeite-quartz-bearing rocks associated with olivine gabbro in the central part of the Monviso metaophiolite are also reported by Schwartz et al. (2000).

went eclogitic metamorphism during Alpine subduction (e.g. Lombardo et al., 1978; MONVISO, 1980; Philippot, 1988; Messiga et al., 1999; Schwartz et al., 2000). The Monviso ophiolite encompasses the whole lithological spectrum of the Piedmont - Liguria ophiolite rocks and comprises six different units (Fig. 2), the stratigraphy of which has been recently reviewed by Lombardo et al., (2002). Specifically, from west to east and from top to bottom, these units are:

i) *Vallanta Unit*, an overturned slab, up to 300 m thick, of fine-grained eclogitic metabasalts, with small relics of a sedimentary cover of carbonate micaschists. This unit is topographically and tectonically the highest one and caps the very top of Monviso.

ii) *Forciolline Unit*, an overturned sequence of metagabbro, massive and pillowed metabasalt, and of banded glaucophane-epidote metabasites derived from pillow basalts and basalt breccias (Fig. 3). The Forciolline metagabbroid sequence generally shows well-preserved igneous textures and includes minor massive and layered troctolite (Compagnoni and Fiora, 1976) surrounded by a large body of isotropic, coarse-grained gabbro, 2 km long and 500 m thick. Rafts of serpentinized peridotite preserved in the gabbro body suggest that it was emplaced in ultramafic ocean crust (Lombardo and Pognante, 1982). Petrographic and major-element data indicate derivation of the isotropic gabbro from olivine gabbro with TiO_2 of 0.3-0.4 wt% and Mg# [= 100 x Mg / (Mg + Fe_{tot})] ranging between 82 and 77 (Piccardo and Fiora in Lombardo et al., 1978). The magmatic clinopyroxene is a chromian diopside, with Mg# = 79-82. Massive and pillowed metabasalts stratigraphically overlie the gabbros; field relationships indicate that basalts were extruded on gabbros previously exposed on the ocean floor. Massive basalts are crosscut by basalt dykes that also cut the gabbro (Fig. 3). The metabasalts are often plagioclase-phyric, more rarely Ol-Pl-phyric. Their Mg# range between 65 and 51, and TiO_2 is between 1.2 and 1.8 wt% (Piccardo and Fiora, in Lombardo et al., 1978). The Forciolline Unit is capped by a sedimentary cover of carbonate micaschists and, locally, of quartz-rich micaschists (Lombardo et al., 1978).

iii) *Passo Gallarino Unit*, a 100 m-thick slab of interlayered eclogite and omphacite metagabbro ("Passo Gallarino Complex") hosted in serpentinized peridotite. The serpentinite is overlain by a thin metabasalt sheet, capped by quartzite and quartz-rich micaschist. The Passo Gallarino Complex consists of metamorphosed FeTi-oxide gabbro, with minor gabbronorite and very thin sheets of metaplagiogranite (Lombardo et al., 1978; MONVISO, 1980). The FeTi-oxide gabbro has Mg# ranging between 39 and 32, with TiO_2 ranging between 4.0 and 5.0 wt%, whereas the gabbronorite has Mg# of ca. 70, with TiO_2 contents of ca. 1.0 wt%.

iv) *Viso Mozzo Unit*, consisting of greenschist and banded glaucophane-epidote metabasites of basaltic parentage. Small bodies of eclogite occur on the southwestern slope of Viso Mozzo (Schwartz et al., 2000) and at its very top; their compositions (Mg# = 39-34, TiO_2 = 1.2-1.6 wt% and Al_2O_3 = 18.0-19.6) suggest derivation from Fe-oxide leucogabbros.

v) *Lago Superiore Unit*, a discontinuous belt of strongly deformed and recrystallized gabbro and olivine gabbro typically with emerald-green spots of chromian omphacite ("smaragdite"). The metagabbros host small bodies of ultramafic cumulates transformed into chloritoid-bearing eclogite, and pods, layers and large bodies of eclogite up to a few tens of meters across. The analyzed metagabbros derive from olivine gabbro with TiO_2 of 0.2-0.5 wt% and Mg# ranging between 83 and 78 (Piccardo and Fiora, in Lombardo et al., 1978). Troctolite layers transformed into magnesiochloritoid-bearing eclogite have Mg# ranging between 88 and 84 (Messiga et al., 1999). No igneous relics are preserved in the eclogites, that have Mg# ranging between 48 and 39, with TiO_2 of 5.8-4.6 wt% (Piccardo and Fiora, in Lombardo et al., 1978; Rubatto and Hermann, 2003). The Lago Superiore metagabbro has no basaltic cover, but it is transected by a few basalt dykes with TiO_2 of 1.3-1.5 wt% and Mg# of 63-60 (Piccardo and Fiora in Lombardo et al., 1978).

vi) *Basal Serpentinite Unit*, a 400 m thick sheet of antigorite serpentinite (derived from a dominantly lherzolitic protolith, with only minor harzburgite and dunite) that hosts bodies of foliated metagabbro, Fe-Ti-oxide metagabbro

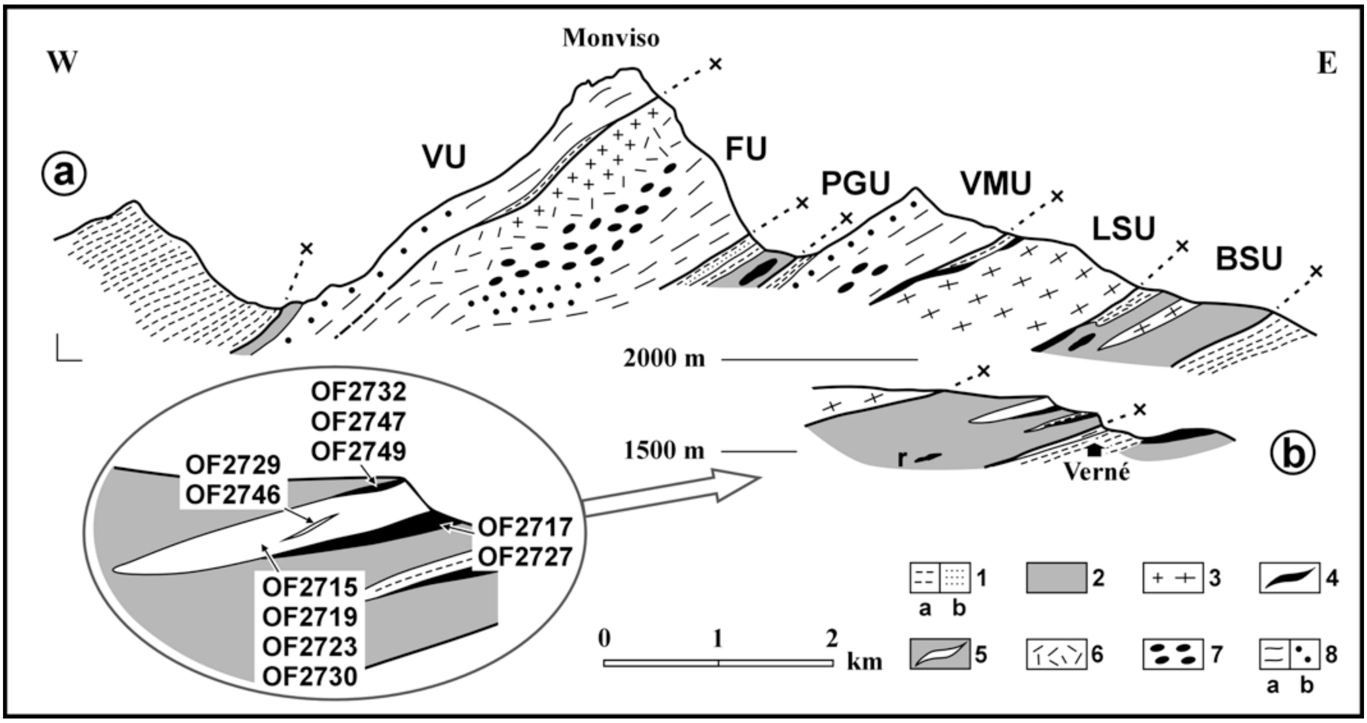

Fig. 2 - Cross sections through the Monviso meta-ophiolite in the upper Valle Po (a) and along the northern side of the middle Val Varaita (b) (modified after Lombardo et al., 2002). Keys to symbols are: 1a) carbonate micaschists; 1b) quartz-rich micaschists and metacherts; 2) serpentinites and antigorite schists; 3) isotropic and foliated metagabbros; 4) FeTi-oxide metagabbros and eclogites (including rodingitized varieties: r); 5) metaplagiogranite; 6) massive metabasalts; 7) pillowed metabasalts; 8a) banded metabasites; 8b) metabasites with breccia texture. VU: Vallanta Unit; FU: Forciolline Unit; PGU: Passo Gallarino Unit; VMU: Viso Mozzo Unit; LSU: Lago Superiore Unit; BSU: Basal Serpentinite Unit. The inset locates the eclogitized metaplagiogranite-metagabbro associaton of Verné within the BSU of Val Varaita and schematically shows field relationships between the studied samples (see also Tables 1 and 2).

(eclogite) and the Verné metaplagiogranite - FeTi-oxide metagabbro association (Figs 2 and 3). The largest eclogite body occurs on the Po-Pellice divide at Colle della Gianna; it has Mg# of 47 and TiO_2 = 2.8 wt% (Piccardo and Fiora, in Lombardo et al., 1978). Relics of a sedimentary cover were found at Punta Rasciassa (about 4 km N of Verné, Mondino et al., 2004). The Basal Serpentinite Unit is actually formed by two serpentinite sheets: a northern one exposed continuously from the Po - Varaita divide to the Po - Pellice divide and farther north; a southern one, exposed on both sides of Val Varaita. In the northern sheet, the upper part consists of serpentine schists with blocks of different eclogite and gabbro possibly representing a tectonic mélange (R. Compagnoni, 2006, pers. comm.). However, this mélange is much thinner than suggested by Blake et al. (1995), who considered the whole Basal Serpentinite Unit as a tectonic mélange, an interpretation clearly in contrast with field evidence.

As emphasized by Lagabrielle and Lemoine (1997), two different types of units occur in the Monviso ophiolite: i) magma-rich units, in which a relatively thick basaltic layer caps gabbros and serpentinized peridotites (e.g. the Forciolline Unit, Fig. 3); ii) magma-poor units in which serpentinized peridotites are directly covered by a thin sedimentary sequence (e.g. the Basal Serpentinite Unit, Fig. 3).

GEOLOGY AND PETROGRAPHY OF THE VERNE PLAGIOGRANITE - FeTi-OXIDE GABBRO ASSOCIATION

In the southern sheet of the Basal Serpentinite Unit, north of the Verné summer settlement, a tabular body of massive, fine-grained jadeite-quartz-bearing metaplagiogranite, about 400 x 250 m wide and 70 m thick, is in primary (magmatic) contact with large eclogite pods deriving from FeTi-oxide metagabbro (Castelli et al., 2002). Field observations indicate that the FeTi-oxide metagabbros form a discontinuous envelope around the metaplagiogranite body (Fig. 3). The FeTi-oxide metagabbro retains relics of the magmatic texture, whereas primary textures are mostly absent in the pale-greenish, medium- to fine-grained metaplagiogranite, where undeformed decimetre-wide domains pass to high-strain domains with a pervasive mylonitic foliation. Folded boudins of the FeTi-oxide metagabbro are typically found within the metaplagiogranite, and relict intrusive relationships between the metaplagiogranite and the metagabbro locally occur (Castelli et al., 2002: Fig. 3). Thin, Ab-Qtz-bearing leucocratic layers, discordant to the weak eclogitic foliation of the host metaplagiogranite, have been interpreted as late-magmatic dikes (Castelli et al., 2002) (Figs. 2 and 3). Relative to Castelli et al. (2002), two additional types of metagabbroids have been recognized that are closely associated to the Verné metaplagiogranite: i) m-thick lenses of jadeite-omphacite-garnet metagabbro and ii) small boudins of omphacitite. Both varieties occur in the metaplagiogranite body, close to the contact with the host serpentinites (Fig. 2).

P-T estimates indicate T = 575°C and P = 1.95 GPa as minimal temperature and pressure for the peak Alpine assemblage in the metaplagiogranite, in agreement with garnet-clinopyroxene geothermometry of the associated FeTi-oxide metagabbro which yields T = 545±35°C at P = 2.0 GPa (Castelli et al., 2002).

The main petrographic and mineralogical features of the four rock-types recognized in the metaplagiogranite-metagabbro association of Verné are summarized in Table 1.

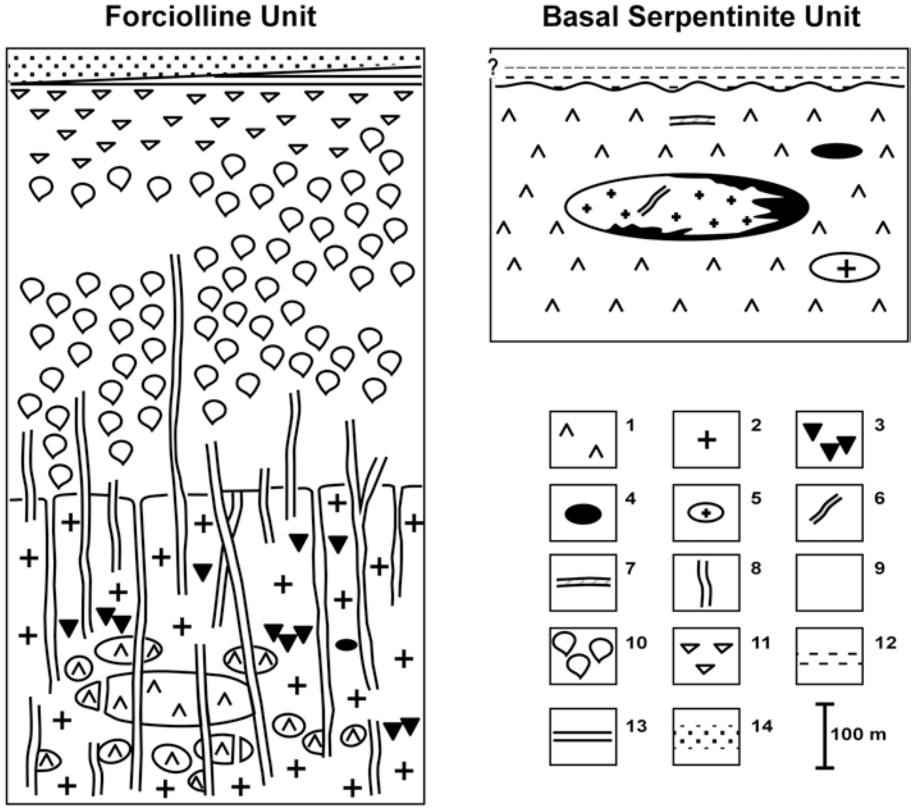

Fig. 3 - Schematic primary relationships of lithologies comprising the Forciolline Unit (a) (modified after Lombardo and Pognante, 1982) and the southern Basal Serpentinite Unit (b) of the Monviso metaophiolite. 1) Tectonite peridotites; 2) gabbros and gabbro dykes; 3) ultramafic and troctolitic cumulates; 4) FeTi-oxide gabbros; 5) plagiogranites; 6) plagiogranite dykes; 7) albitites; 8) basalt dykes; 9) massive basalts; 10) pillowed basalts; 11) basalt breccia; 12) ophicalcites; 13) metacherts; 14) calcschists. See text for discussion.

Table 1 - Rock type, texture and mineralogy of the analyzed samples.

samples	rock-type	texture	mineralogy [1]
OF2715 [2]	metaplagiogranite	medium grained, isotropic	Ab, Qtz, Jd, Agt, Phe, Fe-Gln, Grt, Aln, Rt, Zrn
OF2719	metaplagiogranite	medium grained, weakly foliated, with minor spotted texture (Grt porphyroclasts up to 2 mm)	Ab, Qtz, Jd, Agt, Fe-Gln, Grt, Phe, Aln, Zrn
OF2723	metaplagiogranite	medium grained, isotropic	Jd, Ab, Qtz, Agt, Rt, Fe-Gln, Zrn
OF2730	metaplagiogranite	fine grained, isotropic, with spotted texture (Grt porphyroclasts up to 2 mm)	Ab, Qtz, Grt, Fe-Gln, Agt, Jd, Zrn
OF2729	metaplagiogranite dike	very fine-grained, isotropic, locally with spotted texture (fine grained Fe-Gln and minor Grt)	Ab, Qtz, Fe-Gln, Agt, Phe, Grt, Jd, Zrn
OF2746	metaplagiogranite dike	very fine-grained, isotropic	Ab, Qtz, Fe-Gln, Agt, Grt, Phe, Zrn
OF2717	FeTi-ox metagabbro	fine grained, banded	Grt, Gln, Omp, Ab, Qtz, Chl, Rt, Ilm, Ap
OF2727	FeTi-ox metagabbro	fine grained, foliated	Omp, Grt, Rt, Gln
OF2732	FeTi-ox metagabbro	medium grained, foliated, with relict hypidiomorphic texture	Omp, Grt, Gln, Rt
OF2749	Fe-ox metaleucogabbro	medium to coarse grained, isotropic, with relict porphyric texture	Jd, Omp to Agt, Grt, Chl, Phe, Mag, Aln, Ep
OF2747	omphacitite	fine grained, granoblastic, with scanty relics of porphyric texture	Omp to Agt, Rt

(1) Minerals are listed in order of decreasing abundance (abbreviations after Bucher and Frey, 2002).

Definition of the protoliths is also based on the geochemical data given in Table 2 and is discussed in the next section. Further details on compositions of minerals from the FeTi-oxide metagabbro and metaplagiogranite are given in Castelli et al. (2002).

Jd-Qtz metaplagiogranite

The metaplagiogranite is a leucocratic, medium-grained and mostly isotropic Jd-Qtz-bearing rock; its primary igneous texture and minerals are mostly obliterated by multistage Alpine re-equilibration. This rock now consists of jadeite and its breakdown products, i.e. albite + very fine-grained Fe-oxides, white mica, green amphibole, epidote and scanty K-feldspar (Fig. 4a). Minor, deep-green aegirine-rich clinopyroxene develops as thin reaction rims between the jadeite domains and the interstitial domains of granoblastic quartz. These quartz domains are interpreted as relics of a primary hypidiomorphic fabric, with quartz interstitial to euhedral magmatic plagioclase. Minor zoned ferroglaucophane and phengite are locally arranged in a spaced and discontinuous foliation. Common accessory phases are rutile, and relict allanite and zircon, whose magmatic domains yielded the U-Pb age of 152±2 Ma (Lombardo et al., 2002). Some poorly-defined volumes within the metaplagiogranite body (e.g. samples OF2719 and OF2730) are characterized by a spotted texture given by mm-large porphyroclasts of almandine-rich garnet.

Ab metaplagiogranite dikes

These are leucocratic, fine-grained albite-quartz-rich rocks occurring as cm-thick and a few metre-long layers that mainly consist of poikiloblastic albite, quartz, ferroglaucophane, aegirine-augite to aegirine pyroxene and large subhedral zircons. Their fabric is similar to the metaplagiogranite fabric, but the dikes are enriched in randomly oriented ferroglaucophane and quartz, which concentrates in irregular granoblastic domains. Relict jadeite is uncommon, being almost completely replaced by lens-shaped albite poikiloblasts that are rimmed by the same coronas of aegirine-rich pyroxene that contour the jadeite domains within

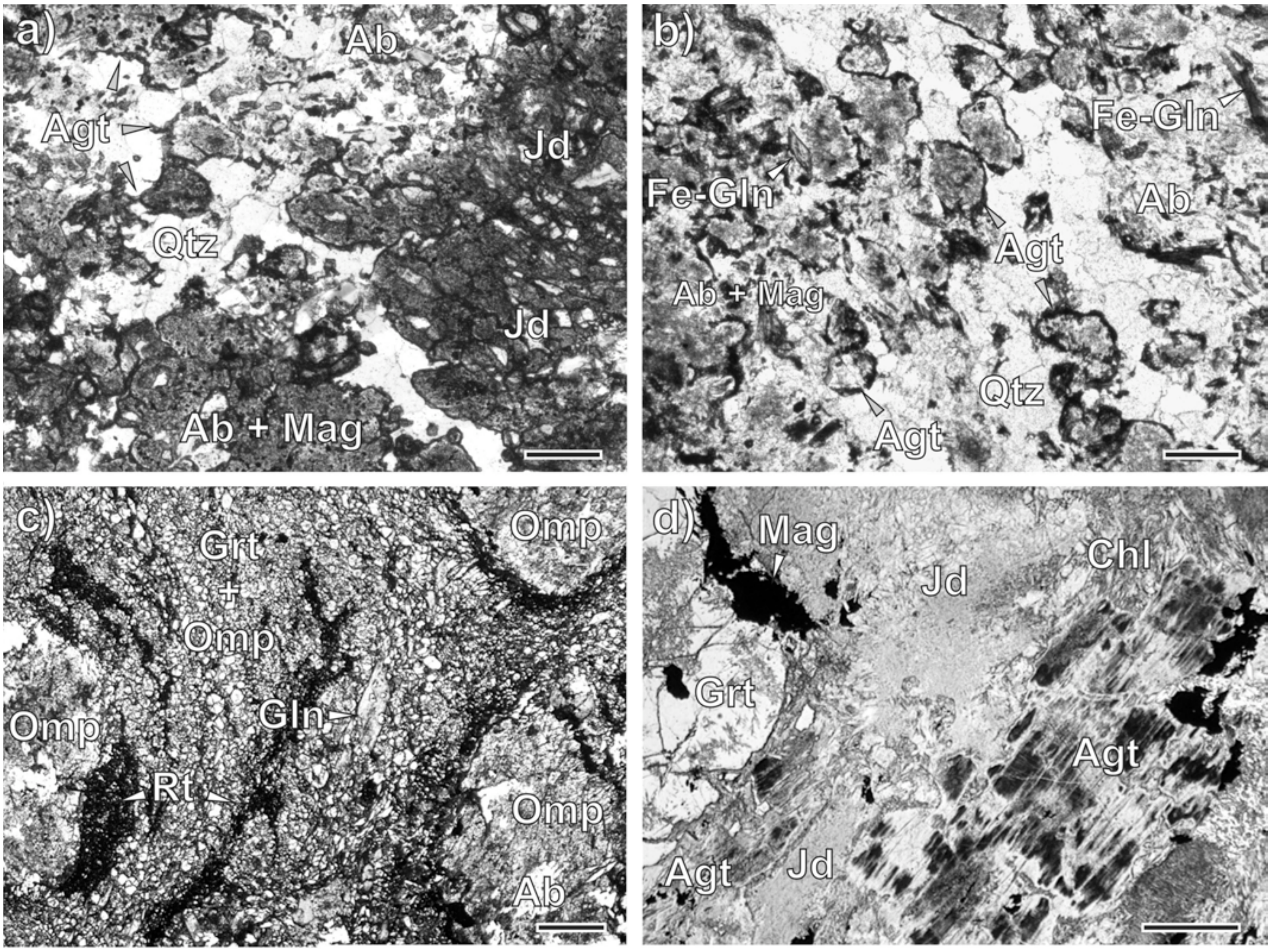

Fig. 4 - (a) Jd-Qtz metaplagiogranite (OF2730/3): porphyroclastic jadeite (Jd) is partly replaced by albite (Ab) and very fine-grained magnetite (Mag). Thin coronas of green aegirine-augite to augite (Agt) continuously rim the jadeite domains. (b) Ab-metaplagiogranite (OF2746): domains of poikiloblastic albite (Ab) ± magnetite (Mag) after jadeite, and minor Fe-glaucophane (Fe-Gln) are set in a matrix of granoblastic quartz and rimmed by thin coronas of aegirine-rich pyroxene (Agt). (c) FeTi-oxide metagabbro (OF2732): large subhedral crystals of omphacite (Omp, partly replaced by albite: Ab) after igneous pyroxenes are set in a matrix of fine-grained omphacite + idioblastic garnet (Grt) and glaucophane (Gln); fine-grained rutile (Rt) replaces primary Fe-Ti oxides. (d) Fe-oxide metaleucogabbro (OF2749/2): pseudomorphic aegirine-augite (Agt), magnetite (Mag) and porphyroclastic garnet (Grt) are set in a fine grained matrix of granoblastic jadeite (Jd) and minor MgFe-chlorite (Chl); structural relics of the magmatic pyroxene are preserved as dusty patches in the metamorphic Na-pyroxene. Plane-polarized light; scale bars are 0.25 mm in (a) and (b), 1 mm in (c) and (d).

Table 2 - Major (wt%), trace and Rare Earth (ppm) element data of the plagiogranite-gabbro association from Verné.

	FeTi-oxide gabbro			Fe-oxide leuco-gabbro	ompha-citite	plagiogranite				plagiogranite dikes	
sample	OF2717	OF2727	OF2732	OF2749	OF2747	OF2719	OF2723	OF2730	OF2715$^{(1)}$	OF2729	OF2746
SiO_2	46,00	43,90	49,20	49,40	54,30	64,70	64,20	65,90	65,68	70,70	71,00
TiO_2	3,14	4,81	4,00	0,99	0,69	0,55	0,60	0,41	0,78	0,40	0,55
Al_2O_3	12,25	13,65	11,70	14,20	10,40	16,60	15,25	16,00	14,37	13,90	13,70
Fe_2O_3	4,08	7,43	6,90	9,00	3,84	2,44	4,71	2,43	n.d.	2,43	2,00
FeO	13,65	9,78	12,15	5,27	2,38	2,83	1,87	3,54	6.99$^{(2)}$	0,96	1,80
MnO	0,29	0,26	0,25	0,20	0,06	0,08	0,10	0,09	0,13	0,07	0,07
MgO	4,82	4,77	4,03	5,22	7,92	0,97	0,83	0,68	0,62	0,34	0,46
CaO	5,45	8,97	6,35	4,50	12,45	2,09	2,74	0,81	2,20	0,77	1,10
Na_2O	4,10	4,99	4,05	9,36	7,02	7,23	8,28	7,59	7,46	7,42	7,41
K_2O	0,34	0,14	0,41	0,08	0,16	0,46	0,10	0,36	0,41	0,89	0,42
P_2O_5	2,18	0,12	0,28	0,09	0,04	0,11	0,10	0,06	0,18	0,04	0,04
LOI	1,23	0,02	0,03	1,26	0,44	0,81	0,68	0,49	0,46	0,67	0,39
Total	97,53	98,84	99,35	99,57	99,70	98,87	99,46	98,36	100,06	98,59	98,94
Mg#	33,1	34,0	28,1	41,0	70,8	25,6	19,5	17,5	13,6	16,1	18,6
Rb	18,8	2,6	8,8	7	21,1	11,2	0,6	9,7	8	6,6	6,9
Sr	195,5	52,9	80,2	155	57,8	196,5	30,2	150	78	24,3	47,4
Ba	65,6	4,6	19,6	387	40,6	133	7	119,5	70	48,5	79,1
Cs	2,8	0,1	0,5	0,7	2,9	0,6	<0.1	0,7	<1	0,5	0,4
Pb	<5	<5	<5	12	17	7	<5	10	4	<5	9
Y	195,5	28,5	67,2	189,5	49,3	160,5	39,6	564	150	168	161,5
Zr	459	183,5	162,5	198,5	344	1300	381	2530	1282	900	662
Hf	14	4	5	6	10	41	9	76	29	28	22
Nb	15	2	8	15	27	24	4	53	13	18	17
Ta	1	<0.5	0,6	1	2,3	1,6	<0.5	4,1	1	1,5	1,3
Th	1	<1	<1	<1	7	2	<1	7	2	2	2
U	<0.5	<0.5	<0.5	<0.5	4,2	1,1	<0.5	2,7	<1	0,9	0,8
Ni	80	12	8	77	1090	40	9	156	20	25	8
Co	51,7	15,8	44,5	86,9	56,1	8,4	3,9	57,1	5	2,7	4,7
V	198	263	360	103	462	21	23	52	8	15	33
Mo	<2	<2	<2	5	4	<2	<2	2	n.d.	<2	<2
Sn	10	1	4	5	10	9	3	10	n.d.	17	15
W	2	<1	<1	2	2	1	<1	2	n.d.	1	2
Cr	10	10	10	200	530	10	10	30	7	20	20
Cu	<5	15	22	67	6	<5	<5	21	8	<5	<5
Ga	37	9	21	95	51	47	13	128	42	39	36
Zn	251	54	159	455	275	60	33	132	135	91	86
La	31,5	3,3	4,9	33,9	9,5	35	5,6	139,5	26,9	35	36,2
Ce	110,5	10,4	16,6	111,5	22,4	109	19,8	414	83,4	108,5	106,5
Pr	18,6	2	2,9	19	2,8	15,4	3,1	55,5	12,8	15,5	15,9
Nd	96,3	10,6	15	103	12,6	69,6	14,6	228	62,3	70	70,4
Sm	28,5	3,5	5,3	28,4	3,9	18,8	4,2	59,6	18,4	20,4	19,5
Eu	6,1	1,2	2	10,6	0,9	3,9	1,2	8,8	4,69	3,7	3,1
Gd	31,2	3,9	7,2	31,2	4,4	19,4	5	64,7	19,5	20	19,6
Tb	5,5	0,7	1,6	5,4	0,9	3,8	0,9	13	3,4	4,1	3,9
Dy	34	4,6	11,4	32,8	8	25,7	6,8	87,5	23,2	28,9	26,7
Ho	7,3	1	2,4	7,3	1,7	6	1,5	19,8	5,22	5,9	5,8
Er	20,3	2,9	7,3	20,2	5,8	19,8	5,2	63,3	13,5	20,1	18,2
Tm	2,9	0,4	1,1	3	1	3,3	0,9	10,4	2,31	3,1	3
Yb	17,6	2,6	7	18	6,8	22,2	5,7	65,3	16,5	20,8	18,8
Lu	2,7	0,4	1,1	3	1	3,7	1	9,9	2,56	3,2	2,9
REE_{tot}	413,00	47,50	85,80	427,30	81,70	355,60	75,50	1239,30	294,68	359,20	350,50
Zr/Nb	30,60	91,75	20,31	13,23	12,74	54,17	95,25	47,74	98,62	50,00	38,94
Zr/Y	2,35	6,44	2,42	1,05	6,98	8,10	9,62	4,49	8,55	5,36	4,10
Y/Nb	13,03	14,25	8,40	12,63	1,83	6,69	9,90	10,64	11,54	9,33	9,50
La_N/Sm_N	0,68	0,58	0,57	0,74	1,50	1,15	0,82	1,44	0,90	1,06	1,15
La_N/Yb_N	1,20	0,85	0,47	1,26	0,93	1,05	0,66	1,43	1,09	1,13	1,29
Tb_N/Yb_N	1,46	1,26	1,07	1,40	0,62	0,80	0,74	0,93	0,96	0,92	0,97
Eu/Eu*	0,60	1,00	1,00	1,10	0,70	0,60	0,80	0,40	0,80	0,60	0,50

$^{(1)}$ Data of sample OF2715 from Castelli et al. (2002); (2) Total Fe as FeO; n.d.: not detected; REE normalizing values after Nakamura (1974).

the metaplagiogranite (Fig. 4b). A few resorbed flakes of phengite are also present, and very minor garnet occurs as small porphyroclasts, locally giving a finely spotted texture.

FeTi-oxide metagabbro

These are fine- to medium-grained, banded to schistose eclogites, consisting of omphacite, almandine-rich garnet and rutile (Fig. 4c). In low-strain, coarser-grained domains, relics of a magmatic hypidiomorphic structure are preserved, with pseudomorphic replacement of euhedral to subhedral magmatic pyroxene by omphacite and of interstitial magmatic ilmenite by rutile. Glaucophane occurs either as fine-grained subhedral crystals at garnet rims and in the omphacite matrix, or as large poikiloblasts hosting corroded relicts of both omphacite and garnet. In the banded varieties, Omp-Grt-Rt-Gln cm-thick layers alternate with layers characterized by the lower-pressure replacement of garnet by chlorite and of omphacite by blue-greenish amphibole + epidote + poikiloblastic albite ± white mica.

Fe-oxide metaleucogabbro

This lithology only occurs as small and rare, metre-thick lenses in the upper portion of the metaplagiogranite body, close to the contact with the host serpentinite (Fig. 2). It is a heterogranular, medium- to coarse-grained two pyroxene-garnet rock, with an isotropic fabric characterized by textural relics of a porphyric pyroxene, which is completely replaced by newly-grown pyroxene of omphacite to aegirine-augite compositions. Such relics are set in finer-grained matrix of granoblastic jadeite (replacing the primary plagioclase) and minor MgFe-chlorite, phengite and epidote (Fig. 4d). Garnet occurs as isolated, rounded and fractured porphyroclasts partly replaced by the MgFe-chlorite. The Fe(Ti)-oxide domains still retain the typical interstitial magmatic shape. Magmatic allanite is preserved as deep-brown and twinned, subhedral crystals surrounded by a thin continuous rim of colourless epidote.

Omphacitite

Omphacitite occurs as isolated, dm-thick boudins within foliated metaplagiogranite at the contact with the host serpentinite (Fig. 2). It is a fine-grained, homogeneous and massive rock solely consisting of granoblastic omphacite to aegirine-augite pyroxene with accessory rutile. A few corroded microporphyroclasts of dusty omphacite occur, that resemble the textural relics of magmatic pyroxene found in the Fe-oxide metaleucogabbro and suggest derivation of the omphacitite from a gabbroic protolith.

GEOCHEMISTRY

Major, trace and Rare Earth element data listed in Table 2 were obtained at ALS Chemex, Vancouver, using ICP-AES and ICP-MS techniques for major and other elements, respectively. Ferrous iron was also determined at ALS Chemex by HCl-HF acid digestion and titrimetric analysis. Detection limit for major elements is 0.01 wt% oxide, those for trace and Rare Earth elements (collected according to

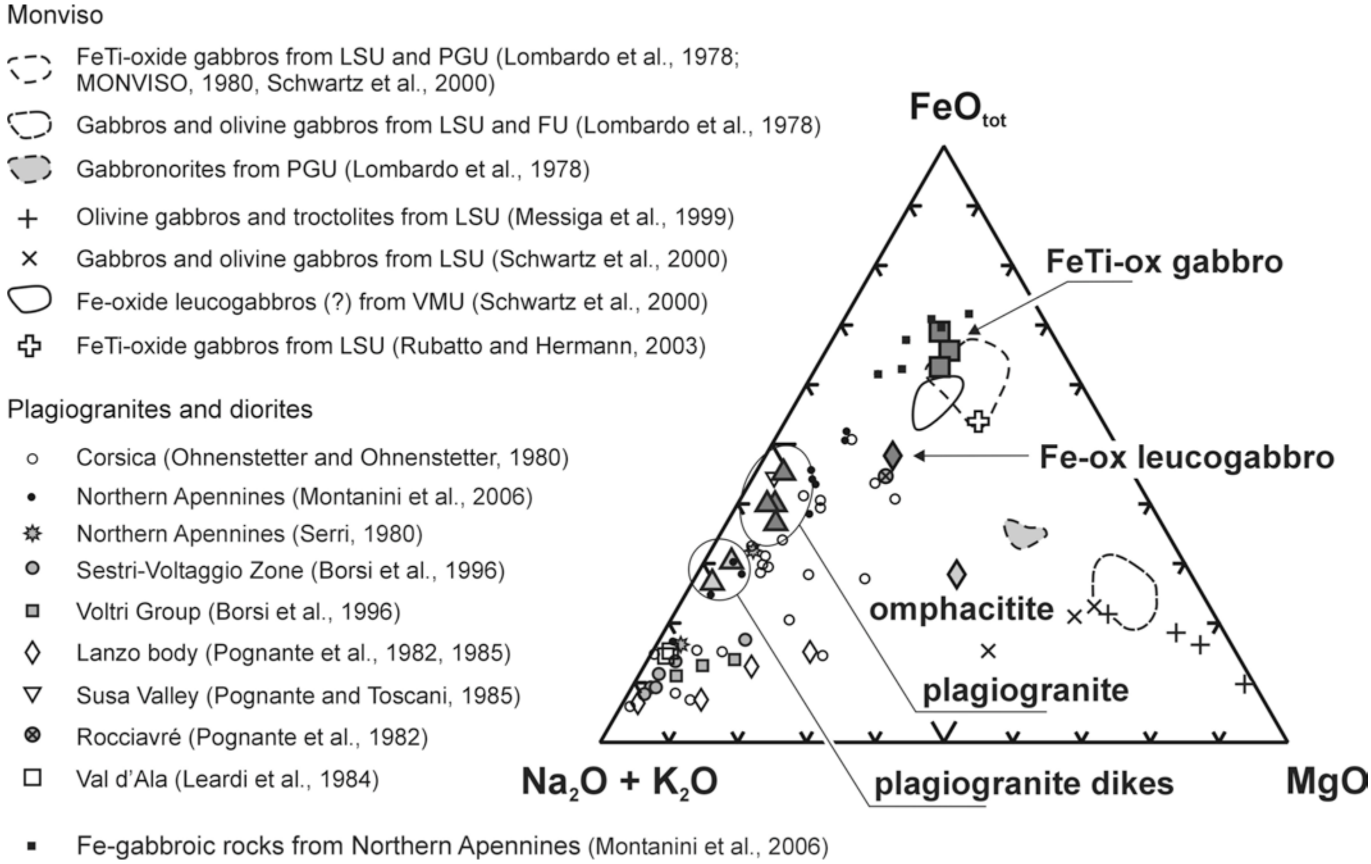

Fig. 5 - AFM diagram for the plagiogranite - FeTi-gabbro association from Verné compared to compositions of gabbro suites from other units of the Monviso ophiolite complex (abbreviations of Monviso units from Fig. 2). Compositions of selected plagiogranites, diorites and Fe-gabbroic rocks from Western Alps, Corsica, and Northern Apennines are also shown.

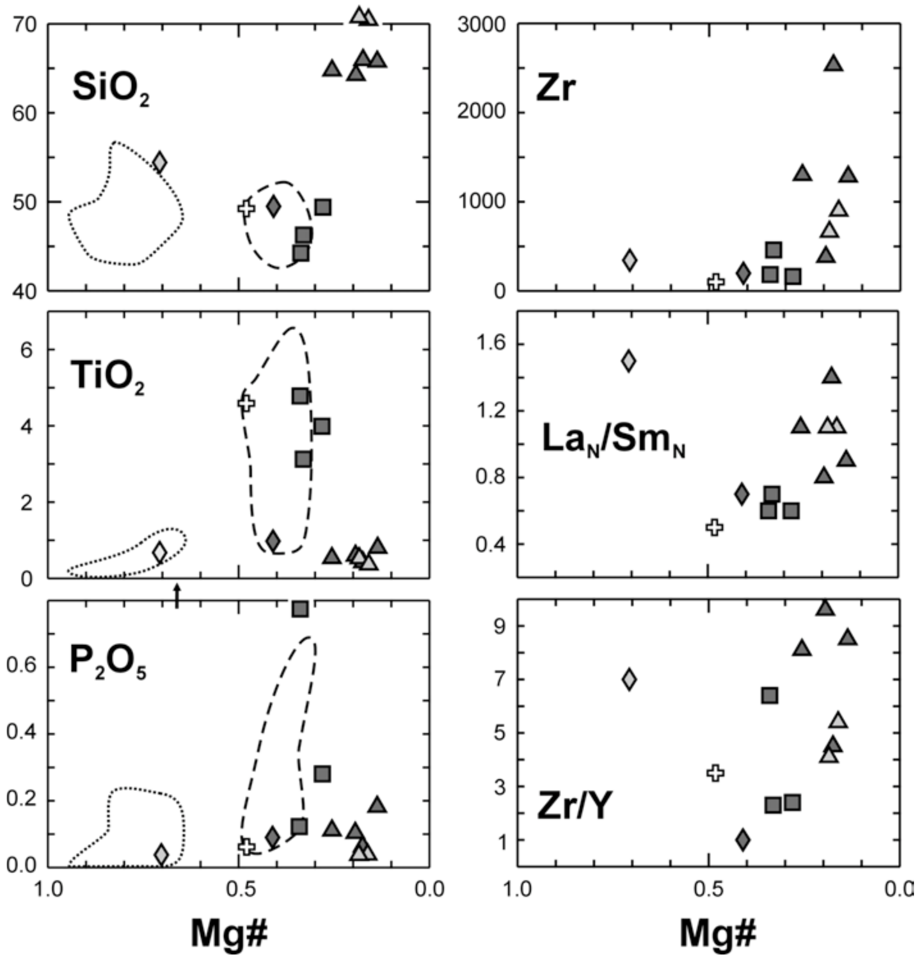

Fig. 6 -Variations of SiO_2, TiO_2, P_2O_5 (wt%), Zr (ppm), La_N/Sm_N and Zr/Y vs Mg#, for the plagiogranite-gabbro association from Verné compared to compositions of gabbro suites from other units of the Monviso ophiolite complex. The dashed and the dotted lines in the major element plots contour the field of FeTi-oxide gabbros and olivine gabbros, respectively (data from Lombardo et al., 1978; MONVISO, 1980; Messiga et al., 1999; Schwartz et al., 2000, sample Vi839-1 not included). Other symbols as in Fig. 5. Note the higher P content in FeTi-oxide gabbro OF2717 (P_2O_5 = 2.18 wt%: square symbol with arrow).

the ME-MS81 Chemex protocol) are detailed at the ALS Chemex web page (<http://www.alschemex.com/learnmore/periodic_me-ms81.htm>).

Hydrothermal alteration in the oceanic environment is known to often induce strong chemical mobilization in ophiolites and ocean ridge rocks (e.g. Beccaluva et al., 1977; Mével and Cannat, 1991; Alt, 1995; Dick et al., 2002). For instance, the investigated plagiogranitic rocks show relatively high amounts of sodium (i.e. 7-8 wt% at SiO_2 contents of about 65 wt%). These are much higher values than those measured in fresh MORB glasses from all normal mid-ocean ridges (e.g. Lehnert et al., 2000) and also much higher than those found in experimental melts at about 65 wt% SiO_2 in tholeiite systems (Berndt et al., 2005 and refs. therein). Hence, major elements (with the exception of Si, Ti, P, Fe, Mg) are taken into account only for descriptive purposes and for calculation of normative compositions that are used to broadly infer the magmatic mineralogy. Only trace elements (e.g. Zr, Y, Hf) and REE that are believed to be relatively immobile during ocean-floor hydrothermal alteration will be considered for the petrogenetic discussion. For the sake of simplicity, the prefix meta- will be omitted in the following sections.

FeTi-oxide gabbros

The chemical composition of the FeTi-oxide gabbros has the following elemental ranges: 43.9 < SiO_2 < 49.2 wt%, 16.5 < FeO_{tot} < 18.4 wt%, 4.0 < MgO < 4.8 wt%, 3.1 < TiO_2 < 4.8 wt%, and 4.1 < Na_2O < 5.0 wt%. These are typical of FeTi-oxide gabbro protoliths and very similar (Figs. 5 and 6) to those of FeTi-oxide gabbros from other units of the Monviso meta-ophiolite (MONVISO, 1980, with refs.; Schwartz et al., 2000; Rubatto and Hermann, 2003); the latter are, on average, slightly lower in Na_2O. The range of Mg# is rather narrow (28.1-34.0, Fig. 6) but the three samples of FeTi-oxide gabbro display different types and amounts of normative mafic minerals (*hy* = 30.2 wt% in sample OF2717, *di* + *ol* = 27.4 wt% in sample OF2727, *di* + *hy* = 27.9 wt% in sample OF2732, respectively) due to the rather variable SiO_2 and CaO contents. The occurrence of some normative nepheline in sample OF2727 (7.1 wt%) is likely due to a strong Na-enrichment that took place during ocean-ridge hydrothermal circulation. The P_2O_5 content is low in two samples (OF 2727 and OF 2732), but very high in sample OF2717 (2.2 wt%) that also displays the highest trace element pattern, with remarkable enrichments in Zr (459 ppm), Y (195.5 ppm) and Sr (Figs. 6 and 7a). These features suggest that sample OF2717 may contain cumulus apatite and zircon.

The REE chondrite-normalized patterns of FeTi-oxide gabbros are characterized by the typical N-MORB depletion in LREE (La_N/Sm_N = 0.57-0.68). Samples OF 2727 and OF 2732 are between 10 and 13 times chondrite (Fig. 8a), they do not display any Eu anomaly (Eu/Eu* = 1.0) and show enrichment in HREE (Tb_N/Yb_N = 1.26 and 1.07 in sample OF2727 and OF2732, respectively). They have the lowest REE contents of the whole plagiogranite - gabbro association (OF2727 = 47.5, OF2732 = 85.8). The almost flat REE pattern of sample OF2727 (La_N/Yb_N = 0.85) overlaps that of the FeTi-oxide gabbro from the Lago Superiore Unit studied by Rubatto and Hermann (2003); both samples fall within the patterns observed in Fe-gabbroids from Northern Apennines (Tiepolo et al., 1997). In contrast, sample OF2717 is about 100 times chondrite (with a total REE of 413 ppm), displays a negative Eu anomaly (Eu/Eu* = 0.6) with $La_N/Yb_N = 1.20$ and, similar to sample OF2727, slightly fractionated HREE ($Tb_N/Yb_N = 1.46$). Its pattern is similar to those of the Bartolina Fe-gabbroic rocks described by Montanini et al. (2006) in the Northern Apennines.

Fe-oxide leucogabbro

This rock (sample OF2749 in Table 2) displays higher SiO_2 and Al_2O_3 contents and twice the Na_2O content (9.4 wt%) relative to the corresponding average values of FeTi-oxide gabbro. TiO_2 is much lower (0.99 wt%) and Mg# (41.0) is slightly higher than in FeTi-oxide gabbro. These features and the abundance of normative nepheline and acmite (18.5 and 5.9 wt%, respectively) are likely due to strong hydrothermal alteration of a primary composition possibly close to that of FeTi-oxide gabbros (Figs. 5 and 6). The Fe-oxide leucogabbro is characterized by strong enrichment in Cr (200 ppm), Y, Ba (Figs. 6 and 7b). The REE pattern (about 100 times chondrite, Fig. 8b; total REE = 427.3 ppm) is LREE-depleted ($La_N/Sm_N = 0.74$) and overlaps that of the FeTi-oxide gabbro OF2717, from which it only differs for a slight positive Eu anomaly (Eu/Eu* = 1.1) that suggests some plagioclase accumulation.

Omphacitite

The omphacitite (sample OF2747) displays a FeO_{tot}/Mgo ratio comparable with that of the gabbronorite from the Passo Gallarino Unit (Lombardo et al., 1978). Its composition (Figs. 5 and 6) clearly points to Na-enrichment (Na_2O = 7.0 wt%, with 13.7 and 6.0 wt% of normative nepheline and acmite, respectively). The calcium content is also very high (CaO = 12.45, *di* = 46.4 wt%). This rock is therefore interpreted as a metasomatized gabbronorite with a primary composition possibly similar to those of the omphacite metagabbro from the Passo Gallarino Unit (Lombardo et al., 1978; MONVISO, 1980) and the gabbronorite from the Rocciavré ophiolite (Pognante et al., 1982). The sample is characterized by very high Ni, Cr and Th contents (1090, 530 and 7 ppm respectively) and by a high Zr/Y ratio (Figs. 6 and 7b). The v-shaped REE pattern (Fig. 8b) is characterized by both LREE and HREE enrichments (La_N/Sm_N = 1.50 and Tb_N/Yb_N = 0.62) and negative Eu anomaly (Eu/Eu* = 0.7).

Plagiogranites

The plagiogranite samples from the main body show silica contents between 64.2 and 65.9 wt%, high contents of iron ($5.0 < FeO_{tot} < 7.0$ wt%, Mg# between 25.6 and 13.6 (Mg# = 19.0 on average) and sodium ($7.2 < Na_2O < 8.3$). TiO_2 and P_2O_5 contents are low (0.41-0.78 and 0.06-0.18 wt%, respectively) and Na_2O/K_2O ratios are very high. Based on both chemical and normative compositions (*Q* = 14.0, *or* = 2.0, *ab* = 65.6, *an* = 5.6, wt% on average), these rocks can be considered as leucocratic, Fe-rich quartz diorites; they plot along a typical MORB differentiation trend (Fig. 5). They show variable, but high contents of Zr (381-2530 ppm, with two samples at about 1300 ppm) Y (39.6-564 ppm), Hf (9-76 ppm) and Th up to 7 ppm (Figs. 6 and 7). The REE chondrite-normalized patterns are set at about 20, 90 and 500 times chondrite (Fig. 8c, total REE = 75.5-1239.3). All samples are HREE enriched (Tb_N/Yb_N = 0.74-0.96) and display negative Eu anomalies, ranging from weak (Eu/Eu* = 0.8: samples OF2715 and OF2723) to strong (Eu/Eu* = 0.4: sample OF2730). LREE are slightly enriched (La_N/Sm_N = 1.15-1.44) in the two samples displaying the stronger negative Eu anomaly. Samples OF2723 and OF2730 show the lowest and highest enrichment in incompatible elements, respectively (Fig. 7c).

The Verné quartz diorites are comparable to some oceanic plagiogranites from Corsica (Ohnenstetter and Ohnenstetter, 1980), the Northern Apennines (Serri, 1980; Montanini et al., 2006) and Western Alps (Pognante and Toscani, 1985). In particular, the REE patterns of samples OF2715 and OF2719 are similar to those of plagiogranites from the Voltri Group (Borsi et al., 1996); REE-patterns of plagiogranite from the Northern Apennines (Montanini et al., 2006) have about the same rock/chondrite ratio but display opposite behaviour in both LREE and HREE relative to the Verné samples (Fig. 8c).

Plagiogranite dikes

The plagiogranite dykes are more differentiated than the host quartz diorite (Fig. 5), with average SiO_2 = 70.9 wt%, FeO_{tot} = 3.4 wt%, Na_2O = 7.4 wt% and Mg# = 17.4; potassium contents are the highest of the whole suite (K_2O = 0.42-0.89). Based on both chemical and normative compositions (*Q* = 23.4, *or* = 4.0, *ab* = 63.8, *an* = 2.4, wt% on average), these dikes display a trondhjemitic composition. In terms of trace elements the two plagiogranite dikes analyzed are closely comparable and their spidergrams are similar to that of plagiogranite OF2715, with slightly lower Zr (662-900 ppm) (Figs. 6 and 7d). Total REE contents (350-359 ppm) and REE patterns (Fig. 8d) are very similar to those of Qtz-diorites OF2715 and OF2719, and to plagiogranites from the Voltri Group (Borsi et al., 1996) and Northern Apennines (Montanini et al., 2006). Not surprisingly, the trondhjemite dikes display a stronger negative Eu anomaly (Eu/Eu* = 0.5-0.6) than the host quartz diorite.

DISCUSSION: PETROGENESIS OF THE VERNE PLAGIOGRANITE - FeTi-OXIDE GABBRO ASSOCIATION

The lack of magmatic minerals (excep for allanite and zircon) in the Verné rocks precludes a detailed geochemical evaluation of petrogenetic models (e.g. Tiepolo et al., 1997; Montanini et al., 2006). Our discussion will be therefore focused on field relationships and bulk compositions in terms of elements believed to be relatively immobile during ocean-floor hydrothermal alteration and regional metamorphism. The discussion will also benefit from the comparison with available data on the mineralogy of fractionated rocks exposed in other meta-ophiolites of the Westerm Alps, e.g. the gabbroic sequence of Fonte Neiretto in the Orsiera-Rocciavré metaophiolite and the gabbro dikes intruded in the Lanzo peridotite massif (Boudier, 1978; Pognante et al., 1982; Kaczmarek and Müntener, 2005, and refs. therein).

Field evidence shows that the Verné plagiogranite is closely associated with FeTi-oxide gabbros. This association is relatively common in the meta-ophiolites of Western Alps, Northern Apennines and Alpine Corsica (see the compilation by Castelli et al., 2002 and references therein), the

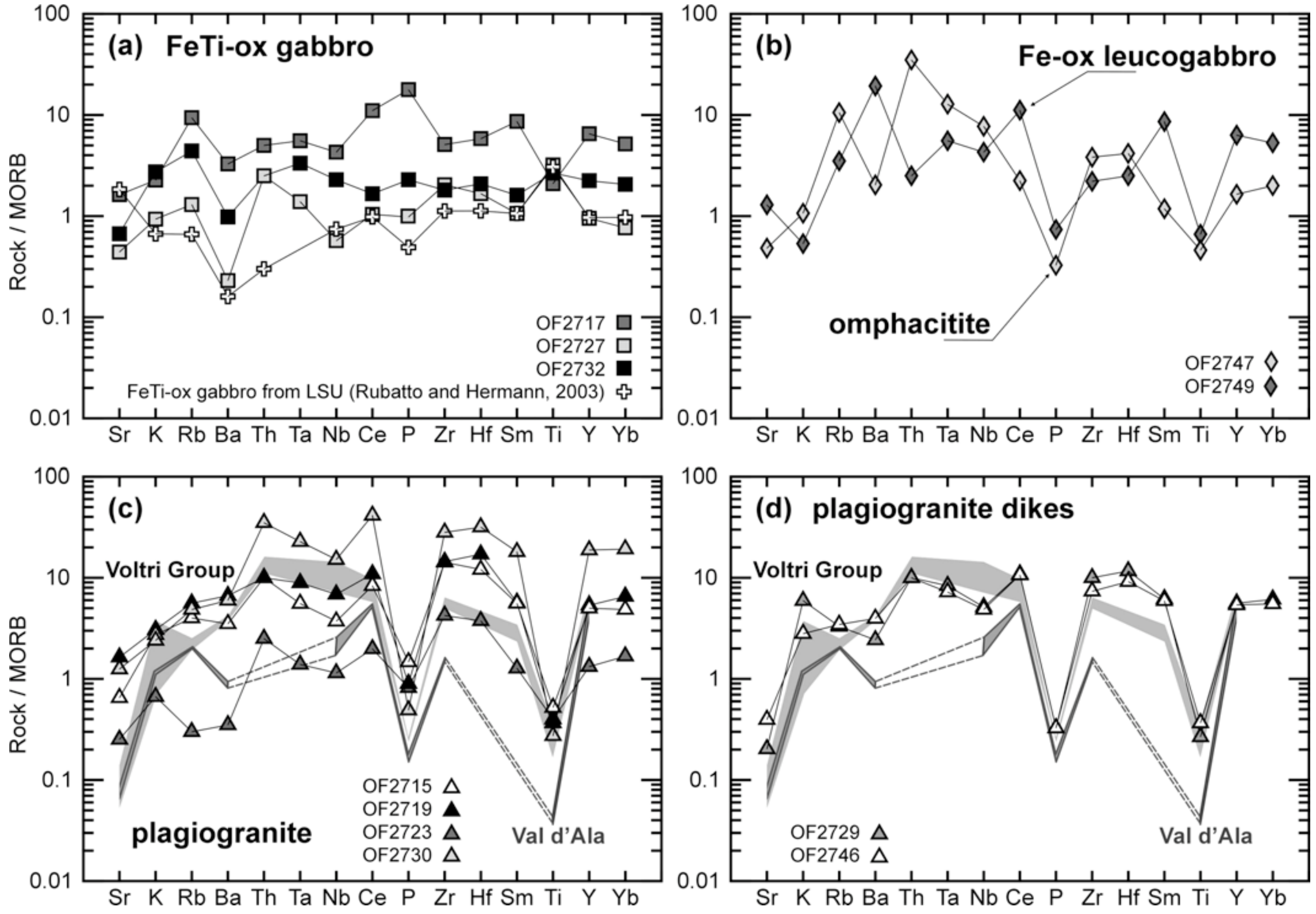

Fig. 7 - MORB-normalized (Pearce, 1982) spider diagrams for FeTi-oxide gabbro (a), Fe-oxide leucogabbro and omphacitite (b), plagiogranite (c) and plagiogranite dikes (d) from Verné. Data for a FeTi-oxide gabbro from LSU (Rubatto and Hermann, 2003: Table 1, Ta value not available) are also shown in (a). Patterns of plagiogranites from the Voltri Group (Borsi et al., 1996: Table 1; Ta, Hf and Yb values not available) and quartz-jadeite rocks from the Val d'Ala (Leardi et al., 1984: Table 3; Th, Ta, Hf, Sm and Yb values not available) are shown for comparison in (c) and (d).

main difference being the large volume of plagiogranite relative to FeTi-oxide gabbro in the Verné association. To our knowledge, such volumetric relationships have never been described, whereas primary relationships between plagiogranites and FeTi-oxide gabbros are not uncommon, even in the same dike (e.g. Montgenèvre ophiolite: Chalot-Prat et al., 2006; Lanzo peridotite massif: Kaczmarek and Müntener, 2005).

Previous workers (e.g. Piccardo, 1984; Hébert et al., 1989; Borsi et al., 1998) interpreted the plagiogranites as the final product of low-pressure differentiation of Na- and FeTi-rich liquids derived from N-MORB abyssal tholeiites. Current petrogenetic models for the origin of plagiogranites (see the recent discussions by Montanini et al., 2006 and Koepke et al., 2007) broadly fall into three categories: i) low-P partial melting, in the presence of a water-rich fluid, of MOR-type gabbroic rocks; ii) unmixing of a Fe-rich basalt liquid into two liquids of rhyolitic and Fe,Ti,P-rich compositions, respectively; iii) fractional crystallization of a basalt parental melt, generating liquids of dioritic composition through removal of Pl + Cpx + Mt+ Ap.

A partial melting origin for the plagiogranite veins and dikelets observed in the oceanic crust of slow spreading ridges (e.g. Niu et al., 2002) and in Alpine ophiolites (e.g. Montgenèvre, Caby, 1995) has been advocated by Koepke et al. (2004; 2007), who showed experimentally that partial melting of typical oceanic gabbros can result in the formation of plagiogranitic melts, provided that temperatures exceed 900°C and that a water-rich fluid phase is present (Koepke et al., 2004). This process does not seem to apply in the petrogenesis of the Verné association mainly for geological reasons, i.e. the association of the Verné plagiogranites with FeTi-oxide gabbros and their emplacement in ultramafic crust with no relationships with olivine gabbros.

Immiscible formation of siliceous and very iron-rich liquids has been invoked to explain some Skaergaard granophyres (McBirney, 1975), as well as siliceous rocks recovered in the ocean crust, that resemble the plagiogranites of certain ophiolites in composition, e.g. the trondhjemite veins described by Natland et al. (1991) in oxide gabbros from Hole 735B of the Southwest Indian ridge. Liquid immiscibility in the latest stages of tholeiite fractionation between two liquids of rhyolitic and Fe,Ti,P-rich compositions, respectively, has been proposed to explain the small volumes of plagiogranite associated with FeTi-oxide metagabbros in the Lanzo peridotite massif and Fonte Neiretto gabbro sequence (Pognante et al., 1982), and in Val d'Ala (Leardi et al., 1984) (Fig. 1). This model, however, suffers from two points of weakness: petrologically, liquid immiscibility was found only in experiments at 1 atm (Dixon and Rutherford, 1979) and was absent in the experiments at 0.1 GPa and low $f(O_2)$ on both primitive and more evolved oceanic tholeiites (Dixon-Spulber and Rutherford, 1983); geochemically, as noted by Montanini et al. (2006) for the Bartolina plagiogranite - FeTi-

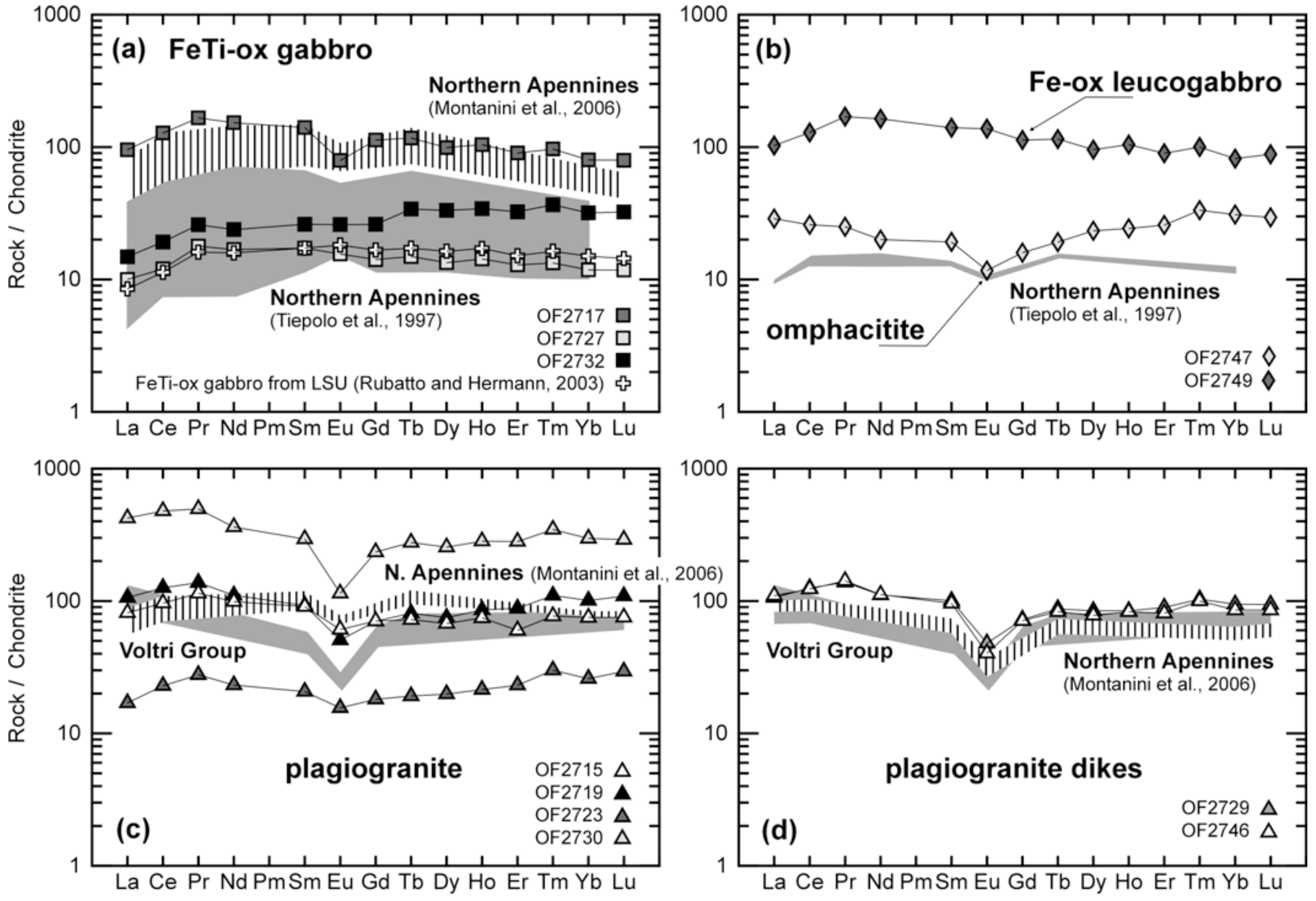

Fig. 8 - Chondrite-normalized REE patterns for FeTi-oxide gabbro (a), Fe-oxide leucogabbro and omphacitite (b), plagiogranite (c) and plagiogranite dikes (d) from Verné. Data of a Monviso FeTi-oxide gabbro from Lago Superiore Unit (Rubatto and Hermann, 2003: Table 1) are also shown in (a). The FeTi-oxide gabbros in (a) are compared to Fe-gabbroids from Northern Apennines (Tiepolo et al., 1997: Table 4; Pr, Ho, Tm, Lu values not available; Montanini et al., 2006: Table 3, Pr, Nd, Pd, Gd, Dy, Ho, Er and Tm values not available). The Fe-oxide leucogabbro in (b) is compared to gabbronorite from Tiepolo et al., 1997: Table 4). The plagiogranite (c) and plagiogranite dikes (d) are compared to plagiogranite REE patterns from the Voltri Group (Borsi et al., 1996: Table 1; Pr, Dy, Ho, Er and Tm values not available) and the Northern Apennines (Montanini et al., 2006: Table 3). Data normalized according to chondrite abundances of Nakamura (1974).

oxide gabbro association, highly-charged cations such as Zr, Hf, Nb, Ta, Y and the REE are variably enriched in the plagiogranites relative to the FeTi-oxide gabbros, as expected in a fractional crystallization process, whereas the opposite trend is expected in conjugate immiscible liquids. As shown in the previous section, the geochemical data indicate that also at Verné the plagiogranites are variably enriched in the above elements relative to the FeTi-oxide gabbros, precluding that liquid immiscibility may have played a major role in the genesis of the Verné association.

Plagiogranite genesis by fractional crystallization of a basalt parental melt (e.g. Niu et al., 2002) has been supported by a number of authors on Alpine and Apennine ophiolites (e.g. Tiepolo et al., 1997; Borsi et al., 1998; Montanini et al., 2006).

Fractional crystallization experiments at low $f(O_2)$ on primitive and more evolved oceanic tholeiites showed that liquid lines of descent at 0.1 GPa fluid pressure are characterized by an early iron enrichment and a gradual increase in silica due to the crystallization of olivine, high-Ca pyroxene and plagioclase (Dixon-Spulber and Rutherford, 1983). After the onset of Fe-Ti oxide crystallization, starting when the TiO_2 content of the residual melt reaches 2.2-2.4 wt%, the residual basaltic melt moves off on a strong silica enrichment trend, reaching andesite-like liquid compositions at about 30% residual liquid in the evolved tholeiite composition, and from 15 to 30% residual liquid in the primitive tholeiite composition. For higher degrees of crystallization, the residual melts produced after 90% crystallization are rhyolitic (SiO_2 = 73.1, Na_2O = 4.32, K_2O = 2.39 wt%) in the case of the evolved tholeiite from Kilauea, and a low-K_2O granitic melt (SiO_2 = 70.9, Na_2O = 3.58, K_2O = 0.43 wt%) in the case of the primitive tholeiite from the Galapagos Spreading Center. This latter liquid is similar in composition to plagiogranites of MOR and ophiolite suites (Dixon-Spulber and Rutherford, 1983). No liquid immiscibility was found in these experiments. More recent experiments at 0.2 GPa fluid pressure both at high and low $f(O_2)$ (Berndt et al., 2005) have confirmed such findings indicating that residual melts at 950°C from primitive MORB systems have compositions approaching those of oceanic plagiogranites in terms of SiO_2 and K_2O, but have Ca/Na ratios and FeO^* contents that are too high compared with the natural rocks, implying that further fractionation processes are necessary to reach typical compositions of natural oceanic plagiogranitic rocks.

In high-P fractional crystallization experiments on primitive tholeiitic basalt (Villiger et al., 2007), olivine and spinel are the liquidus phases at 1270°C. Clinopyroxene cristallizes at 1240°C together with olivine and spinel. The disappearance of olivine and the first occurrence of plagioclase occur at 1210°C. At 1090°C ilmenite begins to crystallize with clinopyroxene, plagioclase and spinel. Although phase relations are obviously different from those in low-P esperiments, also high-P fractionation causes a silica increase and a decrease in absolute iron and titanium concentrations in the last fractionation step, resulting in the production of an andesitic liquid.

As in the case of the Bartolina plagiogranites described by Montanini et al (2006), geochemical evidence suggests that fractionation of the FeTi-oxide gabbro mineral assemblage (Pl + Cpx + Fe-Ti ox + Ap ± Amph) may have been the dominant process generating the Verné plagiogranites. Borsi et al. (1998) modelled the genesis of plagiogranites from the Voltri Group and Sestri-Voltaggio Zone by pure fractional crystallization in a closed system under isobaric conditions (0.1 GPa) using the MELTS algorithm (Ghiorso and Sack, 1995). In the Borsi et al. (1998) model, after initial fractionation of olivine and olivine + plagioclase (in which about 12 mass% of liquid crystallizes), at 1104 °C an important crystallization stage of about 30% liquid produces the Fe-richest bulk composition similar to that of the FeTi-oxide gabbro from Verné. The solid phases at this stage are plagioclase (An_{53}), clinopyroxene ($Wo_{43}En_{47}Fs_{10}$), orthopyroxene ($Wo_4En_{78}Fs_{18}$) and spinel (Mt_{47}); these compositions are comparable to those of relict magmatic phases in the FeTi-oxide gabbro from Fonte Neiretto (Pognante et al., 1982). At this stage, the residual liquid has a broadly andesitic composition.

Afterwards, both liquid and solid compositions modelled by Borsi et al. (1998) are progressively depleted in iron and magnesium, and enriched in alkalies and silica, by fractional crystallization of plagioclase + clinopyroxene + orthopyroxene + spinel. During this process, the remaining liquid decreases from about 58 to 26 mass%. According to the modelled liquid compositions of Borsi et al. (1998), this liquid has a composition (at least in terms of SiO_2, Na_2O, FeO_{tot} and K_2O contents) similar to those of the Verné plagiogranites, suggesting that these rocks formed essentially from direct crystallization of such a residual liquid. Specifically, the average composition of the Verné plagiogranites is similar to that of a liquid intermediate between those of the two last fractionation stages of Borsi et al. in terms of SiO_2 (65.1 vs 65.5 wt%), FeO_{tot} (5.6 vs 5.1 wt%), and Na_2O (7.6 vs 7.8 wt%), but has higher Al_2O_3 (15.6 vs 10.8 wt%), and lower CaO (2.0 vs 4.8 wt%), MgO (0.8 vs 2.0 wt%) and TiO_2 (0.6 vs 1.3 wt%). However, it is worth noting that a major weakness of this approach consists in the assumption that major element compositions (in particular for Na_2O) of both the parental liquid and the ophiolite plagiogranites from Voltri and Sestri-Voltaggio (as well as those from Verné) are primary compositions not modified by hydrothermal alteration. Also, the compositions of residual melts appear to be very sensitive to the assumed composition of the parental melt.

In conclusion, fractional crystallization of an evolved tholeiite liquid of broadly andesite composition, with fractionation of FeTi-oxide gabbro to produce quartz diorite liquids that are suitable for direct crystallization of the main plagiogranite body, appears to be the petrogenetic model that best satisfies both geological and geochemical constraints in the Verné plagiogranite - FeTi-oxide gabbro association. The origin of the andesite liquid remains conjectural: low-P fractionation of primitive, mantle-derived tholeiitic basalt, as described above, or high-P fractionation of the same parental magma, with silica increase and a decrease in absolute iron and titanium concentrations in the last fractionation step, resulting in the production of an andesitic liquid (Villiger et al., 2007), are two equally possible alternatives.

The trondhjemite dikes from Verné, that are the most differentiated liquids, were probably emplaced through a different mechanism, i.e. deformation-controlled, late-stage melt migration in the near-solidified crystal mush of the plagiogranite (Dick and Natland, 1996).

CONCLUSIONS

The plagiogranite - FeTi-oxide gabbro association of Verné testifies at multistage plutonic activity in the Basal Serpentinite Unit of the southern Monviso metaophiolite complex. Differently from other occurrences in the Western Alps, where plagiogranite/trondhjemite are very minor members within olivine gabbro to FeTi-oxide gabbro suites (e.g. Castelli et al., 2002, with refs.), the Verné plagiogranite body is larger in size than the associated FeTi-oxide gabbros. Following actualistic models of the ocean crust (e.g. Dick et al., 1991; Thy, 2003), such an occurrence can be interpreted as the result of crystallization of an evolved tholeiite magma stored in an ephemeral chamber within ultramafic oceanic crust, now represented by the Basal Serpentinite Unit.

The restricted flux of magma, typical of fracture zones and slow-spreading ridges (e.g. Thy, 2003), will provide conditions for efficient fractionation. Geochemical data on the Verné association indicate that it can be interpreted as the product of fractional crystallization of an evolved tholeiite liquid of oceanic andesite composition in which fractionation of FeTi-oxide gabbro produces liquids that are suitable for direct crystallization of the main plagiogranite body. The plagiogranite dikes, representing the most differentiated liquids, were probably emplaced through deformation-controlled, late-stage melt migration.

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