

Geochemistry of eclogitised Fe-Ti-gabbros from various lithological settings (Aosta Valley ophiolites, Italian western Alps). Protolith composition and eclogitic paragenesis

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ABSTRACT. — Eclogitised Fe-Ti metagabbros were collected from the Piemonte ophiolites of the Aosta valley (Italian Western Alps). These rocks are either associated with Mg-metagabbros or serpentinites, and show the same homogeneous metamorphic imprint. Petrographic observations on pseudomorphic replacement in undeformed pods and on mineral assemblages in tectonic portions of the Fe-Ti metagabbros reveal the presence of three different high-pressure mineral parageneses. The first includes garnet, omphacite and rutile; the second consists of garnet, omphacite and glaucophane; and the third contains garnet, omphacite, tremolite and clinozoisite. Bulk rock chemical analyses show that all the studied samples derive from similar magmatic protoliths with tholeiitic affinity. However, differences in the amounts of major elements, namely TiO₂, Na₂O, CaO and REE (particularly LREE) were found between the Fe-Ti metagabbros associated with Mg-metagabbros and those occurring with serpentinites. Different chemical compositions account for the three distinct eclogitic parageneses which developed in the two groups of metagabbros. We infer that both magmatic processes and rock alteration in an oceanic environment may have contributed towards producing these chemical differences. We suggest

that Fe-Ti gabbros crystallizing from similar magmatic protoliths, as a consequence of the different extent of alteration in the oceanic environment, developed distinct mineral assemblages during subduction-related Alpine high-pressure metamorphism. This interpretation indicates that the early pre-Alpine history of the oceanic lithosphere in the Piemonte basin played an important role in determining the petrographic and geochemical features of its metamorphic products.

RIASSUNTO. — Sono stati studiati campioni di Fe-Ti gabbri eclogitici campionati nelle ofioliti Piemontesi della Valle d'Aosta (Alpi Occidentali Italiane). Queste rocce sono associate sia a Mg-gabbri metamorfici che a serpentiniti e mostrano un'impronta metamorfica simile. Lo studio petrografico dei campioni di ferrogabbri ha messo in luce la presenza di zone meno deformate, ove i minerali magmatici sono stati sostituiti pseudomorficamente da minerali metamorfici, e zone di shear dove la matrice cristallina ha subito più intensa ricristallizzazione dinamica. Nel complesso, sono state riconosciute tre diverse paragenesi metamorfiche: la prima è costituita da granato, onfacite e rutile; la seconda da granato, onfacite e glaucofane; la terza contiene granato, onfacite, tremolite e clinozoisite. I dati geochimici di roccia totale dei campioni di ferrogabbro indicano un'origine comune da protoliti ad affinità tholeitica. Tuttavia, i ferrogabbri associati a Mg-metagabbri

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mostrano alcune differenze nel contenuto di TiO_2 , Na_2O , CaO , and REE, in particolare LREE, rispetto ai ferrogabbri associati a serpentiniti. Tali differenze giustificano la presenza delle tre paragenesi eclogitiche distinte nei campioni studiati. Tali differenze composizionali vengono attribuite all'azione di processi sia magmatici, che di alterazione oceanica della roccia. È pertanto possibile che Fe-Ti gabbri cristallizzati da protoliti simili sviluppano, in seguito al diverso grado di alterazione subita in ambiente oceanico, paragenesi distinte durante il metamorfismo di alta pressione legato alla subduzione Alpina. Tale interpretazione suggerisce che la storia pre-Alpina precoce della litosfera oceanica nel bacino Piemontese ha giocato un ruolo importante nello sviluppo dei caratteri petrografici e geochimici dei suoi prodotti metamorfici.

KEY WORDS: *High pressure metamorphism, ophiolite, metagabbro, rodingite, Western Alps.*

INTRODUCTION

The ophiolites of the Western Alps represent a composite nappe system which assembled during the Alpine convergence from the oceanic lithosphere of the Jurassic Western Tethys (Dal Piaz and Ernst, 1978; Ernst and Dal Piaz, 1978; Martin *et al.*, 1994, and refs. therein). Within the ophiolitic rock-suite, magmatic protoliths are largely represented by Mg-rich gabbros and basalts with an N-MORB signature. Products of magmatic differentiation such as Fe-Ti-rich gabbros and trondhjemites have also been described (*e.g.* Bertrand *et al.*, 1982; Lombardo and Pognante, 1982; Baldelli *et al.*, 1985; Novo *et al.*, 1989; Mottana *et al.*, 1990). Since the 1980s, eclogitised Fe-Ti-gabbros from the Western Alps ophiolites have received much attention because of their better preserved magmatic texture and mineralogy (*e.g.* Pognante, 1979, 1981; Pognante *et al.*, 1982). These rocks have therefore been used to study the kinetics of eclogitic reactions (Pognante, 1984, 1985, 1988; Pognante and Kienast, 1987; Wayte *et al.*, 1989; Droop *et al.*, 1990) and post-eclogitic retrograde evolution (Messiga and Scambelluri, 1991). As suggested by Messiga and Scambelluri (1988), oceanic

alteration as well as rodingitic reactions in mafic rocks can modify the chemistry and texture of the magmatic protolith before the onset of high-pressure conditions. Examples of oceanic alteration in Fe-Ti-gabbro dykes enclosed in serpentinised peridotites from the Northern Apennine ophiolites have recently been described (Tribuzio *et al.*, 1997).

This paper presents new data on eclogitised Fe-Ti gabbros occurring in the southern Aosta valley ophiolites (Italian Western Alps). Two types of Fe-Ti-metagabbro are distinguished: type A Fe-Ti metagabbro, associated with metasediments or Mg-metagabbros; type B Fe-Ti-metagabbro, associated with antigorite serpentinites. Fe-Ti metagabbros and serpentinites of the second group underwent the same Alpine high-pressure evolution, suggesting that they were juxtaposed since the early stages of subduction (Battiston *et al.*, 1984). Type B metagabbros developed a peculiar Na-poor and Ca-rich mineral paragenesis which differs from that of type A metagabbros.

The aim of this paper is to unravel the problem of relationships between geological setting, mineral assemblages and geochemical characters of the two types of Fe-Ti metagabbros.

GEOLOGICAL SETTING AND FIELD RELATIONSHIPS

The Piemonte ophiolites of the Aosta valley (fig. 1) are regarded as a composite nappe system overthrusting the Penninic Gran Paradiso and Monte Rosa nappes and interlayered with continental crust slices of the Austroalpine system (Ballèvre *et al.*, 1986; Dal Piaz, 1999). On the basis of differences in the main lithological association and metamorphic evolution, the Piemonte ophiolites from the northern Aosta valley and southern Valais are divided into two main tectonic zones: *i*) Combin Zone, mainly consisting of calcschists showing epidote-blueschist- to greenschist-facies mineral parageneses, and *ii*) Zermatt-Saas Zone, mainly consisting of meta-

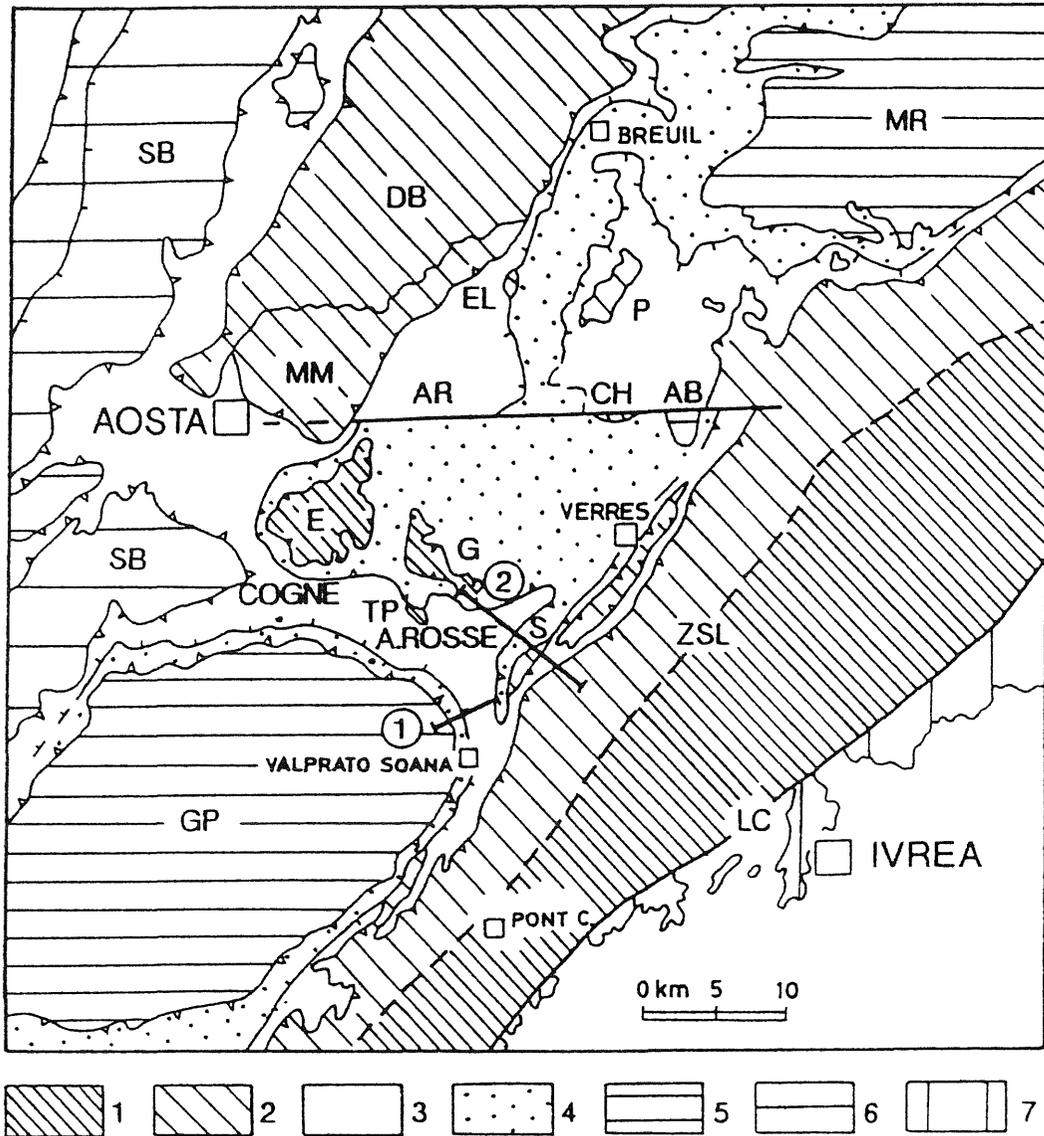


Fig. 1 – Tectonic sketch map of internal north-western Alps and location of geological sections reported in figure 2 (modified after Baldelli *et al.*, 1985). *Austroalpine system*: 1) eclogitic micaschists; 2) «Gneiss Minuti» complex, Arolla gneiss, kinzigitic units and Roisan zone, undifferentiated. SLZ: Sesia-Lanzo zone; DB: Dent Blanche s.s.; MM: Mt. Mary; EL: Etirol Levaz; P: Pillonet; E: Mt. Emilius; TP: Tour Ponton; G: Glacier-Rafray; S: Santanel; CH: Chatillon-St. Vincent. *Piemonte ophiolite nappe system*: 3) dominantly sedimentary units including décollement units of ocean-facing continental edges (Combin Zone in Northern Aosta valley and Valais); 4) dominantly oceanic units with high-pressure metamorphism (Zermatt-Saas zone in Northern Aosta valley and Zermatt). *Upper Internal Penninic units*: 5) Monte Rosa (MR), Gran Paradiso (GP), and Arcesa-Brusson (AB). *Middle Penninic units and Lower-External Penninic units*: 6) Gran San Bernardo multinappe system (Briançonnais) (SB); Sion-Courmayeur (SC) and Valais Zone. *Southern Alps*: 7) Canavese and Ivrea-Verbano zones. AR: Aosta-Ranzola fault system. LC: Canavese tectonic line.

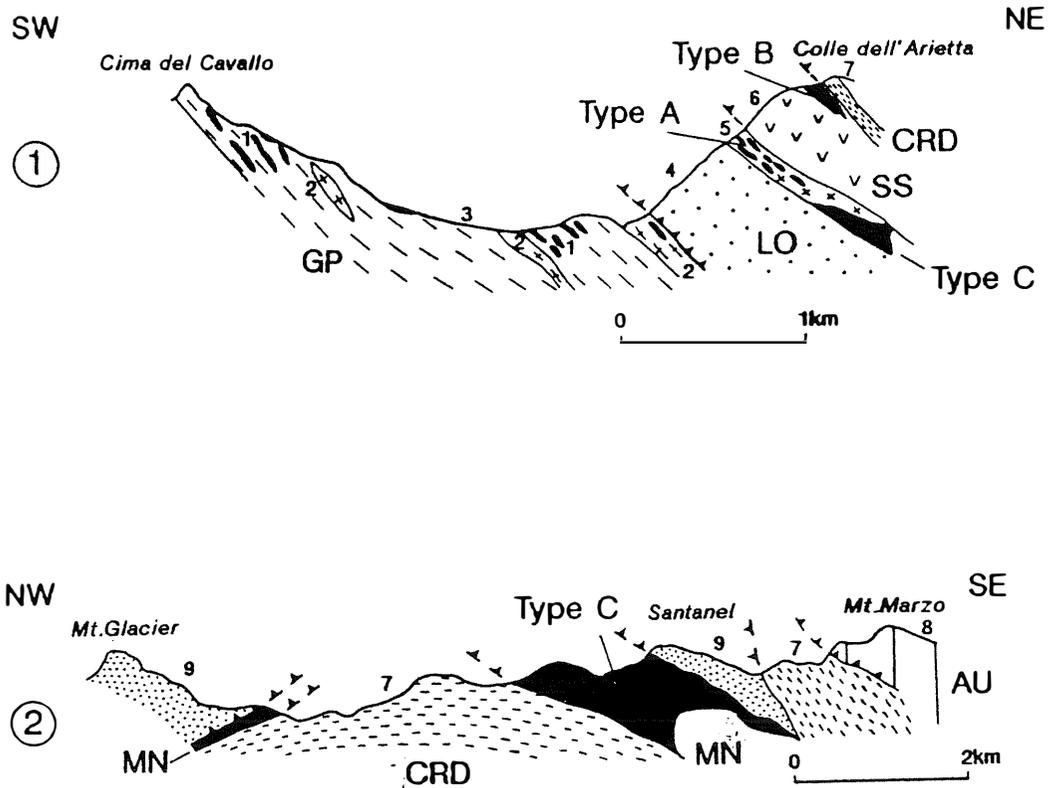


Fig. 2 – Geological sections across study area with ophiolitic units as defined in text (see fig. 1 for location). *Section 1*: Gran Paradiso nappe (GP) consisting of garnet-bearing micaschists (1) with eclogitic and amphibolitic layers and boudins (2), augen gneisses and metagranites (3); Lower Ophiolitic thrust sheet (LO) consisting of eclogitic metabasalts (4), metagabbros and eclogitic boudins (5); Serpentinitic thrust sheet (SS) with antigorite serpentinites (6); Colle della Rosa-Dondena unit (CRD) consisting of metasediments and minor metabasites (7). LO and SS sheets include metagabbros of type A and B, respectively (see text). Modified after Battiston *et al.* (1984). *Sections 2*: Australpine klippen of Glacier-Rafraay and Santanel consisting of retrogressed eclogitic micaschists (9); Monte Nero Upper Ophiolitic unit (MN) including metagabbros of type A; Australpine Sesia-Lanzo zone (AU) mainly consisting of albitic gneiss (8). Modified after Novo *et al.* (1989).

ophiolites with an eclogite-facies overprint (*i.e.* Bearth, 1967; Dal Piaz and Ernst, 1978; Sartori, 1987). In the southern Aosta valley, most of the Piemonte ophiolites exhibit lithological and metamorphic features similar to those of the Zermatt-Saas Zone (fig. 1). They also include thick sequences of prevailing calcschists, which may be compared to the Combin Zone but whose palaeogeographic location is still a matter of debate (*e.g.* Elter, 1971; Battiston *et al.*, 1984; Martin *et al.*, 1994).

In the study area, the following two ophiolitic slices are distinguished (figs. 1, 2): eclogitic Lower Ophiolitic thrust sheet (LO), overlying the eclogitic Penninic Gran Paradiso nappe (fig. 2, section 1); eclogitic Monte Nero Ophiolitic thrust sheet (MN; fig. 2, section 2). The LO sheet is structurally lower than the MN sheet, and the two are tectonically separated by greenschist-facies calcschists («CRD» unit in fig. 2). The upper boundary of the LO is made up of serpentinites forming the Serpentinitic thrust sheet (SS). The LO, MN and SS sheets,

in spite of their complex tectonic setting, are interpreted as deriving from the same original lithospheric section of the Tethyan ocean.

The LO slice shows lithological and metamorphic features similar to the Zermatt-Saas meta-ophiolites and may be correlated with the ophiolitic «Insieme B» defined by Elter (1971) in the Cogne Valley. The LO mainly consists of metagabbros and metabasalts showing an eclogite-facies metamorphic overprint (Battiston *et al.*, 1984; Benciolini *et al.*, 1984). These rocks are overlain by a metasedimentary cover of manganese-bearing metacherts of presumed Jurassic age, and by thin garnet-chloritoid-bearing calcschist layers. In the LO, the Fe-Ti metagabbros occur as decimetric to metric boudinaged layers within dominant Mg-Al metagabbros (type A metagabbros). Original intrusive contacts between these two lithologies are no longer recognizable.

The MN sheet consists of Fe-Ti metagabbros, metabasalts locally preserving pillow structure, scarce antigorite-serpentinite and magnetite-bearing chlorite-schists. In this case, the sedimentary cover has been sheared off. Unlike the LO sheet, the Fe-Ti metagabbros of the Monte Nero occur as 10-50m-scale bodies transposed with metatrandhjemites (Novo *et al.*, 1989). The MN sheet is overthrust by the eclogite-facies Austroalpine continental crust of the Santanel Klippe (Battiston *et al.*, 1984; fig. 2, section 2).

The SS sheet is made up of serpentinite consisting of antigorite, Ti-clinohumite, olivine and diopside, marking the main foliation of the rock. The serpentinites contain layers of eclogitised metabasalts and Fe-Ti metagabbros (type B metagabbros) parallel to the foliation of the country rocks.

Structural setting

In the studied area, Alpine metamorphism was accompanied by intense pervasive deformation. As a consequence, only a few records of the primary stratigraphy and structure of the original oceanic rock suite are

still detectable. The Alpine deformation was heterogeneous in the studied ophiolites on any scale, due to the different rheological behaviour of the rock inside a complex lithological assemblage. In less deformed pods, relics of the magmatic textures are still recognizable within the hardest lithologies (*i.e.* metagabbros, very rare in metabasalts), whereas in sheared zones the original texture has been completely obliterated.

In the LO sheet, the Fe-Ti metagabbro boudins, which show a well-preserved magmatic texture, are locally cross-cut by cm-scale shear zones bearing high-pressure mineral parageneses. The surrounding Mg-metagabbros are pervasively foliated and characterized by a high-pressure zoisite, glaucophane, Cr-rich phengite mineral assemblage, locally replaced by greenschist-facies minerals such as actinolite, chlorite and albite.

Within the strongly sheared SS sheet, the nature (magmatic or tectonic) of the serpentinite-metagabbro contacts is not clear. The Fe-Ti metagabbros of the SS sheet are pervasively deformed, but dm-scale undeformed gabbro pods sometimes occur.

Petrographic and geochemical studies were carried out on both the most and least deformed samples of Fe-Ti metagabbros (Table 1).

Metamorphic imprint

The ophiolites of the LO, MN, and SS thrust sheets underwent the same Alpine metamorphic evolution, as indicated by the similar Alpine eclogite-facies peak temperatures estimated from garnet-pyroxene pairs. Temperature values of 450-550°C were obtained by the garnet-clinopyroxene thermometer, and a minimal pressure of 1.2 GPa was obtained by the jadeite content of the clinopyroxene (Benciolini *et al.*, 1984, 1988). The mineral paragenesis of the serpentinites in the SS sheet, which are associated with eclogitised metabasalts and Fe-Ti metagabbros, includes metamorphic olivine, diopside, Ti-clinohumite and antigorite (Battiston *et al.*,

TABLE 1

Sample list of analysed metagabbros (see fig. 1 for location of sampling areas). A and B: type A and type B metagabbros as defined in text (A1 and A2 refer to different eclogitic parageneses).

| Sample | Sampling area | Tectonic slice | Type of Gabbro* | Magmatic texture | Tectonic texture | Eclogitic vein |
|--------|---------------|----------------|-----------------|------------------|------------------|----------------|
| U 27 | Acque Rosse | LO | A1 | _____ | _____ | |
| U 80 | Cogne valley | LO | A1 | _____ | | _____ |
| U 28 | Acque Rosse | LO | A1 | _____ | | |
| U 76 | Cogne valley | LO | A2 | _____ | _____ | |
| GP 879 | Soana valley | LO | A2 | _____ | | |
| U 69 | Cogne valley | LO | A2 | _____ | | |
| GP 560 | Soana valley | MN | A2 | _____ | _____ | |
| GP 412 | Soana valley | SS | B | _____ | _____ | |
| GP 846 | Soana valley | SS | B | _____ | _____ | |
| GP 860 | Soana valley | SS | B | _____ | _____ | |
| U 72 | Acque Rosse | SS | B | _____ | _____ | |
| U 74 | Acque Rosse | SS | B | _____ | _____ | |

* As defined in text

1984; Benciolini *et al.*, 1984). A similar mineral paragenesis in antigorite-serpentinites from the Erro-Tobbio peridotites is considered consistent with the high-pressure paragenesis of the enclosed metagabbros (Scambelluri *et al.*, 1991). This suggests that both serpentinites and Fe-Ti metagabbros of the SS sheet underwent common tectono-metamorphic evolution related to the subduction event.

MICROSCOPIC OBSERVATIONS

Relict magmatic texture

All the analysed samples are characterized by structural domains in which the gabbroic texture is well preserved, and by the occurrence of Ti-rich mineral phases such as rutile and titanite. These features identify a common origin from Fe-Ti-gabbro protoliths consisting of clinopyroxene (augite), plagioclase (andesine), and Fe-Ti-oxides (ilmenite+magnetite). Relics of olivine or orthopyroxene, as well as their metamorphic replacements in the eclogite facies (*e.g.* Pognante, 1979, 1981; Meyer, 1979; see a

review in Rubie, 1990) are completely absent. The undeformed portions of the metagabbro samples have coarse-grained granular texture (figs. 3a, 3b). The original size of plagioclase and pyroxene was probably of 5-10 mm. During Alpine tectono-metamorphic evolution, the original mineral assemblage was completely replaced by pseudomorphic mineral aggregates (see next section). Magmatic clinopyroxene was replaced pseudomorphically by large crystals of green pyroxene, in turn partially replaced by amphibole (up to 34 vol.%) and crowded with oxides (Fe-Mg site). Pyroxene clasts are rimmed by coronas of omphacite and amphibole. Magmatic plagioclase was in turn replaced by an aggregate of millimetric garnet, with scattered omphacite and clinozoisite (Si-Al site) or by an aggregate of zoisite + paragonite. Because of their rectangular shape and the occurrence of high modal clinozoisite (at least 95 vol.%), we suggest that these aggregates replaced a previous plagioclase. Mm-thick garnet coronas occur between the clinozoisite + paragonite domain and the nearby pyroxene site. Similar textures were observed by Pognante and

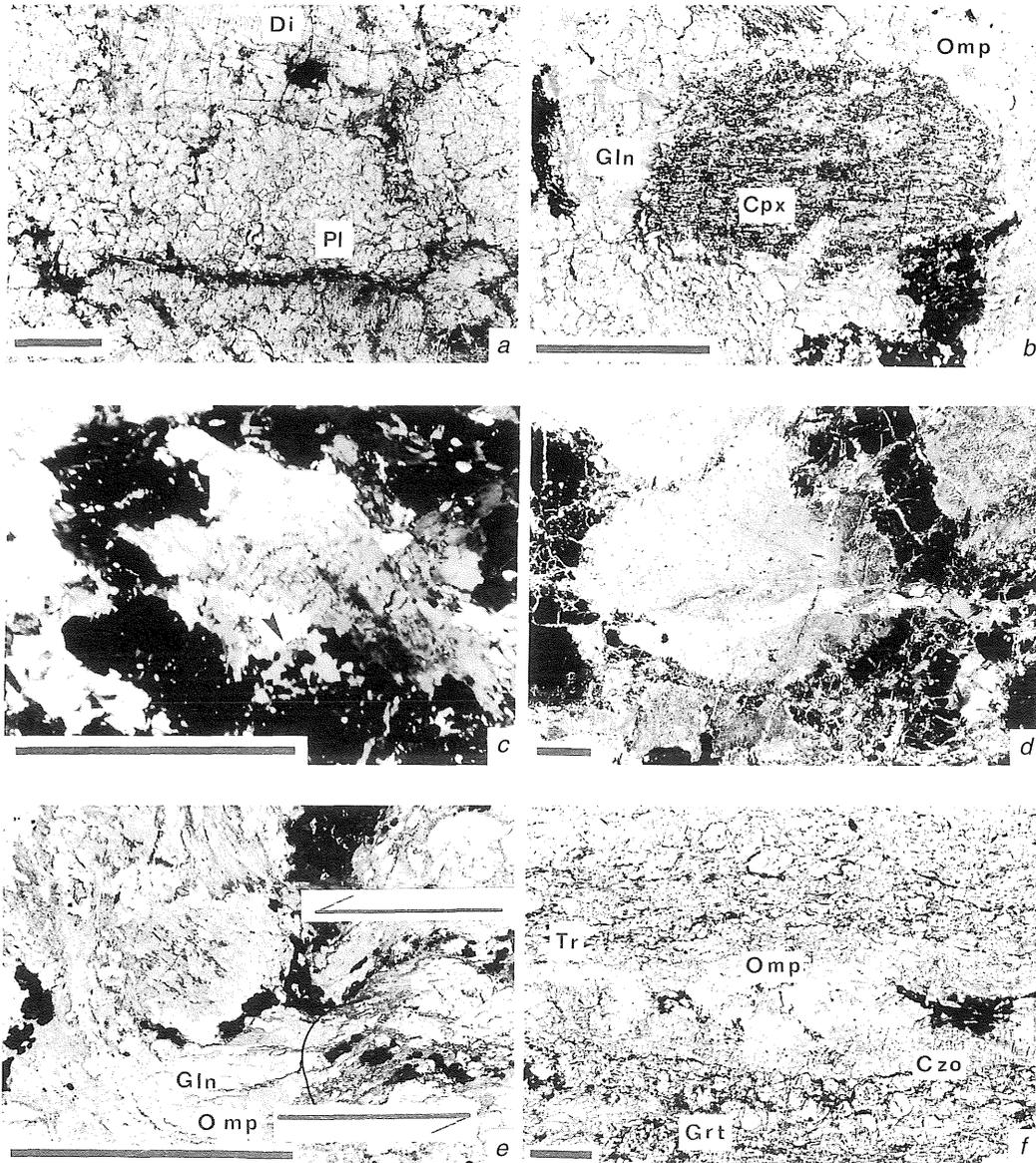


Fig. 3 – Photomicrographs of studied eclogitic metagabbros. *a*) Garnet + clinozoisite aggregates replacing magmatic plagioclase (Pl) and clinopyroxene replacing diopside (Di) in type B metagabbro. *b*) Green clinopyroxene (Cpx) rimmed by omphacite (Omp); glaucophane (Gln) grows along contacts between omphacite and garnet. *c*) Garnet-omphacite intergrowth (arrow); *d*) Eclogitic veins cross-cutting omphacite. *e*) Dynamic recrystallization of omphacite (Omp) and glaucophane (Gln) in a millimetric shear zone (arrows). *f*) Eclogitic paragenesis of type B metagabbro; omphacite (Omp), tremolite (Tr), clinozoisite (Czo), garnet (Grt). Scale bars in all pictures: 2 mm.

TABLE 2
Mineral abundances within tectonic (stable parageneses) and undeformed (metamorphic replacement) in A1, A2 and B type metagabbros.

| HP paragenesis | | | | Magmatic paragenesis | | | | HP paragenesis | | | |
|-----------------|--------------------|-------|-------|---------------------------|-----------------|-------------------------|-------|----------------|--|--|--|
| MINERALS | STABLE PARAGENESIS | | | MINERALS | | METAMORPHIC REPLACEMENT | | | | | |
| | A1 | A2 | B | | | A1 | A2 | B | | | |
| omphacite | ----- | ----- | ----- | Fe-Mg site (magm. Cpx) | green cpx | ----- | ----- | ----- | | | |
| garnet | ----- | ----- | ----- | | glaucophane | ----- | ----- | ----- | | | |
| glaucophane | ----- | ----- | ----- | | Na-Ca amphibole | ----- | ----- | ----- | | | |
| clinozoisite | ----- | ----- | ----- | | omphacite | ----- | ----- | ----- | | | |
| Na-Ca amphibole | ----- | ----- | ----- | Si-Al site (magm. Pl) | garnet | ----- | ----- | ----- | | | |
| rutile | ----- | ----- | ----- | | clinozoisite | ----- | ----- | ----- | | | |
| titanite | ----- | ----- | ----- | | paragonite | ----- | ----- | ----- | | | |
| | | | | | glaucophane | ----- | ----- | ----- | | | |
| | | | | | omphacite | ----- | ----- | ----- | | | |
| | | | | Ti-site | rutile | ----- | ----- | ----- | | | |
| | | | | | ilmenite | ----- | ----- | ----- | | | |
| | | | | | titanite | ----- | ----- | ----- | | | |
| ----- : common | | | | | | | | | | | |
| : rare | | | | | | | | | | | |

Kienast (1987) in the coronitic Fe-Ti metagabbros from Rocciavrè (Italian Western Alps). The Ti-rich domains, which developed after igneous ilmenite, consist of rutile, rimmed or locally replaced, by ilmenite and titanite.

Eclogitic transformations

Within the undeformed and tectonic portions of the studied Fe-Ti metagabbros, the following eclogitic mineral assemblages were observed (Table 2):

Type A metagabbros:

A1 paragenesis. Within undeformed portions, the Fe-Mg domains are composed of green pyroxene ($\text{Aug}_{62}\text{Acm}_{31}\text{Jd}_7$), rimmed by clear inclusion-free omphacite ($\text{Aug}_{44}\text{Acm}_{16}\text{Jd}_{40}$; fig. 3b), locally forming intergrowths with the garnet which grew at the expense of the nearby Si-Al site ($\text{Alm}_{65}\text{Prp}_{12}\text{Grs}_{24}$; fig. 3c). A discontinuous corona of green amphibole ($\text{Prg}_{77}\text{Gln}_{23}\text{Act}_0$) overgrows the green pyroxene. Small amounts of clinozoisite (up to 3 vol.%) have been found in the Si-Al site, but no glaucophane.

In the tectonic portions, garnet ($\text{Alm}_{63}\text{Prp}_{13}\text{Grs}_{24}$), omphacite ($\text{Aug}_{50}\text{Acm}_{25}\text{Jd}_{25}$) and rutile dynamically recrystallized at equilibrium. In this case, as in the other tectonic metagabbros, the dynamic recrystallization revealed by matrix-clast relationships supports the synchronous crystallization of the above-described eclogitic phases.

A sheared eclogite sample (U80) is cross-cut by a mm-thick vein filled with omphacite, titanite and carbonate (fig. 3d): this assemblage most probably crystallized in equilibrium with a syneclogitic fluid. In U80 sample the metamorphic clinopyroxene is a homogeneous omphacite.

A2 paragenesis. Within undeformed portions, glaucophane forms discontinuous coronas between the Fe-Mg-rich and Si-Al-rich sites. Nevertheless, glaucophane may locally include omphacite and vice versa. Both relationships suggest the stable occurrence of glaucophane in the eclogitic paragenesis: its presence along the contact between garnet-dominated or pyroxene-dominated sites may

have depended on the relative diffusion rate of Ca, Na, Fe and H. Rare glaucophane relics may be observed in the core of the Si-Al sites.

In the tectonitic portions, garnet ($\text{Alm}_{65}\text{Prp}_7\text{Grs}_{27}$), omphacite ($\text{Aug}_{50}\text{Acm}_{27}\text{Jd}_{23}$), glaucophane ($\text{Prg}_1\text{Gln}_{9,8}\text{Act}_1$) and rutile dynamically recrystallized at equilibrium (fig. 3e).

In type B metagabbros we observed:

B paragenesis. Within undeformed portions, omphacite represents a thin rim around the Fe-Mg sites, mainly composed of diopside ($\text{Aug}_{81}\text{Acm}_{10}\text{Jd}_9$); the Si-Al sites are characterized by high clinozoisite contents (37 vol.%) and contain Ca-rich garnet ($\text{Alm}_{51}\text{Prp}_9\text{Grs}_{40}$; fig. 3a). Locally, the Si-Al site is only composed of clinozoisite aggregates.

In the tectonitic portions, omphacite ($\text{Aug}_{54}\text{Acm}_{20}\text{Jd}_{26}$), green amphibole ($\text{Parg}_1\text{Gl}_{29}\text{Act}_{70}$), clinozoisite, garnet ($\text{Alm}_{58}\text{Prp}_{11}\text{Grs}_{31}$) and titanite dynamically recrystallized at equilibrium (fig. 3f).

BULK ROCK CHEMISTRY

Major and trace elements

Major and trace elements were determined at the Dipartimento di Scienze della Terra (Milan, Italy) by standard X-ray fluorescence on pressed powder pellets. Calibration was made on the international reference rock standards of appropriate composition, with mathematical corrections of matrix effects. FeO contents were determined by potentiometric titration with $\text{K}_2\text{Cr}_2\text{O}_7$ and loss on ignition (LOI), corrected for FeO oxidation, by gravimetry on powders heated to 1000°C.

Chemical data for eleven samples of type A and B metagabbros are listed in Table 3. The two types display an overall basic composition (Wilson, 1989) with SiO_2 ranging between ≈ 43 and ≈ 49 wt%, total alkalis ($\text{Na}_2\text{O}+\text{K}_2\text{O}$) up to ≈ 5 wt%, and a rather low (43-54) value of mg-number [$\text{Mg}\# = \text{Mg}/(\text{Mg}+\text{Fe}^{2+}+\text{tot})$] (Table 3). However, they show a wide range of variations

in some major and trace element concentrations. TiO_2 contents range from 3.34 to 6.04 wt% in type A and from 1.86 to 2.68 wt% in type B metagabbros (Table 3). Na_2O contents are distinctly higher in type A (ranging from 3.32 to 4.53 wt%) than in type B (from 0.76 to 2.01 wt%; Table 3). In contrast, CaO contents are lower in type A (from 7.87 to 13.16 wt%) than in type B (from 11.89 to 16.27 wt%) samples. Table 3 shows that the two groups also differ in the amount of large-ion lithophile elements such as Sr and Ba which, together with K and Rb, are considered to be mobile during metamorphism. The type B rocks are in fact enriched in Sr and depleted in Ba with respect to type A rocks; instead, K and Rb contents are very low in both rock types.

Trace elements of the transition group (V, Cr, Ni, Cu, Co; see Table 3) are highly variable in both rock types. Relative to oceanic gabbros, the studied samples are comparable or slightly richer in V, and have similar or slightly lower contents of Ni and Cu (Robinson *et al.*, 1989 : V = 634±1173 ppm, Ni = 10±31 ppm, Cu = 71±123 ppm in gabbros from the Indian Ocean; Cannat *et al.*, 1995 : V = 231±524 ppm, Ni = 63±213 ppm, Cu = 40±125 ppm in gabbros from the Atlantic Ocean). Cr is higher in type B rocks (ranging from 98 to 178 ppm) with respect to type A rocks (ranging from 22 to 40 ppm) and to oceanic gabbros (*op.cit.* : Cr = 1±6 ppm, and = 28±58 ppm in gabbros from the Indian and Atlantic Oceans, respectively). In any case, the proportions of V, Ni and Co in both rock types is typical of the middle stage of fractionation of a tholeiitic magma (Ishikawa, 1968).

Variations in high field-strength trace elements (HFSE) such as Zr, Y and Nb (regarded as essentially immobile during metamorphism; Table 3) are similar in both types of metagabbros and fall within the range of oceanic gabbros (*op.cit.* : Zr = 45±52 ppm, Y = 13±24 ppm, Nb = 3±5 ppm in Indian Ocean gabbros; *op.cit.* : Zr = 52±145 ppm, Y = 23±74 ppm, Nb = 4±22 ppm in Atlantic Ocean gabbros).

Variations in iron with the FeO^*/MgO ratio

TABLE 3

Major (wt%) and selected trace element (ppm) contents of analysed type A and type B metagabbros.

| Sample | TYPE A | | | | | | | TYPE B | | | | |
|--------------------------------|--------|--------|-------|--------|--------|--------|--------|--------|--------|--------|-------|-------|
| | U 27 | U80 | U 28 | U76 | GP 879 | U69 | GP 560 | GP 412 | GP 846 | GP 860 | U 72 | U 74 |
| SiO ₂ | 46.05 | 48.27 | 47.84 | 46.03 | 48.41 | 48.30 | 49.47 | 46.23 | 46.23 | 43.02 | 44.06 | 45.93 |
| TiO ₂ | 6.04 | 4.81 | 5.32 | 4.75 | 4.15 | 4.29 | 3.34 | 2.31 | 1.86 | 2.95 | 2.28 | 2.68 |
| Al ₂ O ₃ | 8.55 | 8.81 | 8.58 | 8.86 | 8.27 | 8.73 | 10.75 | 8.16 | 9.23 | 8.46 | 9.70 | 8.72 |
| Fe ₂ O ₃ | 6.99 | 4.37 | 5.75 | 6.67 | 5.99 | 6.64 | 5.91 | 7.46 | 7.67 | 5.11 | 8.67 | 7.21 |
| FeO | 10.31 | 9.43 | 8.44 | 12.11 | 9.37 | 10.42 | 8.59 | 9.23 | 5.79 | 12.51 | 8.32 | 9.44 |
| MnO | 0.24 | 0.28 | 0.14 | 0.21 | 0.23 | 0.29 | 0.21 | 0.36 | 0.19 | 0.29 | 0.36 | 0.25 |
| MgO | 7.09 | 6.22 | 7.12 | 8.68 | 7.40 | 8.01 | 6.11 | 9.34 | 8.36 | 9.63 | 7.93 | 9.21 |
| CaO | 10.18 | 13.16 | 11.02 | 8.71 | 10.81 | 7.87 | 9.87 | 15.78 | 16.27 | 13.35 | 14.08 | 11.89 |
| Na ₂ O | 3.41 | 3.72 | 3.87 | 3.32 | 4.15 | 4.44 | 4.53 | 0.76 | 1.55 | 1.64 | 1.75 | 2.01 |
| K ₂ O | 0.16 | 0.04 | 0.18 | 0.08 | 0.01 | 0.09 | 0.29 | 0.00 | 0.01 | 0.17 | 0.06 | 0.05 |
| P ₂ O ₅ | 0.05 | 0.03 | 0.02 | 0.05 | 0.10 | 0.04 | 0.12 | 0.07 | 0.24 | 0.02 | 0.26 | 0.26 |
| LOI | 1.14 | 1.06 | 0.94 | 1.42 | 1.24 | 1.29 | 1.04 | 1.12 | 1.99 | 2.97 | 2.07 | 1.50 |
| Total | 100.21 | 100.20 | 99.22 | 100.89 | 100.13 | 100.41 | 100.23 | 100.82 | 99.39 | 100.12 | 99.54 | 99.15 |
| FeO*/MgO | 2.34 | 2.15 | 1.91 | 2.09 | 1.99 | 2.05 | 2.28 | 1.71 | 1.52 | 1.78 | 2.03 | 1.73 |
| FeO*/ (FeO*+MgO) | 0.70 | 0.68 | 0.66 | 0.68 | 0.67 | 0.67 | 0.69 | 0.63 | 0.60 | 0.64 | 0.67 | 0.63 |
| FeO* | 16.60 | 13.36 | 13.62 | 18.11 | 14.76 | 16.40 | 13.91 | 15.94 | 12.69 | 17.11 | 16.12 | 15.93 |
| Mg# | 43 | 45 | 48 | 46 | 47 | 47 | 44 | 51 | 54 | 50 | 47 | 51 |
| Rb | 0 | 0 | 3 | 2 | 0 | 0 | 4 | 0 | 0 | 2 | 0 | 0 |
| Sr | 48 | 148 | 51 | 67 | 58 | 42 | 71 | 167 | 173 | 206 | 219 | 105 |
| Ba | 117 | 87 | 85 | 108 | 67 | 114 | 99 | 34 | 26 | 80 | 46 | 53 |
| Cu | 45 | 14 | 51 | 48 | 32 | 44 | 17 | 12 | 29 | 0 | 0 | 25 |
| Zn | 121 | 97 | 75 | 139 | 118 | 131 | 113 | 87 | 126 | 69 | 119 | 134 |
| Pb | 1 | 3 | 2 | 1 | 3 | 6 | 2 | 4 | 4 | 9 | 9 | 6 |
| Ni | 47 | 138 | 58 | 45 | 88 | 34 | 26 | 85 | 70 | 198 | 87 | 99 |
| Zr | 66 | 63 | 59 | 60 | 61 | 65 | 107 | 76 | 82 | 60 | 106 | 108 |
| Nb | 6 | 5 | 4 | 1 | 3 | 2 | 5 | 4 | 3 | 1 | 3 | 4 |
| V | 943 | 908 | 1110 | 1030 | 884 | 971 | 637 | 457 | 420 | 726 | 482 | 626 |
| Y | 44 | 44 | 43 | 39 | 43 | 40 | 38 | 37 | 40 | 38 | 37 | 38 |
| Cr | 26 | 33 | 40 | 30 | 31 | 28 | 22 | 178 | 166 | 98 | 123 | 106 |
| Co | 84 | 70 | 75 | 96 | 78 | 92 | 59 | 65 | 68 | 99 | 74 | 79 |

LOI = loss on ignition; FeO* = total Fe; Mg# = Mg/(Mg+Fe²⁺)

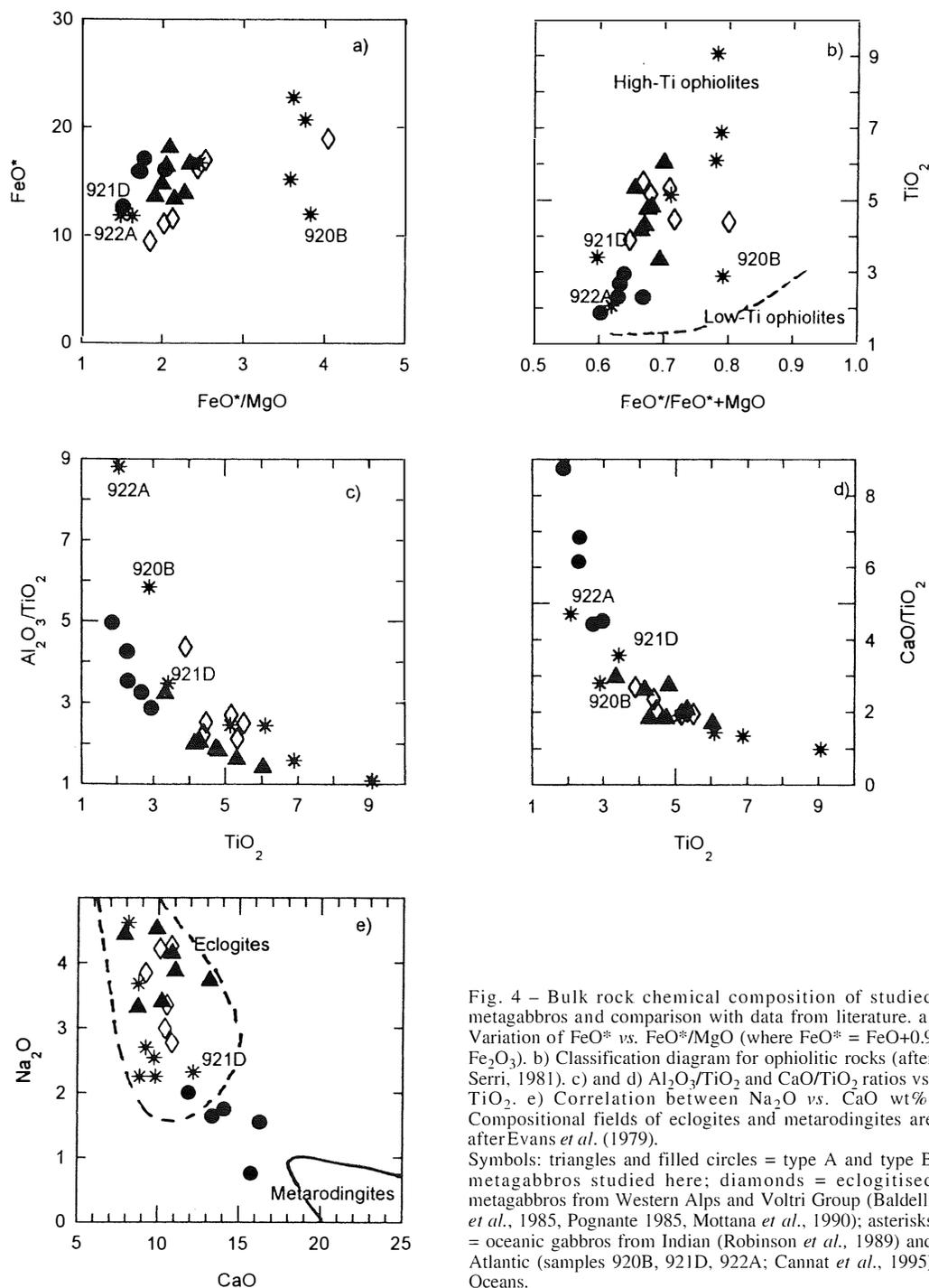


Fig. 4 – Bulk rock chemical composition of studied metagabbros and comparison with data from literature. a) Variation of FeO^* vs. FeO^*/MgO (where $FeO^* = FeO + 0.9 Fe_2O_3$). b) Classification diagram for ophiolitic rocks (after Serri, 1981). c) and d) Al_2O_3/TiO_2 and CaO/TiO_2 ratios vs. TiO_2 . e) Correlation between Na_2O vs. CaO wt%. Compositional fields of eclogites and metarodngites are after Evans *et al.* (1979). Symbols: triangles and filled circles = type A and type B metagabbros studied here; diamonds = eclogitised metagabbros from Western Alps and Voltri Group (Baldelli *et al.*, 1985, Pognante 1985, Mottana *et al.*, 1990); asterisks = oceanic gabbros from Indian (Robinson *et al.*, 1989) and Atlantic (samples 920B, 921D, 922A; Cannat *et al.*, 1995) Oceans.

of the analysed rocks (fig. 4a) are similar to those of other Fe-Ti-rich eclogitised gabbros from the Western Alps and the Voltri Group (Baldelli *et al.*, 1985; Pognante, 1985; Mottana *et al.*, 1990) and of some Fe-Ti-oxide-rich gabbros from the Indian and Atlantic Oceans, and is consistent with a tholeiitic affinity. Figure 4b shows that the analysed samples plot in the field of «high-Ti» ophiolites (Serri, 1981), as well as the Fe-Ti-metagabbros from the Western Alps and Voltri Group. Type B samples have the lowest Ti contents, similar to those of two oceanic gabbro samples from ODP Holes 920B and 922A (Cannat *et al.*, 1995).

All the analysed rocks show a strong antipathetic correlation between TiO_2 and $\text{Al}_2\text{O}_3/\text{TiO}_2$ and CaO/TiO_2 ratios (figs. 4c, 4d). A similar feature was also reported by Sun *et al.* (1979) for mid-ocean basalts (MORB). However, the high contents of TiO_2 of both A and B types, as well as those of the Fe-Ti metagabbros from the Western Alps and Voltri Group, remove them from the field defined by MORBs (Sun *et al.*, 1979). Conversely, the same position is occupied by the Fe-Ti-oxide-rich gabbro samples from the Indian and Atlantic Oceans, *i.e.* the rocks which have been shown to match the present ones most closely.

The relatively low Na_2O and high CaO contents observed in type B samples may be due to either: *i*) inheritance from the magmatic protolith; or: *ii*) metasomatic processes (*e.g.* rodingitisation; see discussion), which affected the gabbros before the high-pressure Alpine metamorphism (Dal Piaz, 1969, 1971; Evans *et al.*, 1979, 1981; Morten *et al.*, 1985). The occurrence of fresh oceanic Fe-gabbros with CaO and Na_2O contents quite similar to those of type B metagabbros (*i.e.* sample 921D in fig. 4e) is in favour of the former hypothesis; however, the occurrence of type B rocks inside serpentinites favours the latter hypothesis. If metasomatic processes did occur, their effects must have been limited. Even type B rocks (enriched in lime and depleted in sodium) plot out of the «eclogite» composition field as

defined by Trommsdorff *et al.* (1975) and Evans *et al.* (1979) for the Cima-Lunga eclogite-metarodingite suite, but none of them plot in the «metarodingite» field ($\text{CaO} > 18$ wt%; $\text{Na}_2\text{O} < 1$ wt%) as defined by Evans *et al.* (1979) (fig. 4e).

K depletion has already been observed in the eclogitic ferrogabbros from the Voltri Group and interpreted to reflect very low contents of K in the parent rocks (Morten *et al.*, 1977, 1978). Instead, K together with Rb and large-ion lithophile elements are considered to be highly mobile during metamorphism or alteration and weathering processes (Evans *et al.*, 1981; Morten *et al.*, 1985).

Rare Earth Elements

REE analyses were carried out at the Centre de Recherches Petrographiques et Géochimiques, CNRS (Vandoeuvre les Nancy, France) by inductively coupled plasma-mass spectrometry (ICP-MS). Results are listed in Table 4. Chondrite-normalised REE patterns (Nakamura, 1974) are shown in fig. 5.

The total amount of REE is generally lower in type A than in type B rocks. The chondrite-normalised REE patterns (fig. 5) of all the examined samples are characterized by a $(\text{La}/\text{Ce})_N$ ratio < 1 , more or less pronounced LREE scattering (from 2 to 40 times chondrite) and convergence towards HREE (from 9 to 10 times chondrite).

The REE patterns of both rock types are relatively flat. The $(\text{La}/\text{Yb})_N$ ratio is < 1 in both metagabbro types (ranging between 0.22 ± 0.91 ; Table 5). Type A metagabbros display a Eu/Eu^* ratio > 1 (1.10-1.54), indicating a slightly positive Eu anomaly. In contrast, the Eu/Eu^* ratio of type B rocks is ≤ 1 (0.97-1.05). The exception is sample GP860 (type B), which has a higher $(\text{La}/\text{Yb})_N$ ratio (1.59) than all the other samples, thus producing a moderately negative slope towards HREE (fig. 5), and a higher Eu/Eu^* ratio (1.26) than that of the other type B rocks.

TABLE 4
REE abundances (ppm) of type A and type B metagabbros.

| Sample | TYPE A | | | | | | | TYPE B | | | | |
|----------------------|--------|-------|-------|-------|--------|-------|--------|--------|--------|--------|-------|-------|
| | U 27 | U80 | U 28 | U76 | GP 879 | U69 | GP 560 | GP 412 | GP 846 | GP 860 | U 72 | U 74 |
| La | 1.52 | 1.24 | 2.45 | 1.28 | 0.89 | 1.72 | 4.57 | 3.53 | 3.85 | 9.39 | 4.83 | 3.64 |
| Ce | 5.26 | 3.59 | 7.74 | 4.65 | 3.22 | 5.83 | 14.51 | 9.76 | 12.73 | 29.11 | 14.46 | 15.02 |
| Pr | 1.01 | 0.62 | 1.35 | 0.92 | 0.65 | 1.01 | 2.32 | 1.64 | 2.25 | 4.71 | 2.75 | 2.93 |
| Nd | 6.12 | 3.72 | 7.67 | 5.50 | 3.80 | 5.88 | 12.26 | 9.09 | 12.57 | 24.95 | 15.35 | 17.91 |
| Sm | 2.40 | 1.19 | 2.30 | 2.12 | 1.75 | 2.52 | 4.01 | 3.45 | 4.61 | 6.74 | 5.46 | 7.31 |
| Eu | 1.34 | 0.54 | 0.87 | 1.19 | 0.92 | 1.38 | 1.41 | 1.30 | 1.58 | 2.49 | 1.90 | 2.38 |
| Gd | 2.96 | 1.35 | 2.46 | 2.73 | 2.57 | 3.42 | 3.89 | 4.19 | 5.20 | 5.46 | 6.29 | 7.79 |
| Tb | 0.60 | 0.33 | 0.52 | 0.59 | 0.64 | 0.69 | 0.87 | 0.92 | 1.05 | 1.01 | 1.24 | 1.54 |
| Dy | 3.96 | 2.46 | 3.40 | 4.05 | 4.43 | 4.87 | 6.45 | 7.39 | 7.04 | 6.63 | 7.90 | 9.54 |
| Ho | 0.97 | 0.67 | 0.80 | 0.96 | 1.09 | 1.19 | 1.51 | 1.92 | 1.68 | 1.57 | 1.97 | 2.20 |
| Er | 2.35 | 1.73 | 1.87 | 2.34 | 2.72 | 3.13 | 3.92 | 4.87 | 4.08 | 3.70 | 4.77 | 5.39 |
| Tm | 0.39 | 0.28 | 0.28 | 0.37 | 0.38 | 0.50 | 0.61 | 0.77 | 0.65 | 0.60 | 0.75 | 0.84 |
| Yb | 2.38 | 1.94 | 1.80 | 2.53 | 2.69 | 3.60 | 4.05 | 5.00 | 4.45 | 3.94 | 5.13 | 5.58 |
| Lu | 0.39 | 0.33 | 0.29 | 0.40 | 0.42 | 0.53 | 0.66 | 0.78 | 0.67 | 0.61 | 0.80 | 0.89 |
| Total | 31.65 | 19.99 | 33.80 | 29.63 | 26.17 | 36.27 | 61.04 | 54.61 | 62.41 | 100.91 | 73.60 | 82.96 |
| LREE/HREE | 1.17 | 1.14 | 1.88 | 1.04 | 0.69 | 0.94 | 1.72 | 1.06 | 1.45 | 3.19 | 1.49 | 1.39 |
| (La/Ce) _N | 0.76 | 0.91 | 0.83 | 0.72 | 0.73 | 0.78 | 0.83 | 0.95 | 0.80 | 0.85 | 0.88 | 0.64 |
| (La/Yb) _N | 0.43 | 0.43 | 0.91 | 0.34 | 0.22 | 0.32 | 0.76 | 0.47 | 0.58 | 1.59 | 0.63 | 0.44 |
| (La/Sm) _N | 0.39 | 0.64 | 0.66 | 0.37 | 0.31 | 0.42 | 0.70 | 0.63 | 0.52 | 0.86 | 0.55 | 0.31 |
| (Ce/Sm) _N | 0.51 | 0.71 | 0.79 | 0.52 | 0.43 | 0.54 | 0.85 | 0.66 | 0.65 | 1.01 | 0.62 | 0.48 |
| (Tb/Yb) _N | 1.18 | 0.80 | 1.35 | 1.09 | 1.11 | 0.90 | 1.01 | 0.86 | 1.10 | 1.20 | 1.13 | 1.29 |
| Eu/Eu* | 1.54 | 1.12 | 1.12 | 1.52 | 1.33 | 1.45 | 1.10 | 1.05 | 0.99 | 1.26 | 1.00 | 0.97 |

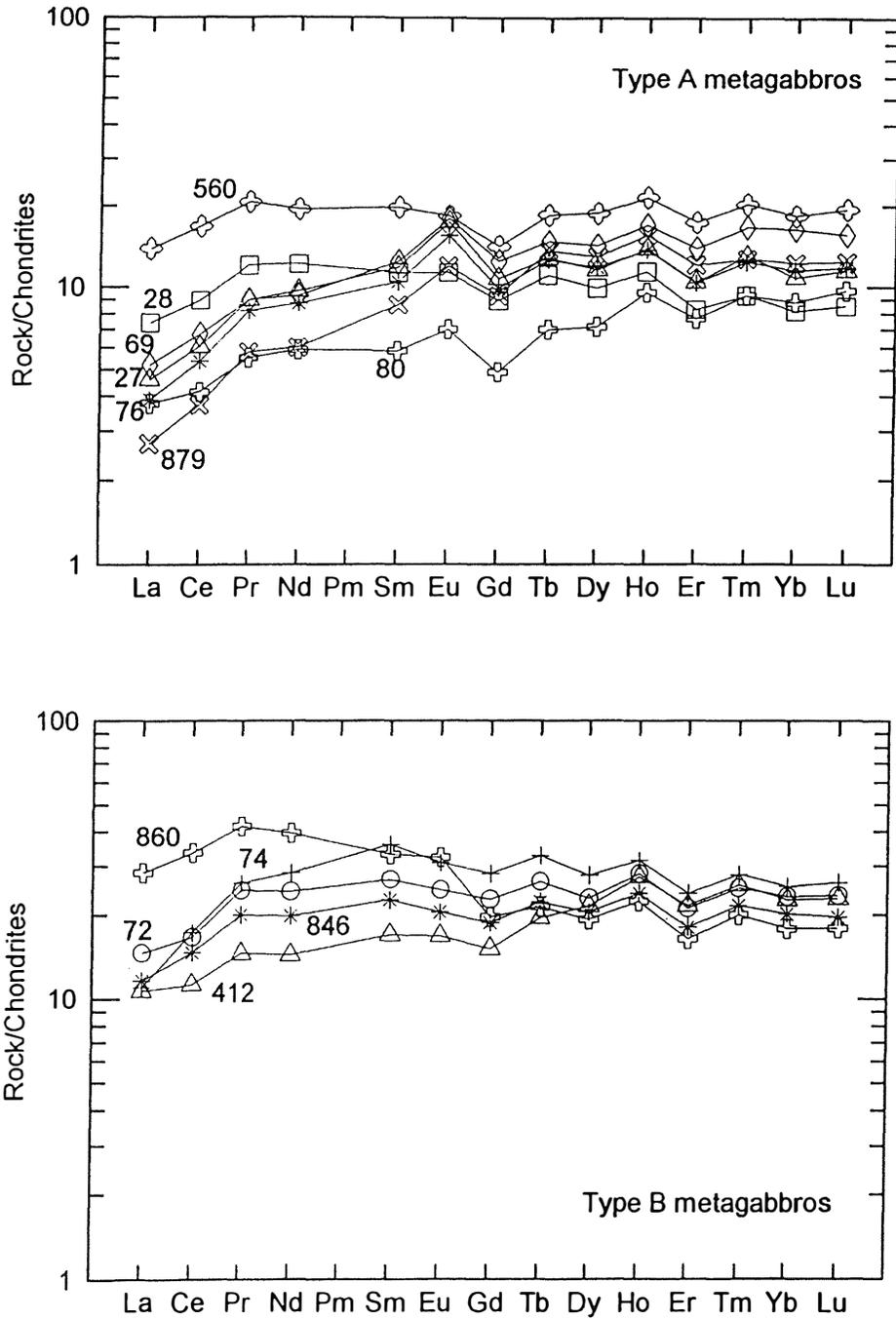


Fig. 5 – Chondrite-normalized REE abundances for studied Fe-Ti metagabbros of types A and B.

The chondrite-normalised REE patterns of the studied samples, excluding GP 860, resemble those of the N-MORBs (Saunders, 1984), which is characterised by a $(La/Ce)_N$ ratio <1 , and those of oceanic gabbros from the Mid-Atlantic Ridge (Kay *et al.*, 1970; Ghose, 1997; Ross and Elthon, 1997; Barling *et al.*, 1997). Type B rocks are enriched in La and Ce with respect to type A rocks: this may be due to effects of either low-temperature alteration (*cf.* Zimmer *et al.*, 1995) or a metasomatic process (Cotkin, 1997). Instead, type B rocks display LREE patterns different from those observed in metarodingites from the Central Alps (Evans *et al.*, 1981), indicating that the presumed process of metasomatism did not significantly change the REE concentrations of type B metagabbros, and confirming the generally accepted immobility of REE during eclogite mineral crystallization (*e.g.* Shatsky *et al.*, 1990).

Discussion

On the basis of major-, trace- and rare earth-element data, types A and B metagabbros appear to have originated from tholeiitic melts with N-MORB affinity, although mobile elements such as Ca, Na, Ba, Sr and K are highly variable. Petrographic observations highlight the absence of orthopyroxene and olivine in the magmatic mineralogy. Consequently, our samples may be compared with oceanic Fe-Ti oxide gabbros (Robinson *et al.*, 1989; Cannat *et al.*, 1995). Instead, their Na_2O and CaO contents are different from those observed in unaltered orthopyroxene- and olivine-free oceanic Fe-gabbros. This question may be unravelled by considering the correspondence between bulk Na_2O , CaO contents and compositions of eclogitic parageneses in type A (A1 and A2 parageneses) and type B rocks. The CaO- Na_2O -(FeO+MgO+MnO) diagram plots the bulk rock chemical compositions of these metagabbros and compares them with the compositional field defined by magmatic mineral parageneses from oceanic gabbros (fig. 6a), and with that defined by the observed

eclogitic parageneses (fig. 6b). Figure 6a shows that low Na_2O and high CaO contents are restricted to samples of type B, which therefore plot, at least partly, outside of the field defined by magmatic parageneses. Nevertheless, Na_2O contents inversely correlate with CaO contents in all samples (see fig. 4e), suggesting the importance of plagioclase alteration and the possibility of rock-seawater interaction. We have also seen (fig. 4) that CaO is inversely correlated with TiO_2 and Al_2O_3 contents, suggesting the interference of magmatic processes. Figure 6b shows that the different eclogitic parageneses are explained by their different chemical bulk compositions. Glaucophane-bearing A2 paragenesis is found in Na_2O -rich samples and clinzoisite-bearing B paragenesis in Na_2O -poor and CaO-rich ones. These chemical differences may reflect either varying plagioclase and clinopyroxene modal proportions in the protolith, or secondary pre- or syn-eclogitic alteration. The second hypothesis is also supported by the field location of type B metagabbros within serpentized peridotites.

On the basis of petrographic and geochemical data, we infer that both magmatic and secondary processes contributed towards distinguishing type A from type B metagabbros. These two aspects are discussed in the following sections.

Magmatic processes

The composition of the gabbroic protolith was mainly controlled by varying proportions of plagioclase and clinopyroxene, magnetite and/or ilmenite. Since all the examined rocks were variably metamorphosed (Benciolini *et al.*, 1988 and refs. therein), quantitative evaluation of the fractional crystallization process is precluded. Moreover, the compositions of the two gabbro types may have been influenced by different depths of crystallization and oxidation states (Pognante *et al.*, 1982; Ernst *et al.*, 1983).

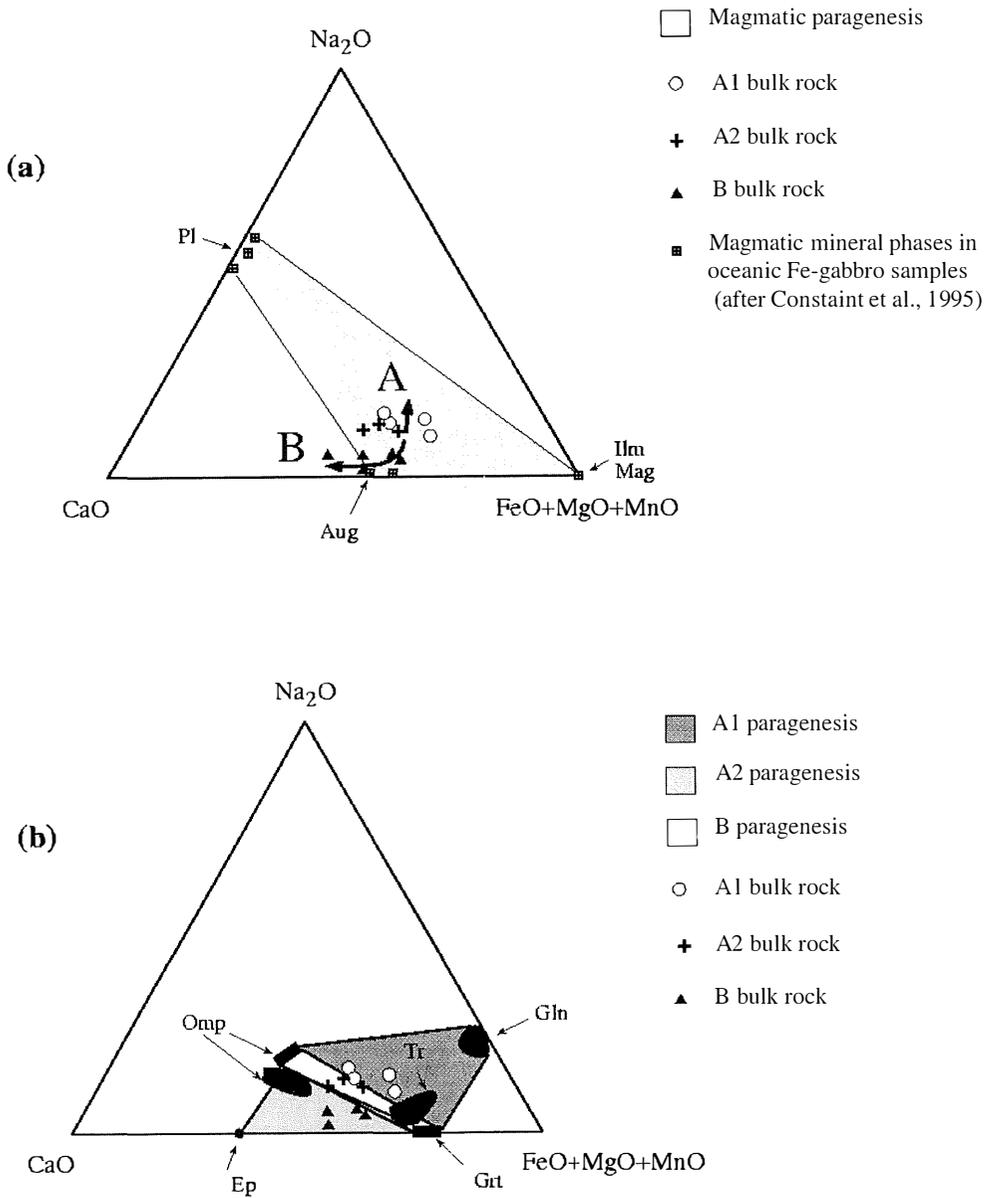


Fig. 6 – Na₂O-CaO-(FeO+MgO+MnO) diagram showing relationships between bulk rock chemistry and magmatic (a) and eclogitic (b) mineral parageneses in studied metagabbros. a) Possible magmatic paragenesis inferred following mineral chemistry reported in Constantin *et al.* (1995). Arrows A and B suggest possible chemical pre-eclogitic evolution of type A2 and type B samples respectively, as discussed in text. b) Bulk rock compared with observed eclogitic A1, A2 and B eclogitic parageneses. Mineral compositions detected with conventional microprobe analysis (Benciolini *et al.*, 1984).

The higher TiO₂ contents of type A Fe-Ti-metagabbros are consistent with the greater depth of crystallization of the original mafic bodies. Moreover, the lower concentrations of REE in these rocks, although within the range of REE in fresh oceanic gabbros, associated with positive Eu anomalies, suggest that substantial amounts of calcic plagioclase crystallized together with clinopyroxene. This differentiation trend is also a reflection of relatively low oxygen fugacities (ilm>mag), once again reflecting a greater depth of crystallization. By contrast, the lower TiO₂ and higher REE contents of type B rocks testify that their protoliths probably crystallized at shallow depths in higher oxidation conditions (mag>ilm). These conditions also favoured enrichment of LREE and chromium.

Alteration and metamorphic processes

All type B samples show very low Na₂O and relatively high CaO contents with respect to unaltered oceanic gabbros. Therefore, their composition may have been affected by chemical exchanges with the surrounding serpentinites (rodingitization?; e.g. Morten *et al.*, 1985) or high-temperature oceanic alteration (T> 300°C, Harper *et al.*, 1988; Rose and Bird, 1994). The high Ca values of these samples are accompanied by low Ti values. This correlation cannot easily be explained in terms of alteration or metasomatic reactions and must reflect the magmatic features described above.

Type A metagabbros show variable amounts of mobile elements. Only samples with relatively low Na₂O contents (e.g. U76 and U27) can be compared with unaltered oceanic gabbros. The relatively high Na₂O contents of the other samples (e.g. sample GP560) may have been caused by alteration processes, as described below.

Hydrothermal alteration. Rock-seawater interactions in the oceanic environment have been extensively studied (e.g. Humphris and Thompson, 1978; Erzinger, 1989). The effects of such interactions on bulk rock chemistry mainly depend on temperature and rock-

seawater ratio. Both low- (T< 150°C) and high-temperature (T> 200°C) alterations with low rock-seawater ratios lead to leaching of Na. Alteration at high temperatures (T> 200°C) with high rock-seawater ratios is characterized by enrichment in Na and Fe and depletion in Zn, Si, Mn, Cu, Ca, and Mg.

Alteration by metamorphic fluids. Interactions between rock and metamorphic fluids in high-pressure conditions have recently been investigated by fluid inclusion studies in eclogite-facies ophiolites from the Monviso area (Western Alps), where significant concentrations of Na, Mg, Fe, K, Ca, Ba, Ti and LREE were found in syneclogitic veins (Philippot and Kienast, 1989); Philippot and Selverstone, 1991; Nadeau *et al.*, 1993). This does not necessarily imply that the transformation of Fe-gabbros into eclogites is accompanied by large-scale REE mobilization, as suggested by Tribuzio *et al.* (1996). However, it may partly explain some Ca, Na, Ti and LREE anomalies in the type B metagabbros. Mantle serpentinites associated with mafic rocks in the subducting slab are a potential source for REE during metasomatic reactions (Tribuzio *et al.*, 1996). Lastly, the possible occurrence of mm-thick eclogitic veins near the studied samples may also be taken into account, as well as the glaucophane concentration in high-pressure shear zones.

Summing up, we suggest that type B metagabbros characterized by high Ca and low Na contents represent partly rodingitized rocks, and that type A metagabbros with high Na contents represent Fe-Ti-gabbros that were altered in the oceanic environment in high-temperature conditions and at a high rock-seawater ratio. The relevance of high-pressure metamorphic fluids is restricted to samples in which eclogitic veins were found.

The inconsistency of the Na₂O and CaO contents of our samples with the magmatic mineralogy must be confirmed by mass transfer calculations, and inferred pre-eclogitic alteration must be confirmed by isotope geochemistry. These works are in progress, and mass transfer calculations, in accordance with

the given hypothesis, will be presented in a forthcoming paper. They confirm the inconsistency of the bulk CaO and Na₂O wt% contents of the studied samples with microstructural and microchemical features.

CONCLUSIONS

We studied two groups of eclogitised Fe-Ti gabbros (type A and type B metagabbros, respectively) showing different bulk rock compositions and mineral assemblages. All the analytical data are compatible with the origin of their protoliths from consanguineous magmas with tholeiitic affinity. However, the protoliths of type B gabbros, depleted in titanium and enriched in REE, probably crystallized at shallower levels and in higher oxidation conditions than the protoliths of type A gabbros. Field relations as well as metamorphic and chemical features suggest that type B metagabbros were associated with serpentinites and were partly rodingitized in an oceanic environment. Only the Na₂O-poor and glaucophane-free type A metagabbros are similar to unaltered oceanic lithologies. It is suggested that the Na₂O- and glaucophane-rich type A samples were affected by high-temperature hydrothermal alteration.

As a general conclusion, we suggest that Fe-Ti gabbros that have crystallized from similar magmatic protoliths, as a consequence of their different oceanic evolution, developed distinct mineral assemblages during Alpine high-pressure metamorphism (see fig. 6). This interpretation suggests that the early pre-Alpine history of the oceanic lithosphere in the Piemonte basin played an important role in determining the petrographic and geochemical features of its metamorphic products.

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