Zeitschrift: Eclogae Geologicae Helvetiae

Herausgeber: Schweizerische Geologische Gesellschaft

Band: 89 (1996)

Heft: 1

Artikel: Composite P-T paths in the Internal Penninic Massifs of the western Alps : petrological constraints to their thermo-mechanical evolution

Autor: Borghi, Alessandro / Compagnoni, Roberto / Sandrone, Riccardo

DOI: https://doi.org/10.5169/seals-167905

Eclogae geol. Helv. 89/1: 345–367 (1996)
0012-9402/96/010345-23 $1.50 + 0.20/0
Birkhäuser Verlag, Basel

Composite P-T paths in the Internal Penninic Massifs of the Western Alps: Petrological constraints to their thermo-mechanical evolution

ALESSANDRO BORGHI[1], ROBERTO COMPAGNONI[1] & RICCARDO SANDRONE[2]

Key words: P-T paths, P-T estimates, Alpine metamorphism, Internal Penninic Nappes, Western Alps

Parole chiave: Traiettorie P-T, stime termo-barometriche, metamorfismo alpino, Massicci cristallini interni, Alpi occidentali

ABSTRACT

This paper reports a summary of recent investigations focused on the reconstruction and interpretation of exhumation P-T paths for the Internal Penninic Nappes (IPN) of the Western Alps.

These three tectonic units (Monte Rosa, Gran Paradiso and Dora Maira Nappes) exhibit a similar Alpine metamorphic evolution marked by two main events. The older (early-Alpine) event occurred under LT eclogite facies conditions (T = 500–550 °C and P = 11–13 kbar) and has been well described in the literature. The eclogitic climax is followed by a retrograde decompressional evolution, developed at P-T conditions lower than the garnet stability field. For the younger (late-Alpine) event a peak T = 500–550 °C and a peak P below 5 kbar were estimated from Grt-Bt geothermometry and mineral compatibilities.

Therefore, the P-T paths of the IPN consist of two metamorphic peaks, which developed approximately at the same T, but at significantly different P. The whole Alpine P-T path is characterized by a prograde evolution up to the eclogitic climax, followed by a significant retrograde decompression, in its turn followed by a prograde decompressional trajectory peaking at the greenschist – low-amphibolite facies boundary. The climax of this low-P metamorphic event is followed by a continuous cooling under moderate decompressional conditions. Consequently, the inferred tectono-metamorphic history of the Internal Penninic Nappes is characterized by a geothermal gradient progressively increasing from 12 to 40 °C/km.

The prograde part of the early-Alpine trajectory is consistent with a process of subduction of oceanic lithosphere; its decompressional part is compatible with a moderately rapid uplift, which occurred while subduction of cold oceanic lithosphere was still active. The late-Alpine trajectory is consistent with the thermal re-equilibration, consequent to the continental collision.

RIASSUNTO

In questo lavoro vengono riassunti i risultati di un progetto di ricerca finalizzato alla ricostruzione e alla interpretazione tettonica delle traiettorie di esumazione alpina registrata in campioni provenienti da aree tipo dei massicci cristallini interni (Monte Rosa, Gran Paradiso e Dora Maira) delle Alpi occidentali. Queste tre unità tettoniche mostrano un'evoluzione metamorfica alpina comune, caratterizzata da due distinti eventi. Il primo evento, di età eo-alpina, è avvenuto in condizioni eclogitiche di bassa T (T = 500–550 °C, P = 11–13 kbar). Successivamente si è sviluppata una paragenesi retrograda decompressionale a temperature inferiori al campo di stabilità del granato.

[1] Dip. Scienze Mineralogiche e Petrologiche, Univ. Torino Via Valperga Caluso, 35, I–10125 Torino
[2] Dip. Georisorse e Territorio, Politecnico Torino Corso Duca degli Abruzzi, 24, I–10100 Torino

Il secondo evento metamorfico, di età meso-alpina, si è sviluppato in condizioni prograde e decompressionali, come testimoniato dalla successione delle paragenesi metamorfiche e dalle zonature delle fasi mineralogiche. Le stime termobarometriche hanno fornito T = 500–550 °C per P inferiori a 5 kbar.

La traiettoria di esumazione post-eclogitica è quindi caratterizzata da un primo stadio decompressionale associato ad una moderata diminuzione della T, seguito da un secondo tratto progrado e decompressionale ed, infine, da un terzo tratto definito da un forte raffreddamento associato ad una moderata decompressione. La traiettoria risultante è pertanto caratterizzata da due picchi termici, che hanno raggiunto approssimativamente la stessa T a P molto differenti, che riflettono gradienti geotermici nettamente diversi.

Il tratto progrado della traiettoria eo-alpina è consistente con un processo di subduzione di litosfera oceanica, mentre il suo tratto decompressionale è compatibile con una esumazione di crosta continentale avvenuta in condizioni di basso flusso termico.

La traiettoria meso-alpina è, invece, consistente con la riequilibrazione termica conseguente alla collisione continentale tra il margine passivo paleo-europeo ed il margine insubrico, che ha portato ad un progressivo ispessimento crostale e all'interruzione della subduzione.

Introduction

During the last years, the reconstruction and the interpretation of the P-T paths recorded by metamorphic rocks has contributed considerably to the understanding of orogenic belts (e.g. Thompson & England 1984, Davy & Gillet 1986, Thompson & Ridley 1987). Particularly, the retrograde P-T trajectories of high-P belts provide important constraints on the tectonic evolution of convergent plate junctions (Ernst 1988).

For this reason, a petrographic and geo-thermobarometric study was performed on selected samples of micaschists, orthogneisses and metabasites from the Monte Rosa, the Gran Paradiso and the Dora-Maira Nappes (Internal Penninic Nappes of the Western Alps) to better constrain their metamorphic evolution and, particularly, their P-T paths exhumation (Borghi & Sandrone 1990; Sandrone & Borghi 1992; Borghi et al. 1994). It was possible to recognize a relict assemblage of HP type and a later assemblage indicating lower pressure. We found it convenient to ascribe those assemblages to two metamorphic events, namely early-Alpine and late-Alpine.

This study reports a summary on the reconstruction and interpretation of the P-T history of the eclogitic Penninic Units of the Western Alps using geothermobarometers to determine peak metamorphic conditions, garnet zoning modeling to derive P-T paths for individual samples, and mineral textural relationships to relate these P-T paths to the sequence of tectonic events in the area.

Geological Setting

The Monte Rosa (MR), Gran Paradiso (GP) and Dora Maira (DM) internal Penninic nappes (IPN) are three eclogitized continental crust units belonging to the Penninic Domain of the Western Alps. They crop out in the Pennine, Graian and Cottian Alps, respectively (Fig. 1). They are the deepest tectonic element in the central sector of the Western Alps, and crop out at large axial culminations, overthrust by various structural elements of the Piemonte Zone and the Austroalpine Domain. They consist of a composite crystalline basement and a Permo-Liassic cover, which is preserved locally at the borders of the nappes.

The metamorphic basement consists of a polymetamorphic complex formed of pre-Carboniferous metasediments and metabasites, and a monometamorphic complex com-

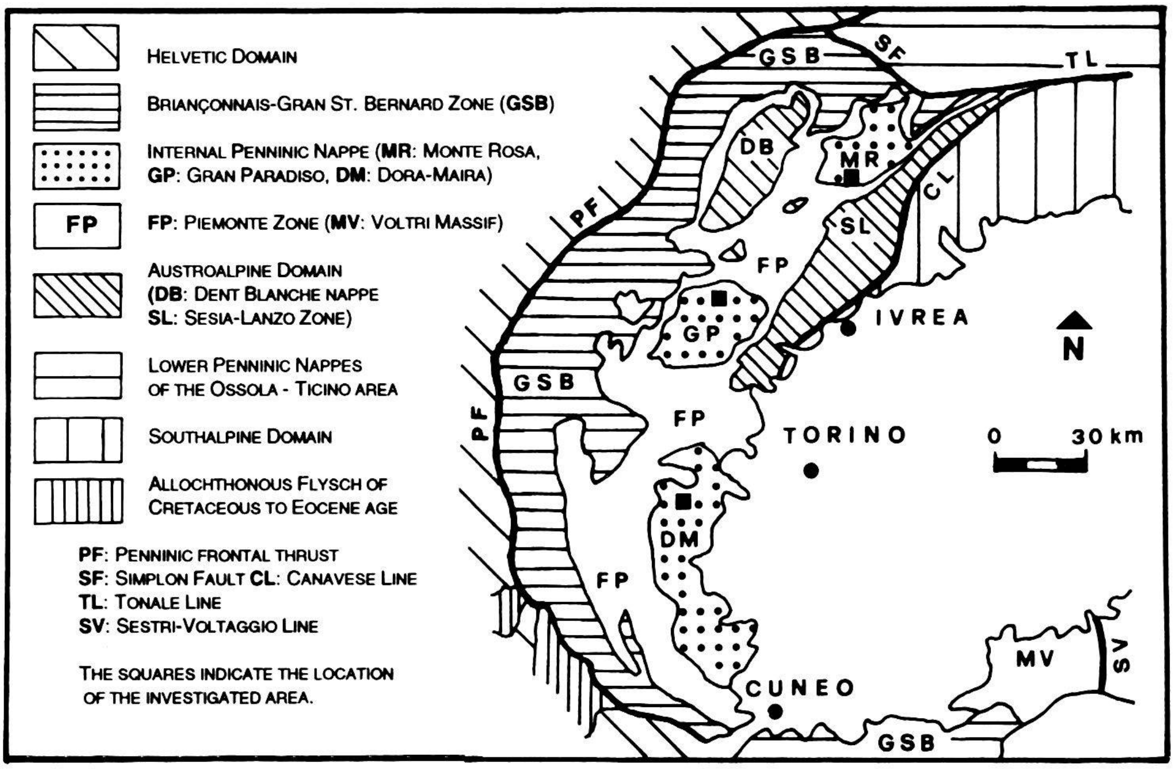


Fig. 1. Simplified tectonic sketch map of the Western Alps.

posed of probably (Permo)-Carboniferous metasediments known as Furgg Zone in MR (Bearth 1952), Money Complex in GP (Compagnoni et al. 1974) and Pinerolese Complex in DM (Vialon 1966). Both complexes contain metaintrusives with granite to diorite composition. They are mainly regarded as Variscan (review and discussion in Hunziker et al. 1992). The sedimentary protoliths in the polymetamorphic basement are mainly represented by pelites with subordinate limestones (± dolomitic) and basic intercalations, whereas coarser clastic facies predominate in the monometamorphic basement, with widespread metabasite and marble in the Furgg Zone.

The polymetamorphic nature of the first complex is illustrated by occasional relicts of pre-Alpine parageneses in an amphibolite facies (Ms-Bt-Grt-Sil; mineral symbols are from Kretz 1983), together with relicts of the original intrusive contacts with the late-Variscan orthoderivates (MR: Dal Piaz, 1971; GP: Compagnoni & Prato 1969; Callegari et al. 1969; DM: Sandrone et al. 1986, 1992).

The tectonic position of the IPN is uncertain. Classic paleogeographic reconstructions usually place the internal crystalline massifs on the paleo-European edge of the Ligure-Piemontese ocean. Recent work, however, has suggested a new model in which all the eclogite units are restored on the same paleomargin in keeping with their common pre-collisional metamorphism (Polino et al. 1990, and references therein).

The Internal Penninic Nappes of the Western Alps record an Alpine metamorphic evolution characterized by two main events (MR: Frey et al. 1976; Chopin & Monié 1984; Dal Piaz & Lombardo 1986; GP: Vearncombe 1983; Benciolini et al. 1984; Dal Piaz & Lombardo 1986; Goffè & Chopin 1986; Pognante et al. 1987; Ballèvre 1988; Biino & Pognante 1989; Massonne & Chopin 1989; Le Goff & Ballèvre 1990, Borghi et al. 1994; DM: Borghi et al. 1985; Pognante & Sandrone 1989; Cadoppi 1990): a low-T eclogite facies "early-Alpine" event, usually regarded Cretaceous in age (review in Hunziker et al. 1992) and a low-P greenschist facies "late-Alpine" event of Late Eocene age (37–43 Ma, Ar/Ar plateaux ages) documented over the whole Pennine zone (Chopin & Maluski 1980; Chopin & Monié 1984; Monié 1985; Scaillet et al. 1990; Monié & Chopin 1991; Scaillet et al. 1992).

The southern part of the DM also includes an ultra high pressure (UHP) tectonic unit (Chopin et al. 1991) whose Alpine P-T trajectory is only partly similar to those discussed in this paper (Compagnoni et al., in press).

Moreover, some radiometric data are recently found, which are in contrast with the classic chronologic picture of high-P metamorphism in the internal Western Alps. Monié & Philipphot (1989) found a middle Eocene (ca. 50 Ma) age for the high-P metamorphism in the eclogitized ophiolites of Monviso. Furthermore, Sm/Nd isotopic data of eclogitic metabasalts from the Zermatt – Saas Fee unit, suggest that the HP metamorphism occurred at 52 ± 18 Ma (Bowtell et al. 1994). Even in the continental crust of the UHP unit of the southern Dora Maira Nappe ages of 38–40 Ma were found by Tilton et al. (1989; 1991), in marked contrast with the Ar/Ar ages obtained by Monié & Chopin (1991) and Scaillet et al. (1990; 1992), which support a Cretaceous age. Finally, an Eocene age for high-P metamorphism in the Central Alps was found by Gebauer et al. (1992) and Becker (1993).

If the above mentioned Tertiary ages will be supported by future radiometric works, a critical revision of all geochronological data of the Western and Central Alps will be required.

The transition between the HP metamorphic event and the greenschist overprinting at lower P is poorly constrained. The exhumation of the whole internal Pennine Zone is generally thought to have proceded via a post-eclogitic isothermal decompression followed by quasi-isobaric cooling (MR: Chopin & Monié 1984; Monié 1985; Ellis et al. 1989; GP: Dal Piaz & Lombardo 1986; Ballèvre 1988; Massonne & Chopin 1989; Northern DM: Pognante & Sandrone 1989; Southern DM: Chopin et al. 1991). The petrologic results reported in this study indicate that an alternative P-T path involving a more complex thermal evolution may also be considered, not only for selected areas of the DM (Sandrone & Borghi 1992) and GP (Borghi et al. 1994) Nappes, but even for the MR Nappe. Similar P-T-t trajectories were recently suggested for some tectonic units of the Great St Bernhard nappe (Desmons 1992) and the Piemonte Zone (Desmons 1989; Messiga & Scambelluri 1991).

Petrography and mineral chemistry

To better constrain the whole P-T paths and, particularly, the relations between the two Alpine metamorphic events, a petrographic and geo-thermobarometric study was performed on representative samples from selected areas of the polymetamorphic complex of the Monte Rosa, Gran Paradiso and Dora-Maira Nappes (Fig. 1 and Tab. 1).

The rocks discussed in this paper have been described by Borghi et al. (1985), Pognante & Sandrone (1989), Borghi & Sandrone (1990), Sandrone & Borghi (1992), Borghi et al. (1994) and Compagnoni et al. (1974). The petrographic characters of the main li-

Tab. 1. Estimated modes of the analyzed rock-samples. Mineral symbols according to Kretz (1983).

sample	lithology	locality	QTZ	PL	MB	CHL	BT	GRT	CLD	AMP	others
1 MR 13	HP micaschist	Stolenberg	35	10	30	10	--	10	5	--	Rt
2 MR 14	LP paragneiss	Alta Luce	25	20	15	10	15	10	--	5 (Hbl)	Ilm
3 MR 16	orthogneiss	Plateaux Lys	35	15	15	--	5	--	--	--	Kfs, Zo
4 GP 664	HP micaschist	V. Bardoney	30	10	20	15	--	10	10	5 (Gln)	Rt, Pg
5 GP 913	LP paragneiss	P. Tseseré	25	25	15	10	10	10	--	5 (Hbl)	Ilm
6 GP 355	orthogneiss	Valnontey	35	30	15	--	5	5	--	--	Kfs, Zo
7 DM 10	HP micaschist	Val Chisone	20	15	25	15	--	10	10	5 (Gln)	Rt
8 DM 16	LP paragneiss	Val Chisone	25	25	20	--	15	5	--	10 (Hbl)	Ilm
8 DM 3	orthogneiss	V. Bourset	35	30	15	--	5	5	--	--	Kfs, Zo

thologies are very similar and can thus be briefly described for the three IPN as a whole. The most widespread lithologies of the polymetamorphic complex are micaschists and fine-grained gneisses, consisting of Qtz, phengitic mica, Pl, Chl, Pg, Cld, zoned Grt, Ky, Bt, Zo, Rt, Gln, Ca-amph, Ilm and Ttn (Tab 1). Gln is usually replaced by pseudomorphic aggregates to Cam + Ab + Bt. Both micaschists and fine-grained gneisses exhibit a well-developed HP-foliation defined by the preferential orientation of white mica, Chl I, Cld, and by lens-like polycrystalline quartz aggregates. This schistosity is locally obliterated by the growth of albitic poikiloblasts with an oligoclase (Olig) rim (An up to 30%) that have developed at the expense of the white mica.

Microprobe examination of di-octohaedral micas from both the late-Variscan orthogneisses and the metapelites of the polymetamorphic complex showed the existence of potassic white mica and sodic mica (paragonite). The former showed a zoned muscovite / phengite composition with a Si content from 3.03 atoms p.f.u. in the rim up to 3.47 in the core of single laminae.

In the MR nappe Ky + Grt + Cld aggregates after a Fe-Al silicate are present (Dal Piaz 1971). Ky has also been observed in the GP nappe (Dal Piaz & Lombardo 1976).

Two garnet generations (Grt I and Grt II) with distinct microstructural relations and chemical compositions have been recognised. The geometric relations between these two generations, their inclusions, and their presence in the micaschists of the monometamorphic complex as well, enable them to be assigned to the Alpine metamorphism. Grt I oc-

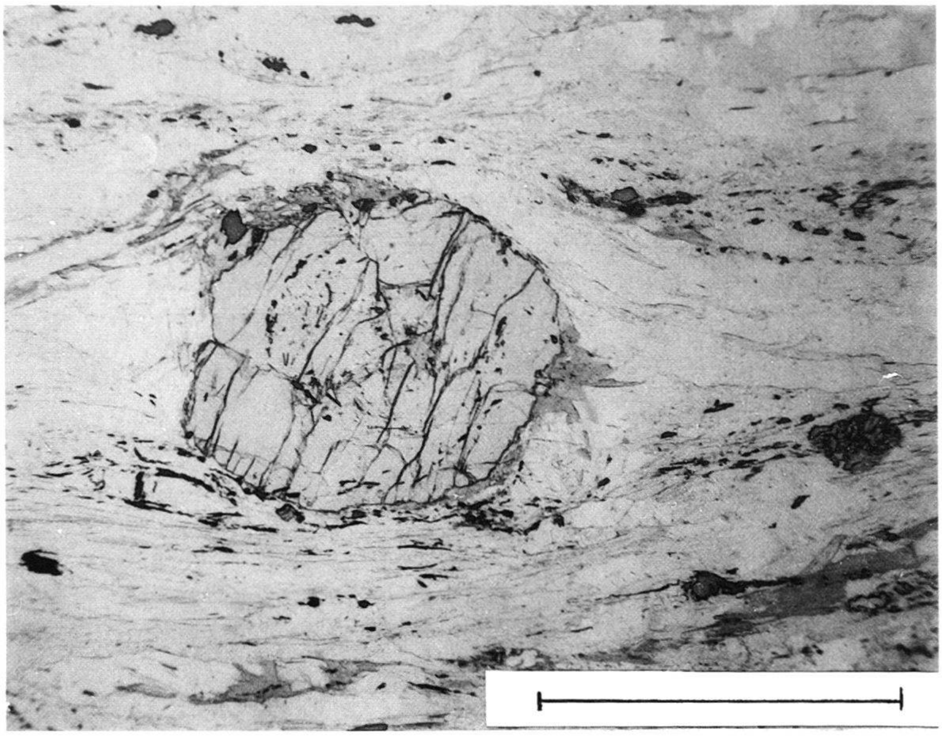


Fig. 2. High-P garnet I with inclusions of chloritoid and rutile anostomosed by schistosity defined by phengitic mica and chlorite I. High-P micaschist from Monte Rosa polymetamorphic complex. MR 13. Only pol., scale bar = 1 mm.

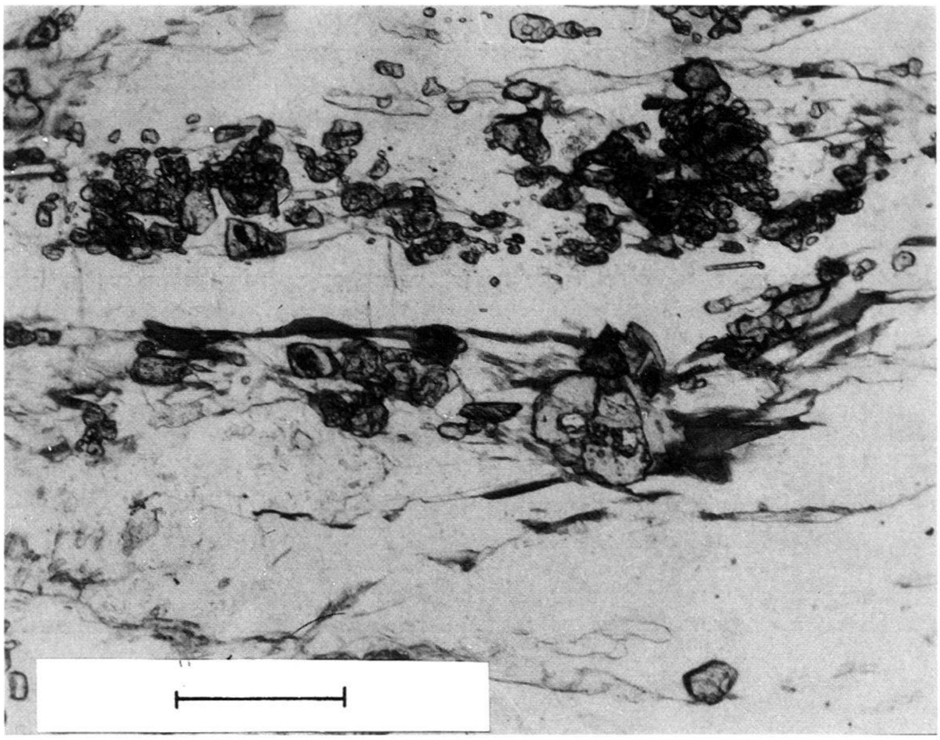


Fig. 3. Low-P garnet II of small dimension in equilibrium with biotite. Fine-grained paragneiss from the Gran Paradiso polymetamorphic complex. GP 913. Only pol., scale bar = 0.5 mm.

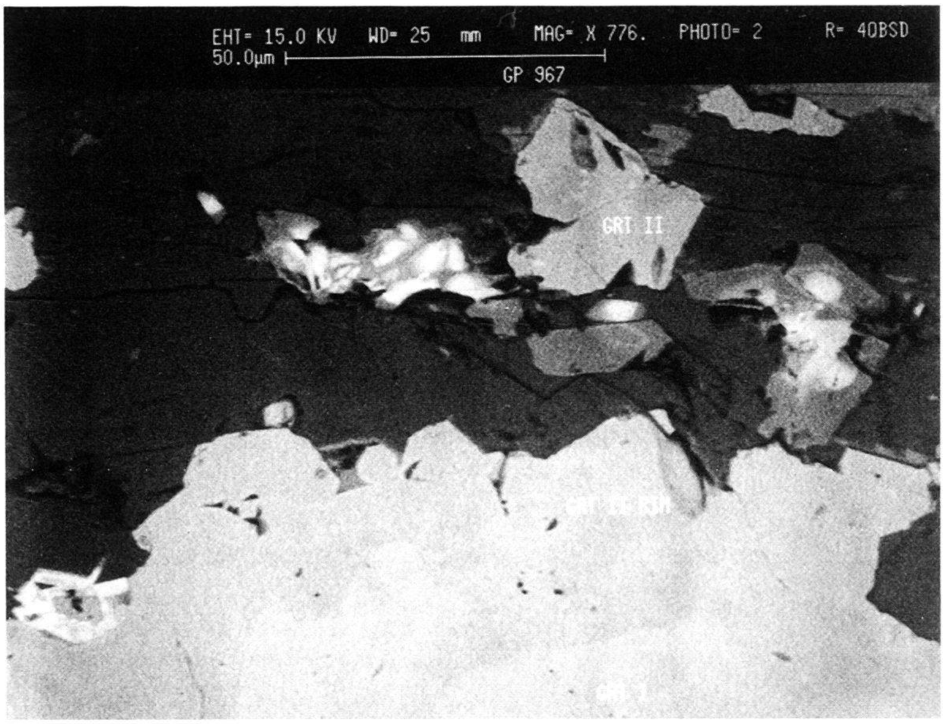


Fig. 4. Fe-rich rim of retrogred garnet I (light grey) overgrowth by new crystals of euhedral Grt II (dark grey). In the upper part of the photo, an isolated Grt II crystal, with the same compositions of coronitic garnet II is also present. Sample GP 967. Back-scattered microphotograph.

curs in deformed and fractured plurimillimetric porphyroclasts enclosing chloritoid, Rt, Zo and lozenge-shaped Pg + Qtz pseudomorphs regarded as the metamorphic product of an original sodic amphibole (Fig. 2). Grt II forms small (<100 μm) idioblasts, whose rims are in equilibrium with Bt (Fig. 3). These two generations sometimes coexist at the single-specimen scale, where Grt II can grow as a narrow rim around the porphyroclastic crystals of Grt I (Fig. 4). In the HP-micaschists, Grt I compositions are relatively uniform considering its plurimillimetric dimensions. However, Grt I porphyroclasts are strongly zoned, when they are associated with Grt II. In the garnet of Figure 5, the composition varies progressively from Alm_{62}-Pyr_{6}-Sps_{7}-Grs_{25} at the core to Alm_{76}-Pyr_{8}-Sps_{7}-Grs_{9} at the rim. This zoning, characterised by a strong increment of Fe coupled with a depletion of Ca from core to rim, may be interpreted as a diffusion effect due to the post-eclogitic retrograde compositional re-equilibration of the garnet I. The outer rim (few μm wide) consists of coronitic Grt II, with a quite different composition. Grt II shows often well-developed concentric zoning with cores (Alm_{69}-$Pyr_{4.5}$-$Sps_{2.5}$-Grs_{24}) notably enriched in grossular component relative to the rim (Alm_{74}-Pyr_{8}-$Sps_{1.5}$-$Grs_{17.5}$), where there are more abundant almandine and pyrope end members (Fig. 6). The Mg/(Mg + Fe) ratio increases from core to rim. Continuous, smooth zoning profiles and the lack of retrograde diffusion processes evidence, point to uninterrupted Grt II growth during a single prograde and decompressional metamorphic event, which, in our opinion, can be attributed to the late-Alpine event.

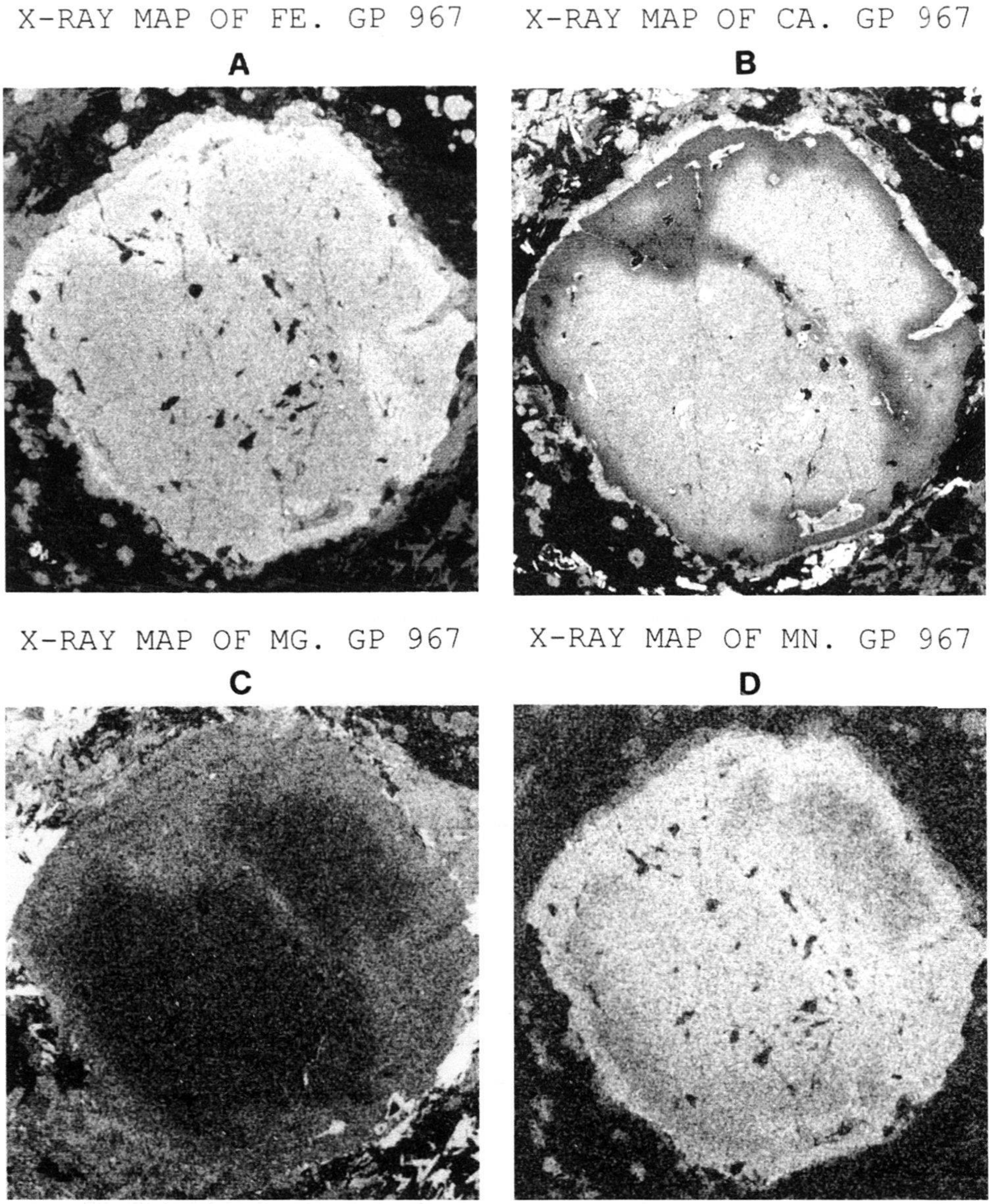


Fig. 5. Compositional X-ray map of an early-Alpine retrogred garnet porphyroblast for **Fe** (A), **Ca** (B), **Mg** (C) and **Mn** (D) elements acquired with an EDS-microprobe and elaborated with the Photostyler software. The garnet shows a marked Ca decrease and Fe and, subordinately, Mg increase from core to rim. The outer rim (Few μm wide) consists of coronitic Grt II, with a quite different composition. Sample GP 967. The garnet I width is 1.5 mm.

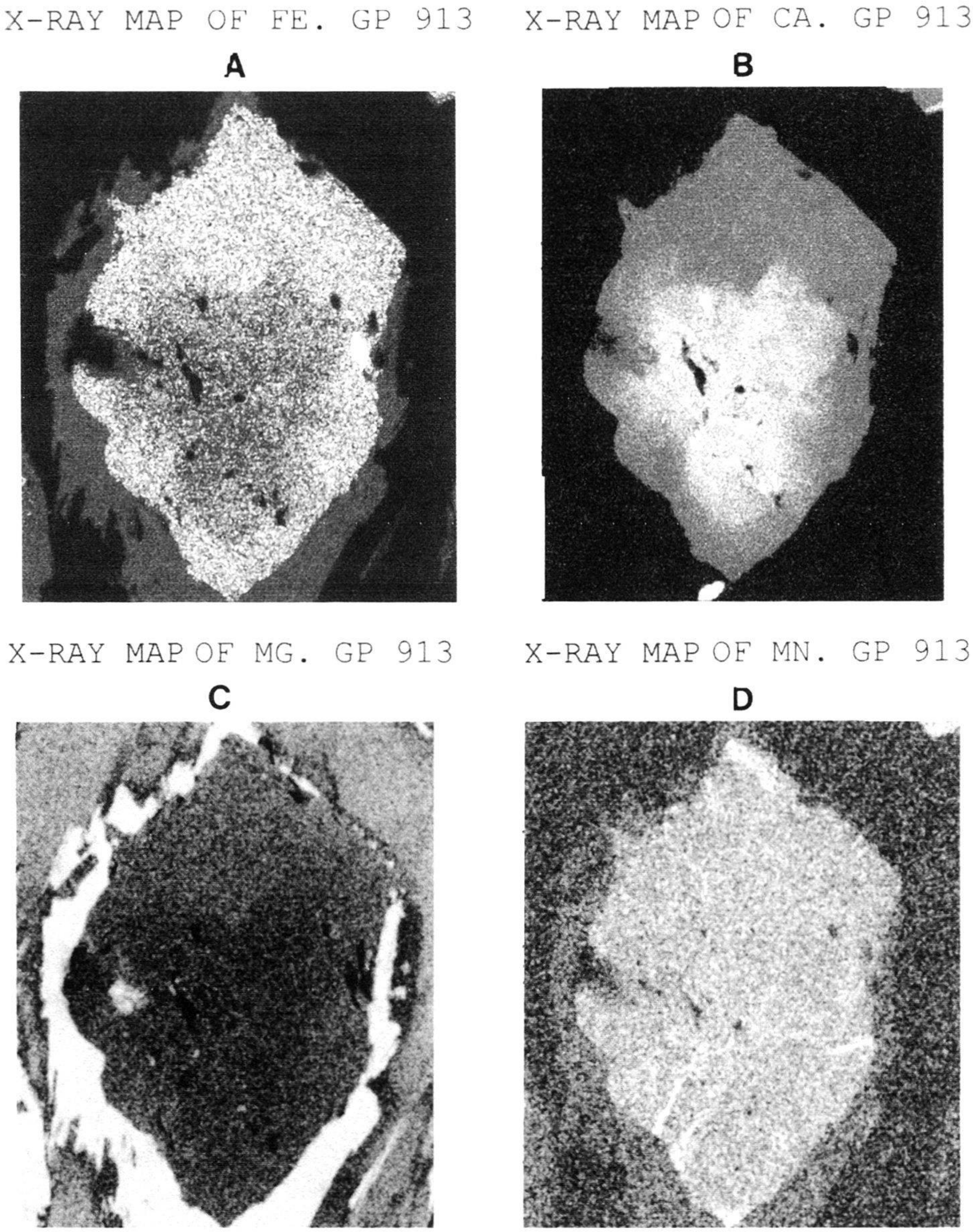


Fig. 6. Compositional X-ray map of the late-Alpine garnet generation for **Fe** (A), **Ca** (B), **Mg** (C) and **Mn** (D) elements acquired with an EDS-microprobe and elaborated with the Photostyler software. Garnet II exhibits a well-shaped growth zoning, characterized by Fe and, with less evidence, Mg increase and Ca decrease from core to rim. The Mn content remains constantly very low. Sample GP 913. Garnet dimensions are 60 vs. 80 μm.

Monte Rosa Nappe								
	Grt I core	Grt I I core	Grt I rim	Grt I I rim	Ph	Bt	Amp core	Amp rim
An. n°.	1	2	3	4	5	6	7	8
SiO_2	36.64	37.19	36.77	38.20	51.77	36.81	49.47	44.91
TiO_2	--	--	--	--	0.25	1.27	0.22	0.36
Al_2O_3	20.73	21.00	20.95	21.53	27.39	18.03	10.53	13.29
FeO	35.62	28.49	35.36	29.24	1.98	19.21	15.49	15.93
MnO	2.17	1.46	0.22	0.27	--	--	--	--
MgO	1.71	0.82	3.66	1.78	3.06	11.19	11.37	10.08
CaO	3.59	11.28	2.21	10.30	0.04	--	8.27	10.30
Na_2O	--	--	--	--	0.40	0.20	1.85	1.95
K_2O	--	--	--	--	10.34	9.21	0.33	0.29
Total	100.47	100.24	99.16	101.32	95.23	95.92	97.53	97.10
Si	2.96	2.97	2.97	3.00	6.88	5.54	7.11	6.55
Ti	.00	--	.00	--	.03	.14	.02	.04
Al IV	.04	.03	.03	.00	1.12	2.46	.89	1.45
AlVI	1.94	1.95	1.97	1.99	3.29	.74	.89	.83
Fe^3	.07	.05	.03	.01	.00	--	.41	.72
Fe^2	2.34	1.84	2.36	1.91	.22	2.42	1.24	1.22
Mn	.15	.10	.02	.02	.00	--	.00	.00
Mg	.21	.10	.44	.21	.61	2.51	2.44	2.19
Ca	.31	.96	.19	.87	.01	--	1.27	1.61
Na	--	--	--	--	.10	.06	.52	.55
K	--	--	--	--	1.75	1.77	.06	.05

Gran Paradiso Nappe								
	Grt I core	Grt I I core	Grt I rim	Grt I I rim	Ph	Bt	Amp core	Amp rim
An. n°.	1	2	3	4	5	6	7	8
SiO_2	37.39	36.62	36.84	37.47	51.06	36.64	47.95	44.12
TiO_2	–	–	–	–	0.00	1.55	0.00	0.00
Al_2O_3	20.73	20.59	20.41	21.03	12.13	19.43	12.13	14.86
FeO	32.07	31.70	32.92	33.03	15.07	19.78	15.07	16.65
MnO	0.74	1.01	0.00	0.65	–	–	–	–
MgO	2.52	1.09	1.84	1.93	10.52	9.29	10.52	9.01
CaO	6.51	8.53	6.53	5.98	8.66	–	8.66	10.50
Na_2O	–	–	–	–	2.23	–	2.23	2.18
K_2O	–	–	–	–	2.28	9.08	0.28	0.46
Total	99.97	99.54	98.54	100.13	97.83	96.68	97.83	97.79
Si	2.99	2.96	3.00	3.00	6.90	5.52	6.90	6.45
Ti	—	—	—	—	.00	.18	.00	.00
Al IV	01	.04	.00	.00	1.10	2.48	1.10	1.55
AlVI	1.96	1.96	1.96	1.99	.97	.96	.97	1.00
Fe^3	.05	.08	.04	.01	.70	.00	.70	.55
Fe^2	2.09	2.06	2.20	2.21	1.11	2.49	1.11	1.48
Mn	.05	.07	.00	.04	–	–	–	–
Mg	.30	.13	.22	.23	2.26	2.06	2.26	1.96
Ca	.56	.74	.57	.51	1.34	–	1.34	1.64
Na	—	—	—	—	.68	.00	.68	.62
K	—	—	—	—	.05	1.74	.05	.09

Dora Maira Nappe								
	Grt I core	Grt I I core	Grt I rim	Grt I I rim	Ph	Bt	Amp core	Amp rim
An. n°.	1	2	3	4	5	6	7	8
SiO_2	37.71	37.90	37.53	36.77	50.50	37.16	56.39	50.68
TiO_2	--	--	--	--	0.24	0.37	0.05	0.06
Al_2O_3	20.89	20.80	20.91	20.75	28.59	20.53	4.05	11.95
FeO	33.53	31.92	35.80	36.75	1.93	18.63	7.63	12.16
MnO	0.29	0.09	0.22	0.46	--	--	--	--
MgO	2.75	2.01	3.17	2.48	3.31	11.62	18.55	12.16
CaO	4.77	7.32	3.00	2.92	0.00	--	10.83	8.99
Na_2O	--	--	--	--	0.25	0.15	1.23	2.31
K_2O	--	--	--	--	9.75	9.75	0.14	0.40
Total	99.94	100.04	100.63	100.13	94.57	98.21	99.87	98.71
Si	3.01	6.02	3.00	2.98	6.74	5.43	7.76	7.15
Ti	--	--	--	--	.02	.04	.01	.01
Al IV	.00	.00	.00	.02	1.26	2.57	.24	.85
AlVI	1.97	1.96	1.97	1.96	3.24	.97	.12	1.14
Fe^3	.03	.03	.03	.04	.00	.00		
Fe^2	2.21	2.09	2.36	2.46	.21	2.28	.88	1.43
Mn	.02	.01	.15	.03	--	--	--	--
Mg	.33	.24	.38	.30	.66	2.53	3.81	2.56
Ca	.41	.63	.26	.26	.00	--	1.60	1.36
Na	--	--	--	--	.06	.04	.33	.63
K	--	--	--	--	.00	1.82	.02	.07

Ab/Olig, Ep, Ca-amph and Bt developed during the last metamorphic stage, which is post-kinematic with respect to the main HP-foliation. The amphibole has a core of Mg-Hbl and a rim of tschermakitic Mg-Hbl, while the Na_{M4} content decreases from the core (0.69) to the rim (0.30). The amphibole thus displays prograde, decompressional zoning of low to medium metamorphic grade.

Bt (homogeneous in composition) replaced K-white mica and grew in equilibrium with Grt II (Fig. 3). One ripidolitic Chl generation is synkinematic with the regional schistosity, another has grown subsequently at the expense of Grt I and Cld.

The associated metabasites are scattered through the Massifs as small lenses or boudins enclosed in the micaschists. They usually show pervasive recrystallization in the greenschist facies and eclogitic parageneses are only preserved in the core of 100 m-scale bodies. The eclogitic paragenesis consists of Na-Cpx + Grt I + Zo + Rt + Ph, usually retrogressed to a lower-P assemblage (Ca-amph + Chl + zoned Pl + Czo + Bt ± Ttn and a garnet probably corresponding with Grt II of the metapelites). The pyroxene may exhibit a simplectitic rim and / or replacement by sodic amphibole, garnet shows coronas of Na-amphibole and epidote. Actinolite is always variously rimmed by more tschermakitic amphibole or is transformed into a biotite-bearing symplectite, albite is occasionally surrounded by a thin, An-richer rim. A more detailed description of metabasites is reported in Pognante & Sandrone (1989).

The orthoderivates consist of Qtz, Ab/Olig (from An 0 to An 30), K-feldspar, phengitic mica, Bt and Ep. They display a pervasive schistosity defined by the preferential orientation of phyllosilicates and lenticular aggregates of granoblastic Qtz. The grain is heterogeneous by the presence of centimetric porphyroclasts of magmatic potassic feldspar. The magmatic Pl has been partly recrystallised into small Ab granoblasts in the foliated matrix.

Representative compositions of mineral phases from MR, GP and DM Nappe are reported in Table 2a–c.

Metamorphic evolution

Metapelites and metabasites from all three IPN display a common Alpine metamorphic evolution. The phases observed have been grouped into two parageneses on the basis of microstructural relations. As can be seen from the blastesis-deformation relationships, these parageneses represent the HP early-Alpine event, the subsequent retrograde decompressional stage, and the LP late-Alpine event (Fig. 7).

The prograde part of the early-Alpine event is poorly constrained. The presence of Zo, Cld and Na-amph (now pseudomophed) and the absence of Lws may indicate that the upper part of the burial path was bounded by the thermal equilibrium curve of the reactions 3 and 5 of Figure 8. The early-Alpine event was marked by a thermal peak para-

Tab. 2. Representative microprobe analyses and atomic proportions of garnets (12 ox.) biotites (22 ox.), phengitic micas (22 ox.) and Ca-amphiboles (23 ox.) of the Monte Rosa Nappe (A), Gran Paradiso Nappe (B) and Dora Maira Nappe (C). Tab. 2a: an. 1-3-5 = MR 13, an. 2-4-6-7-8 = MR 14. Tab. 2b: an. 1-3-5 = GP 664, an. 2-4-6-7-8 = GP 913. Tab. 2c: an. 1-3-5 = DM 10, an. 2-4-6-7-8 = DM 16.

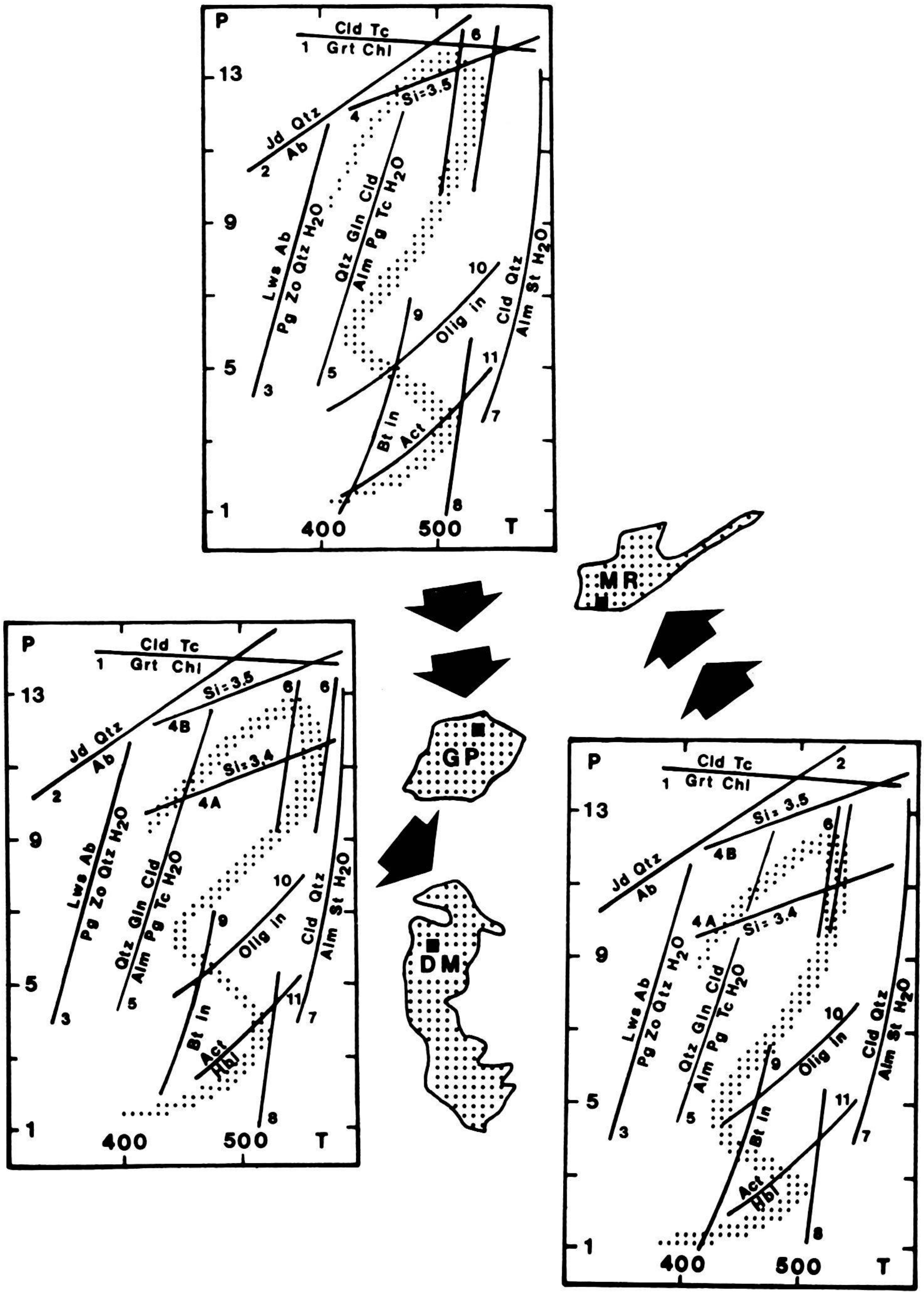
Metapelitic system	METAMORPHIC EVOLUTION	
1 EVENTS / MINERALS	High - P (early - Alpine)	Low - P (late - Alpine)
QUARTZ	———	———
PLAGIOCLASE	Ab ———	Ab Olig ———
MUSCOVITE	High Cel ———	Low Cel ———
PARAGONITE	———	
CHLORITE	I ———	II ———
BIOTITE		———
GARNET	I ———	II ———
KYANITE	———	
CHLORITOID	———	
AMPHIBOLE	Gln ———	Act Hbl ———
RUTILE	———	
ILM - TTN		———
EPIDOTE	Zo Czo ———	Czo Ps ———

Mafic system	METAMORPHIC EVOLUTION	
2 EVENTS / MINERALS	High - P (early - Alpine)	Low - P (late - Alpine)
OMPHACITE	———	
GARNET	I ———	II ———
WHITE MICA	High Cel ———	Low Cel ———
PARAGONITE	———	
EPIDOTE	Zo Czo ———	Czo ———
RUTILE	———	
AMPHIBOLE	Gln Ktp ———	Act Hbl ———
PLAGIOCLASE	Ab ———	Ab Olig ———
CHLORITE	———	———
BIOTITE		———
ILM - TTN		———

Fig. 7. Mineral parageneses characteristic for the main metamorphic events of the evolution of the Internal Penninic Nappes. **1** = metapelitic system, **2** = mafic system.

genesis with Qtz-Ab-Ph-Chl I-Grt I-Cld-Ky-Rt ± Gln ± Pg. Its metamorphic conditions were constrained by the common Grt-Chl-Cld association, or, less frequently, by the Grt-Cld-Ky association, and the absence of Tc (Fig. 8). Omphacitic pyroxene occurring in the basic rocks indicates that the IPN attained eclogitic grade during the early-Alpine event. The presence of chlorite I means that T did not exceed the upper limit of the Qtz + Chl stability field (Massonne 1989). The Grt-Cld-Chl association is stable from approximately 4 to 18 kbar, as shown by its common occurrence in high-pressure metapelites (Vuichard & Ballèvre 1988 with ref.). The occurrence of Grt-Cld-Ky or Grt-Cld-Chl associations is dependent on the bulk chemistry of the protoliths, though they are stable under the same

Fig. 8. Petrogenetic grid for the Monte Rosa (MR), Gran Paradiso (GP) and Dora Maira (DM) Nappes. The Alpine P-T paths followed during post-eclogitic exhumation are dotted. The squares indicate the location of the investigated area.
1: Cld + Tc = Grt + Chl (Chopin 1985); **2**: Ab = Jd + Qtz (Holland 1980); **3**: Lws + Ab = Pg + Zo + Qtz + V (Heinrich & Althaus 1980); **4**: isopleths of Si content in phengites (**A**: Si = 3.4 p.f.u., **B**: Si = 3.5 p.f.u.) (Massonne & Schreyer 1987); **5**: Qtz + Gln + Cld = Alm + Pg + Tc + H_2O (Holland & Powell 1990); **6**: iso-K_D curves for the Grt-Ph geothermometer (calibration of Green & Hellman 1982); **7**: Cld + Qtz = St + Alm + V (Rao & Johannes 1979); **8**: iso-K_D curves for the Grt-Bt geothermometer (calibration of Perchuk & Lavrent'eva 1983); **9**: Bt + Ms in (Nitsch 1970); **10**: Olig in (Maruyama et al. 1983); **11**: Act / Hbl transition (Ernst 1979).


P
T
13
9
5
1
400
500
1 Cld Tc
Grt Chl
2 Jd Qtz
Ab
3 Lws Ab
Pg Zo Qtz H2O
4 Si=3.5
4A Si=3.4
4B
5 Qtz Gln Cld
Alm Pg Tc H2O
6
7 Cld Qtz
Alm St H2O
8
9 Bt in
10 Olig in
11 Act
Hbl
MR
GP
DM

Tab. 3. Thermobarometric estimates for the early-Alpine and the late-Alpine metamorphic events. Temperatures are in °C. Reference P is 13 kbar for the early-Alpine event and 5 kbar for the late-Alpine event. GH = Green & Hellman (1983), HS = Hodges & Spear (1982), PL = Perchuk & Lavrent'eva (1983), KR = Kleemann & Reinhardt (1994). The first value represents the T average calculated for several pairs, the second value is the standard deviation of the calculated T range. The T estimates obtained with KR calibration were calculated using the pairs 4–6 of the Tab. 2a–c.

THERMOMETRIC ESTIMATES

Internal Penninic Massifs

early-Alpine event (Grt - Ph pairs at 13 kbar)

	Grt I core - Ph	Grt I rim - Ph	
MR	546 ± 21	518 ± 10	(GH)
GP	546 ± 21	518 ± 10	(GH)
DM	533 ± 12	537 ± 15	(GH)

late-Alpine event (Grt - Bt pairs at 5 kbar)

Grt II rim - Bt

MR	494 ± 20	(PL)	GP	527 ± 17	(PL)	DM	515 ± 9	(PL)
MR	531 ± 50	(HS)	GP	546 ± 20	(HS)	DM	520 ± 16	(HS)
MR	465	(KR)	GP	494	(KR)	DM	482	(KR)

P-T conditions (Vuichard & Ballèvre 1988). Absence of Jd (or its alteration products) in the late-Variscan orthogneisses offers further evidence that the Ab = Jd + Qtz curve was not exceeded, as already shown for the IPN (MR: Dal Piaz 1971; GP: Dal Piaz & Lombardo 1986 with refs.; Le Goff & Ballèvre 1990; DM: Borghi et al. 1985), except for the Bonneval zone in the GP (Saliot 1975).

Thermobarometric estimates for this event were obtained using the Grt-Ph geothermometer according to the calibration of Green & Hellman (1982) and the geobarometer of Massonne & Schreyer (1987), which is based on the Si content of phengite. Grt I core compositions of crystalls belonging to HP micaschist were used (MR 13, GP 664, DM 10). The results of these calculations are plotted as lines of constant K_D in Figure 8 and reported in Table 3. A range of 515–545 °C and 11–14 kbar was obtained. These values are in agreement with those reported in the literature for the early-Alpine event (MR: Dal Piaz & Lombardo 1986; Chopin & Monié 1984; GP: Massonne & Chopin 1989; Borghi et al. 1984; DM: Pognante & Sandrone 1989; Cadoppi 1990). These values are also consistent with Grt-Cpx geothermometry (Ellis & Green calibration) applied to metabasites of

MR (Dal Piaz & Lombardo 1986), GP (Biino & Pognante 1989) and DM (Pognante & Sandrone 1989).

The eclogitic peak was followed by strong decompression accompanied by moderate cooling, which led to lower P-T parageneses. In the metapelites, Grt I and Cld were replaced by Chl II, phengitic mica by Ab, and Rt by titanite, while zoisite was transformed into clinozoisite. The P-T conditions during this retrograde stage were lower than the Grt stability field. Moreover, the development of Act at the expense of a previous Na-amphibole in the metabasites suggests pressure values lower than 5 kbar, according to the equilibrium curves of Ernst (1979).

The late-Alpine event, on the other hand, displays low- to medium-grade prograde characters at LP conditions. In metapelites, it resulted in the development of an oligoclase rim around albitic poikiloblasts, crystallisation of Grt II and calcic amphibole (both with prograde zoning), and replacement of Chl by biotite. A T rise during this event is also indicated by the microstructures observed in metabasites. Act is always more or less extensively transformed at the rim by a Hbl or Bt – bearing symplectite and the Ab blasts are sometimes surrounded by oligoclase rim (reaction 10 and 11 in Fig. 8). The physical conditions reached during this event are therefore constrained by the thermal stability fields of Grt II, Bt, calcic amphibole and oligoclase (Fig. 8).

The P-T estimates for this event were obtained with the Grt-Bt geothermometer and with the Grt-Pl-Bt-Qtz geobarometer, applied to the parageneses re-equilibrated at low-P conditions (MR 14, GP 913, DM 16). The calibration of Perchuk & Laurent'eva (1983) and Hodges & Spear (1987) for T and of Ghent & Stout (1981) for P were used. Bt matrix - Grt II rim couples gave mean T of about 500–530 °C for MR, 525–550 °C for GP, and 515–520 °C for DM (Tab. 3). A lower T of about 30 °C with respect to Perchuk & Lavrent'eva calibration was obtained applying the new geothermometer of Kleemann & Reinhardt (1994) to the Grt II and Bt compositions reported in Table 2a, 2b, 2c. A P value of about 4.5 kbar for MR, 6.4 kbar for GP and 4.9 kbar for DM was obtained with the Ghent & Stout (1981) geobarometer. The P-T estimates thus suggest that the thermal conditions reached in the three IPN during this event were similar, and always consistent with the petrological constraints imposed by the paragenesis observed.

Discussion and conclusion

The differences in composition between the garnet generations have been combined with the petrological constraints imposed by the sequences of metamorphic parageneses to construct a relatively complete Alpine P-T path for the Internal Penninic Nappes, which can be used in the elucidation of the tectonic processes operative during orogenesis (Spear et al. 1984).

The IPN of the Western Alps show a very similar Alpine exhumation trajectory, which is significantly different from all the previously proposed paths for these tectonic units (Fig. 8). The proposed post-eclogitic trajectory consists of an initial retrograde decompressional step, during which the eclogitic and blueschist parageneses were progressively replaced by lower pressure greenschist facies associations. The second step is characterised by a relatively late, decompressional prograde trajectory, as shown by the garnet-biotite-oligoclase assemblages and P-T data ($P < 5$ kbar and $T > 500$ °C). Lastly, there is a marked fall in temperature accompanied by weak decompression. The possible

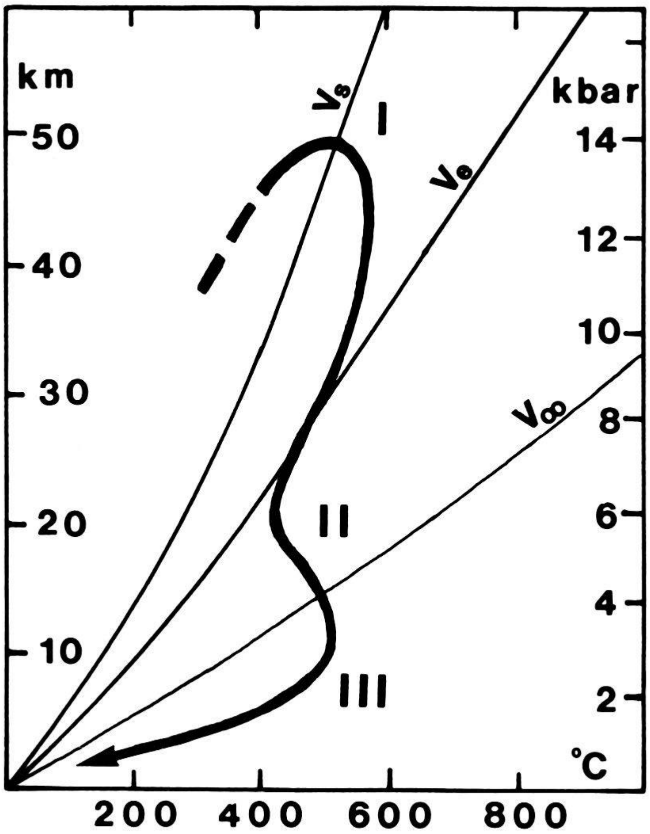


Fig. 9. Alpine P-T path for the Internal Crystalline Massifs. The $\mathbf{V_s}$ curve represents the subduction geotherm compatible with the early-Alpine eclogitic peak. The $\mathbf{V_e}$ curve represents the undisturbed geotherm of normal continental crust; the $\mathbf{V_\infty}$ curve represents the maximum relaxed geotherm after continental collision (from Thompson & England, 1984). **I** = low-thermal gradient field (subduction geodynamic range); **II** = normal thermal gradient field (continental collision geodynamic range); **III** = high-thermal gradient field (extensional? geodynamic range).

existence of this late thermal pulse in the IPN is also compatible with the isotopic data of Scaillet et al. (1992).

Therefore, the inferred P-T path is characterized by two metamorphic peaks at approximately the same T but significantly different P, reflecting distinct geothermal gradients and geodynamic conditions. Thus, the thermotectonic evolution of IPN is characterized by a continuous decompression and by a more complex thermal evolution with a progressive increase of the thermal gradient from early-Alpine peak (12 °C/km) to the late-Alpine peak (ca. 40 °C/km).

In order to constrain the mechanisms which acted during the exhumation of these rocks, the P-T paths obtained for the IPN have been compared with tectono-thermal models for orogenic processes. The P-T histories of metamorphic rocks in subduction and collisional zones show distinct differences. Whereas subduction-zone rocks show characteristically high P/T ratio, and a retrograde P-T path nearly parallel to the prograde path (Cloos 1982), metamorphic rocks in collisional orogens more commonly evolve towards a Barrowian (medium P/T ratio) type, and the P-T path describes a loop following an isothermal decompression path, or an increase in T as P decrease (Thompson & England 1984).

Several tectonic models were applied to explain the exhumation of H-P units of the Western Alps. They are based on different mechanisms, implying that exhumation occurred while convergence was still active: erosion and isostatic adjustement alone (Rubie 1984; Gillet et al. 1986; Hsü 1991), expulsion or extrusion (Merle & Guillier 1989), large-scale extension faults (Platt 1986; Avigad 1992), corner flow of low-viscosity material (models of Cowan & Silling 1978 and Pavlis & Bruhn 1983, applied by Polino et al. 1990 and Michard et al. 1993).

From Figure 9 it is evident that different tectonic processes during Alpine exhumation of the continental eclogitic unit of the Penninic domain of the Western Alps must be invoked to explain the shape of the inferred P-T paths. The Alpine P-T path of the IPN consists of two main steps. The first step, early-Alpine in age, is characterized by a very low thermal gradient (**I** in Fig. 9), whereas the second one, late-Alpine in age, shows a higher thermal gradient and it may be divided into two stages (**II** and **III** in Fig. 9). The first, early-Alpine, step (**I**) comprises the burial and part of the post-eclogitic exhumation. It plots over the normal continental crust geotherm (V_e), i.e. in the field typical for oceanic lithospheric subduction regime. In particular, the geotherm (based on the equation for the thermal flux of Turcotte & Schubert 1982) consistent with the thermo-barometric estimates attributed to the early-Alpine eclogitic peak, is characterized by a mantle heat flow (0.027 W/m^2) lower than the value commonly assigned to the geotherm of normal continental crust (0.030 W/m^2).

The first stage of the second step (**II** in Fig. 9), corresponds to the prograde decompressional path, and plots in the field bounded by the normal continental crust geotherm (V_e) and by the maximum-relaxed geotherm after continental collision (V_∞). This field is commonly attributed to the tectonic regime of continental collision (Thompson & England 1984). Finally, the last part of the second step (**III** in Fig. 9), plots below the V_∞ geotherm, in the field characterized by an high thermal gradient.

In Figure 9, the first exhumation trajectory (**I**) is nearly parallel to the burial path. Such a result may be compared with a suggestion by Cloos (1982). According to this author, material moving in a mature flow melange will follow similar P-T paths during both downward and upward transit. Thus, both the burial and exhumation metamorphic histories are similar but reversed. Because the rate of upward motion is slow, relative to the rate of downward movement, the rising material would be closer to thermal equilibrium with its boundaries than would be the underlying material moving downward in the wedge. According to the corner flow model of Cowan & Silling (1978) and Pavlis & Bruhn (1982), material can be uplifted in a flow melange because of the change of flow direction within the wedge. In this case, during retrograde metamorphism, the rocks must have traversed the same P-T path during prograde metamorphism, but in the opposite direction.

The prograde part of the Alpine P-T paths for the IPN up to the high – P event, therefore, is consistent with a subduction process of Tethyan oceanic lithosphere that involves even part of the overriding continental crust (the future IPN) as proposed by Polino et al. (1990) by means of tectonic erosion (e.g. Karig 1974) or ablative subduction (Tao & O'Connell 1992) processes. Its post-eclogitic decompression is compatible with an exhumation of continental crust with a low thermal flux from the mantle. The uplift rate value was more than the value of erosional rate (0.1–0.5 mm/y, England & Thompson 1984), even if it was not extremely high, because the P-T path would have been isothermal. Other processes, of tectonic origin, are therefore necessarily involved in the exhumation of the IPN. Thus, it may be supposed that exhumation of the eclogitic nappes started while the subduction of oceanic crust was still active, in agreement with the stratigraphic and palaeontological data pointing to an Upper Cretaceous-Palaeocene sedimentation age for the calcschists (Lemoine et al. 1984). On the other hand, the 50 Ma Ar/Ar plateaux ages from well preserved eclogites of the Monviso ophiolite unit suggests that complete closure of the oceanic basin was not achieved until mid-Eocene times. H-P rocks of the IPN, therefore, were buried and then at least partly exhumed early in the orogenic history, before full collision occurred. This geodynamic setting inhibited not only the geotherm uplift, but it produced a moderate cooling, favouring the conservation of eclogitic parageneses, too.

The late-Alpine trajectory, however, was characterized by a higher geothermal gradient continuously growing up to the metamorphic peak, where it reached about 40 °C/km. Several models have been proposed to explain such high-gradient conditions. The required abnormal amount of heat can be related to magmatic underplating of basic magma or by intrusion of granitic plutons, or by thinning of the crust during a regime of extensional tectonics (Lardeaux & Spalla 1990). For the late-Alpine event, this high thermal gradient can be attributed to thermal re-equilibration due to the continental collision between the Paleo-European and the Insubric margins. This event caused the interruption of oceanic lithosphere subduction and was responsible for the progressive thickening of the continental crust. In this tectonic setting, in the heat flow equation of Turcotte & Schubert (1982) the advection component (directly proportional to uplift rate) decreases, while the heat conduction component (proportional to heat mantle flow) and, especially, the heat production component (proportional to radioactive decay) increase.

In conclusion, the Alpine P-T paths for the IPN proposed in this paper are composed of two strictly distinct parts showing different thermal gradients. These may be taken as evidence of changing exhumation processes during uplift of these tectonic units. Therefore, we suppose that different tectonic processes operate in different times during exhumation of the Internal Penninic Nappes of the Western Alps.

Acknowledgements

This study was carried out with the financial support of the M.U.R.S.T., grant 60% to R. Compagnoni and C.N.R. - Centro Studio Catene Collisionali, Torino. The authors express their thanks to M. Frey and M. Ballèvre for suggestions and comments which much improved the paper.

REFERENCES

AVIGAD, D. 1992: Exhumation of coesite-bearing rocks in the Dora Maira massif (western Alps, Italy). Geology 20, 947–950.

BALLEVRE, M. 1988: Collision continentale et chemins P-T. L'unité Pennique du Grand Paradis (Alpes Occidentales). Thèse d'Etat, Univ. Rennes.

BALLEVRE, M. & MERLE, O. 1993: The Combin fault: compressional reactivation of a Late Cretaceous – Early Tertiary detachment fault in the Western Alps. Schweiz. mineral. petrogr. Mitt. 73, 205–227.

BEARTH, P. 1952: Geologie und Petrographie der Monte Rosa. Beitr. Geol. Karte Schweiz. 96.

BENCIOLINI, L., TARTAROTTI, P., DAL PIAZ, G. V., DE VECCHI, P. & POLINO, R. 1984: Il metamorfismo eclogitico nel basamento del Gran Paradiso ed in unità Piemontesi della Valle di Campiglia. Mem. Soc. Geol. It. 29, 127–151.

BECKER, H. 1993: Garnet peridotite and eclogite Sm-Nd mineral ages from the Lepontine dome (Swiss Alps): New evidence for Eocene high-pressure metamorphism in the Alps. Geology 21, 599–602.

BIINO, G. & POGNANTE, U. 1989: Palaeozoic continental-type gabbros in the Gran Paradiso nappe (Western Alps, Italy): Early-Alpine eclogitization and geochemistry. Lithos 24, 3–19.

BORGHI, A. & SANDRONE, R. 1990: Structural and metamorphic constraints to the evolution of a NW sector of the Dora-Maira Massif (Western Alps). Mem. Soc. Geol. It. 45, 135–141.

BORGHI, A., CADOPPI, P., PORRO, A. & SACCHI, R. 1985: Metamorphism in the North part of the Dora-Maira Massif (Cottian Alps). Boll. Mus. Sci. Nat. Torino 3, 369–380.

BORGHI, A., COMPAGNONI, R. & SANDRONE, R. 1994: Evoluzione termo-tettonica alpina del settore settentrionale del Massiccio del Gran Paradiso (Alpi Occidentali). Atti Tic. Sc. Terra ser. sp. 1, 137–152.

BOWTELL, S. A., CLIFF, R. A. & BARNICOAT, A. C. 1994: Sm-Nd isotopic evidence on the age of eclogitization in the Zermatt-Saas ophiolite. J. metamorphic Geol. 12, 187–196.

CADOPPI, P. 1990: Geologia del basamento cristallino nel settore settentrionale del Massiccio Dora-Maira (Alpi Occidentali). Tesi di dottorato, Consorzio Univ. Torino-Genova-Cagliari.

CALLEGARI, E., COMPAGNONI, R. & DAL PIAZ, G. V. 1969: Relitti di strutture intrusive erciniche e scisti a silimanite nel Massiccio del Gran Paradiso. Boll. Soc. Geol. It. 88, 59–69.

CHOPIN, C. 1985: Les relations de phase dans les metapélités de haute pression. Approche expérimentale et naturaliste. Conséquences géodinamiques pour les Alpes occidentales. Thèse doctorat d'Etat, Univ. Paris VI.

CHOPIN, C. & MALUSKI, H. 1980: ^{40}Ar-^{39}Ar dating of high pressure metamorphic micas from the Gran Paradiso area (Western Alps): evidence against the blocking-temperature concept. Contrib. Mineral. Petrol. 74, 109–122.

CHOPIN, C. & MONIÉ, P. 1984: A unique magnesiochloritoid bearing, high-pressure assemblage from the Monte Rosa, Western Alps: A petrologic and $^{40}Ar/^{39}Ar$ study. Contrib. Mineral. Petrol. 87, 388–398.

CHOPIN, C., HENRY, C. & MICHARD, A. 1991: Geology and petrology of coesite bearing terrain, Dora Maira Massif, Western Alps. Eur. J. Mineral. 3, 263–291.

CLOOS, M. 1982: Flow melanges: Numerical modelling and geologic constraints on their origin in the Franciscan subduction complex, California. Geol. Soc. Amer. Bull. 93, 330–345.

COMPAGNONI, R. & PRATO, R. 1969: Paramorfosi di cianite su sillimanite in scisti pregranitici del Massiccio del Gran Paradiso. Boll. Soc. Geol. It. 88, 547–549.

COMPAGNONI, R., ELTER, G. & LOMBARDO, B. 1974: Eterogeneità stratigrafica del complesso degli "Gneiss Minuti" nel massiccio cristallino del Gran Paradiso. Mem. Soc. Geol. It. 13, 227–239.

COMPAGNONI, R., HIRAJIMA, T. & CHOPIN, C. 1994: Ultra-high-pressure metamorphic rocks in Western Alps. In: Ultrahigh pressure metamorphism (Ed. by COLEMAN, R. G. & WANG, X.) Cambrigde Univ. Press, chapter 8, in press.

COWAN, D. S. & SILLING, R. M. 1978: A dynamic model of accretion at trenches and its implications for the tectonic evolution of subduction complexes. J. Geophys. Res. 83, 5389–5396.

DAL PIAZ, G. V. 1971: Nuovi ritrovamenti di cianite alpina nel cristallino antico del Monte Rosa. Rend. Soc. It. Miner. Petrol. 27, 437–477.

DAL PIAZ, G. V. & LOMBARDO, B. 1986: Early-alpine eclogitic metamorphism in the Penninic Monte Rosa – Gran Paradiso basement nappes of northwestern Alps. Geol. Soc. Am. Mem. 164, 249–265.

DAVY, P. & GILLET, P. 1986: The staking of thrust slices in collision zones and its thermal consequences. Tectonics 5, 913–929.

DESMONS, J. 1989: Different metamorphic evolutions in the Alpine-Apenninic ophiolites (France-Italy-Switzerland-Austria). Chem. Geol. 77, 229–250.

– 1992: The Briancon basement (Pennine Western Alps): Mineral composition and polymetamorphic evolution. Schweiz. mineral. petrogr. Mitt. 72, 37–55.

ELLIS, D. J. & GREEN, D. H. 1979: An experimental study of the effects of Ca upon garnet-clinopiroxene Fe-Mg exchange equilibria. Contrib. Mineral. Petrol. 71, 13–22.

ELLIS, A. C., BARNICOAT, A. C. & FRY, N. 1989: Structural and metamorphic constraints on the tectonic evolution of upper Pennine Alps. In: Alpine Tectonics (Ed. by COWARD, M. P., DIETRICH, D. & PARK, R. G.) Geol. Soc. Sp. Publ. 45, 173–188.

ERNST, W. G. 1979: Coexisting sodic and calcic amphiboles from high-pressure metamorphic belts and the stability of barroisitic amphibole. Mineral. Mag. 43, 269–278.

– 1988: Tectonic history of subduction zones inferred from retrograde blueschist P-T path. Geology 16, 1081–1084.

FREY, M., HUNZIKER, J. C., O'NEIL, J. R. & SCHWANDER, H. W. 1976: Equilibrium disequilibrium relations in the Monte Rosa granite, western Alps: petrological Rb/Sr and stable isotope data. Contrib. Mineral. Petrol. 55, 147–179.

GEBAUER, D., GRÜNENFELDER, M., TILTON, G., TROMMSDORFF, V. & SCHMID, S. 1992: The geodynamic evolution of garnet-peridotites, garnet pyroxenites and eclogites of Alpi Arami and Cima di Gagnone (Central Alps) from Early Proterozoic to Oligocene. Schweiz. mineral. petrogr. Mitt. 72, 107–111.

GILLET, P., CHOUKROUNE, P., BALLEVRE, M. & DAVY, P. 1986: Thickening history of the western Alps. Earth and planet. Sci. Lett. 78, 44–52.

GHENT, E. D. & STOUT, M. Z. 1981: Geobarometry and Geothermometry of Plagioclase-Biotite-Garnet-Muscovite Assemblages. Contrib. Mineral. Petrol. 76, 92–97.

GOFFÉ, B. & CHOPIN, C. 1986: High-pressure metamorphism in the Western Alps: zonegraphy of metapelites, chronology and consequences. Schweiz. mineral. petrogr. Mitt. 66, 41–52.

GREEN, T. H. & HELLMAN, P. L. 1982: Fe-Mg partitioning between coexisting garnet and phengite at high pressure and comments on a garnet-phengite geothermometer. Lithos 15, 253–266.

HEINRICH, W. & ALTHAUS, E. 1980: Die obere Stabilitätsgrenze von Lawsonit plus Albit bzw. Jadeit. Fortschr. Miner. 58, 49–50.

HODGES, K. W. & SPEAR, F. S. 1982: Geothermometry, geobarometry and the Al_2SiO_5 triple point at Mt. Moosilauke, New Hampshire. Am. Mineral. 67, 1118–1134.

HOLLAND, T. J. B. 1980: The reaction albite = jadeite + quartz determined experimentally in the range 600–1200 °C. Amer. Mineral. 65, 129–134.

HSÜ, K. J. 1991: Exumation of high-pressure metamorphic rocks. Geology 19, 107–110.

HUNZIKER, J. C., DESMONS, J. & HURFORD, A. J. 1992: Thirty-two years of geochronological work in the Central and Western Alps: a review on seven maps. Mém. Géol. Lausanne 13.

KARIG, D. E. 1974: Tectonic erosion at Trenches. Earth and planet. Sci. Lett. 21, 209–212.

KRETZ, R. 1983: Symbols for rock forming minerals. Amer. Mineral. 68, 277–279.

KLEEMANN, U. & REINHARDT, J. 1994: Garnet-biotite thermometry revisited: The effect of Al^{VI} and Ti in biotite. Eur. J. Mineral. 6, 925–944.

LARDEAUX, J. M. & SPALLA, M. J. 1990: Tectonic significance of P-T-t paths in metamorphic rocks: examples from ancient and modern orogenic belts. Mem. Soc. Geol. It. 45, 51–69.

LE GOFF, E. & BALLEVRE, M. 1990: Geothermobarometry in albite-garnet orthogneisses: A case study from the Gran Paradiso nappe (Western Alps). Lithos 25, 261–280.

LEMOINE, M., MARTHALER, M., CARON, M., SARTORI, M., AMAUDRIC DU CHAFFAUT, M., DUMONT, T., ESCHER, A., MASSON, H., POLINO, R. & TRICARD, P. 1984: Découverte de Foraminifères planctoniques du Crétacé supérieur dans les Schistes Lustrés du Queyras (Alpes Occidentales): Conséquences paléogéographiques et tectoniques. C. R. Acad. Sci. Paris 299 sér II, 727–732.

MARUYAMA, S., SUZUKI, K. & LIOU, J. G. 1983: Greenschist- amphibolite transition equilibria at low pressures. J. Petrol. 24, 583–604.

MERLE, O. & GUILLER, B. 1989: The building of the Central Swiss Alps: An experimental approach. Tectonophysics 165, 41–56.

MASSONNE, H. J. 1989: The upper thermal stability of chlorite + quartz: an experimental study in the system $MgO-Al_2O_3-SiO_2-H_2O$. J. metam. Geol. 7, 567–581.

MASSONNE, H. J. & CHOPIN, C. 1989: P-T history of the Gran Paradiso (Western Alps) metagranites based on phengite geobarometry. In: Evolution of metamorphic belts (Ed. by DALY, G. S., CLIFF, R. A. & YARDLEY, B. W. D.) Geol. Soc. Sp. Publ. London 43, 545–549.

MASSONNE, H. J. & SCHREYER, W. 1987: Phengite geobarometry based on the limiting assemblage with K-feldspar, phlogopite and quartz. Contrib. Mineral. Petrol. 96, 212–224.

MESSIGA, B. & SCAMBELLURI, M. 1991: Retrograde P-T-t path for the Voltri Massif eclogites (Ligurian Alps, Italy): some tectonic implications. J. metam. Geol. 9, 93–109.

MICHARD, A., CHOPIN, C. & HENRY, C. 1993: Compression versus extension in the exumation of the Dora – Maira coesite-bearing unit, Western Alps, Italy. Tectonophysics 221, 173–193.

MONIÉ, P. 1985: La méthode $^{40}Ar/^{39}Ar$ appliquée au métamorphisme alpin dans le massif du Monte Rose (Alpes occidentales). Chronologie détaillée depuis 110 Ma. Eclogae Geol. Helv. 78, 487–516.

MONIÉ, P. & CHOPIN, C. 1991: $^{40}Ar/^{39}Ar$ dating in coesite bearing and associated units of the Dora Maira massif. Western Alps. Eur. J. Mineral. 3, 239–262.

MONIÉ, P. & PHILIPPHOT, P. 1989: Mise en évidence de l'age éocène moyen du métamorphisme de haute-pression dans la nappe ophiolitique du Monviso (Alpes Occidentales) par la méthode 39Ar-40Ar. C. R. Acad. Sci. Paris 309, 245–151.

NITSCH, K. H. 1970: Experimentelle Bestimmung der oberen Stabilitätsgrenze von Stilpnomelan. Fortschr. Miner. 47, 48–49.

PAVLIS, T. L. & BRUHN, R. L. 1983: Deep seated flow as mechanism for the uplift of broad forearc ridges and its role in the exposure of high P/T metamorphic terranes. Tectonics 2, 473–497.

PERCHUK, L. L. & LAVRENT'EVA, I. V. 1983: Experimental investigation of exchange equilibria in the system cordierite-garnet-biotite. In: Kinetics and equilibrium in mineral reactions (Ed. by SAXENA, S. K.). Springer, 199–240.

POGNANTE, U. & SANDRONE, R. 1989: Eclogites in the northern Dora-Maira nappe (Western Alps, Italy). Mineral. Petrol. 40, 57–71.
POGNANTE, U., TALARICO, F., RASTELLI, N. & FERRATI, N. 1987: High pressure metamorphism in the nappes of the Valle dell'Orco traverse (Western Alps). J. metam. Geol. 5, 397–414.
POLINO, R., DAL PIAZ, G. V. & GOSSO, G. 1990: Tectonic erosion at the Adria margin and accretionary processes for the Cretaceous orogeny of the Alps. In: Deep structure of the Alps (Ed. by ROURE, F., HEITZMANN, P. & POLINO, R.). Mém. Soc. Geol. Fr. 156, Mém. Soc. Geol. Suisse 1, Vol. Spec. Soc. Geol. It. 1, 345–367.
POWELL, R. & HOLLAND, T. J. B. 1990: An enlarged and updated internally consistent thermodynamic data-set with uncertainties and correlations: the system K2O-Na2O-CaO-MgO-MnO-FeO-Fe2O3-Al2O3-TiO2-SiO2-C-H-O2. J. metam. Geol. 8, 89–124.
PLATT, J. P. 1986: The uplift of high-pressure low-temperature metamorphic rocks. Phil. Trans. Soc. London A 321, 87–103.
RAO, B. B. & JOHANNES, W. 1979: Further data on the stability of staurolite + quartz and related assemblages. N. Jb. Miner. Mh. 10, 437–447.
RUBIE, D. C. 1984: A thermal-tectonic model for high-pressure metamorphism and deformation in the Sesia Zone, Western Alps. J. Geol. 92, 21–36.
SALIOT, P. 1973: Les principales zones du métamorphisme dans les Alpes françaises. Répartition et signification. C. R. Acad. Sc. Paris 276, 3081–3084.
SANDRONE, R. & BORGHI, A. 1992: Zoned garnets in the northern Dora-Maira Massif and their contribution to reconstruction of the regional metamorphic evolution. Eur. J. Mineral. 4, 465–474.
SANDRONE, R., SACCHI, R., CORDOLA, M., FONTAN, D. & VILLA, I. M. 1988: Meta-diorites in the Dora-Maira polymetamorphic basement (Cottian Alps). Rend. Soc. It. Min. Petr. 43, 593–608.
SANDRONE, R., CADOPPI, P., SACCHI, R., VIALON, P. 1992: The Dora-Maira Massif. In: Pre-Mesozoic geology in the Alps (Ed. by VON RAUMER J. F. & NEUBAUER, F.). Springer, Berlin, 317–325.
SCAILLET, S., FERAUD, G., LAGABRIELLE, Y., BALLEVRE, M. & RUFFET, G. 1990: $^{40}Ar/^{39}Ar$ laserprobe dating by step heating and spot fusion of phengites from the Dora Maira nappe of the Western Alps, Italy. Geology 18, 741–744.
SCAILLET, S., FERAUD, G., BALLEVRE, M. & AMOURIC, M. 1992: Mg/Fe and [(Mg,Fe)Si-Al_2] compositional control on argon behaviour in high-pressure white micas: A $^{40}Ar/^{39}Ar$ continuous laserprobe study from the Dora-Maira nappe of the internal western Alps, Italy. Geochim. Cosmochim. Acta 56, 2851–2872.
SPEAR, F. S., SELVERSTONE, J., HICKMOTT, D., CROWLEY, P. & HODGES, K. V. 1984: P-T paths from garnet zoning: a new technique for deciphering the tectonic processes in crystalline terranes. Geology 12, 87–90.
TAO, W. C. & O'CONNEL, R. J. 1992: Ablative Subduction: A Two-Sided Alternative to the Conventional Subduction Model. J. Geophys. Res. 97, 8877–8904.
THOMPSON, A. B. & ENGLAND, P. C. 1984: Pressure-Temperature-time path of regional metamorphism. II: Their inference and interpretation using mineral assemblages in metamorphic rocks. J. Petrol, 24. 929–955.
THOMPSON, A. B. & RIDLEY, J. R. 1987: Pressure – Temperature – time (P-T-t) histories of orogenic belts. Phil. Trans. R. Soc. London A321, 27–45.
TILTON, G. R., SCHREYER, W. & SCHERTL, H. P. 1989: Pb-Sr-Nd isotopic behavior of deeply subducted crustal rocks from Dora Maira Massifs, Western Alps, Italy. Geochim. Cosmochim. Acta 53, 1391–1400.
– 1991: Pb-Sr-Nd isotopic behavoir of deeply subducted crustal rocks from the Dora-Maira Massifs, Western Alps, Italy II: what is the age of the ultrahigh pressure metamorphism? Contrib. Mineral. Petrol. 108, 22–33.
TURCOTTE, D. L. & SCHUBERT, G. 1982: Geodynamics. John Wiley & Sons, New York.
VIALON, P. 1966: Etude géologique du Massif Cristallin Dora-Maira (Alpes Cottiennes internes-Italie). Trav. Lab. Géol. Grenoble mém. 4.
VEARNCOMBE, J. R. 1983: High-pressure low-temperature metamorphism in the Gran Paradiso basement, Western Alps. J. metam. Geol. 1, 103–115.
VUICHARD, J. P. & BALLEVRE, M. 1988: Garnet-chloritoid equilibria in eclogitic pelitic rocks from the Sesia Zone (Western Alps): their bearing on phase relations in high pressure metapelites. J. metam. Geol. 6, 135–157.

Manuscript received April 7, 1995
Revision accepted October 6, 1995