Very-high pressure metamorphism of the Brossasco coronite metagranite, southern Dora Maira Massif, Western Alps

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Abstract

The Brossasco metagranite, Dora Maira Massif, Western Alps, underwent (early?) Alpine very-high pressure metamorphism and (meso/late?) Alpine amphibolite to greenschist-facies retrogressions. The Brossasco metagranite is part of the Brossasco Isasca unit of the southern Dora Maira Massif, in which pyrope + talc + coesite assemblage and kyanite eclogite indicate temperatures greater than 700 °C and pressures in excess of 2.8 GPa.

The Brossasco metagranite consists of small, relatively undeformed volumes of porphyritic granite separated by anastomosing mylonitic shear zones. The undeformed volumes grade into augen gneiss. The augen gneiss lacks any evidence of eclogite facies metamorphism.

The granite magmatic assemblage consisted of K-feldspar phenocrysts, plagioclase, quartz and biotite. The eclogitic assemblage is jadeite, garnet, phengite, zoisite, rutile and possibly coesite. The complex retrograde metamorphic evolution produced a peculiar mineral association with an igneous appearance. Late metamorphic plagioclase and biotite replaced the eclogitic minerals developed after magmatic plagioclase and biotite.

Chemical compositions and zoning of jadeite, biotite, phengite and garnet are investigated in detail. Zoning of the metamorphic phases, despite the relatively high metamorphic temperature, indicates a low rate of inter- and intra-crystalline diffusion. Phengite, which developed at the expense of the igneous K-feldspar, shows a progressive decrease in Tschermak substitution with time. The zoning is interpreted as evidence for progressively decreasing activity of H_2O in a closed system.

Keywords: Very-high pressure metamorphism, metagranite, corona reactions, Dora Maira Massif, Western Alps, Italy.

1. Introduction

The continent-continent collisional belt of the Western Alps is well suited for the study of high pressure metamorphism, since both continental- and oceanic-derived terrains underwent eclogite and blueschist facies metamorphic events. In the Western Alps very high pressure coesite-bearing assemblages are described in a continental unit (Dora-Maira massif) by Chopin (1984), and recently also in the oceanic Zermatt-Saas zone by Reinecke (1991).

In the 1970s and 1980s important geological information is collected from the continental nappes of the Western Alps, and petrographic and petrological studies are performed on the non-mafic high pressure rocks (general references in: Droop et al., 1990). The Sesia Lanzo Zone (a portion of the high temperature Adria Variscan continental crust) is metamorphosed in the early-Alpine event under pressure in excess of 1.5 GPa and at temperatures of approximately 550–600 °C (Compagnoni, 1977; Desmons and O'Neil, 1978). In the same unit the first occurrence of a jadeite + quartz-bearing metagranite is reported from Monte Mucrone (Dal Piaz et al., 1972; Compagnoni and Maffeo, 1973; Hy, 1984; Oberhänsli et al., 1985; Koons et al., 1987). In the southern part

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of the Dora Maira Massif (part of high temperature European Variscan continental crust) the assemblage pyrope + coesite + kyanite + phengite + talc is described by CHOPIN (1984). Chopin suggests that this paragenesis is stable above 2.8 GPa and at temperatures between 700–800 °C.

The aim of this study is to describe the metamorphic evolution of an undeformed metagranite (Brossasco metagranite) cropping out in the southern part of the Dora Maira Massif, in the same unit in which coesite and very high pressure assemblage are described (CHOPIN, 1984; CHOPIN et al., 1991; KIENAST et al., 1991).

2. Geological setting

In the classical tectonic subdivision of the Western Alps, the Dora Maira Massif (Fig. 1) is part of the Internal Crystalline Massifs of the Penninic domain. These terrains are characterized by the Mesozoic cover of the European plate margin overprinted by the Alpine orogeny.

The Dora Maira Massif consists of a pre-Alpine basement and of a Mesozoic cover (VIALON, 1966; MICHARD, 1967; BORTOLAMI and DAL PIAZ, 1970; BORGHI et al., 1984, 1985; POGNANTE and SANDRONE, 1989). In the southern part of the Dora Maira Massif, VIALON (1966) described the micaschist and quartzite with pyrope megablasts in which CHOPIN (1984) discovered coesite inclusions. These unusual rock types occur over an area of several square kilometres within an orthogneiss which lacks any clear evidence of eclogitic mineral assemblages. Nevertheless, the occurrence on a regional scale of kyanite-bearing eclogites and coesite support the existence of a very-high pressure event (CHOPIN et al., 1991; KIENAST et al., 1991), believed to have affected a single coherent very-high pressure unit (CHOPIN, 1987; HENRY, 1987; BIINO et al., 1988; KIENAST et al., 1991).

The very-high pressure unit, referred to as Brossasco Isasca unit (BIINO et al., 1988), consists of orthogneiss, subordinate micaschist and minor eclogite, with local occurrences of kyanite-bearing eclogite and marble (CHOPIN, 1984, 1986, 1987; KIENAST and LOMBARDO, 1987; BIINO et al., 1988; KIENAST et al., 1991; CHOPIN et al., 1991; SCHERTL et al., 1991). The pre-Alpine nature of the polymetamorphic basement, intruded by large bodies of late-Variscan granitoids, is proved by the local

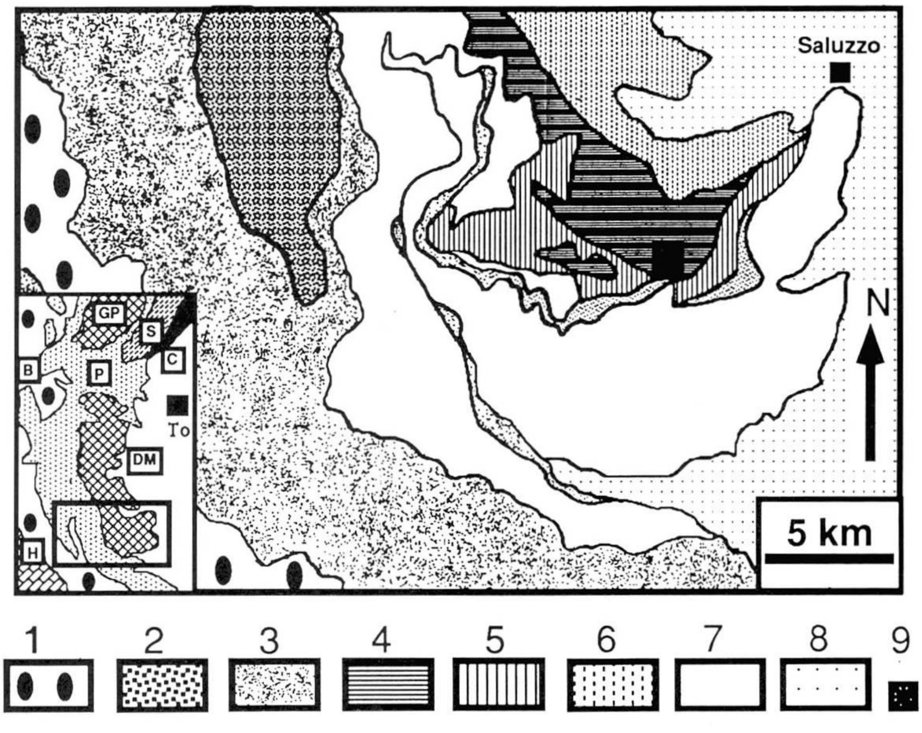


Fig. 1 Geological sketch-map of southern Dora-Maira Massif and adjoining areas (mainly after Carta geologica d'Italia 1:100.000, VIALON [1966] and HENRY [1987]). 1: Acceglio zone of the St. Bernhard nappe. 2: Piedmont zone, meta-ophiolites. 3: Piedmont zone, meta-sediments ("schistes lustres"). 4–7: Dora-Maira Massif. 4: Brossasco Isasca unit (with relics of coesite). 5: Brossasco Isasca (?) unit without relics of coesite. 6: Dronero unit. 7: Pinerolo graphitic unit. 8: Quaternary. 9: Location of the Brossasco metagranite. In the inset, the simplified tectonic map of the central part of the western Alps. S: Sesia-Lanzo zone; P: Piedmont zone; GP: Gran Paradiso massif; DM: Dora-Maira Massif; B: St. Bernhard nappe; E: Helminthoides Flysch; To: Torino.

preservation of relic pre-Alpine metamorphosed rocks (KIENAST and LOMBARDO, 1987; BIINO et al., 1988; BIINO and COMPAGNONI, 1991) and porphyric granite (sheet 79–80 Dronero-Argentera, Geological Map of Italy; VIALON, 1966) about 304 Ma old (MONIÉ and CHOPIN, 1991).

Two main Alpine metamorphic events are described in the Brossasco Isasca unit. An early-Alpine event is dated at approximately 100–110 Ma (MONIÉ, 1984; PAQUETTE, 1987; PAQUETTE et al., 1989; MONIÉ and CHOPIN, 1991) and it is characterized by very-high pressure and intermediate temperature eclogitic conditions. The second, later event(s) seems to be of late Eocene-early Oligocene age (MONIÉ in CHOPIN, 1987; MONIÉ and CHOPIN, 1991; TILTON et al., 1989; SANDRONE et al., 1988) and it is characterized by amphibolite to greenschist facies conditions. New isotopic studies yield a different scenario because the Pb–Sr–Nd isotopic systems recorded only Tertiary ages (TILTON et al., 1989; TILTON et al., 1991).

The Brossasco metagranite is an undeformed portion of the late-Variscan intrusives in the Brossasco Isasca unit. Undeformed rocks in the Brossasco Isasca unit are rare because a strong deformation phase coincided with the very-high pressure metamorphic event. It crops out on the southern side of middle Val Varaita, approximately 600 m SE of the village of Brossasco, and is mapped on the sheet 79–80, Dronero-Argentera, of the 1:100,000 Geological Map of Italy. Brossasco metagranite occurs within augen gneiss, and crops out as an approximately 50 m wide and 100 m long body. It consists of massive portions of homogeneous porphyritic metagranite, separated by shear zones. The transition between the massive metagranite and the surrounding augen gneiss is gradual and occurs over a few decimetres to a few metres by progressive foliation development. Aplitic and pegmatitic dikes cut sharply across the metagranite. The metagranite contains small cognate dark microgranular enclaves and xenoliths of foliated biotite-rich schist.

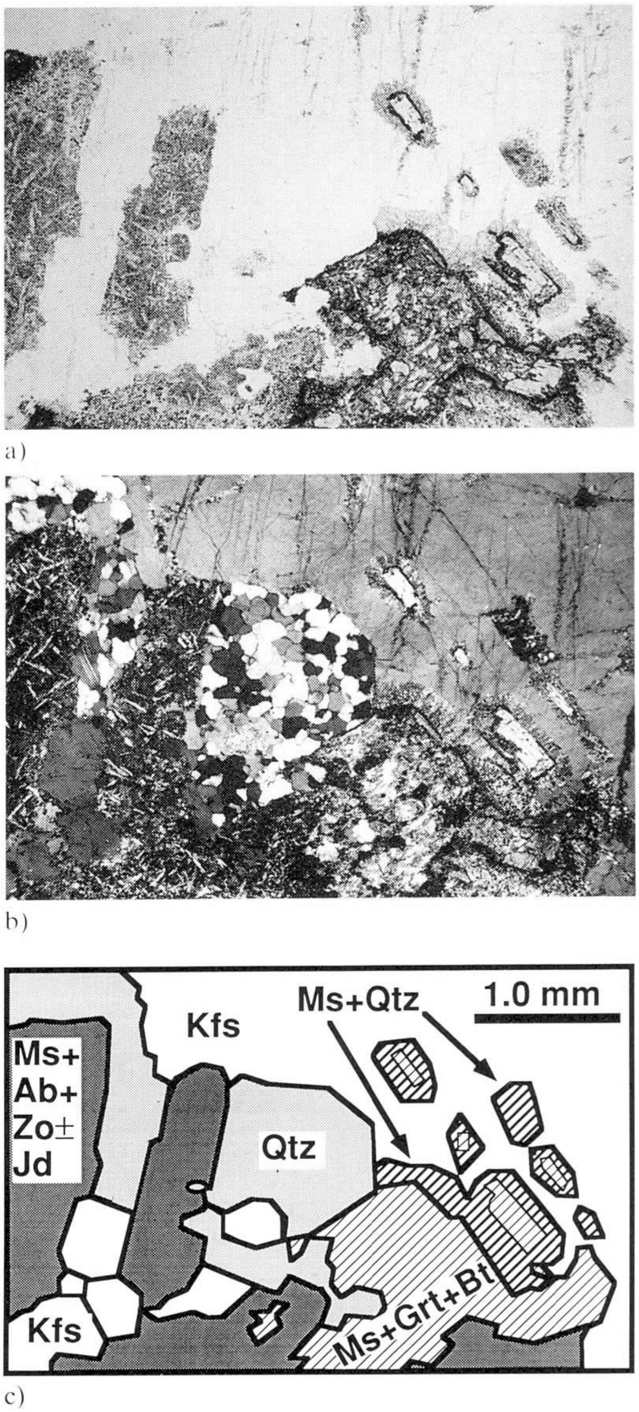


Fig. 2 Thin section photograph (a, b) and drawing (c) of the Brossasco metagranite. A large relic of igneous K-feldspar (upper right) includes several relic igneous biotite crystals completely altered to Ti-bearing phengite and coronitic garnet: note the thick rim of dactylitic phengite + quartz intergrowths around igneous biotite sites. A granoblastic aggregate of quartz crystals occurs in the center. Two euhedral plagioclase crystals (left) originally corroded by igneous quartz, are replaced by an aggregate of jadeite (mostly retrograded to albite), zoisite and muscovite. Large flakes of igneous biotite (lower right) are rimmed by coronitic garnet and replaced by Ti-bearing phengite, in turn partially altered to metamorphic red biotite.

3. Petrography

In the relatively undeformed volumes, the metagranite did not undergo complete textural reconstruction and the igneous (hypidiomorphic) texture and crystallization order are still recognizable. Metamorphic recrystallization is limited to the formation of both pseudomorphs and corona reactions (Figs 2a and 2b). The metagranite originally consisted of quartz, plagioclase, K-feldspar, biotite and accessory apatite, zircon and a Ti-(Fe-)rich phase. In one sample a pre-Alpine

Tab. 1 Mineralogical evolution of the Brossasco metagranite.

magmatic crystallization late-Variscan	metamorphic recrystallization early-Alpine	meso/late-Alpine
Kfs	phengite + coesite* (?)	microperthite
Bt*	Ti-bearing phengite + Grt + Rt	red Bt → green Bt
Pl*	Jd + Zo + coesite* (?) 1 ± Grt	Pl + Czo + Ms
Qtz*	coesite* (?)	Qtz
Ti-(Fe-)rich phase*	Rt	Tit + Ilm
Grt**		
Ap**		
Zrn**		
Tur** (?)		

* mineral pseudomorphosed
** accessory phases

xenocrystic garnet is also observed. With the exception of K-feldspar, apatite, zircon and xenocrystic garnet, all the other pre-Alpine phases are completely replaced by Alpine metamorphic minerals. At present the Brossasco metagranite contains both igneous, eclogite, amphibolite, and greenschist facies assemblages. According to textural relations, a polyphase metamorphic evolution may be inferred, and the different parageneses can be distinguished. The metamorphic evolution occurred in at least two different phases. The older phase is referred to as the early-(Cretaceous or Tertiary) Alpine very-high pressure metamorphism and the younger Tertiary phase as the meso- (or late-) Alpine lower pressure retrograde metamorphism(s). Primary igneous minerals and the metamorphic evolution of the Brossasco metagranite is summarized in table 1.

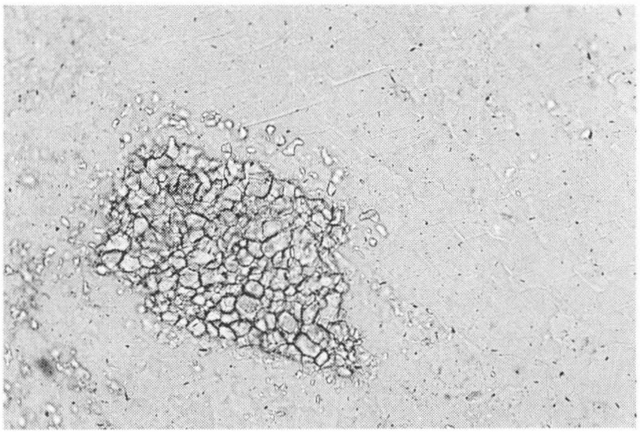
Most eclogitic minerals are preserved only as relics. Retrogression-free microdomains of the eclogitic assemblage occur only if armoured in igneous K-feldspar phenocrysts.

4. Metamorphic evolution and mineral chemistry

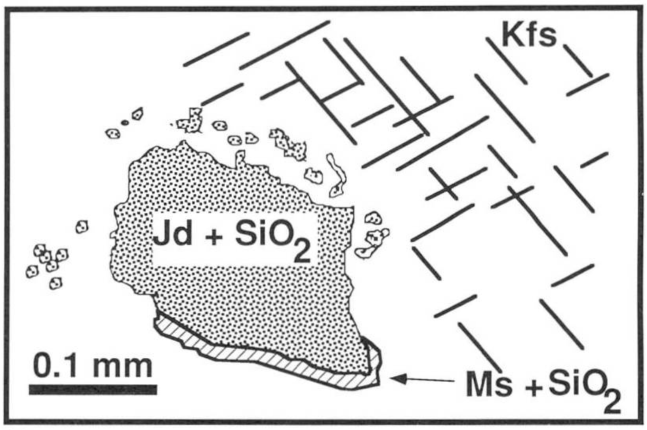
This study is based on the assumption that equilibrium tends to be maintained locally even though the granite as a whole is distinctly out of equilibrium. Consequently, the granite system may be split into several sub-systems that constitute the reaction sites. The evolution of each reaction site will be described both texturally and chemically. Each reaction site can be represented by a succession of partial equilibrium states, all irreversible related to the initial state of the system formed by the whole-rock. Chemical exchange between different reaction sites possibly occurred, but at present, without information on the composition and quantity of the reacting fluid phase, a mass balance is speculative. It also cannot be proved that all the reactions characterizing each metamorphic event occurred simultaneously.

Chemical analyses of minerals are performed both with a Cambridge SEM, equipped with a Link EDS System 860 (University of Torino, reducing data by a ZAF-4 program) and with an ARL WDS Microprobe (University of Milano, reducing data by a MAGIC IV program). Natural silicates and oxides are used as standards and no significant differences are observed between analyses obtained from the two instruments.

Clinopyroxene and garnet end-members are calculated according to CAWTHORN and COLLERSON (1974) and RICHWOOD (1968), respectively. Ferric iron contents of garnets are estimated using the method suggested by LAIRD and ALBEE (1981). For all minerals, the Mg-number is the atomic Mg/(Mg+Fe) ratio. To estimate the amount of the Tschermak substitution in white micas, both Si and (Mg+Fe) contents per formula unit are reported (calculated on the basis of 11 oxygens).



a)



b)

Fig. 3 Thin section photograph (a) and drawing (b) of a granoblastic aggregate of nearly pure jadeite (Jd_{96}) and quartz after igneous plagioclase (probably albitized) included in relic igneous K-feldspar. The jadeite aggregate is surrounded by an irregular rim of recrystallized K-feldspar, which contains remnants of corroded jadeite blasts. The lower face of the jadeite pseudomorph after plagioclase is rimmed by a very thin intergrowth of dactylitic phengite + quartz.

4.1. PSEUDOMORPHIC REACTIONS

4.1.1. K-feldspar igneous site

Relic igneous K-feldspar commonly occurs up to 2–3 cm long and as Carlsbad-twinned phenocrysts, which exhibit film microperthite texture (Smith and Brown, 1988) and include pseudomorphs after plagioclase, biotite, and quartz crystals. The exsolved albite lamellae, approximately 1 μm thick and 5 μm apart, occur frequently, except close to the grain boundaries. Locally, K-feldspar includes needles of zoisite.

A second generation of an optically homogeneous metamorphic K-feldspar is also present. It forms polygonal granoblastic aggregates, recrystallized from igneous K-feldspar along deformation bands or around mineral inclusions.

The optically homogeneous portion of relic microperthitic K-feldspar has a composition $Or_{90}Ab_{10}$. If the contribution of the film microperthite (Ab:Or = 1:5 in vol.) is taken into consideration, the bulk composition of the igneous K-feldspar is approximately $Or_{70-75}Ab_{30-25}$. The metamorphic K-feldspar has a composition close to $Or_{80}Ab_{20}$.

4.1.2. Plagioclase igneous site

Mineral assemblages pseudomorphically developed after igneous plagioclase during the early-Alpine event (eclogitic plagioclase site) and during later retrogression (retrograde plagioclase site). They will be discussed separately.

Eclogitic plagioclase site: The eclogitic alteration of igneous plagioclase results in the assemblage jadeite + zoisite + SiO_2 ± garnet.

Jadeite forms an aggregate of granoblasts (grain size ranges from 4 to 20 μm) (Fig. 3). Zoisite occurs as needles from 50 to 100 μm long and 5 to 10 μm across, it is a very minor phase and is not ubiquitous. SEM analysis of this site shows SiO_2 occurring as a 1 μm thick intergranular layer between the jadeite granoblasts. Idioblastic garnet (approximately 10 μm across) is distributed mainly at the rims of the igneous plagioclase domain, in proximity to the igneous biotite domain.

Electron microprobe analyses show the presence of both pure and impure jadeite at the eclogitic plagioclase site. The pure jadeite occurs in the core of plagioclase domains, whereas the impure jadeite is present at the rim of plagioclase domains usually devoid of zoisite (a few tens of μm wide and usually thicker close to the biotite domains). The pure jadeite (Jd_{96}) has very low iron content (ranging from 0.00 to 0.01 p.f.u., calculated on 4 cations). The Mg-number ranges from 0.00 to 0.08, due to the random variation of Mg. The Ca-Tschermak content (average 3.5%) appears to be moderately proportional to the jadeite content. The impure jadeite composition ranges from $Jd_{84}Wo_7En_4Fs_4$ to $Jd_{88}Tsch_4Wo_4En_2Fs_2$ (Tab. 2). The Mg-number (averaging 0.47 ± 0.07) shows a slightly inverse relation with jadeite content. Close to the rim the Ca-Tschermak content is around 3.15% (± 0.87%) and decreases towards the core to 0.68%, while the Wo, En and Fs end-members increase proportionally. Zoisite composition is close to the end-member, with X_{Fe} = 0.04 (X_{Fe} = Fe/Fe+Al) (Tab. 2). Garnet is a weakly zoned almandine-rich grossular (Tab. 2)

Tab. 2 Representative microprobe analyses of minerals from plagioclase site.

Mineral	Grt	Grt	Jd	Jd	Jd	Jd	Zo	Zo	Czo	Ms	Ms
Number	1	2	3	4	5	6	7	8	9	10	11
SiO_2	39.31	37.70	59.05	59.75	57.74	57.98	39.38	39.08	38.28	47.26	47.56
TiO_2	BD	BD	0.07	BD	BD	BD	BD	BD	BD	0.38	BD
Al_2O_3	21.25	21.41	24.87	24.92	20.89	22.80	32.59	31.14	26.54	33.67	32.76
FeO	16.37	20.31	0.18	0.17	3.10	1.79	BD	1.10	6.74	1.79	1.17
MnO	0.37	1.31	0.08	BD	0.14	BD	BD	BD	BD	BD	BD
MgO	0.52	0.48	0.06	BD	1.65	1.12	BD	BD	BD	0.56	1.56
CaO	22.20	18.79	1.72	1.62	3.88	3.63	24.83	23.70	24.19	BD	BD
Na_2O	BD	BD	13.95	13.78	12.50	12.85	BD	BD	BD	0.63	0.47
K_2O	BD	BD	BD	BD	BD	BD	BD	BD	BD	10.32	10.27
Total	100.02	100.00	99.98	100.24	99.95	100.17	96.80	95.02	95.75	94.61	93.79
oxygens	12	12	6	6	6	6	12.5	12.5	12.5	11	11
Si	3.005	2.960	2.008	2.030	1.992	1.984	3.020	3.062	3.031	3.164	3.204
Al^{IV}	0.000	0.040	0.000	0.000	0.008	0.016	0.000	0.000	0.000	0.836	0.796
Al^{VI}	1.947	1.942	0.997	0.998	0.842	0.905	2.946	2.876	2.477	1.821	1.802
Ti	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.019	0.000
Fe^{3+}	0.000	0.057	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000
Fe^{2+}	1.069	1.275	0.005	0.004	0.088	0.051	0.000	0.072	0.447	0.100	0.066
Mn	0.024	0.087	0.002	0.000	0.004	0.000	0.000	0.000	0.000	0.000	0.000
Mg	0.060	0.057	0.003	0.000	0.084	0.057	0.000	0.000	0.000	0.055	0.157
Ca	1.848	1.580	0.062	0.059	0.143	0.133	2.041	1.990	2.052	0.000	0.000
Na	0.000	0.000	0.919	0.907	0.836	0.853	0.000	0.000	0.000	0.082	0.062
K	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.881	0.884
Total	8.003	7.998	4.059	3.998	3.999	8.007	8.000	8.007	8.007	6.958	6.971

with Ca and Mg decreasing and Fe increasing from core to rim (Figs 4 and 5).

According to LOMBARDO et al. (1977) and KOONS et al. (1987) the composition of pyroxene is mainly related to the bulk-rock chemistry. The observed differences in jadeite composition can be explained by low diffusion rates producing chemical subdomains with a potential gradient of cations developing from core to rim. Zoisite has a random distribution and within several plagioclase domains the zoisite is absent. This distribution may be inherited from a pre-Alpine or prograde early-Alpine albitization of plagioclase. The antithetic garnet/zoisite distribution is suggested.

Retrograde plagioclase site: During retrogression, pure jadeite is generally preserved only when the former plagioclase is armoured by K-feldspar. In the other microstructural sites only rare relics of impure jadeite are preserved. The eclogitic assemblage is replaced by oligoclase + low substituted phengite + clinozoisite (Fig. 6).

Oligoclase (An_{10-12}) forms a peculiar aggregate of lobate crystals (each blast approximately 0.1 mm across). Due to small differences in optical orientation, the whole aggregate mimics a coarser single crystal characterized by undulatory extinction. Low substituted phengite occurs as randomly oriented flakes from 0.1 to 0.2 mm long and approximately 0.01 mm thick. Usually, the mica flakes are surrounded by plagioclase and not by clinozoisite or zoisite. The zoisite relics show a deeply corroded habit. Clinozoisite occurs as equant idioblasts approximately 10 μm across.

Low substituted phengite is a K-deficient mica with paragonite substitution ranging from 0.06 to 0.08 p.f.u. (calculated on 11 oxygens). The Ti content is very low and ranges from 0.00 to 0.02 p.f.u. This generation of mica has an ideal Tschermak substitution ($Al_2(Fe,Mg)_{-1}Si_{-1}$) ranging from 16 to 20%. The Mg-number ranges from 0.36 to 0.70, and a direct relation between Mg-number and Tschermak substitution is evident. The clinozoisite has $X_{Fe} = 0.15$ (Tab. 2). Platelets of colourless to very pale yellowish allanite (several tens of μm long) have been found. Judging from its shape, grain size and corroded habit the allanite may have formed either during the igne-

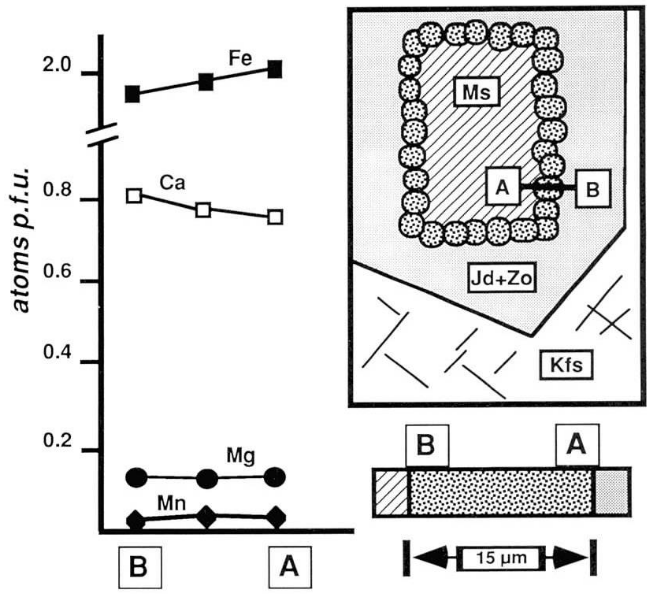


Fig. 4 Garnet zoning between biotite and plagioclase sites armoured by K-feldspar (normalized to 8 cations).

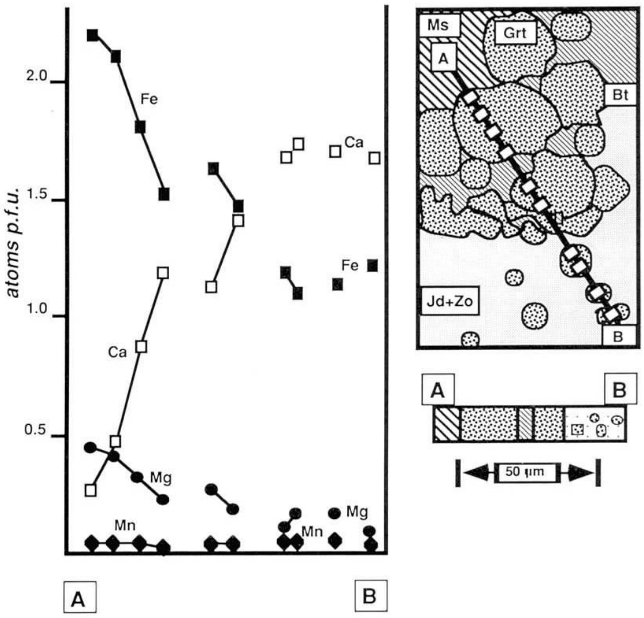


Fig. 5 Asymmetric garnet zoning between biotite and plagioclase sites (normalized to 8 cations).

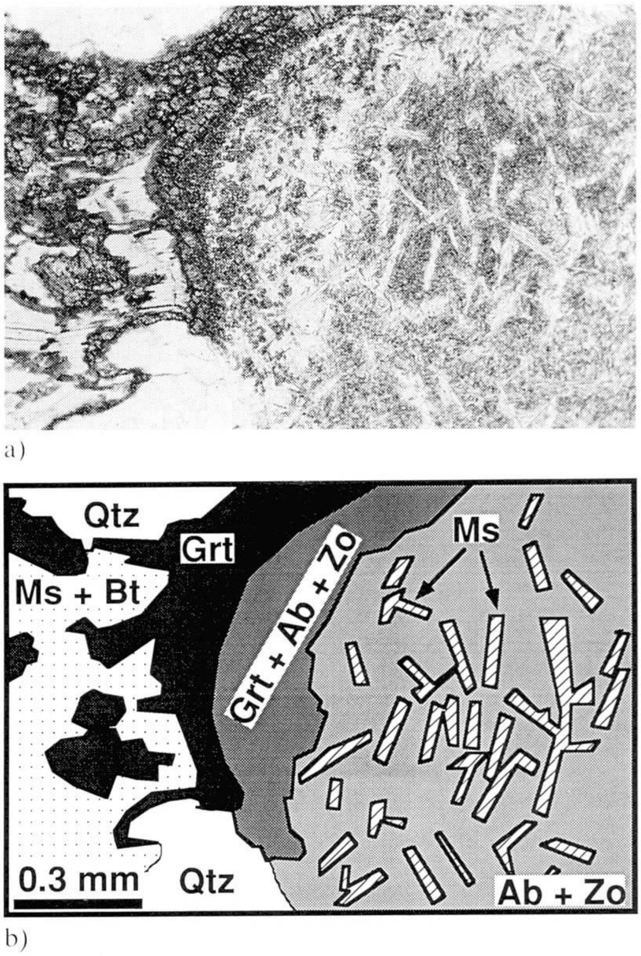


Fig. 6 Thin section photograph (a) and drawing (b) of a garnet corona developed between biotite (left) and plagioclase (right) sites. Zoisite and jadeite (after plagioclase) are replaced by albite + low substituted phengite. The corona consists of grossular-rich garnet and skeletal muscovite. The igneous biotite was replaced by Ti-bearing phengite. The muscovite is later partially altered to metamorphic red biotite along grain boundaries and kink-bands.

ous crystallization or during the early-Alpine event.

4.1.3. Quartz site

Quartz occurs only as polycrystalline granoblastic aggregates (grain size ranges from 0.15 to 0.05 mm). The habit of the aggregate is pseudomorphic after euhedral igneous crystals (Figs 2 a and b). The texture occurs also when quartz is included in relic igneous K-feldspar phenocrysts. Polycrystalline granoblastic aggregates are interpreted as being derived from static transition from coesite to quartz (Smith, 1988; Okay et al., 1989). The presence of similar aggregates in the surrounding rocks which still preserve relics of coesite supports this interpretation (Chopin, 1984; Schreyer, 1985; Biino et al., 1988). Furthermore, in the Monte Mucrone metagranite which has experienced lower pressure eclogitic conditions (Compagnoni and Maffeo, 1973; Oberhänsli et al., 1985; Koons et al., 1987) the original igneous crystals of quartz are commonly preserved both in the inclusions armoured by K-feldspar phenocrysts and in the matrix.

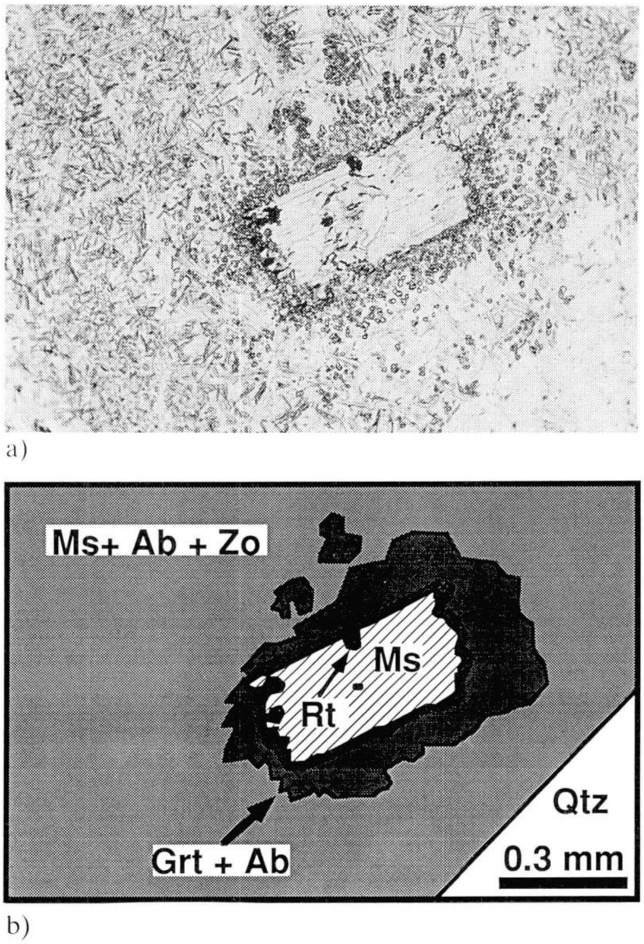


Fig. 7 Thin section photograph (a) and drawing (b) of a flake of igneous biotite, included in a plagioclase site, is pseudomorphosed by Ti-bearing phengite and thin garnet corona. In the plagioclase an irregular zone formed by grossular-rich garnet surrounds the biotite site. The plagioclase (first replaced by jadeite + zoisite) now consists of oligoclase, small clinozoisite needles and muscovite flakes.

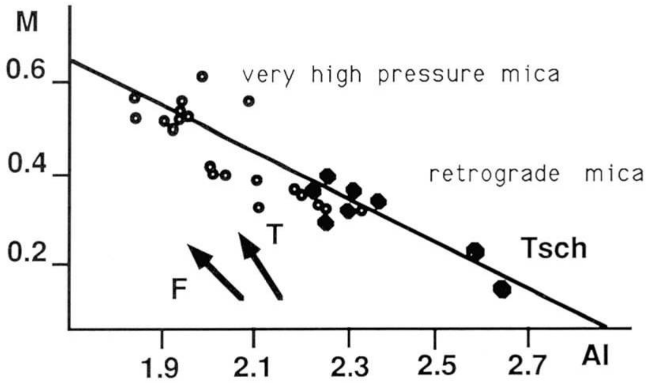


Fig. 8 (Mg+Fe) vs Al (cations calculated on 11 oxygens) diagram of Ti-bearing phengite. Circles = very high pressure muscovites; Diamond: retrograde muscovites; F: ferri-muscovite substitution vector; T: trioctahedral substitution vector; Tsch: Tschermak substitution.

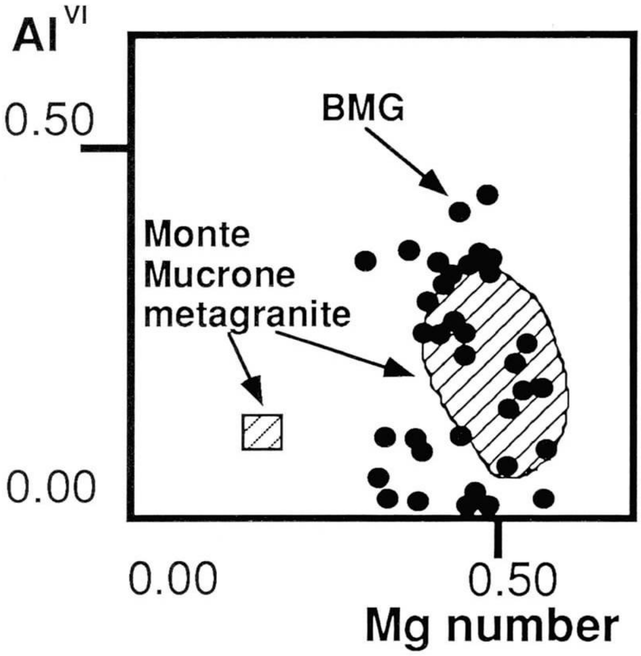


Fig. 9 Octahedral Al vs Mg-number of biotites from BMG and Monte Mucrone metagranite. Dot = biotites from BMG; Square: magmatic biotites from Monte Mucrone metagranite (Biino, pers. comm.); Field: metamorphic biotites from Monte Mucrone metagranite.

4.1.4. Biotite site

During early-Alpine very-high pressure metamorphism, the igneous biotite is replaced by Ti-bearing phengite + garnet + rutile (Figs 6 and 7). The garnet aggregate forms a continuous rim around the biotite site, and must be related to corona reactions. The garnet corona is 0.01 to 0.02 mm thick. Biotite is replaced by a single Ti-bearing phengite flake. The excess Ti is either exsolved as sagenitic rutile along the basal muscovite planes or is formed as coarser-grained rutile crystals along biotite-muscovite reaction boundaries. Within muscovite, alignments of 1 μm long rutile needles locally occur, which seem to define subdomains with distinct outlines.

The garnet composition is strongly dependent on the chemical composition of the phase to which it is in contact. The Ti-bearing phengite has a Ti-content ranging from 0.07 to 0.19 p.f.u. and a high K-content (ranging from 0.90 to 0.96 p.f.u.), with Na and Ca usually below the detection limit. The Mg-number (ranging from 0.46 to 0.73) is proportional to the Tschermak substitution. Tschermak substitution ranges from 30 to 55% (Tab. 3, Fig. 8).

During meso-Alpine metamorphism under amphibolite facies conditions, both muscovite and

Tab. 3 Representative microprobe analyses of muscovite and biotite (11.00 oxygens p.f.u.).

Mineral	Ms	Ms	Ms	Ms	Ms	Ms	Ms	red Bt
Number	1	2	3	4	5	6	7	8
Event	HP	HP	HP	HP	HP	HP	HP	retrograde
SiO_2	51.92	48.50	49.83	49.97	51.62	49.49	48.01	38.81
TiO_2	0.47	2.95	1.94	3.70	0.11	0.20	0.11	4.28
Al_2O_3	25.16	27.75	23.99	25.35	24.84	26.71	28.19	14.04
FeO	2.43	1.57	2.97	2.24	2.82	3.79	4.24	17.57
MnO	BD	BD	0.09	BD	0.23	0.04	0.00	0.07
MgO	3.65	2.63	3.47	2.81	4.42	2.54	2.25	9.89
CaO	BD	BD	BD	BD	BD	0.10	BD	BD
Na_2O	BD	0.28	0.31	BD	0.28	0.38	0.14	0.15
K_2O	11.02	10.53	10.41	10.79	11.22	10.68	10.87	9.66
Total	94.65	94.21	93.01	94.86	95.54	93.93	93.81	94.47
Si	3.493	3.279	3.433	3.367	3.466	3.385	3.301	2.952
Al^{IV}	0.507	0.721	0.567	0.633	0.534	0.615	0.699	1.048
Al^{VI}	1.488	1.490	1.381	1.380	1.431	1.539	1.585	0.209
Ti	0.024	0.150	0.100	0.187	0.006	0.011	0.005	0.244
Fe	0.137	0.089	0.171	0.126	0.158	0.217	0.231	1.116
Mn	0.000	0.000	0.006	0.000	0.014	0.003	0.000	0.005
Mg	0.366	0.265	0.356	0.282	0.442	0.259	0.231	1.120
Ca	0.000	0.000	0.000	0.000	0.000	0.008	0.000	0.000
Na	0.000	0.036	0.041	0.000	0.036	0.052	0.019	0.023
K	0.945	0.908	0.915	0.927	0.961	0.932	0.954	0.936
Total	6.960	6.938	6.970	6.961	7.047	7.020	7.038	6.653

garnet are replaced by metamorphic red biotite + quartz. The eclogitic rutile is not completely consumed by new biotite. In the most retrograded samples Ti-bearing phengite is topotactically replaced by single red biotite flakes, which can be easily mistaken for primary igneous biotite. Green biotite and late chlorite developed during the later greenschist facies metamorphism.

Metamorphic red biotite (Tab. 3, Fig. 9) is characterized by a high Si content (ranging from 2.80 to 2.93 cations per 11 oxygens), especially when the Mg-number is considered (always less than 0.60). The Ti content is inversely proportional to the Al content. Mg-number is proportional to the octahedral vacancies. Since the lowest Mg-numbers are measured in red biotite from completely retrograded sites, it is evident that the biotite Mg/Fe ratio is related to the garnet dissolution; the garnet retrograde zoning also supports this conclusion. Ti-bearing phengite partial re-equilibration also occurred during biotite growth, and in the more retrograded sites Tschermak substitution decreases to 20–30%.

4.2. CORONA REACTIONS

4.2.1. Quartz/plagioclase and quartz/K-feldspar contacts

The sharp boundaries between the quartz and feldspar sites suggest that no reactions occurred

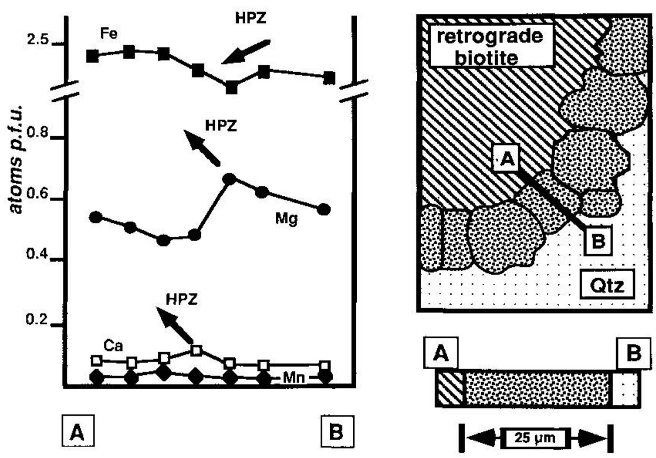


Fig. 10 Garnet zoning between biotite and quartz sites. HPZ is the probable trend of high pressure zoning later modified by growth of retrograde green biotite.

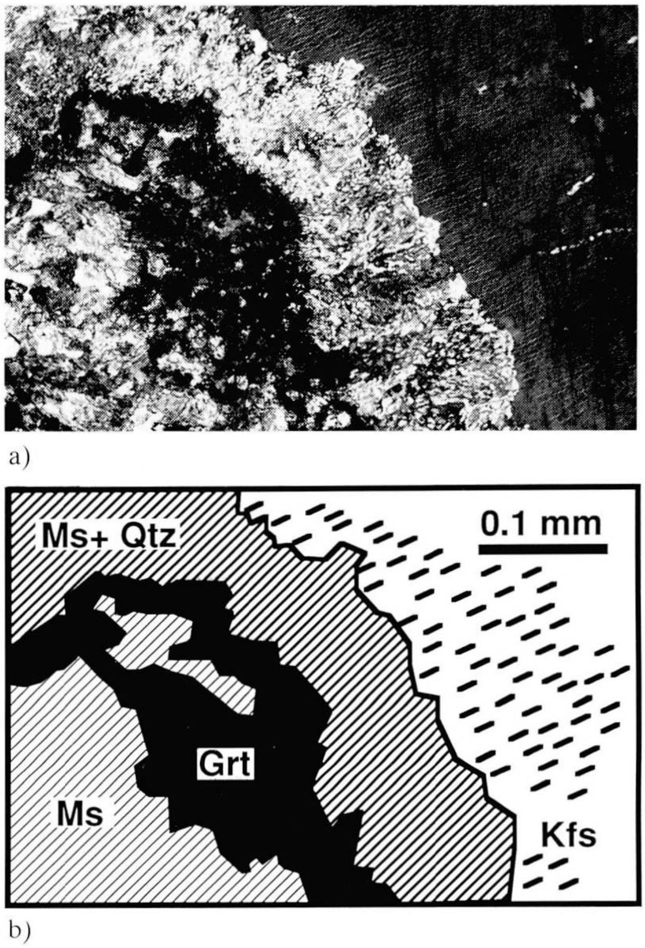


Fig. 11 Thin section photograph (a) and drawing (b) of a corona of dactylitic phengite intergrown with quartz wich developed between igneous K-feldspar (right side) and biotite (left side). The Ti-bearing phengite and garnet (black) replace biotite. K-feldspar shows film microperthite.

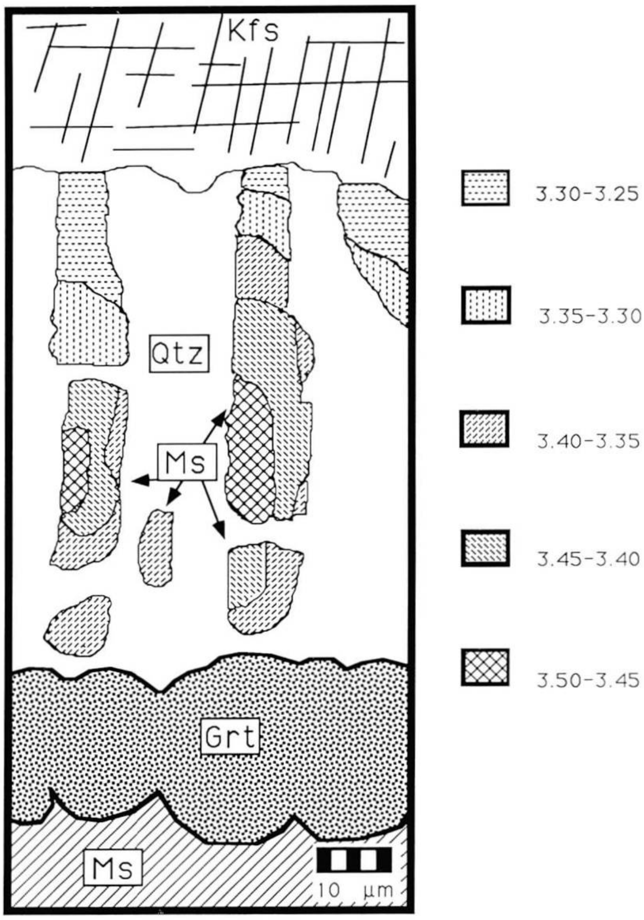


Fig. 12 A corona of dactylitic phengite intergrown with quartz developes between igneous K-feldspar and biotite (replaced by muscovite). The fields represent the amount of silica in the phengite.

during the metamorphic evolution. In some retrograded samples, a narrow layer of albite is observed at the feldspar-quartz interfaces.

4.2.2. Plagioclase/K-feldspar contact

The contacts between K-feldspar and plagioclase are usually sharp. An irregular, 1 µm thick corona of dactylitic white mica ± quartz is observed at the grain boundaries. White mica replaces K-feldspar and the plagioclase is now a jadeite aggregate. Within the K-feldspar, approximately 5 to 10 µm from the plagioclase domain, small corroded grains of jadeite exist, which developed during recrystallization of granoblastic K-feldspar. These are probably relics of the original plagioclase/K-feldspar interface.

During the retrogression a double plagioclase corona (a few tens of µm thick) formed between the retrograde plagioclase domain and K-feldspar. These double coronas consist of plagioclase (An_{12}) in contact with the K-feldspar and albite (An_6) in contact with the plagioclase. Worm-like quartz is observed within K-feldspar near the plagioclase corona. Usually a film of pure albite is observed between plagioclase and K-feldspar.

4.2.3. Biotite/quartz contact

This contact is marked by corona garnet, which exhibits idioblastic shapes against the granoblastic quartz aggregates.

This corona garnet is weakly zoned. When in contact with quartz it is an $Alm_{77}Py_9Grs_2Spes_2$.

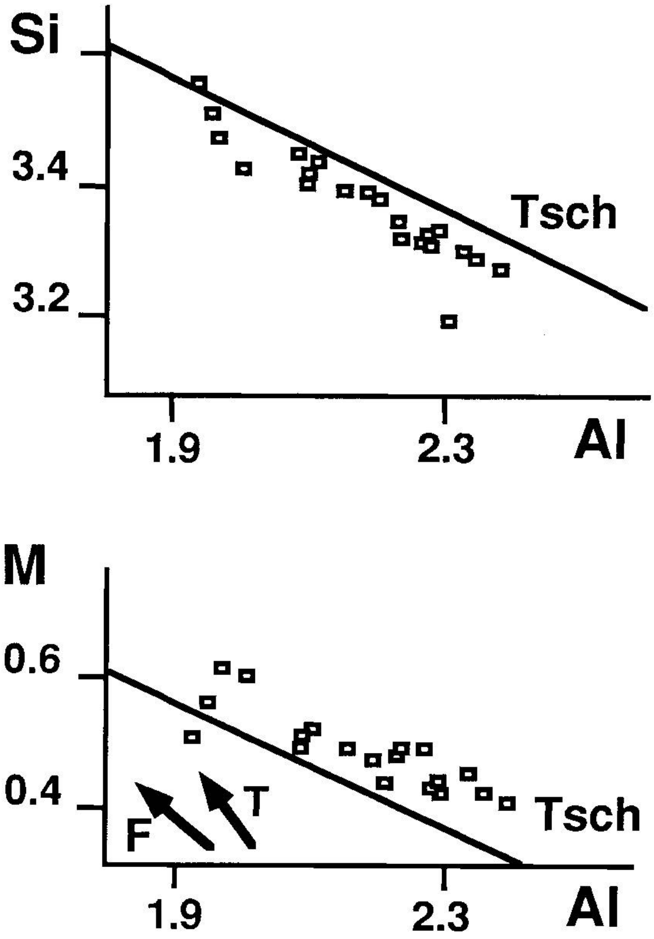


Fig. 13 Si vs Al and (Mg+Fe) vs Al diagrams of dactylitic phengite. F: ferri-muscovite substitution vector; T: trioctahedral substitution vector; Tsch: Tschermak substitution.

When in contact with the magmatic biotite site, garnet zoning shows two distinct trends, illustrated in the profile in figure 10. According to microscopic and SEM observations these trends are due to the development of retrograde green biotite from garnet.

4.2.4. Biotite/K-feldspar contact

At the biotite/K-feldspar contact a double corona is observed. It consists of garnet in contact with the biotite site and dactylitic phengite intergrown with quartz in contact with K-feldspar. Idioblastic garnet is observed locally within K-feldspar and in contact with the dactylitic phengite. The lobate dactylitic phengite + quartz intergrowths are 0.1 to 0.3 mm thick and project from the garnet corona into the K-feldspar, indicating that they formed at the expense of K-feldspar (Fig. 11). Each single dactylitic phengite crystal consists of several branches 4 to 8 μm wide and approximately 15 μm apart. During retrogression, garnet and dactylitic phengite are partially replaced by early red or later green biotite.

The dactylitic phengite is Ti-free (Ti content lower than 0.01 p.f.u.), while potassium is close to 1 p.f.u. The Mg-number, clearly related to the Tschermak substitution, (average 0.51 ± 0.05, Fig. 12) illustrates the growth zoning of the dactylitic phengite. In contact with biotite the Tschermak content of muscovite is higher than in contact with K-feldspar. In a single crystal, Si may decrease from 3.40 to 3.28 p.f.u. and (Mg+Fe) from 0.51 to 0.40 p.f.u. (Fig. 13).

In the less retrograded samples, corona garnet is homogeneous $Alm_{78}Py_{15}Grs_4Spes_1$. Idioblastic garnets within K-feldspar in proximity to dactylitic phengite have the same composition (Fig. 14).

4.2.5. Biotite/plagioclase contact

During the eclogitic metamorphism, a double-layer reaction corona developed between igneous plagioclase and biotite, consisting of garnet in contact with biotite and dactylitic phengite + quartz intergrowths in contact with the plagioclase. This corona is perfectly preserved in the less retrograded microdomains when armoured by relict igneous K-feldspar. The phengite pseudomorphs after igneous biotite are surrounded by a continuous garnet corona (Tab. 4, Fig. 7) consisting of small idioblastic garnets. Garnet compositional zoning across a corona ranges from $Alm_{73}Py_{16}And_6Grs_3Spe_3$ (near the biotite magmatic site) to $Alm_{45}Py_6And_4Grs_{43}Spe_1$ (near the plagioclase magmatic site) as shown in figure 5. Almandine-rich grossular blasts (Grs = 60–70%; Alm = 20–28%; Py = 4–5%; Spe = 1–2%) are also detected.

5. Discussion of mineral composition and fluid phase behaviour

Garnet grew in different microstructural domains and its composition is constrained by diffusion in the small scale chemical domains. At temperatures near or above the sillimanite + K-feldspar isograde, garnet is commonly homogeneous (Loomis, 1983; Chakraborty and Ganguly, 1991). Nevertheless, in the Brossasco metagranite the grossular-rich garnet shows a strong zoning. In the absence of pervasive deformation, it seems that garnet zoning is preserved up to at least 700 °C. Similar zoning is reported by Mørk (1985, 1986) from the middle temperature corona eclogites of the Norwegian Caledonides.

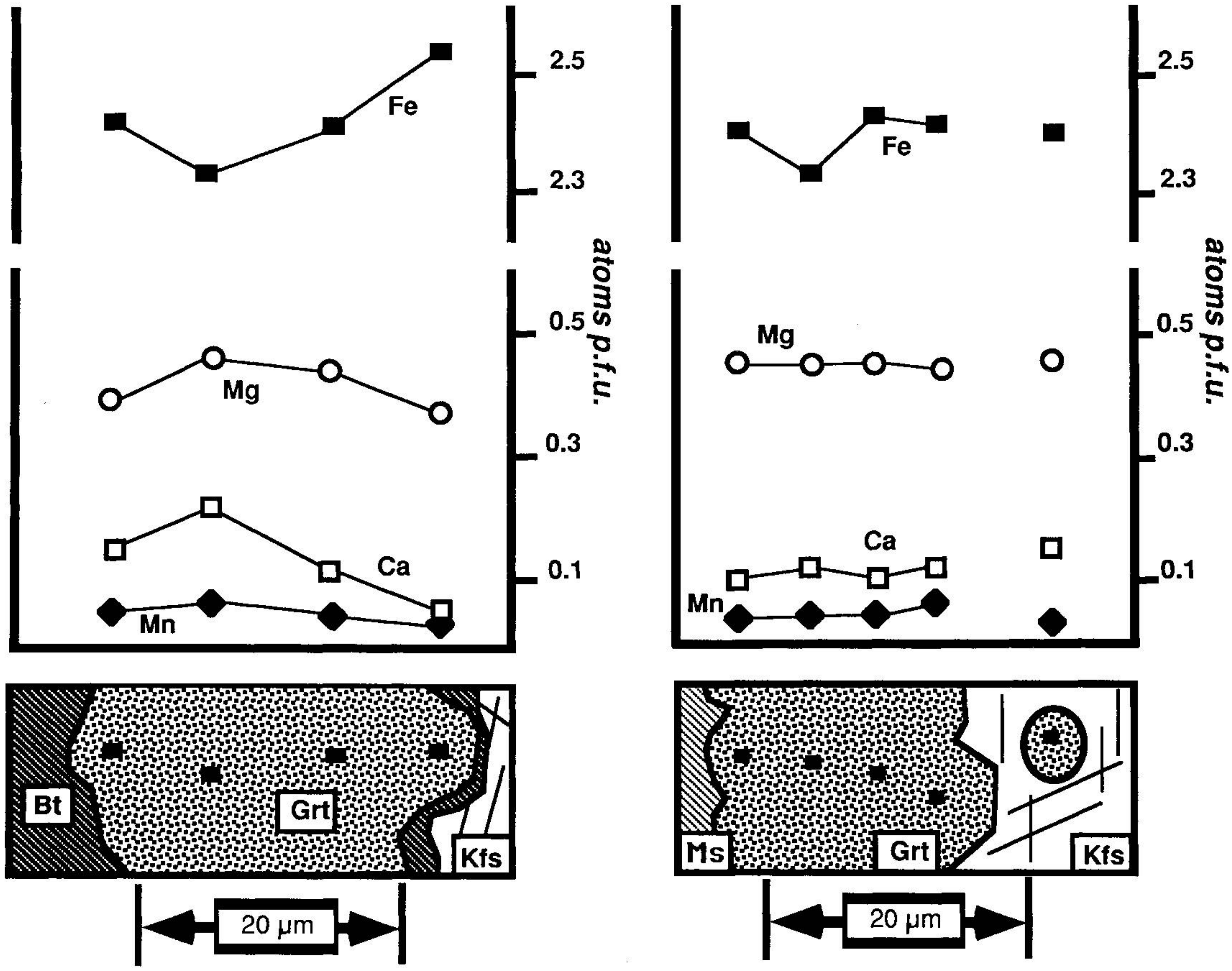


Fig. 14 Garnet zoning between biotite and K-feldspar sites. In the left profile the probable trend of HP zoning later modified by growth of retrograde biotite.

Microperthite exsolved albite is usually present in the relic igneous alkali-feldspar. The film microperthite cannot be inherited from late-Variscan cooling, because the exsolved albite would have been converted to jadeite + quartz during the eclogitic event (as occurred in the Monte Mucrone metagranite, Sesia-Lanzo zone). The possible cyclic transformation of albite into jadeite + quartz and later into retrograde albite can be ruled out because jadeite is usually preserved in K-feldspar. Probably the K-feldspar rehomogenized during the prograde path and albite exsolved during the following retrograde path.

Biotite breakdown produces a muscovite with a high Tschermak substitution and very high concentration of Ti. Similar Ti-rich muscovite is described in the metagranite of the Monte Mucrone by KOONS et al. (1987). Under the electron micro-

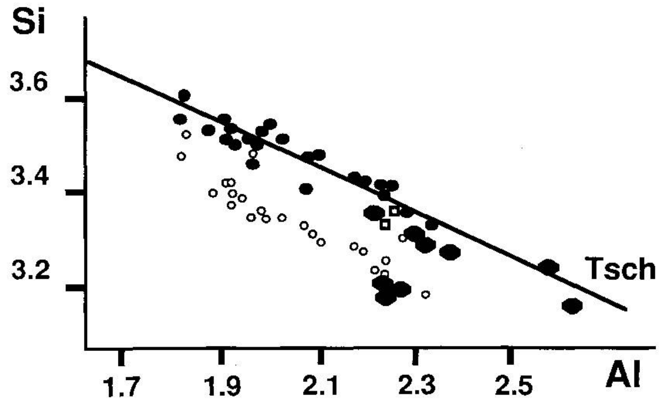


Fig. 15 Si vs Al diagram of Ti-bearing phengite. Circles = very high pressure muscovites; Dot = very high pressure muscovites assuming Ti in the exchange vector; Diamond: retrograde muscovites assuming Ti in the exchange vector (see text). Square: retrograde muscovites in plagioclase site. Tsch: Tschermak substitution.

Tab. 4 Representative microprobe analyses of garnet (12.00 oxygens p.f.u.) from coronas around biotite. The phase in contact with biotite is shown in line PCB (Phase in Contact with Biotite).

Mineral	Grt	Grt	Grt	Grt	Grt	Grt
Number	1	2	3	4	5	6
PCB	Kfs	Pl	Pl	Pl	Pl	Qtz
SiO_2	37.07	37.71	37.28	37.80	38.03	37.72
TiO_2	BD	0.19	0.04	BD	BD	BD
Al_2O_3	21.10	21.26	21.49	21.00	20.96	21.11
FeO	36.59	33.08	31.69	27.56	22.16	32.98
MnO	0.68	0.86	0.68	0.67	0.57	0.62
MgO	3.82	3.82	3.61	2.74	1.65	5.45
CaO	1.22	3.17	5.17	10.37	16.75	2.17
Total	100.48	100.09	99.96	100.14	100.12	100.05
Si	2.961	3.004	2.963	2.983	2.977	2.983
Al^{IV}	0.039	0.000	0.037	0.017	0.023	0.016
Al^{VI}	1.949	1.997	1.977	1.937	1.913	1.950
Ti	0.000	0.011	0.002	0.000	0.000	0.000
Fe^{3+}	0.050	0.000	0.020	0.062	0.086	0.049
Fe^{2+}	2.394	2.218	2.085	1.756	1.364	2.132
Mn	0.045	0.058	0.045	0.044	0.038	0.041
Mg	0.455	0.453	0.428	0.321	0.192	0.642
Ca	0.104	0.270	0.440	0.877	1.405	0.183
Total	7.997	8.007	7.997	7.997	7.998	7.997

scope the muscovite flakes are chemically and mineralogically homogeneous. Theoretically, ideal Tschermak substitution (on the basis of 11 oxygens) imposes the relation Si–3 = (Mg+Fe). The very-high pressure muscovites show silicon ranging from 3.30 to 3.40 p.f.u., but (Mg+Fe) ranging from 0.45 to 0.55 p.f.u. suggesting Si deficiency (Figs 8 and 15). The very-high pressure muscovite show in figure 15 a possible substitution resulting by the sum of the Tschermak and the ferrimuscovite vectors, but this possibility is not confirmed in figure 8. The following two relations are both consistent with the analytical data and charge balance:

(Si+Ti) –3 = (Mg+Fe), or Mg = Mg'+Mg" and (Si+Mg') –3 = Mg"+Fe+Ti.

At present the location of Ti in the structure of micas (tetrahedral or octahedral coordination) is not well understood, but tetrahedral magnesium and octahedral Ti is the most probable structure.

Microstructural observations indicate that the igneous K-feldspar is altered to dactylitic phengite + SiO_2 when in contact with the igneous biotite site (Figs 2a and 2b). This reaction also occurs when biotite is armoured by K-feldspar (Figs 2a, 2b and 12). Dactylitic phengite is characterized by a progressive decrease in the silica content from the magmatic K-feldspar/biotite interface towards the core of the K-feldspar crystal (Figs 12 and 13). The deficiency of silicon in the growth zones cannot explain this zoning, because the mica is always intergrown with a SiO_2 phase (either quartz or possibly coesite). The reduction of P_{H_2O} (under constant lithostatic pressure) shifts the isopleths towards higher pressure, and it can explain the observed zoning. Zoning in phengite is seldom described in the literature, but the muscovite of the Brossasco metagranite is not unique (FRANZ et al., 1986; HAMMERSCHMIDT and FRANK, 1991; DEMPSTER, 1992). Microscopic evidence indicates that the dactylitic phengite crystallized since biotite breakdown. In a closed system, biotite breakdown is the only reaction to supply H_2O to the muscovite.

Under very-high pressure K-feldspar is stable only under H_2O-poor fluid phase conditions (GOLDSMITH, 1988). The breakdown of K-feldspar into muscovite consumes the H_2O component of the fluid, and produces a significant volume decrease. This prograde hydration reaction proceeds only until the H_2O trapped along grain boundaries or in partially weathered (sericitic) feldspars, is consumed. There is no evidence that H_2O originated from fractures or veins (e.g. muscovite trail in K-feldspar such as in the Monte Mucrone metagranite), and the granite can be compared to a closed system in which reactions are capable of buffering the composition of the pore fluid. It is possible to conclude that the absence of an H_2O-rich fluid phase characterized the pressure climax. This conclusion is also supported by the scarcity of metamorphic veins (which are widespread in the other high pressure terrains of the Western Alps). During the prograde path the zoisite-in reaction occurs before (at lower pressure) the K-feldspar-out reaction (WYLLIE, 1983). The formation of zoisite is not inconsistent with the absence of an H_2O-rich fluid at climax.

6. General considerations

6.1. DID PARTIAL MELTING OCCUR IN THE BROSSASCO METAGRANITE DURING THE METAMORPHIC CLIMAX ?

Since the climax conditions inferred for the Brossasco Isasca unit are P > 2.8 GPa and T > 700 °C, the Brossasco metagranite is metamorphosed above the solidus of an H_2O-saturated granite (HUANG and WYLLIE, 1975; WYLLIE, 1983). In the absence of evidence of partial melting, CHOPIN (1984, 1986) assumed at climax H_2O-poor fluid phase conditions. SCHREYER et al. (1987) suggested that the granitic rocks may have been partially melted, but during the following polyphase deformation and recrystallization the evidence of melting is obliterated. The Brossasco metagranite perfectly preserves the plutonic pre-Mesozoic texture and there is no evidence for partial melting also at the grain boundary interfaces. From this observation it is possible to conclude that, in undeformed, fluid absent conditions partial melting did not occur due to the shifting to higher P-T conditions of the minimum melting curve (HUANG and WYLLIE, 1975; WYLLIE, 1983).

6.2. RETROGRADE EVOLUTION

In the Brossasco metagranite the eclogitic phases are mainly preserved when armoured by K-feldspar. In the rock matrix, the dehydration reaction (eclogitic Ms → Kfs + fluid phase) provides a source of H_2O that leads the retrograde reactions towards completion.

During the first step of retrogression of the plagioclase domain, zoisite and jadeite are replaced by oligoclase (4 Zo + Qtz → 5 Pl + Grt + 2 H_2O) and minor low pressure muscovite (Ms II). In the biotite domains metamorphic Ti-bearing biotite replaces eclogitic muscovite + rutile (BIINO, 1991). In the K-feldspar domains K-feldspar replaces the eclogitic muscovite. The resulting paragenesis is Qtz + Kfs + An_{10-12} + Bt + Ms II + Grt. The Tschermak substitution in muscovite defines pressures of approximately 0.6 GPa (MASSONNE and SCHREYER, 1987; RAZ and PETERS, 1989). According to LE GOFF (1989) this paragenesis is stable under high temperature amphibolite facies conditions, and garnet-biotite thermometers yield temperature ranging from 600 to 650 °C. A later stage of retrogression includes epidote in the stable assemblage (epidote amphibolite facies). The later assemblages (greenschist facies) are poorly developed in undeformed samples (Ab + Ms II + Qtz + Chl ± Ep ± Kfs).

Due to the slope in a P-T diagram of the oligoclase-in reaction (4 Zo + Qtz → 5 An + Grt + 2 H_2O), the retrograde evolution is consistent with a high temperature quasi adiabatic uplift. This stage of the retrogression presumably occurred under fluid-present conditions, and the intersection of oligoclase-in with the partial melting reaction curve (JOHANNES, 1984) constrains the high temperature amphibolite retrogression to a temperature below 600–650 °C and a pressure not higher than 1.0 GPa. The beginning of retrograde reactions at P close to 1.0–1.2 GPa is also consistent with experimental observation of the garnet-out biotite-in reaction (LE BRETON and THOMPSON, 1988). The lower P-T limit of retrogression is defined by the intersection of the partial melting curve with the Ms + Qtz → Kfs + Sil reaction curve. Considering the effect of Tschermak substitution in muscovite this intersection occurs between 0.3 and 0.4 GPa ($P_{H_2O} = P_{lit}$). Temperatures lower than approximately 400 °C for 0.5 GPa may be inferred for perthitic $Or_{90}Ab_{10}$ (SMITH and BROWN, 1988).

The retrograde evolution of the Brossasco metagranite is in agreement with the history of the Brossasco Isasca unit inferred from other rock types (CHOPIN, 1984; CHOPIN et al., 1991; KIENAST et al., 1991).

7. Conclusions

The Brossasco Isasca unit is a single coherent tectonic unit metamorphosed under conditions of approximately 700–750 °C and at least 2.8 GPa (CHOPIN, 1987; HENRY, 1987; BIINO et al., 1988;

KIENAST et al., 1991; CHOPIN et al., 1991). The field observations indicate that the Brossasco metagranite belongs to the Brossasco Isasca unit (CHOPIN et al., 1991; COMPAGNONI, pers. com.). This petrographic study shows that the igneous granite assemblage recrystallized under eclogitic conditions consistent with those of the Brossasco Isasca unit.

The estimates of very-high pressure-medium temperature conditions of the Brossasco metagranite metamorphism are supported by the following qualitative evidences:

1) the occurrence of polycrystalline quartz aggregates after igneous quartz both in the undeformed rock matrix and in the inclusions in K-feldspar; these aggregates are interpreted as pseudomorphs after former coesite;

2) the presence of jadeite + SiO_2 + almandine-rich grossular garnet after plagioclase, and of phengite after K-feldspar;

3) the complete breakdown of biotite into phengite;

4) the retrograde evolution indicates the highest temperature path observed in the Western Alps. The retrograde path is only compatible with the P-T path of the coesite unit (see Fig. 11, p. 285, in CHOPIN et al., 1991).

The following qualitative evidences are not inconsistent with very-high pressure medium temperature conditions:

1) the absence of partial melting, because under H_2O-poor fluid conditions partial melting occurs at higher temperatures;

2) the preservation of garnet zoning, because garnets in the medium temperature eclogites of Norway show comparable zoning;

3) the presence of local equilibrium, because local equilibrium conditions are described also at higher temperatures (e.g. TRACY and MCLELLAN, 1985).

Brossasco metagranite is a good example of the eclogitic evolution of a metagranite and several similarities with the Mucrone metagranite can be recognized. But in the Brossasco metagranite the magmatic biotite and plagioclase are replaced by eclogitic minerals and later partially converted back to (metamorphic) plagioclase and biotite. It is also evident that retrograde reactions are very pervasive. This conclusion suggests that the eclogitic assemblages in metagranite are ephemeral, as HEINRICH (1982) concluded for micaschists. The different behaviour of the mafic versus non-mafic chemical systems during the post eclogitic retrograde evolution may explain why in many crystalline terrains eclogites are the only proof of an older eclogitic facies metamorphism. Considering this point of view, the partial retrogression of the very-high pressure assemblage in the Brossasco metagranite and the complete retrogression of surrounding orthogneiss, deriving by the same Late Variscan plutonic body, validate the hypothesis of "in-situ" eclogitization of this high pressure terrain.

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