

Prograde metamorphic evolution and development of chloritoid-bearing eclogitic assemblages in subcontinental metagabbro (Sesia–Lanzo zone, Italy)

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Abstract

In the coronitic metagabbroic rocks of the Corio and Monastero metagabbro bodies in the continental Sesia–Lanzo zone of the western Italian Alps, a variety of mineral reactions that testify to prograde conditions from greenschist to eclogite-facies can be recognised. A microstructural and microchemical study of a series of samples characterized by coronitic textures and pseudomorphic replacement of the original igneous minerals has allowed the prograde reactions undergone by the rocks to be established.

In completely eclogitized coronitic samples, paragonite, blue amphibole, garnet, epidote, fine grained jadeite and chloritoid occur in plagioclase microdomains (former igneous plagioclase). The mafic mineral microdomains consist of glaucophane and garnet. Complexly-zoned amphiboles constrain changing metamorphic conditions: cores of pre-Alpine brown hornblende and/or tremolite are preserved inside rims of a sodic–calcic amphibole that are in turn surrounded by a sodic amphibole. The main high-pressure mineral assemblage, as seen in mylonites, involves glaucophane, chloritoid, epidote, garnet±phengite, ±paragonite. Some layers within the gabbro contain garnet, omphacite, ±glaucophane, and acid dykes crosscutting the gabbro body contain jadeite, quartz, garnet, epidote and paragonite.

The presence of chloritoid-bearing high-pressure assemblages reflects hydration of the gabbros during their pre-Alpine exhumation prior to subduction, as well as the composition of the microdomains operating during subduction. The pressure and temperature conditions of gabbro transformation during subduction are inferred to be 450–550 °C at up to 2 GPa on the basis of the chloritoid-bearing assemblages. The factors controlling the reaction pathway to form chloritoid-bearing high-pressure assemblages in mafic rocks are inferred from these observations.

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1. Introduction

The typical anhydrous eclogite-facies assemblage garnet-omphacite was first described by Haüy (1822)

almost two centuries ago (see [Godard, 2001](#)). Since then, such a high-pressure assemblage also involving hydrous phases has been described from various parts of the world. It is known that the study of these assemblages can give an insight into the mechanisms working in subduction zones ([Poli, 1993](#); [Poli and Schmidt, 1995](#); [Forneris and Holloway, 2003](#)). In

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particular devolatilization in subduction zones is essential to arc magmatism and volatile recycling. The principal volatile components (H_2O and CO_2) are contained in hydrous and carbonate minerals. In the oceanic crust, volatile components in basalts are introduced by hydrothermal alteration at mid-ocean ridges. In the continental crust, hydrothermal alteration of basaltic rocks may occur by several mechanisms, and in rocks such as those studied here, it is ascribed to hydration of gabbroic rocks of the lower continental crust during exhumation in a rifting setting (Rebay and Spalla, 2001). One world-known example of continental rocks having been subducted is represented by the Sesia–Lanzo zone, in which the rocks studied here occur. It is therefore important to estimate the relevance of the continental crust to the budget of fluids that can go to mantle depths during subduction.

In the Western Alps several units, either of oceanic or continental origin have rocks that preserve high pressure assemblages with chloritoid that were exhumed before the final collision. The presence of chloritoid in mafic compositions is particularly interesting because this mineral is stable at high pressures (Poli and Schmidt, 1995; Schmidt and Poli, 1998) and has been envisaged as one of the main carriers of fluids in the subducted plates (together with amphibole, zoisite and lawsonite). Experimentally determined stability conditions in basaltic compositions suggest that chloritoid is stable in mafic rocks at pressures between 2.2 and 3.1 GPa (Schmidt and Poli, 1998, and refs. therein). On the other hand, many other experimental and thermodynamic models do not observe chloritoid in basaltic compositions (Liu et al., 1996). It is therefore interesting to understand what are the factors leading to chloritoid formation, in order to understand in what tectonic setting (for example, hot vs. cold subduction) chloritoid is formed.

The Corio and Monastero metagabbro of the western Alps displays variably developed, locally chloritoid-bearing eclogite-facies mineral assemblages of Alpine age. Hence it has been studied here in order to throw light on the stability of chloritoid-bearing HP-mineral assemblages and the role of fluids in such continental gabbros.

The increasing percentage of Alpine high-pressure metamorphic minerals observed in a series of samples of these rocks allowed the identification of the different steps leading to the formation of a sequence of different high-pressure metamorphic associations in coronitic metagabbros. The sequence is recognizable both in space, that is in different microdomains (in the original plagioclase, amphibole and pyroxene grains), and in time, that is in relation to the pre-eclogitic transformations.

Samples coming from slightly deformed lenses in the eclogitized metagabbro body (Rebay, 2003) have been studied. These lenses are separated by mylonitic zones completely transformed under eclogite-facies and/or later greenschist-facies Alpine conditions. The rocks in the lenses preserve pre-eclogitic, pre-Alpine relics (Rebay and Spalla, 2001) and rocks with coronitic textures (coronites) display different Alpine metamorphic imprints (prograde assemblages). They show incomplete Alpine high-pressure re-equilibration, preserve prograde to peak mineral assemblages, and are only slightly retrogressed under greenschist-facies conditions. Moreover they preserve zoned minerals, especially amphiboles, whose compositional changes witness the progressive change of pressure–temperature (PT) conditions.

The variety of reactions leading to the high-pressure assemblages allows determination and quantification of both the factors influencing prograde metamorphism (i.e. the actual paragenesis present in the rock and microdomain composition in undeformed rocks), and those controlling the formation of the chloritoid-bearing high-pressure parageneses (i.e. mineralogy of the original rock, pre-Alpine metamorphism and whole rock composition).

2. Geological setting

The Sesia–Lanzo Zone (SLZ) is a tectonic unit of the western Alps consisting of eclogitized continental rocks deriving from the African margin (Fig. 1). The Variscan continental crust had a complex evolution (Nicot, 1977; Lardeaux and Spalla, 1991; Venturini, 1995; Rubatto and Gebauer, 1997). It was intruded, mainly in Permian times, by gabbro bodies (Dal Piaz et al., 1977; Lardeaux and Spalla, 1991; Rebay and Spalla, 2001) and granitoids, for example at Monte Mucrone, (Compagnoni and Maffeo, 1973; Compagnoni et al., 1977; Oberhänsli et al., 1985; Rubbo et al., 1999; Zucali et al., 2002). The SLZ was then subducted to depths of at least 60 km, with estimated P – T conditions of 550 ± 50 °C and 1.8–2.1 GPa (Dal Piaz et al., 1972; Compagnoni, 1977; Pognante et al., 1980; Lardeaux et al., 1982; Oberhänsli et al., 1985; Pognante, 1989; Lardeaux and Spalla, 1991; Venturini, 1995; Inger et al., 1996; Tropper et al., 1999). The late Cretaceous age of the high-pressure re-equilibration (60–70 Ma, Inger et al., 1996; 69.2 ± 2.7 Ma, Duchêne et al., 1997; 75–73 Ma, Cortiana et al., 1998; 65 ± 5 Ma, Rubatto et al., 1999) is older than the high-pressure re-equilibration of the ophiolites of the Penninic nappes. Before the metamorphic peak, a pre-eclogitic stage in the glaucophane–zoisite or glaucophane–lawsonite stability field is recorded (Reinsch, 1979; Pognante et al., 1980). Following

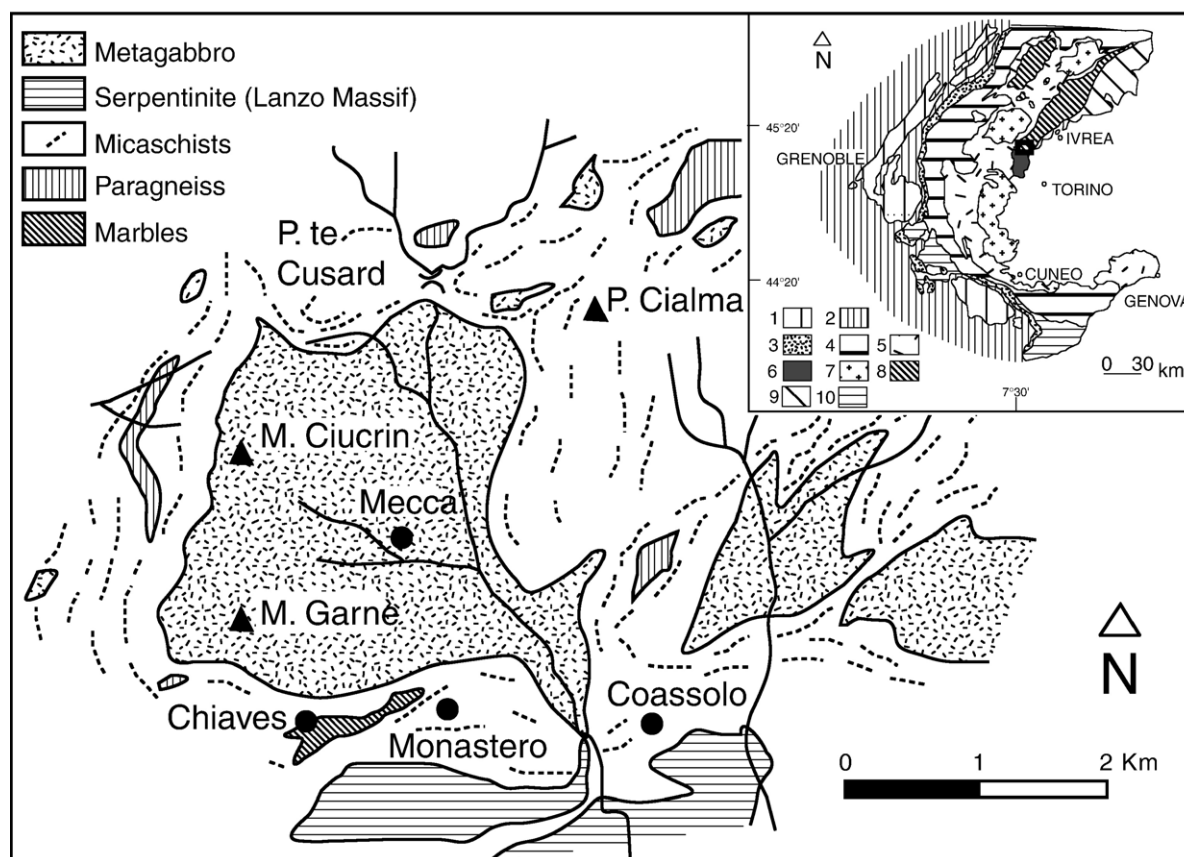


Fig. 1. Geological map of the Corio and Monastero area. In the inset, simplified tectonic map of the Western Alps with location of the Corio and Monastero metagabbro (thick square). (1) Helvetic basement; (2) Helvetic–Dauphinois cover; (3) Sub-Briançonnais zone; (4) Gran San Bernardo nappe system; (5) Piemontese ophiolites; (6) Lanzo Ultramafic massif; (7) Monte Rosa, Gran Paradiso and Dora Maira; (8) Sesia–Lanzo and Dent Blanche; (9) Southern Alps; (10) Flysch.

the attainment of maximum pressures conditions, decompression and cooling to blueschist-facies conditions (e.g. Pognante et al., 1980; Lardeaux et al., 1982; Pognante, 1989) took place. The entire SLZ recorded a final greenschist-facies overprint, varying in intensity from East to West.

The Corio and Monastero metagabbro outcrops at the southern border of the SLZ, where the *Micaschisti eclogitici* are folded together with the ophiolites of the Piemontese ocean and the northern part of the Lanzo Ultrabasic massif (Novarese, 1894; Bianchi et al., 1965; Spalla et al., 1983, 1991; Rebay, 2003).

The metagabbro displays banded textures and likely consisted mainly of interlayered Fe-gabbro and gabbro precursors. This heterogeneous sequence underwent a complex and polyphase pre-Alpine metamorphic evolution from granulite to greenschist-facies during the exhumation of the gabbro. The process was accompanied by episodes

of hydration, as well as intrusion of dykes, in pre-Alpine times (Rebay and Spalla, 2001). The majority of the rocks retained gabbroic textures, but these were locally recrystallized in anastomosing mylonitic zones and cut by a widespread network of crosscutting veins. Both the mylonite zones and veins formed at a range of grades during exhumation.

Therefore, at the onset of the Alpine metamorphism, the metagabbro body had already experienced metamorphism and deformation and consisted of gabbro-norites, basic granulites, amphibolites and greenschist-facies metabasites.

3. Microstructures

Corona-textured metagabbros are slightly deformed rocks preserving the original igneous textures. In these rocks garnet or amphibole coronae occur between the original, now pseudomorphed minerals. A set of

samples with increasing high-pressure transformation (from 5% to 100%) has been selected in order to decipher the progression of metamorphic reactions and related mineral assemblages. The degree of eclogitization is estimated by the modal amount of high-pressure minerals present in each sample at different scales of observation.

In rocks with a low degree of Alpine transformation, the pre-Alpine mineral assemblage (see Rebay and Spalla, 2001) is:

- (a1) *plagioclase microdomains*: either (i) relic anorthite-rich plagioclase or (ii) albitic plagioclase $\pm$ epidote $\pm$ actinolitic amphibole, $\pm$ chlorite, $\pm$ Cl-rich amphibole (in veins);
- (a2) *mafic mineral microdomains*: either (i) relic orthopyroxene, clinopyroxene or Ti-rich brown amphibole, or (ii) tremolitic–actinolitic amphibole, $\pm$ chlorite, $\pm$ talc.

In rocks with a degree of higher eclogitic overprint the observed assemblages are:

- (b1) *plagioclase microdomain*: paragonite replaces albite. Garnet coronas develop between relic anorthite-rich plagioclase and pre-Alpine chlorite veins, where Mg-rich garnet grows (Fig. 2a). Garnet + glaucophane + chloritoid may be found in chlorite-bearing veins transecting the albite + epidote-bearing, former plagioclase microdomains (Fig. 2b). In the latter, tremolitic amphiboles are rimmed by green Na–Ca amphibole and glaucophane. Neoblastic minerals may be oriented according to the original plagioclase lamellae. Epidote is also found as radial acicular aggregates.

High-pressure minerals in plagioclase microdomains form near its rim towards mafic minerals or pre-Alpine veins. With the increase of the extent of the high pressure transformation, the growth of green and then blue amphibole, together with chloritoid, is observed. Chloritoid is usually idioblastic and has a grain size of a few

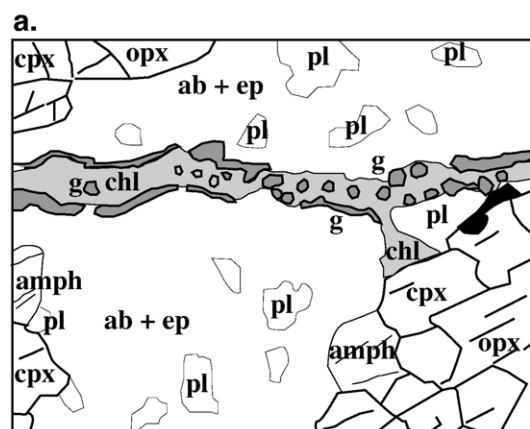
hundred microns. In some samples garnet occurs together with glaucophane, chloritoid, epidote $\pm$ paragonite (Fig. 2c). Glaucophane, garnet and chloritoid grains can be up to 1 cm in diameter. Glaucophane is commonly anhedral at the rim of the mafic mineral microdomain, garnet size increases toward this microdomain, and chloritoid can be found as prisms or as radial acicular crystals scattered through the plagioclase microdomain. In mylonitic rocks aligned chloritoid and glaucophane are up to 5 mm in length, and chloritoid occurs as a porphyroclast in a glaucophane matrix. Garnet includes glaucophane, chloritoid and epidote, while chloritoid and glaucophane contain only quartz and epidote inclusions. Samples preserving An-rich plagioclase have a thick garnet corona between plagioclase and chlorite-rich veins;

- (b2) *mafic minerals microdomain*: blue sodic amphibole develops, partially or completely overgrowing previous amphiboles. Sometimes a garnet corona grows towards the plagioclase microdomain. Amphibole is zoned, with a brown core surrounded sequentially by green actinolitic, deep green and, externally, blue rims (Fig. 2d). A few samples have blue amphiboles with cloudy cores rich in rutile inclusions (probably deriving from a former Ti-rich brown amphibole). These amphiboles are surrounded by blue rims with a thin colorless outer rim. In more deformed samples the blue amphibole has only a colorless granoblastic rim. Blue amphibole often has epidote inclusions. In retrogressed samples, corroded margins against another green actinolitic rim, sometimes overgrown by chlorite, are common.
- (c) Eclogitic rocks with a coronitic texture are composed of:
- (c1) *the plagioclase microdomain* consists of a very fine grained (tens of microns) association of epidote, paragonite $\pm$ jadeite (albite if retrogressed) $\pm$ garnet.

Fig. 2. Photomicrographs, sketches after photomicrographs and SEM/BSE images of observed microtextures of Corio and Monastero metagabbro. (a) In slightly eclogitised rocks pre-Alpine high grade minerals (plagioclase (pl), partially transformed to fine grained albite + epidote + paragonite, clinopyroxene (clinopyroxene), orthopyroxene (ortopyroxene) amphibole (amph)) are recognised. They are crosscut by a chlorite vein. Mg-rich garnet overgrows chlorite (in veins), and garnet corona form between relic anorthite-rich plagioclase and pre-Alpine chlorite veins. (b) In samples with more effective eclogitic reactions, the same veins as in panel a, are now made of garnet (g) + glaucophane (gl) + chloritoid (ctd) crosscutting albite (ab) + epidote (ep) plagioclase microdomains with thin glaucophane (gl) veinlets. (c) SEM BSE scattered image of the same vein. Note that chloritoid is present in the vein together with glaucophane and garnet, and in the plagioclase microdomain adjacent to the vein. (d) Plagioclase microdomain of a completely eclogitised rock. Chloritoid (ctd) is usually idioblastic and occurs together with garnet (g) glaucophane (gl), and fine grained epidote $\pm$ paragonite (ep). Glaucophane, garnet and chloritoid can be up to 1 cm. (e) Eclogitic coronite: in the plagioclase microdomain very fine grained epidote + paragonite (ep + pa) $\pm$ jadeite (albite if retrogressed) $\pm$ garnet; in the mafic mineral microdomain blue amphibole (gl) growing radially around granoblastic quartz (q). (f) Mylonite with granoblastic blue amphibole (gl), garnet (g), chloritoid (ctd). Note secondary chlorite (dark) on chloritoid.

(c2) *the mafic mineral microdomain* consists of blue amphibole growing radially around granoblastic quartz (Fig. 2e). Amphiboles include epidote and, rarely, zircon and have a dark green rim towards the core of the microdomain. Garnets are aligned

along the cleavage planes of original igneous pyroxenes. Between the mafic mineral and plagioclase microdomains a garnet corona forms with larger garnets towards the plagioclase microdomain. A colorless-amphibole corona is



c. — 0.1 mm

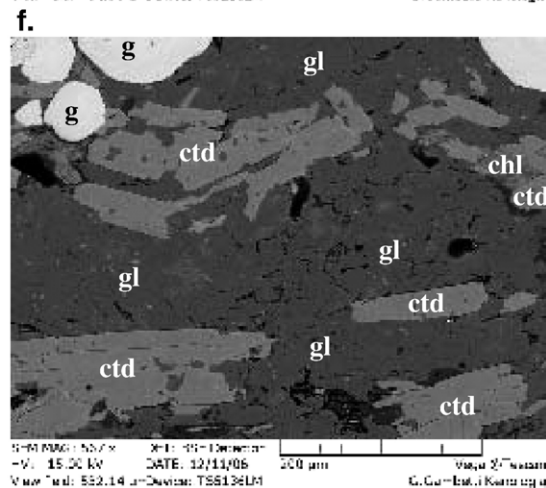
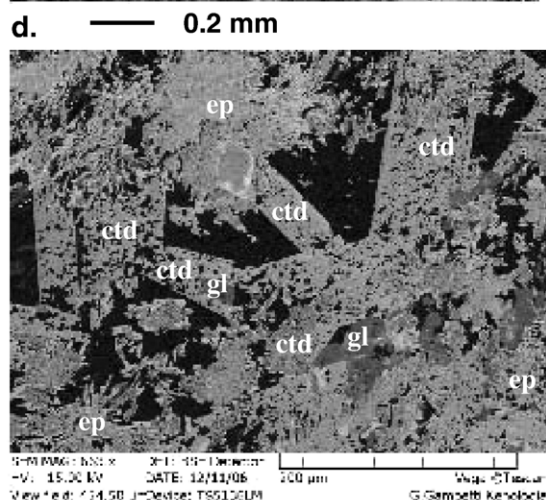
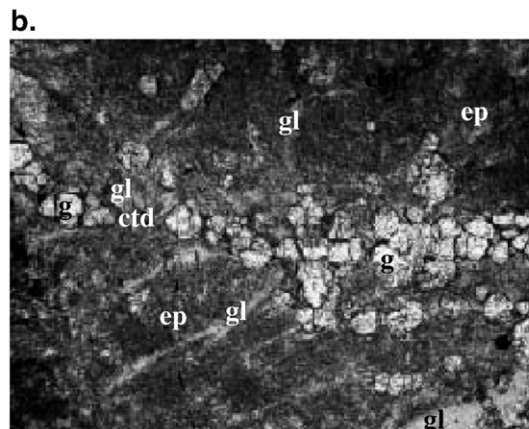
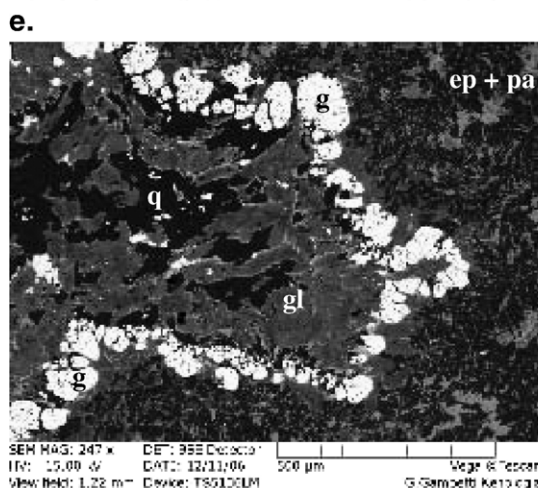
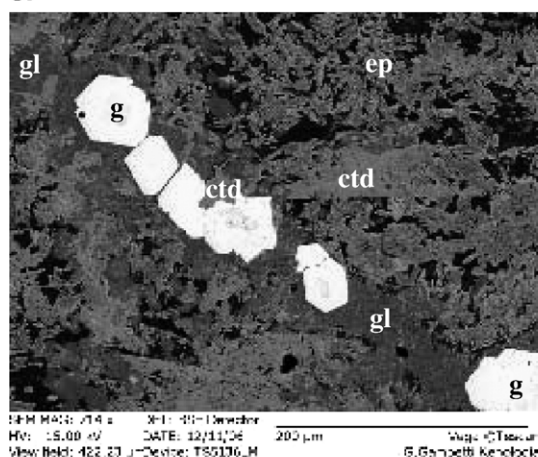


Table 1

Representative sodic pyroxene analyses (–=below detection limits, c=core, r=rim)

No.	19r	3r	9r	11r	9c	11r	2c	15c	38c
Sample	sl53	sl53	sl53	sl53	sl67	sl67	sl69	sl69	sl69
SiO ₂	54.41	54.96	55.24	55.36	56.96	55.92	57.53	57.78	56.71
TiO ₂	0.06	0.12	0.10	0.15	0.03	0.05	–	0.03	0.03
Cr ₂ O ₃	–	0.07	0.03	–	0.01	0.27	–	0.02	–
Al ₂ O ₃	7.18	7.11	9.33	9.16	17.91	9.96	22.46	22.69	21.87
Fe ₂ O ₃ ^a	5.78	3.77	4.42	3.95	2.97	2.93	0.00	0.81	1.97
FeO	3.33	5.51	4.47	4.68	1.55	1.83	3.27	1.32	0.85
MnO	0.06	0.03	–	–	0.09	0.07	–	–	0.03
MgO	8.06	8.28	6.87	7.19	2.99	7.92	0.13	0.28	0.16
CaO	13.97	15.41	12.75	13.61	5.56	13.50	1.51	1.48	0.71
Na ₂ O	6.55	5.72	7.31	6.96	12.02	7.25	13.54	14.08	14.01
K ₂ O	0.02	–	0.02	0.04	–	0.02	0.07	0.02	0.04
Total	99.42	100.98	100.54	101.10	100.09	99.72	98.51	98.51	96.38
Si	1.986	1.986	1.985	1.982	1.982	1.996	2.001	1.999	2.005
Ti	0.002	0.003	0.003	0.004	0.001	0.001	0.000	0.001	0.001
Cr	0.000	0.002	0.001	0.000	0.000	0.008	0.000	0.001	0.000
Al	0.309	0.303	0.395	0.387	0.735	0.419	0.921	0.925	0.911
Fe ³⁺ ^a	0.159	0.103	0.120	0.107	0.078	0.079	0.000	0.021	0.053
Fe ²⁺	0.102	0.167	0.134	0.140	0.045	0.055	0.095	0.038	0.025
Mn	0.002	0.001	0.000	0.000	0.003	0.002	0.000	0.000	0.001
Mg	0.439	0.446	0.368	0.384	0.155	0.421	0.007	0.014	0.008
Ca	0.546	0.597	0.491	0.522	0.207	0.516	0.056	0.055	0.027
Na	0.464	0.401	0.509	0.483	0.811	0.502	0.913	0.944	0.960
K	0.001	0.000	0.001	0.002	0.000	0.001	0.003	0.001	0.002
^{IV} Al	0.014	0.014	0.015	0.018	0.018	0.004	0.000	0.001	0.000
^{VI} Al	0.295	0.289	0.380	0.368	0.717	0.415	0.921	0.924	0.911
Sum cat	4.009	4.008	4.007	4.010	4.017	4.000	3.996	3.999	3.993

^a Fe³ recalculated by charge balance.

observed towards the plagioclase microdomain. In deformed samples the mafic mineral microdomain (Fig. 2f) contains small granoblastic blue amphibole and garnet. Between the mafic and plagioclase microdomains, a “retrograde”, optically continuous corona of colorless amphibole locally occurs. The deformed samples also display a greater extent of post-eclogitic transformation: garnets and amphibole are overgrown by chlorite and, in the plagioclase microdomain, albite is found together with epidote.

- (d) Acid dykes intruded in the gabbro have jadeite, quartz, garnet, epidote and glaucophane assemblages. Some fine grained bands in the gabbro (mylonites?) contain an assemblage of omphacite + garnet ($\pm$ glaucophane and epidote).

4. Mineral chemistry

Analyses have been performed with a JEOL JXA-840A electron microprobe of the Centro Grandi Strumenti of Pavia University. Acceleration was 20 kV

with a current of 20 nA with a 5 μ m diameter spot (20 μ m for mica and plagioclase). Eleven elements have been measured for each mineral, using natural standards; Fe³⁺ has been estimated imposing charge balance during mineral formulae recalculation. Analyses are reported in Tables 1–4.

Sodic clinopyroxene (Table 1) is omphacite in the metagabbro and omphacite and jadeite in the acid dykes (Fig. 3). The range of omphacite composition is Jd_{28–48}, Ae_{3–20}, Di + Hd_{47–60}. In the metagabbro omphacite has Fe/Ti ratio between 0.6 and 0.7 and Mn is below detection limits; the Jd content decreases from core to rim, from Jd₄₈ to Jd₂₈.

In the acid dykes sodic clinopyroxene reaches Jd₉₉ in composition and the Jd content slowly increases from core (Jd_{90–93}) to rim (Jd_{48–51}), where “true” omphacite composition is found.

Amphiboles (Table 2) have a wide compositional range due to the high number of substitutions and to the fact that they are stable through the whole metagabbro history. All amphibole analyses are reported in the Na/(Na+Ca) vs. Al/(Al+Si) diagram of Fig. 4 where two

Table 2

Representative amphibole and white mica analyses (– = below detection limits/not measured, c = core, r = rim, gbl = granoblast)

No.	23c (gbl)	41r	63r	20r	88r	79r	80r	85r	86r
Sample	sl4	sl4	sl4	sl53	sl5	sl4a197	sl4a197	sl4a197	sl4a197
SiO ₂	58.00	58.31	56.72	57.53	57.61	50.94	49.27	50.54	51.64
TiO ₂	0.05	0.05	0.08	0.16	0.12	0.10	0.11	0.16	0.18
Al ₂ O ₃	11.58	11.20	11.21	10.96	9.47	28.38	30.42	27.81	27.44
Cr ₂ O ₃	0.00	0.00	0.00	0.02	0.00	0.05	0.05	0.04	0.01
FeO	9.32	9.16	9.82	11.52	13.03	1.47	1.34	2.06	1.67
MnO	0.03	0.03	0.09	0.03	0.09	0.02	0.02	0.02	0.01
MgO	10.55	10.83	11.04	9.47	10.01	3.51	2.82	3.64	3.73
CaO	0.64	0.45	1.03	0.67	1.22	0.02	–	–	–
Na ₂ O	7.10	7.19	7.51	7.35	6.47	0.27	0.33	0.16	0.32
K ₂ O	0.08	0.08	0.10	0.01	0.09	11.15	10.90	10.67	10.84
Total	97.34	97.29	97.60	97.71	98.10	95.91	95.26	95.10	95.84
Si	7.954	7.992	7.769	7.920	7.977	3.37	3.28	3.38	3.42
Ti	0.005	0.005	1.810	1.779	1.547	0.01	0.01	0.01	0.01
Al _{tot}	1.872	1.809	0.008	0.016	0.012	2.213	2.39	2.189	2.139
Cr	0.000	0.000	0.000	0.002	0.000	0.003	0.003	0.002	0.001
Fe _{tot}	1.069	1.050	1.125	1.326	1.509	0.081	0.075	0.115	0.092
Mn	0.003	0.003	0.010	0.003	0.010	0.001	0.001	0.001	0.001
Mg	2.157	2.213	2.253	1.943	2.066	0.346	0.280	0.362	0.368
Ca	0.094	0.066	0.152	0.098	0.181	0.001	0.000	0.000	0.000
Nat	1.887	1.911	1.995	1.962	1.737	0.035	0.043	0.021	0.041
K	0.014	0.014	0.017	0.002	0.016	0.941	0.926	0.909	0.914
^{IV} Al	0.046	0.008	0.231	0.080	0.023				
^{VI} Al	1.826	1.801	1.579	1.699	1.524				
Cat	15.055	15.061	15.139	15.052	15.054	6.997	7.001	6.982	6.980

main trends are recognised. Here prograde zoning is indicated by the full-line arrow, retrograde zoning by the dashed-line arrow. Increasing pressure (prograde zoning) is testified by the increase of glaucophane substitution in amphibole. Using the classification of [Leake et al. \(1997\)](#), we can distinguish three main groups. Calcic amphiboles are actinolites related to the post-eclogitic retrogression of the metagabbros but also rims of pre-Alpine amphiboles rimmed by glaucophane (see [Rebay and Spalla, 2001](#), for textures and compositions). Na–Ca amphiboles are barroisites and winchites found either as rims of pre-Alpine actinolites or as rims of glaucophanes in partially retrogressed eclogites. Sodic amphiboles are glaucophanes. They have Mg# (Mg/(Mg + Fe)) between 0.2 and 0.65, depending on the microdomain in which they grow: in mylonitic samples they have narrowest compositional ranges.

White mica (Table 2) in the plagioclase microdomain is paragonite. Due to its extremely small (few microns) grain size, analyses are inaccurate (especially in the determination of Na₂O and K₂O). It has low Mg contents (<0.06 apfu), Fe is 0.2–0.3, Al 2.47–2.55 and Si 3.36–3.45 apfu. Paragonite in a mylonite has higher contents in Al, Na and K. Phengite is found both in

metagabbro and in meta-dykes. It has Si up to 3.5 apfu, high Mg and Fe contents (respectively, 0.26–0.39 and 0.06–0.15 apfu) and K between 0.78 and 0.81. K in phengite in the acid dykes is 0.33–0.38 apfu.

Garnet (Table 3) usually has Alm + Sps contents >60, Py <15 and Grs + Adr between 10 and 35. Garnet composition is often highly dependent on the type of microdomain in which it grows and on the type of prevalent metamorphic imprint of the rock. For example, as showed in [Fig. 5](#), garnet growing after chlorite in veins is extremely Mg-rich (e.g. Alm₇₄Py₂₄Grs₀₁Sps₀₁), and garnet rims between relic anorthitic plagioclase and chlorite have a very steep variation in Ca, Mg and Fe (e.g. Alm₆₅Py₀₅Grs₂₉Sps₀₁ towards plagioclase and Alm₇₅Py₂₂Grs₀₂Sps₀₁ towards chlorite). On the other hand, garnet in coronas in samples with widespread development of high-pressure assemblages is not zoned. Garnet in mylonites is slightly zoned, with Mn-rich cores (e.g. Alm₆₆Py₀₄Grs₁₉Sps₁₁) and Mg-rich rims (e.g. Alm₆₇Py₀₈Grs₂₃Sps₀₂). Finally garnet composition reflects also the whole rock composition: garnets from omphacite-garnet rocks have the higher Ca-content (reflecting the higher Ca of the whole rock).

Table 3

Representative garnet analyses (–=below detection limits, c=core, r=rims)

No.	1r	9r	19r	20r	55r	56	69c	4r	12r	15r
Sample	sl4	sl4	sl4	sl4	sl5	sl5	sl5	sl53	sl53	sl53
SiO ₂	36.72	36.93	37.25	37.41	37.42	37.35	37.08	37.43	37.35	36.13
TiO ₂	1.09	0.13	0.16	0.16	0.04	0.04	0.14	0.28	0.17	0.29
Al ₂ O ₃	20.40	20.64	20.87	20.83	20.67	20.93	20.46	21.25	21.29	19.77
Cr ₂ O ₃	0.03	0.02	0.04	–	–	–	0.02	0.01	0.03	0.02
Fe ₂ O ₃ ^a	0.81	1.25	0.43	0.52	0.90	0.52	0.76	0.29	0.45	1.90
FeO	29.49	30.00	30.08	25.53	31.22	33.27	31.73	25.33	25.70	28.20
MnO	1.90	0.81	0.82	5.67	1.49	1.77	3.51	0.54	0.59	1.84
MgO	1.64	1.75	1.41	1.22	3.43	3.36	1.99	0.53	0.68	1.63
CaO	7.85	8.31	8.82	8.81	4.57	2.80	4.19	14.28	13.75	8.41
Na ₂ O	0.09	0.03	–	0.04	0.06	0.06	0.08	–	–	0.03
K ₂ O	0.03	0.04	–	–	–	0.02	0.02	0.01	0.02	0.02
Total	100.05	99.91	99.88	100.18	99.79	100.10	99.97	99.96	100.03	98.23
Si	2.950	2.963	2.988	2.994	2.994	2.991	2.995	2.974	2.967	2.957
Ti	0.066	0.008	0.010	0.009	0.002	0.002	0.009	0.017	0.010	0.018
Cr	0.002	0.001	0.002	0.000	0.000	0.000	0.001	0.001	0.002	0.001
Al	1.933	1.953	1.974	1.965	1.949	1.976	1.949	1.991	1.994	1.907
Fe3	0.049	0.076	0.026	0.031	0.054	0.031	0.046	0.018	0.027	0.117
Fe2	1.982	2.013	2.018	1.709	2.089	2.228	2.144	1.683	1.708	1.930
Mn	0.129	0.055	0.056	0.385	0.101	0.120	0.240	0.037	0.040	0.127
Mg	0.196	0.209	0.168	0.145	0.409	0.401	0.240	0.063	0.080	0.199
Ca	0.676	0.714	0.758	0.756	0.392	0.240	0.363	1.216	1.170	0.737
Na	0.014	0.005	0.000	0.006	0.009	0.009	0.012	0.000	0.000	0.005
K	0.003	0.004	0.000	0.000	0.000	0.002	0.002	0.001	0.002	0.002
Aliv	0.050	0.037	0.012	0.006	0.006	0.009	0.005	0.026	0.033	0.043
Alvi	1.883	1.916	1.962	1.959	1.943	1.967	1.944	1.965	1.961	1.864
Sum cat	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000

^a Value calculated by charge balance.

Epidote varies in composition from clinozoisite to epidote, with minor amounts of piemontite. Usually zoned epidotes have a zoisitic (zoisite/clinozoisite) core ($\text{Fe}^{3+}=0.15\text{--}0.45$) and pistacitic rim ($\text{Fe}^{3+}=0.7\text{--}0.8$), even though in some retrogressed sample there are inverse zonations. Acicular or radial epidote linked to the post-eclogitic retrogression has Fe^{3+} contents between 0.35 and 0.45 apfu.

Chloritoid is Fe-rich ($\text{Fe}=1.45\text{--}1.94$, $\text{Mg}=0.15\text{--}0.58$ apfu, $X_{\text{Mg}}=0.17\text{--}0.27$), Table 4. Al is 3.64–4 apfu while all other elements are negligible. In large crystals from core to rim there is both a Fe_{-1}Mg substitution and a Mg_{-1}Mn substitution. The extent of these substitutions depends both upon the deformation of the sample (coronite vs. mylonite) and the microstructural domain in which chloritoid crystallizes. Chloritoid in mylonites or growing in pre-Alpine chlorite veins has high Mg and Mn, in coronites Mg and Mn values are the lowest. Chloritoid growing in Cl-amphibole rich microdomain may have Cl contents up to 0.04 apfu.

In summary the chemical composition of the minerals reflects the metamorphic conditions (intensive variables P, T, X, f_{O_2} , and fluids) and the composition of the microdomain where they occur.

5. Discussion

5.1. Amphibole zoning

Amphibole was stable throughout the pre-Alpine and Alpine evolution in the studied rocks. Variations in Na, Al and Ti content are ruled by the changing metamorphic conditions (Ungaretti et al., 1983). In samples with increasing high-pressure transformation, a gradual, continuous increase of the glaucophanic substitution is evident, even within a single zoned amphibole.

Besides this general trend, in coronitic samples, the control exerted by microstructures and fluids over reaction kinetics is significant. This is also reflected in different amphibole compositions in some microstructural domain and depends on the degree of deformation

Table 4

Representative chloritoid analyses (–=below detection limits, c=core, r=rims)

No.	14r	84r	86r	39r	51c	84r
Sample	sl4	sl4	sl4	sl5	sl5	sl5
SiO ₂	23.84	24.88	24.34	23.97	24.61	24.12
TiO ₂	0.02	0.02	0.08	0.05	0.03	0.10
Cr ₂ O ₃	0.04	0.05	0.04	0.14	0.05	–
Al ₂ O ₃	40.26	41.37	40.29	40.10	38.68	40.07
FeO	22.15	22.82	21.67	23.54	24.16	22.86
MnO	0.09	0.13	0.07	0.20	0.25	0.26
MgO	4.49	4.27	4.62	3.35	3.25	3.67
CaO	0.01	0.02	0.01	0.02	0.01	0.01
Na ₂ O	–	–	–	–	0.03	0.01
K ₂ O	0.01	–	–	0.02	0.02	0.01
Total	90.90	92.74	91.12	91.38	91.08	91.12
Si	1.983	2.001	2.002	1.998	2.045	2.009
Ti	0.001	0.001	0.005	0.003	0.002	0.007
Cr	0.003	0.003	0.003	0.009	0.003	0.000
Al	3.948	3.938	3.926	3.940	3.825	3.933
Fe ³ ^a	0.067	0.051	0.057	0.059	0.108	0.051
Fe ²	1.480	1.496	1.446	1.588	1.598	1.546
Mn	0.006	0.009	0.005	0.014	0.018	0.018
Mg	0.557	0.514	0.570	0.416	0.407	0.456
Ca	0.001	0.002	0.001	0.002	0.001	0.001
Na	0.000	0.000	0.000	0.000	0.005	0.002
K	0.001	0.000	0.000	0.002	0.002	0.001
Sum cat	8.05	8.01	8.01	8.03	8.01	8.02

^a Value calculated by charge balance.

of the sample. As an example, Fig. 5a shows the variations in sodic amphiboles composition within a single sample according to the microstructural domain

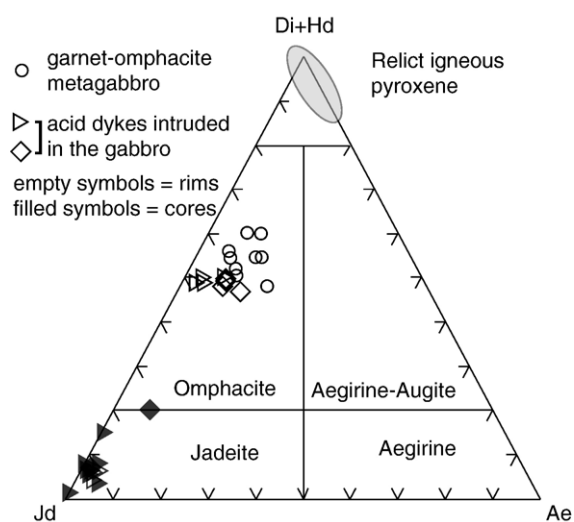


Fig. 3. Pyroxene compositions. Symbols: triangle and lozenge=acid dykes; circles=fine grained bands in metagabbro. Filled symbols are cores, empty symbols are rims.

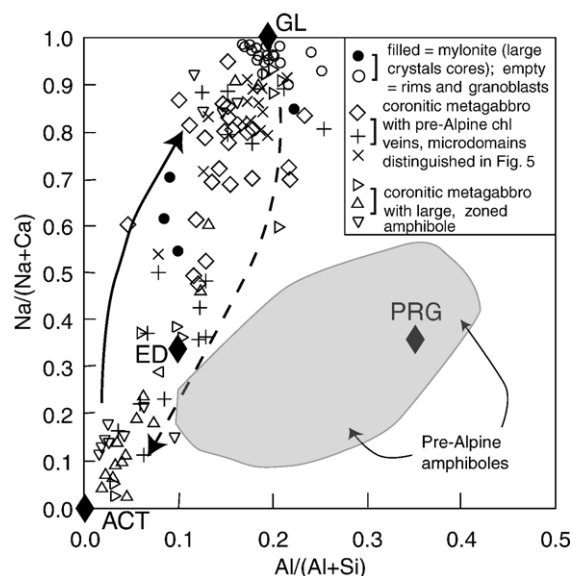


Fig. 4. Summary of amphibole compositions. Analyses that correspond to pre-Alpine amphiboles fall in the shaded field. Each symbol represents a different sample. Samples are grouped in mylonites (circles), coronitic metagabbro with pre-Alpine relics (lozenge and cross) and coronitic metagabbro with large, zoned amphiboles. See text for explanation. Diamonds locate the end-member compositions (ACT=actinolite; ED=edenite; GL=glaucophane; PRG=pargasite).

in which the amphiboles are found. In such a case, variations in chemical composition of microdomains are more evident due to the presence of pre-Alpine Cl-rich amphiboles, whose composition is strongly correlated to the Cl content of the rock (see Kullerud, 1996, and refs. therein). Amphiboles growing in the plagioclase microdomain near Cl-amphibole veins are Fe-glaucophanes, with a lower Na/(Na+Ca) ratio with respect to the glaucophane in the plagioclase microdomain near a mafic site completely substituted by Cl-amphiboles. The latter have a higher Si content. In the same plagioclase microdomain glaucophanes growing near pyroxene have compositions even richer in Si and poorer in Al than the amphiboles described above.

In samples still preserving some pre-Alpine relics, the prograde evolution is testified by the growth of multi-layered amphibole coronas between pyroxene and plagioclase. Such coronas are made of Na–Ca amphiboles, sometimes bounded by Fe–glaucophane, while glaucophane rims grow toward mafic minerals (Fig. 5b).

In completely eclogitized samples, Na–amphibole in the mafic microdomain is Fe–glaucophane, whereas amphibole in the plagioclase microdomain has lower Mg/(Mg+Fe) ratios and higher Ca and Al contents. Differences between microdomains are no longer noticeable, and amphibole composition is comparatively

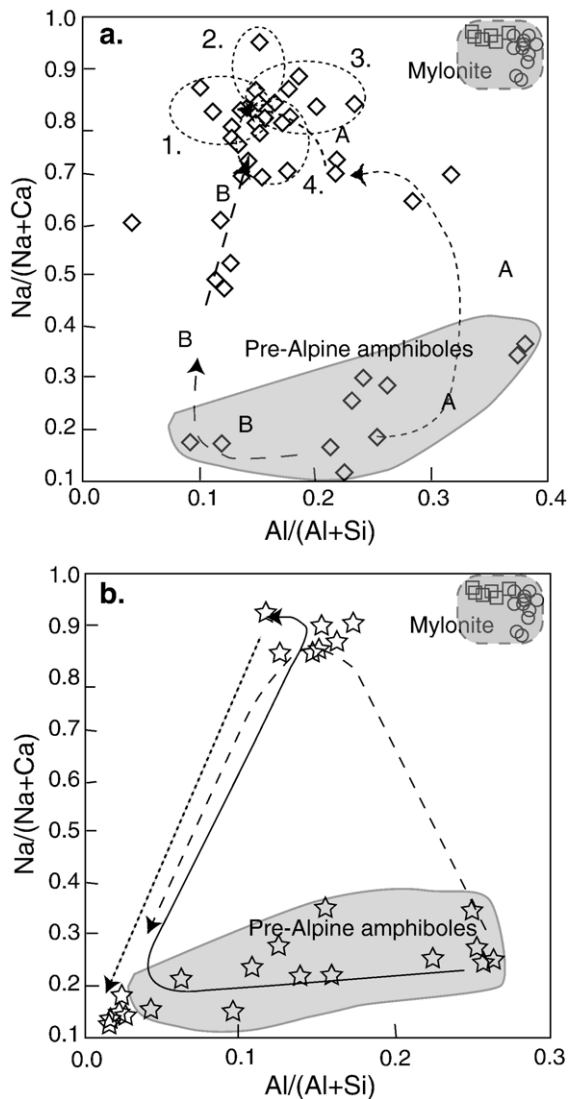


Fig. 5. Compositional variations in zoned amphibole observed in two samples. (a) Sample sl46f, rock with relics of clinopyroxene and orthopyroxene, but with >60% Alpine transformation. Note that prograde amphibole have different compositions when they grow after igneous hornblende (path A) or after pre-Alpine actinolite amphibole (path B). Composition of high-pressure Na-amphibole depends on the textural position: (1) in plagioclase microdomain; (2) in mafic mineral microdomain; (3) in mafic mineral previously overgrown by Cl-rich amphibole; (4) in veins rich in chlorite and Cl-rich amphibole in plagioclase microdomain. (b) Compositional variation in zoned amphibole in sample sl8d207, a rock with no relics of igneous assemblage, except for brown hornblende cores in amphibole. Differently ornamented arrows indicate the compositional zonation in different microdomains (and not the PT evolution). The solid line arrow represent the zonation of a single amphibole, the dotted line represents rims of actinolitic amphibole around glaucophane in the plagioclase microdomain, the striped line a brown amphibole with glaucophane rim. Composition of sodic amphibole in mylonite is reported for reference in both figures.

more homogeneous in mylonized samples (Fig. 5). In these samples, the composition of the amphibole is ruled by the bulk rock composition, but occasionally relics of different compositions are also found. Nonetheless, within a narrow compositional range, Na-amphibole in mylonites are zoned.

5.2. Reactions driven by microstructures and mineral chemistry

Prograde parageneses in the gabbro are always present in the plagioclase microdomain and in the crosscutting veins. Mafic igneous minerals were commonly transformed to amphiboles during the pre-Alpine retrogression: their subsequent observed compositional variations are then a record of the Alpine history. All the following considerations are based on the assumption that the different microdomains were characterized by different mineral associations prior to eclogitization, as deduced from textures and mineral chemistry. In this light, a single microdomain at the end of the pre-Alpine episode may contain different mineral associations that will then give rise to different eclogite-facies assemblages.

Since chlorite veins are Ca-poor, they contain Mg-rich garnet. When veins crosscut the plagioclase microdomain, two different transformations are observed:

- relic An-rich plagioclase is transected by veins: up to millimetre-scale garnet coronas form between the vein and the plagioclase. These coronas are strongly zoned, with Py-rich garnet towards the vein and Grs-rich garnet towards the plagioclase (Fig. 6);
- where the plagioclase has been already transformed to albite+epidote during pre-Alpine exhumation of the gabbro: epidote is stable (small variations in composition are registered in zoned epidotes) and albite is transformed to paragonite. Glaucophane, with epidote and paragonite, ±garnet and chloritoid, grows in plagioclase microdomains containing chlorite or actinolite.

In mafic mineral microdomains, amphibole is common and the pargasitic substitution is more advanced, forming Na–Ca-amphibole and then Na-amphibole. Pre-Alpine relics (orthopyroxene, clinopyroxene and talc) react with albite to form glaucophane±epidote and paragonite. The different observed prograde parageneses are summarized in Fig. 7.

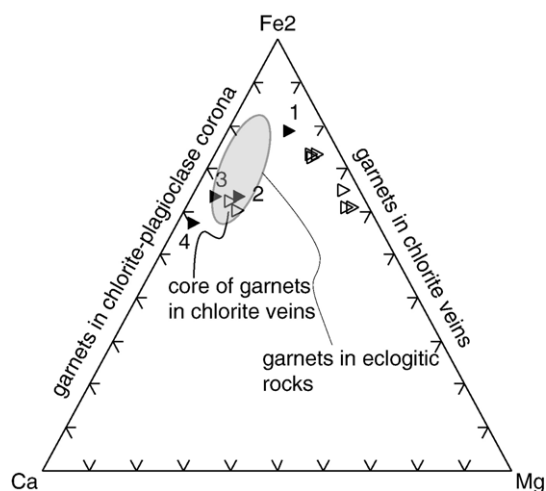


Fig. 6. Garnet composition — the composition of garnets from eclogitic rocks (milonites and coronites) falls in the shaded area. The triangles are garnets growing in pre-Alpine chlorite veins (empty symbols). Filled symbols are garnet along a section of the corona between the chlorite-bearing vein (n. 1) and the igneous plagioclase (n. 4). See Fig. 2a for the texture.

5.3. Chloritoid growth

High-pressure garnet–glaucophane–chloritoid–epidote bearing assemblages are widespread in the Corio and Monastero metagabbro. The chemical and kinetic factors leading to the crystallization of such uncommon high-pressure parageneses are here inferred from the microstructural and microchemical observations (Fig. 7).

Chloritoid has never been found in garnet coronites. This is likely due to the fact that a mineral with wide solid-solution of the divalent cation, such as garnet, acts as a barrier to chemical exchange between adjacent

Table 5
Whole rock compositions and residuals

Whole rock			Residuals			
	wt. %	sl4	sl53	R1 (pl md)	R2 (Sl4)	R3 (Sl53)
SiO ₂	45.26	39.98		Si 0	0	0
TiO ₂	2.12	2.36		Ti 0	0	0
Al ₂ O ₃	15.37	16.18		Al 0	0	0.01
Fe ₂ O ₃	17.15	16.18		Fe 0	0	0.02
MgO	8.09	10.31		Mg 0	0.01	0.04
CaO	6.26	11.00		Ca 0	0	0.01
Na ₂ O	3.41	1.72		Na 0	0.01	0

microdomains. Chloritoid nucleation requires also a high Al content, such as that found in plagioclase microdomains, together with some amount of Fe and Mg coming from the mafic microdomain (or from Fe–Mg-rich pre-Alpine minerals crystallizing in the plagioclase microdomain). In undeformed samples with different degrees of high-pressure re-equilibration, chloritoid is found in the plagioclase microdomain either near veins or in the vicinity of mafic minerals. It is therefore inferred that chloritoid growth is achieved only in metagabbros that were hydrated at some point of their pre-subduction history.

Mass balance calculations have been performed using the Pétrocalc software, a linear equation solver (Godard and Chat, 1994), in order to evaluate and quantify the reactions leading to chloritoid growth. The first mass balance calculation has been performed for minerals in a chlorite-rich vein crosscutting the plagioclase microdomain (sample sl5/2, see Fig. 2b). The reactants considered in the reaction are the minerals observed in the plagioclase domain adjacent to the vein. The composition of epidote and amphibole is that measured in the core, whereas the compositions of the

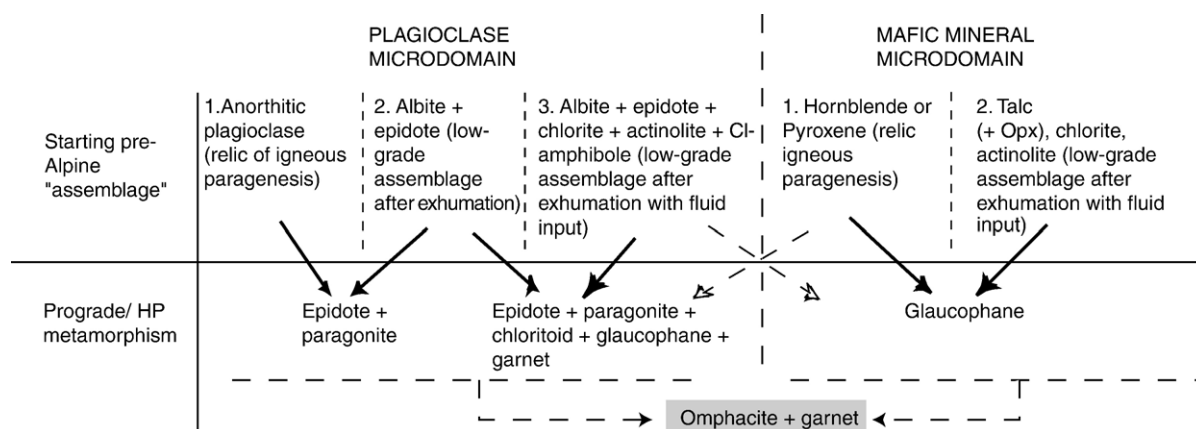


Fig. 7. Scheme summarizing different pre-Alpine assemblages and the deriving high-pressure Alpine assemblages. Dotted arrows indicate interaction with nearby microdomains, full arrows indicate the different high-pressure assemblages after various pre-Alpine assemblages.

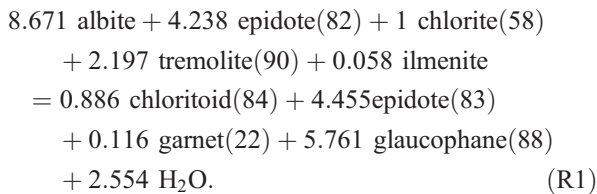
Table 6

Calculated temperatures based on clinopyroxene–garnet pairs (mean of 10 analyses)

Method	R&G	E&G	G	P	K	S	Kr
<i>T</i> (°C)	371.5	468.6	530.7	448.9	410.9	440.1	510.3
Estimated errors	80	110	100	110	100	110	100

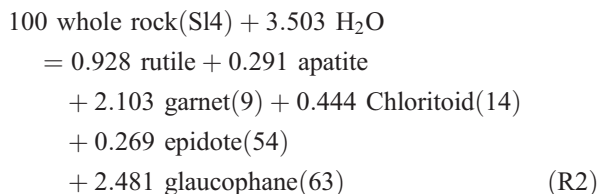
R&G=Raheim and Green, 1974; E&G=Ellis and Green, 1979; G=Ganguly, 1979; P=Powell, 1985; K=Krogh, 1988; S=Sengupta et al., 1989; KR=Krogh, 2000. *P*=1.5 Gpa.

products are measured rim compositions. The balanced reaction is:



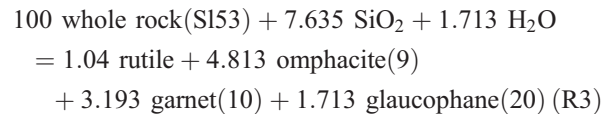
where the numbers in parentheses after a mineral name indicate the analysis number reported in Tables 1–4. Residuals for the calculation are reported in Table 5. In the above reaction the amount of minerals are consistent with the quantities observed in our sample.

The assemblage of garnet, glaucophane, rutile and chloritoid observed in mylonites (sample sl4) is modeled starting from the whole-rock composition determined by XRF (see Table 5), since deformation has concealed the microdomains. Residuals in the calculation are below 3% for every element suggesting the correctness of the assumptions, and modal amounts of products correspond to those observed in the rock (see Fig. 2f). The mass balance is:



The fact that no Al-silicates have been found in the metagabbro could indicate that temperatures needed for

chloritoid break-down (Guiraud et al., 1990) have not been reached. It is likely that, as observed by Messiga et al. (1999) in metatroctolites of the Monviso ophiolite, orthopyroxene in the protholiths further controlled the formation of chloritoid. In contrast, in samples with a high modal abundance of Ca-clinopyroxene the most common eclogite-facies mineral is omphacite. This is confirmed by the following mass balance calculation concerning the only omphacite–garnet bearing sample (sl53 in Table 5):



Note that in order to balance reaction R3 an introduction of silica is required and that there are higher residuals of Ca and Mg, which are nonetheless reduced by the addition of apatite and oxides because some Ca and Mg is used up by these minerals.

5.4. *PT determinations — thermobarometry*

Even though the studied rocks show disequilibrium textures, which make pseudosections unreliable, a number of thermobarometric calculations have been attempted. For these calculations mineral pairs in coronas of samples with a high degree of Alpine re-equilibration have been used. The obtained *T* values must be considered as minimum values.

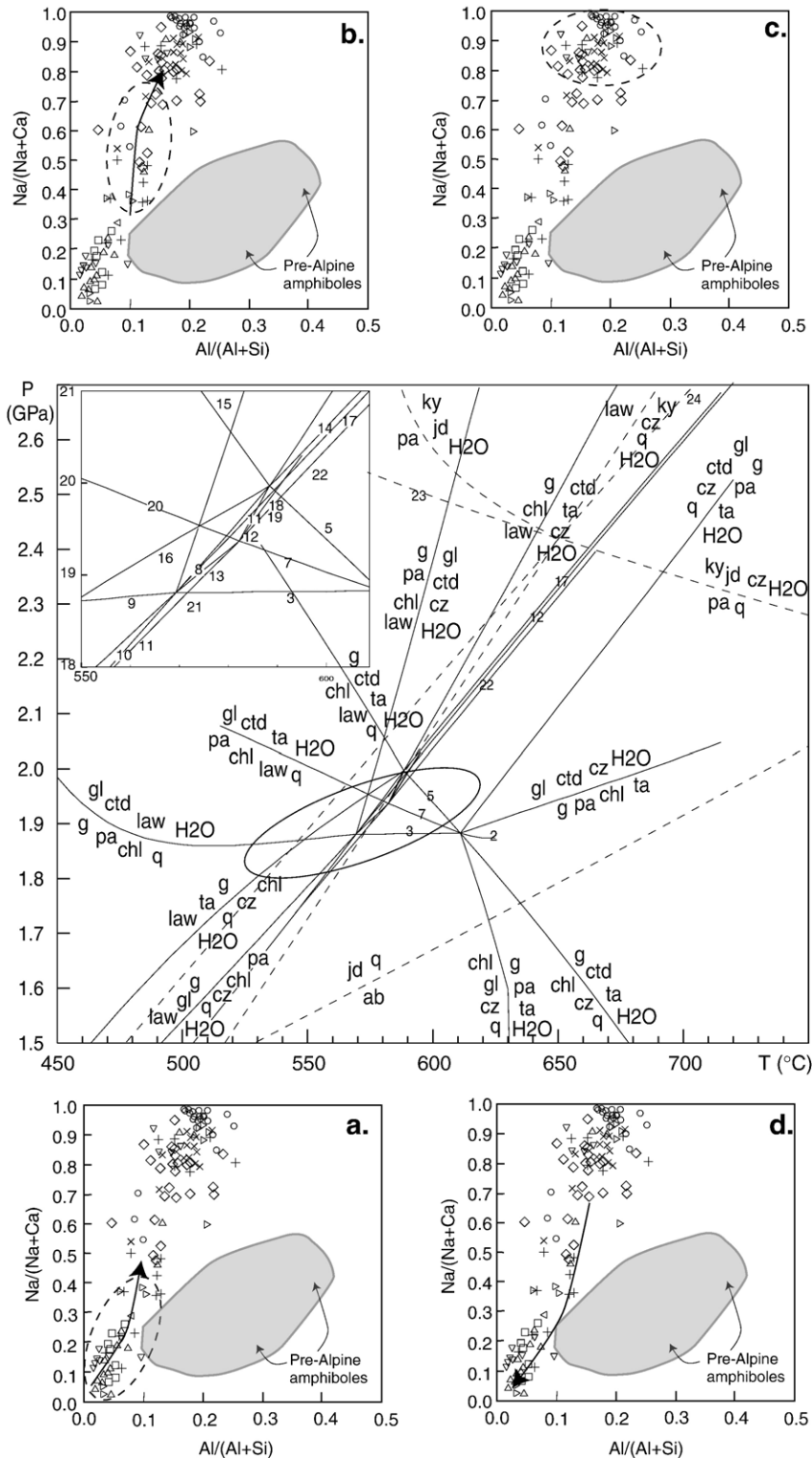
Garnet–chlorite thermometer (Perchuk, 1991) was applied to garnet–chlorite pairs (Alpine garnet growing in chlorite pre-Alpine veins). Temperature are in the range 460–550 °C and could represent prograde temperatures attained during chlorite breakdown.

Garnet–clinopyroxene thermobarometry was applied in a single sample in which both garnet and clinopyroxene were present and sharp boundaries between them were preserved, in spite of a evident retrogression. Different geothermometers (Raheim and Green, 1974; Ellis and Green, 1979; Ganguly, 1979; Powell, 1985; Krogh, 1988; Sengupta et al., 1989; Krogh, 2000) have been applied, see Table 6, but probably the one that better approaches the conditions attained by our rocks

Fig. 8. *P–T* projection, calculated with THERMOCALC (version 3.25) for NCFMASH system. The enlargement shows numbers of not labelled reactions, as follows: 2 — g pa chl q = gl ctd ta H₂O; 3 — g pa chl q = gl ctd cz H₂O; 4 — chl gl q = g pa ta H₂O; 5 — chl cz q = g ctd ta H₂O; 7 — pa chl cz q = gl ctd ta H₂O; 8 — g pa chl law = gl ctd cz H₂O; 9 — g pa chl q = gl ctd law H₂O; 10 — g gl law = pa chl cz q H₂O; 11 — g chl law = ctd cz q H₂O; 12 — g gl law = pa ctd cz q H₂O; 13 — gl ctd law = pa chl cz q H₂O; 14 — g chl law = ctd ta cz H₂O; 15 — chl law q = g ctd ta H₂O; 16 — g ta law = chl cz q H₂O; 17 — g ta law = ctd cz q H₂O; 18 — chl law q = ctd ta cz H₂O; 19 — chl gl law = pa ctd ta cz H₂O; 20 — pa chl law q = gl ctd ta H₂O; 21 — gl law = pa chl ta cz q H₂O; 22 — gl law = pa ctd ta cz q H₂O; 23 — pa q = ky jd law H₂O. In the insets composition and zonations of amphiboles corresponding to prograde (a and b), peak (c) and retrograde (d) *PT* conditions (see also Fig. 4). The ellipse shows the *PT* values (with estimated errors) calculated for the assemblage glaucophane–chloritoid–garnet–rutile–quartz observed in a mylonite (sample sl4).

are those from Krogh (2000), as this thermometer was calibrated on rocks similar to our metagabbro. The minimum temperatures for the Corio metagabbro are

thus 510 ± 100 °C. This T range fits with the minimum ranges determined in the entire SLZ (Compagnoni, 1977; Pognante et al., 1980; Lardeaux et al., 1982;



Oberhänsli et al., 1985; Pognante, 1989; Lardeaux and Spalla, 1991; Venturini, 1995; Inger et al., 1996; Tropper et al., 1999). When not stated by the authors, errors on published values have been derived from regression on calculated data, and have to be considered as minimum values.

Si content in phengite has been taken into account as a valid thermometer for biotite + k-feldspar + quartz assemblages (Massonne and Schreyer, 1987). Phengites of the acid dykes have Si ranges of 3.4–3.6 a.pfu, which would imply P of 1.3–1.5 GPa for T of 500–550 °C. The lack of the buffering assemblage implies that these are minimum pressures.

Jd content in clinopyroxene has been considered as an indicator of pressure. In dykes we found almost pure jadeites, which implies a minimum P of 1.4 GPa for T of 500 °C.

A PT projection in the NCFMASH system considering nine mineral phases (chloritoid, chlorite, talc, garnet, paragonite, glaucophane, clinozoisite, lawsonite and quartz), and excess water (Fig. 8), has been calculated using the dataset and the activity–composition relationships of minerals used in Wei et al. (2003) with the THERMOCALC software (Holland and Powell, 1998). The grid is divided into two halves by a bundle of reactions marking the consumption of lawsonite. The rocks have no mineralogical or textural relics of lawsonite. The reactions that are of interest in our rocks are those around the invariant point at $P=1.8$ GPa and $T=610$ °C (or [law]).

A calculation of PT has been performed using the assemblage observed in mylonite sl4 (glaucophane, epidote, chloritoid, garnet, quartz and rutile): the result obtained is $P=1.9\pm0.1$ GPa and $T=570\pm50$ °C. This result is in good agreement with that calculated using the garnet–clinopyroxene geothermometer of Krogh (2000): considering the uncertainties, for instance relating to Fe^{3+} content, the T values obtained overlap. Moreover the temperatures obtained considering the assemblage rather than a pair of minerals, display a smaller uncertainty.

6. Conclusions

The Corio and Monastero metagabbros preserve in undeformed domains pre-Alpine parageneses, allowing recognition of a prograde evolution from greenschist pre-Alpine facies to high-pressure Alpine parageneses. This evolution is recorded by amphibole zonation (see Fig. 8), the growth of different mineral assemblages in different microdomains and the preservation of incomplete reactions.

The growth of high-pressure chloritoid-bearing parageneses has been influenced by: (a) whole rock composition; (b) original mineralogy of the protolith; (c) the kind and extent of pre-eclogitic transformations. Moreover, as suggested by Guiraud et al. (2001), water must have played a crucial role in the development and preservation of different assemblages.

The Alpine metamorphic evolution inferred from the observed equilibrium assemblages, mineral zoning and corona reactions may be sketched as follows:

- (1) prograde metamorphism is recorded by the growth of garnet after chlorite in veins, the growth of chloritoid and Na-amphibole after chlorite, tremolite and Cl-rich amphibole $\pm$ albite, the growth of paragonite and rarely jadeite in the plagioclase microdomain, the formation of garnet corona around the mafic microdomain, the continuous change in amphibole composition from actinolite to glaucophane;
- (2) peak assemblages (as observed in mylonites and different microdomains in mafic eclogites) are glaucophane, garnet, chloritoid, epidote, rutile; omphacite, garnet, rutile in relatively Ca-rich bands and garnet, jadeite, glaucophane, in meta-dykes. Thermobarometric calculations indicate minimum PT conditions of 450–550 °C and 1.5–1.8 GPa. Nonetheless, taking into account experimental studies (for example Poli, 1993) and thermodynamic calculations (Guiraud et al., 1990; Rebay and Powell, 2002), one may infer that it is possible that the Corio and Monastero metagabbros reached pressures up to 2.0 GPa during the Alpine eclogitic climax (in agreement with PT determinations in other parts of the western Alps). This is consistent with conditions determined in the present work.
- (3) retrograde assemblages formed during exhumation after the HP peak correspond to the growth of chlorite after chloritoid, garnet and amphibole, the growth of albite in the plagioclase microdomain, the change in amphibole composition (tremolite rimming Na-amphibole).

Depending on the type of pre-eclogitic transformations undergone by adjacent gabbro portions, different high-pressure assemblages form in single microdomains (i.e. the original igneous minerals). Chloritoid-bearing assemblages formed on domains re-homogenized during pre-Alpine hydration. In contrast, in samples where pre-eclogitic hydration did not occur, either omphacite-bearing assemblages, or classic garnet corona formed

(the latter being located between adjacent microdomains in which relics of igneous minerals are still preserved).

Kinetics played an important role in the undeformed rocks. In fact, samples where garnet coronas grew early in the metamorphic history maintained a sharper chemical distinction between the adjacent microdomains, and little or no chloritoid is observed. In contrast, samples where some chemical homogenization among different microdomains was achieved through hydration and low-grade reactions before eclogitization, are characterized by abundant chloritoid, both in plagioclase and mafic mineral microdomains. Another way to achieve this chemical homogenization is by deformation at high-pressure, as testified by the chloritoid–garnet–glaucofan–rutile mylonites. The presence of intermediate cases, in which anhydrous pre-Alpine assemblages (granulitic gabbro) coexist with chlorite-bearing pre-Alpine veins, show that eclogitic minerals (garnet, blue amphibole, chloritoid) formed only where hydrous minerals were present.

Available data on other chloritoid-bearing rocks from the western Alps support the above conclusions. In the Voltri Massif, relics of serpentine minerals and prograde formation of orthopyroxene have been observed by [Messiga et al. \(1995\)](#); in Monviso, hydrated troctolite displays different assemblages and has different zoning and types of corona depending on the hydration of the protholith prior to eclogitization ([Messiga et al., 1999](#)); in the Zermatt–Saas ophiolites ([Widmer et al., 2000](#); [Rebay et al., 2004](#)) different degrees of hydration of the oceanic crust correspond to the formation of the peculiar chloritoid-bearing assemblages.

All the above examples are relevant for metabasites deriving from a former oceanic crust, while the Corio and Monastero Gabbro is located within continental crust and should be considered as intracontinental gabbro ([Rebay and Spalla, 2001](#); [Rebay, 2003](#)). This opens up the interesting possibility that the hydration of deep continental rocks during exhumation accompanying rifting can form fluid reservoirs in the continental crust. These fluids can then be released during subduction of continental crust, influencing the behaviour of the subducted crust and the metamorphic transformations taking place in subduction zones.

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References

- Bianchi, A., Dal Piaz, G., Viterbo, C., 1965. Le masse di anfiboliti gabbriche a gastaldite di Corio e Monastero e di altre località della Zona Sesia–Lanzo (Alpi Occidentali). *Memorie Accademia Scienze Torino* 4 (3), 1–36.
- Compagnoni, R., 1977. The Sesia–Lanzo Zone: high-pressure-low temperature metamorphism in the AustroAlpine Continental Margin. *Rendiconti Società Italiana Mineralogia Petrologia* 33, 335–374.
- Compagnoni, R., Maffeo, B., 1973. Jadeite-bearing metagranites l.s. and related rocks in the Mount Mucrone Area (Sesia–Lanzo Zone, Western Italian Alps). *Schweizerische Mineralogische und Petrographische Mitteilungen* 53, 355–378.
- Compagnoni, R., Dal Piaz, G.V., Hunziker, J.C., Gosso, G., Lombardo, B., Williams, P.F., 1977. The Sesia–Lanzo Zone, a slice of continental crust with Alpine high-pressure low-temperature assemblages in the Western Alps. *Rendiconti Società Italiana Mineralogia Petrologia* 33, 281–334.
- Cortiana, G., Dal Piaz, G.V., Del Moro, A., Hunziker, J.C., Martin, S., 1998. ^{40}Ar – ^{39}Ar and Rb–Sr dating of the Pillonet klippe and Sesia–Lanzo basal slice in the Ayas valley and evolution of the AustroAlpine–Piedmont nappe stack. *Memorie Scienze Geologiche Padova* 50, 177–194.
- Dal Piaz, G.V., Hunziker, J.C., Martinotti, G., 1972. La Zona Sesia–Lanzo e l'evoluzione tettono-metamorfica delle Alpi Nord–Occidentali interne. *Memorie Società Geologica Italiana* 11, 433–460.
- Dal Piaz, G.V., De Vecchi, G., Hunziker, J.C., 1977. The AustroAlpine layered gabbros of the Matterhorn and Mt. Collon–Dents de Bertol. *Schweizerische Mineralogische und Petrographische Mitteilungen* 57, 59–88.
- Duchêne, S., Blichert-Toft, J., Luais, B., Téluk, P., Lardeaux, J.-M., Albarède, F., 1997. The Lu–Hf dating of garnets and the ages of the Alpine high-pressure metamorphism. *Nature* 387, 586–589.
- Ellis, D.J., Green, D.H., 1979. An experimental study on the effect of Ca upon garnet–clinopyroxene Fe–Mg exchange equilibria. *Contributions to Mineralogy and Petrology* 71, 13–22.
- Forneris, J.F., Holloway, J.R., 2003. Phase equilibria in subducting basaltic crust: implications for H₂O release from the slab. *Earth and Planetary Science Letters* 214, 187–201.
- Ganguly, J., 1979. Garnet and clinopyroxene solid solutions and geothermometry based on Fe–Mg distribution coefficient. *Geochimica and Cosmochimica Acta* 43, 1021–1029.
- Godard, G., 2001. Eclogites and their geodynamic interpretation: a history. *Journal of Geodynamics* 32, 165–203.
- Godard, G., Chat, C., 1994. Petrocalc: a petrological software to manage relational database of chemical analyses. IMA 94 book of abstracts. International Mineralogical Association, Pisa 147.
- Guiraud, M., Holland, T.J.B., Powell, R., 1990. Calculated mineral equilibria in the greenschist–blueschist–eclogite–facies in Na₂O–FeO–MgO–Al₂O₃–SiO₂–H₂O. Methods, results and geological applications. *Contributions to Mineralogy and Petrology* 104, 85–98.
- Guiraud, M., Powell, R., Rebay, G., 2001. On H₂O in metamorphism and an unexpected behaviour in the preservation of metamorphic assemblages. *Journal of Metamorphic Geology* 19, 445–454.
- Haüy, R.J., 1822. *Traité de minéralogie*. Seconde édition, revue, corrigée et considérablement augmentée par l'auteur. Bachelier et Huzard, Paris (4 volumes+atlas, t. II, pp 456; t.IV, pp 548).
- Holland, T.J.B., Powell, R., 1998. An internally consistent thermodynamic data set for phases of petrological interest. *Journal of Metamorphic Geology* 16, 309–343.

- Inger, S., Ramsbotham, W., Cliff, R.A., Rex, D.C., 1996. Metamorphic evolution of the Sesia–Lanzo Zone. Western Alps: time constraints from multi-system geochronology. *Contributions to Mineralogy and Petrology* 126, 152–168.
- Krogh, E.J., 1988. The garnet-clinopyroxene Fe–Mg geothermometer — a reinterpretation of existing experimental data. *Contributions to Mineralogy and Petrology* 99, 44–48.
- Krogh, R.E., 2000. The garnet-clinopyroxene Fe²⁺–Mg geothermometer: an updated calibration. In: Liou, J.G., Carswell, D.A. (Eds.), *Garnet peridotites and ultrahigh-pressure minerals*. Blackwell, Oxford, United Kingdom.
- Kullerød, K., 1996. Chlorine-rich amphiboles: interplay between amphibole composition and an evolving fluid. *European Journal of Mineralogy* 8, 355–370.
- Lardeaux, J.M., Spalla, M.I., 1991. From granulites to eclogites in the Sesia zone (Italian Western Alps): a record of the opening and closure of the Piedmont ocean. *Journal of Metamorphic Geology* 9, 35–59.
- Lardeaux, J.M., Gosso, G., Kienast, J.R., Lombardo, B., 1982. Relations entre le métamorphisme et la déformation dans la zone de Sesia–Lanzo (Alpes occidentales) et le problème de l'éclogitisation de la croûte continentale. *Bulletin de la Société Géologique de France* 24 (7), 793–800.
- Leake, B.E., Woolley, A.R., Arps, C.E.S., Birch, W.D., Gilbert, M.C., Grice, J.D., Hawthorne, F.C., Kato, A., Mandarino, J.A., Maresch, W.V., Nickel, E.H., Rock, N.M.S., Schumacher, J.C., Smith, D.C., Stephenson, N.C.N., Ungaretti, L., Whittaker, E.J.W., Youzhi, G., 1997. Nomenclature of amphiboles: report of the subcommittee on amphiboles of the international mineralogical association, commission on new minerals and mineral names. *American Mineralogist* 82, 1019–1037.
- Liu, J., Bohlen, S.R., Ernst, W.G., 1996. Stability of hydrous phases in subducting oceanic crust. *Earth and Planetary Science Letters* 143, 61–171.
- Massonne, H.J., Schreyer, W., 1987. Phengite geothermometry based on the limiting assemblages with K-feldspar, phlogopite and quartz. *Contributions to Mineralogy and Petrology* 96, 212–224.
- Messiga, B., Scambelluri, M., Piccardo, G.B., 1995. Chloritoid-bearing assemblages in mafic systems and eclogite-facies hydration of Alpine Mg–Al metagabbros (Erro-Tobbio unit, Ligurian Western Alps). *European Journal of Mineralogy* 7, 1149–1167.
- Messiga, B., Kienast, J.R., Rebay, G., Riccardi, M.P., Tribuzio, R., 1999. Chloritoid-eclogites from the Monviso ophiolites (Western Alps, Italy). *Journal of Metamorphic Geology* 17, 287–299.
- Novarese, V., 1894. Relazione sul rilevamento eseguito nelle Alpi occidentali (valli dell'Orco e della Soana) nella campagna del 1893. *Bollettino Regio Comitato Geologico* 5 (3), 215–230.
- Oberhänsli, R., Hunziker, J.C., Martinotti, G., Stern, W.B., 1985. Geochemistry, geochronology and petrology of Monte Mucrone: an example of Eo-Alpine eclogitization of Permian granitoids in the Sesia–Lanzo zone, Western Alps, Italy. *Chemical Geology* 52, 165–184.
- Perchuk, L.P., 1991. Derivation of a thermodynamically consistent set of geothermometers and geobarometers for metamorphic and magmatic rocks. In: Perchuk, L.L. (Ed.), *Progress in Metamorphic and Magmatic Petrology*. Cambridge University Press.
- Pognante, U., 1989. Tectonic implications of lawsonite formation in the Sesia zone (Western Alps). *Tectonophysics* 162, 219–227.
- Pognante, U., Compagnoni, R., Gosso, G., 1980. Micro- mesostructural relationships in the continental eclogitic rocks of the Sesia–Lanzo Zone (Italian Western Alps): a record of subduction cycle. *Rendiconti della Società Italiana di Mineralogia e Petrologia* 36, 169–186.
- Poli, S., 1993. The amphibolite–eclogite transformation: an experimental study on basalt. *American Journal of Sciences* 293, 1061–1107.
- Poli, S., Schmidt, M.W., 1995. H₂O transport and release in subduction zones: experimental constraints on basaltic and andesitic systems. *Journal of Geophysical Research* 100, 22299–22314.
- Powell, R., 1985. Regression diagnostics and robust regression in geothermometer and geobarometer calibration: the garnet–clinopyroxene geothermometer revisited. *Journal of Metamorphic Geology* 3, 231–243.
- Raheim, A., Green, D.H., 1974. Experimental determination of the temperature and pressure dependence of the Fe–Mg partition coefficient for coexisting garnet and clinopyroxene. *Contributions to Mineralogy and Petrology* 48, 179–203.
- Rebay, G., 2003. A metamorphic map of the Corio and Monastero gabbro (Southern Sesia–Lanzo zone, NW Italy). *Memorie di Scienze Geologiche di Padova* 55, 21–30.
- Rebay, G., Spalla, M.I., 2001. Granulite facies emplacement of the Sesia–Lanzo metagabbros: early record of Permian rifting? *Lithos* 58, 85–104.
- Rebay, G., Powell, R., 2002. The formation of eclogite facies metatroctolites and a general petrogenetic grid in Na₂O–CaO–FeO–MgO–Al₂O₃–SiO₂–H₂O (NCFMASH). *Journal of Metamorphic Geology* 20, 813–826.
- Rebay, G., Godard, G., Messiga, B., Kienast, J.R., 2004. Eclogite-facies coronitic metagabbro and metatroctolite from valtournanche, Italy. 32nd International Geological Congress, Abstract Volume.
- Reinsch, D., 1979. Glaucophanites and eclogites from Val Chiusella, Sesia–Lanzo Zone (Italian Alps). *Contributions to Mineralogy and Petrology* 70, 257–266.
- Rubatto, D., Gebauer, D., 1997. The Bonze Unit (Sesia–Lanzo Zone, Western Alps): a gabbroic Early Carboniferous intrusion that recorded the Hercynian and the Alpine metamorphism. *Quaderni di Geodinamica Alpina e Quaternaria* 4, 106–107 (Abstracts of the 3rd Workshop on Alpine Geological Studies).
- Rubatto, D., Gebauer, D., Compagnoni, R., 1999. Dating of eclogite-facies zircons: the age of Alpine metamorphism in the Sesia–Lanzo Zone (Western Alps). *Earth and Planetary Science Letters* 167, 141–158.
- Rubbo, M., Borghi, A., Compagnoni, R., 1999. Thermodynamic analysis of garnet growth zoning in eclogite facies granodiorite from M. Mucrone, Sesia zone, Western Italian Alps. *Contributions to Mineralogy and Petrology* 137, 289–303.
- Schmidt, M.W., Poli, S., 1998. Experimentally based water budgets for dehydrating slabs and consequences for arc magma generation. *Earth and Planetary Science Letters* 163, 361.
- Sengupta, P., Dasgupta, S., Bhattacharya, P.K., Hariya, Y., 1989. Mixing behaviour in quaternary garnet solid solution and an extended Ellis and Green garnet-clinopyroxene geothermometer. *Contribution to Mineralogy and Petrology* 103, 223–227.
- Spalla, M.I., De Maria, L., Gosso, G., Miletto, M., Pognante, U., 1983. Deformazione e metamorfismo della zona Sesia–Lanzo meridionale al contatto con la Falda Piemontese e con il Massiccio di Lanzo, Alpi occidentali. *Memorie della Società Geologica Italiana* 26, 499–514.
- Spalla, M.I., Lardeaux, J.M., Dal Piaz, G., Gosso, G., 1991. Métamorphisme et tectonique à la marge externe de la Zone Sesia–Lanzo (Alpes occidentales). *Memorie di Scienze Geologiche* 43, 361–369.
- Tropper, P., Essene, E.J., Sharp, Z.D., Hunziker, J.C., 1999. Application of K-feldspar–jadeite–quartz barometry to eclogite facies

- metagranites and metapelites in the Sesia Lanzo Zone (Western Alps, Italy). *Journal of Metamorphic Geology* 17, 195–209.
- Ungaretti, L., Lombardo, B., Domeneghetti, C., Rossi, G., 1983. Crystal–chemical evolution of amphiboles from eclogitized rocks of the Sesia–Lanzo Zone, Italian western Alps. *Bulletin de Minéralogie* 106, 645–672.
- Venturini, G., 1995. The geology, geochemistry and geochronology of the inner central Sesia Zone (Western Alps, Italy). *Mémoires de Géologie Lausanne* 25 (148 pp.).
- Widmer, T., Ganguin, J., Thompson, A.B., 2000. Ocean floor hydrothermal veins in eclogite facies rocks of the Zermatt–Saas Zone, Switzerland. *Schweizerische Mineralogische und Petrographische Mitteilungen* 80, 63–73.
- Zucali, M., Spalla, M.I., Gosso, G., 2002. Fabric evolution and reaction rate as correlation tool: the example of the Eclogitic Micaschist complex in the Sesia–Lanzo zone (Monte Mucrone–Monte Mars, Western Alps, Italy). *Schweizerische Mineralogische und Petrographische Mitteilungen* 82, 429–454.