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Autor: Gardien, Véronique / Reusser, Eric / Marquer, Didier

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Pre-Alpine metamorphic evolution of the gneisses from the Valpelline series (Western Alps, Italy)

by *Véronique Gardien*[1], *Eric Reusser*[1] and *Didier Marquer*[2]

Abstract

The Valpelline series in the western Alps belongs to the Austroalpine domain which corresponds to the southern continental margin of the Tethys during Jurassic times. In the Valpelline gneisses which are a part of the pre-Alpine basement, microscopic observations evidence two generation of garnets: Gr I consists of the centimeter-sized inclusion rich core, Gr II of the inclusion-poor rim of the centimeter garnets and millimeter garnets in the foliation plane. The inclusions in Gr I consist of kyanite, alkali feldspar, plagioclase and rutile. Both rutile and kyanite have been observed in the matrix of the rock. Microstructural observations demonstrate that kyanite occurs before sillimanite recording a pre-Alpine polymetamorphic evolution. Microstructural and petrological investigations involve a progressive metamorphic evolution consisting of an early intermediate pressure granulitic stage recorded by rare relics of kyanite, rutile and alkali feldspar and the first generation of garnet. Later the Valpelline gneisses have experienced an intensive reequilibration under HT amphibolite facies conditions, characterized by the association garnet II, sillimanite, biotite, cordierite and ilmenite and associated with a main deformation stage. The earlier granulitic and the amphibolitic stages are related to the pre-Alpine metamorphic evolution but, so far few radiometric ages are available in the Dent Blanche nappe, in this case this evolution can be related either to a late Variscan or Permo-Jurassic period. The Alpine evolution s.s. occurred under greenschists facies conditions characterized by chlorite, sericite, muscovite, clinozoisite and albite assemblage preferentially developed in narrow shear zones throughout the valley and in the contact zone between the Valpelline and the Arolla units.

Keywords: granulitic metamorphism, metamorphic evolution, lower crust, Variscan, Dent Blanche unit, Western Alps.

Introduction

The Dent Blanche nappe located in the Western Alps (Fig. 1), comprises two main units classically described as the structurally lower Arolla series and the structurally higher Valpelline series (ARGAND, 1906, 1908; STUTZ and MASSON, 1938). The Dent Blanche nappe, because of lithologic similarities is thought to have been coherent with the Sesia-Lanzo zone. The Arolla series composed mainly of late Paleozoic massive granites and granodiorites (northern part of the series) and mafic to ultramafic rocks (southern part of the series) and the Pillonet klippen are equivalent to the intermediate unit of the Sesia-Lanzo zone, the Gneiss Minutti. The Valpelline series consisting of metapelites, mafics and carbonates, is structurally and lithologically similar to the upper unit of the Sesia-Lanzo zone, the II-zona Dioritico Kinzigitica (II-DK) (Fig. 1). The Mt Emilius-Glacier Rafray klippen correspond to the lower unit of the Sesia-Lanzo zone, the Eclogitic Micaschists (VENTURINI et al., 1994). Both units, Dent Blanche and Sesia-Lanzo which represent the uppermost units of the western Alps, preserve high temperature / low pressure assemblages (KIÉNAST and NICOT, 1971; LARDEAUX, 1981; BALLÈVRE et al., 1986; GARDIEN, 1994). In the Dent Blanche nappe a relative HP stage is locally recorded by occurrences of glaucophane and Si-rich white micas (PENNACCHIONI and GUERMANI, 1993; CANEPA et al., 1990; AYRTON et al., 1982; DE LEO et al., 1986, DAL PIAZ and MARTIN, 1986) and by occurrences of kyanite and chloritoide

[1] Institut für Mineralogie und Petrographie, ETH-Zentrum, CH-8092 Zürich, Switzerland.
present address: Laboratoire des Sciences de la Terre, ENS, 46, Allée d'Italie, F-69366 Lyon Cedex 07, France.
[2] Geological Institute, Université de Neuchâtel, rue E. Argand 11, CH-2047 Neuchâtel, Switzerland.

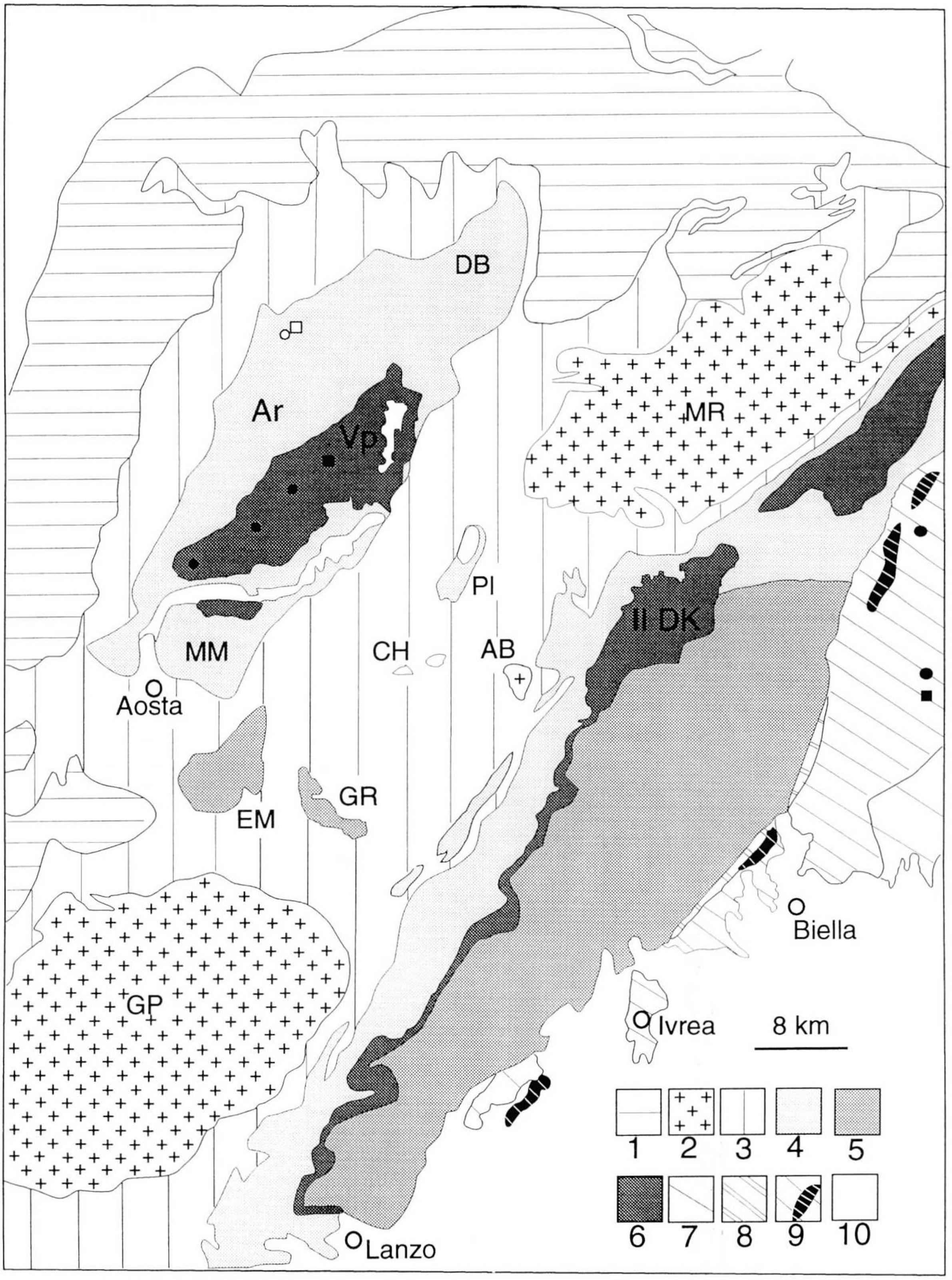


Fig. 1 Map of the mains tectonic units from the North-western Alps. 1) Bernhard Nappe. 2) Monte Rosa (MR) Arceza-Brusson (AB) Gran Paradiso (GP) Nappe. 3) Piemonte zone. 4), 5), 6), Austro-Alpine Domain: 4) Arolla gneiss of the Dent Blanche, (Ar) Pillonet klippe (Pl), and gneiss Minutti Complex of the Sesia-Lanzo zone. 5) Emilius (EM)-Glacier Rafray (GR) klippen and Eclogitic Micaschists unit of the Sesia-Lanzo zone. 6) Valpelline (Vp) unit and Mt Mary (MM) klippe of the Dent Blanche and 2nd Zona Diorito-Kinzigitica (II DK) of the Sesia-Lanzo zone. 7) Serie dei Laghi. 8) Oligocene Trachyandesite volcanics. 9) Ivrea-Verbano zone with ultramafics in black. 10) Mesozoic cover of Mt Dolin and Roisan zone. DB = Dent Blanche, CH = Châtillon St Vincent klippe. From DAL PIAZ et al. (1991) and VENTURINI et al. (1994) .

(KIÉNAST and NICOT, 1971) which suggested a temperature of about 550 °C and a pressure of 7–8 kbar. According to PENNACCHIONI and GUERMANI (1993) this values seem to be overestimated, this question will be discussed later. So far, high pressure metamorphism (adequate to develop eclogitic parageneses) related to an Alpine subduction event have never been described in the Valpelline unit.

Radiometric studies to determine the age of the Valpelline series were undertaken by HUNZIKER (1974) which gave ages between 200 and 180 My (K/Ar and Rb/Sr on biotites), and 135 My (K/Ar on muscovites). DAL PIAZ (1972) also give Hercynian ages on biotites for the Ivrea Zone basement and on the II DK (see Fig. 1 for location of the area), confirming the correspondence between these two zones. In the Western Alps, metamorphism and radiometric dates are inconsistent with those obtained in the Austroalpine domain. Indeed, the internal nappes in the Western Alps record two main metamorphic events during the Alpine evolution, which both are characterized by a low thermal gradient. The first one dated between 130 to 60 Ma (HUNZIKER, 1974) produces eclogitic to blueschist mineral assemblage typical of subduction type environment, the second dated at 38 Ma produces greenschists to low grade amphibolite mineral assemblages. For all this reasons the Dent Blanche, Sesia-Lanzo units are believed to correspond to the well preserved continental margin of Apulia which results of the opening of the Liguro-Piemont ocean during Jurassic times (TRÜMPY, 1980; DAL PIAZ, 1983). Those units are thrusted with the Piemonte Ocean basin over the Pennine Basement during Tertiary Alpine collision (TRÜMPY, 1980; RUBIE, 1984).

The purpose of this work is to describe more precisely the pre-Alpine metamorphic evolutions of the Valpelline series and to discuss the thermal signature of this evolution.

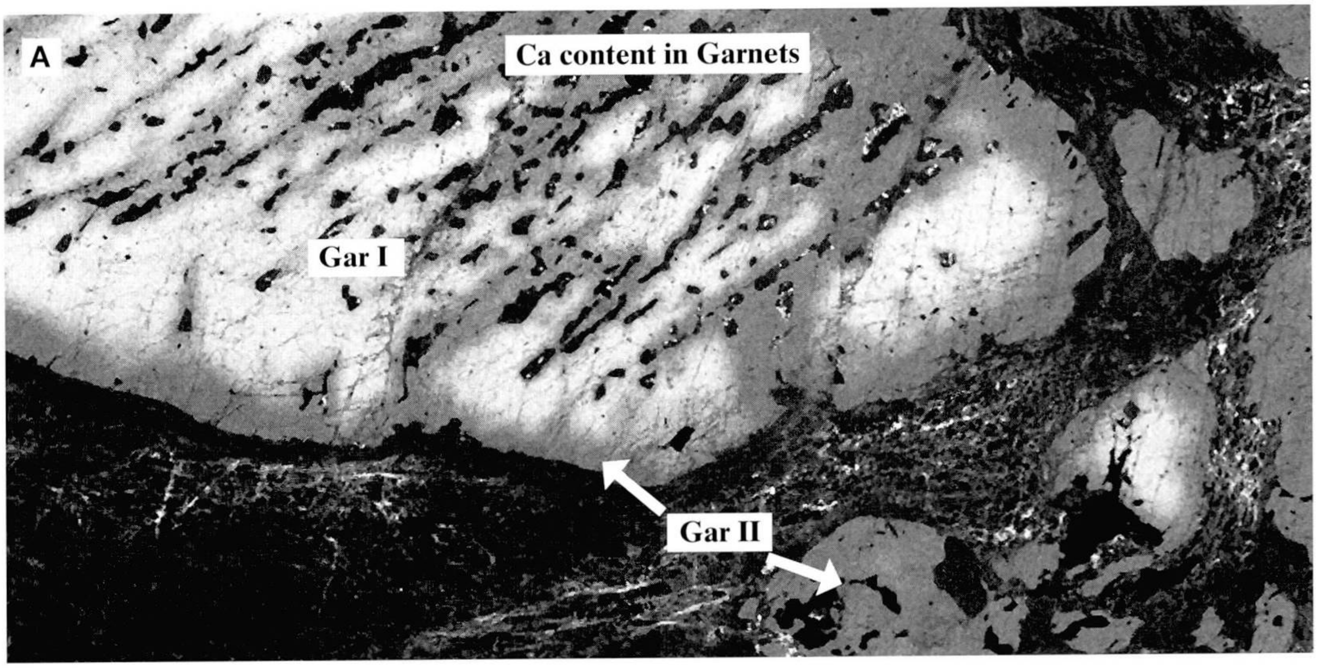
The paragneisses of the Valpelline series

The paragneisses described by STUTZ and MASSON (1938), DIEH et al. (1952), DAL PIAZ et al. (1977), COMPAGNONI et al. (1977) are the most common of the Valpelline rock types and exhibit several degrees of metamorphism. The northeastern part of the valley is characterized by the presence of high-grade paragneisses with interlayered basic granulites, amphibolites and marbles (NICOT, 1977). The southwestern part consists mainly of low to medium grade mica schists with interlayered calc-silicates bands (PENNACCHIONI and GUERMANI, 1993). In a large number of regions the metapelites are banded in texture, the strong regional foliation is expressed by the alignment of micas and sillimanite and the alternation of dark (biotite and garnet) and lighter (quartz and plagioclase) bands. The common mineralogy of the gneisses consists of garnet, aluminum silicate, biotite, plagioclase, quartz, rutile and opaque and locally little alkali feldspar, muscovite and cordierite, all the minerals exhibit a variety of textures and show replacing relationships between them. In the field alternating unmigmatized gneisses and partially melted gneisses define a stromatitic variety of migmatites. The leucosomes layers are disharmonically folded and form boudined veins in the limb of folds. The leucosomes are granitic in composition with plagioclase, quartz, feldspars plus garnet. The stromatitic migmatites are replaced progressively by pegmatitic patches associated with the occurrence of cordierite. Different generation of dykes also occur throughout the area.

The following petrological descriptions refer to Gar-Bio-Sil-bearing gneisses outcroping between the villages of Oyace and Bionnaz, more precisely in the northern part of Dzovennoz (between Cretes and Perquis). The granulitic gneisses with relics of kyanite have been found in gneisses on the road between Valpelline and Oyace and close to the Lac Mort. The migmatitic gneisses (Bio-Sil-Crd) outcrop in the valley south to Oyace in the direction of Verdona.

Each studied sample contains garnet showing differences in grain size, inclusion density and chemistry. Garnet may occur as inclusion-rich porphyroblasts rimmed by paler and relatively inclusion-free garnet. The cores of the porphyroblasts preserve as relics an earlier foliation marked by ilmenite, alkali feldspar, plagioclase and rare biotite that form a high angle with the external foliation. Biotite, alkali feldspar and plagioclase inclusions are often replaced by chlorite or white micas.

Inclusions in the rim of garnet porphyroblasts are quartz, biotite, sillimanite and rare kyanite. In highly deformed paragneisses the rims of garnet porphyroblasts are not very well defined and seem to grow in pressure shadows of inclusion-rich garnet cores. On the contrary in less deformed domains the rims are continuous all around the inclusion-rich garnet cores giving rise to coronitic texture. This suggests that the rims of garnets grew during or slightly after the main deformation stage responsible for the development of the regional foliation. In some samples we observed small garnet grains elongated in the foliation plane, they are somewhat deformed and



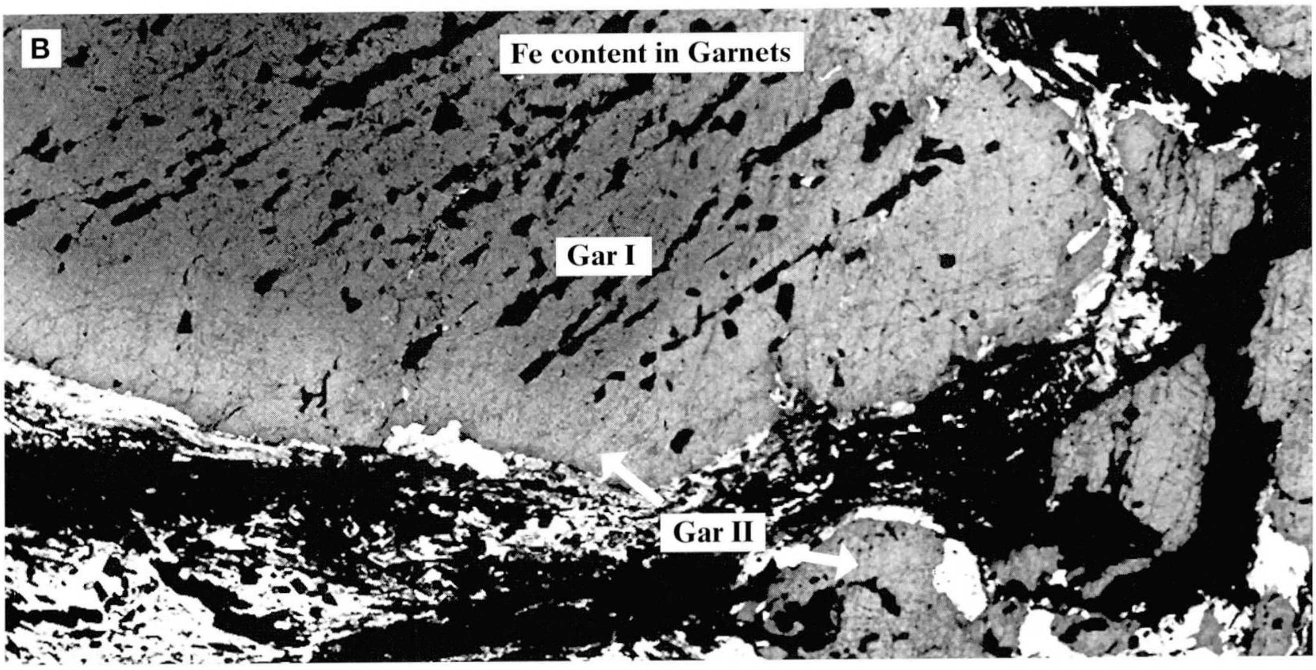


Fig. 2 Chemical map of porphyroblastic garnet showing the distribution of elements in two dimension in garnets from the Valpelline gneisses. Dark areas are high concentration in Ca (A) and Fe (B) and light areas are low concentration in Ca (A) and Fe (B). In this figure inclusion-rich core rimmed by a second generation of inclusion-poor garnet are observed. We can observe similar compositions between the rim of the porphyritic garnet and the small garnet in the foliation plane. Scale bar is 1 cm for A and B.

the ends are stretched and bent (Fig. 2). Very often they contain biotite and sillimanite inclusions which are parallel to the external foliation. They appear to have grown completely during the main deformation stage or slightly after. In some other samples only the small garnets are present.

Three types of aluminum silicates are present in the rocks: fibrous and prismatic sillimanite and kyanite which occurs as rare relics in garnet and in the matrix of the rock (GARDIEN, 1994). The close association of biotite and fibrous sillimanite in the foliation plane indicates that they have grown during the main deformation stage. Fibrous sillimanite is observed as non oriented inclusions in the rim of porphyritic garnets and as inclusions parallel to the main foliation in millimeter-sized garnets. This suggests that the

Tab. 1 Selected microprobe analyses of garnet porphyroblast, the first generation of garnet. (Gar I) is represented by the inclusion-rich core compositions; the second generation of garnet (Gar II) is represented by the inclusion-poor layer compositions. Structural formulae are calculated on the basis of 7 cations and 24 charges.

	Rim		Inclusion-poor layers									Inclusion-rich core		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SiO_2	37.3	37.12	37.04	37.38	37.46	37.25	38.57	36.93	37.32	38.17	36.91	37.42	37.08	37.26
TiO_2	0.03	0.03	0.04	0.05	0.04	0.05	0	0.03	0.04	0.03	0.02	0.01	0	0.04
Al_2O_3	21.52	21.22	21.49	21.8	21.52	21.65	21.49	21.31	21.63	21.65	21.49	21.84	21.89	21.97
Fe_2O_3	0.41	0.45	4.05	2	1.22	1.79	2.19	0.01	2.06	0.29	2.69	0.10	0.40	0.33
FeO	35.28	35.91	27.67	29.66	29.58	29.64	28.96	30.97	29.8	30.67	30.01	33.58	34.63	34.78
MnO	0.56	0.71	0.36	0.31	0.34	0.35	0.39	0.35	0.27	0.32	0.34	0.52	0.56	0.68
MgO	3.57	2.76	4.25	4.54	4.48	4.57	4.51	4.34	4.54	4.36	4.45	4.81	4.26	4.73
CaO	1.87	2.22	4.74	5.03	5.21	5	5.27	5.29	5.24	5.16	4.55	2.49	2.01	1.93
Na_2O	0	0	0.55	0.05	0.04	0.01	0.01	0	0.01	0.04	0.01	0.01	0.03	0
K_2O	0.01	0.01	0.04	0.01	0.02	0	0	0	0.01	0.04	0	0.02	0.02	0
Total	100.6	100.42	100.22	100.9	99.96	100.3	99.61	100.9	101.14	100.72	100.5	100.84	100.88	100.73
Endmembers														
Gros	0.04	0.05	0.10	0.08	0.11	0.09	0.08	0.09	0.15	0.15	0.14	0.067	0.05	0.05
Alm	0.79	0.81	0.66	0.67	0.66	0.67	0.66	0.67	0.68	0.67	0.68	0.73	0.76	0.78
Pyr	0.14	0.11	0.18	0.18	0.18	0.18	0.18	0.17	0.18	0.18	0.17	0.19	0.17	0.15
Spes	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0	0	0.01	0.01	0.01	0.02
And	0.01	0.01	0.03	0.06	0.04	0.05	0.07	0.06	0.04	0.06	0.01	0.03	0.01	0.01

growth of fibrous sillimanite occurred contemporaneously or slightly prior to the deformation stage. On the contrary the prismatic crystals of sillimanite crosscut biotite and fibrolite on the foliation plane, they do not exhibit undulatory extinctions – this suggest that they have grown after the main deformation event. Thus the crystal habit of sillimanite changes from fibrous in the early stage of growth to prismatic, needle-like, in the later stage. The initial Al-silicate in the gneisses was kyanite (relics in garnets and in the matrix), later pseudomorphosed by sillimanite (GARDIEN, 1994). Some fibrolitic sillimanite are completely replaced by kyanite aggregates (PENNACCHIONI and GUERMANI, 1993) but very often sillimanite is destabilized into white micas.

Biotites are always present in the gneiss and also exhibit several generation of growth. The earliest stage of growth of biotite is recorded as inclusions within porphyritic garnet cores but, in most sections large oriented biotite flakes are intergrown with fibrous crystals of sillimanite oriented in the foliation plane. This suggests that the main stage of growth is synchronous (and possibly slightly earlier) to the main deformation stage of the paragneisses. Muscovite is never observed as primary mineral, but occurs later as small aggregates at the expense of alkali feldspar, biotite and cordierite or as flakes at the expense of sillimanite.

Alkali feldspar and plagioclase exhibit also several generations of growth as they occur as inclusions within garnet and as constituent of the matrix. Alkali-feldspar inclusions are always destabilized into white mica whereas plagioclase inclusions are well preserved in the core of porphyritic garnets.

The matrix of the rock consist of quartz and plagioclase and few cordierite grains including biotite, sillimanite, quartz oxides and garnets. They are difficult to identify because they show a complete replacement by the typical micaceous, pinite alteration products. Sometimes cordierite grains occur in veins associated with quartz. In this case the veins are parallel to the main foliation. Quartz grains show undulatory extinctions and the plagioclase is partially altered to sericite. Rutile is included in garnets and also present in the matrix, some of them are rimmed by ilmenite. Ilmenite grains are present as inclusions in garnet and in the matrix, chlorite occurs in the rim of altered biotite and muscovite and also in the cracks of garnets.

Chemical composition of minerals

Minerals analyses were performed on the Cameca SX50 electron microprobe with 5 spectrometers at ETH Zürich, using natural silicates and oxides as standards, the accelerating voltage was 15 kv and the sample current 20 nA.

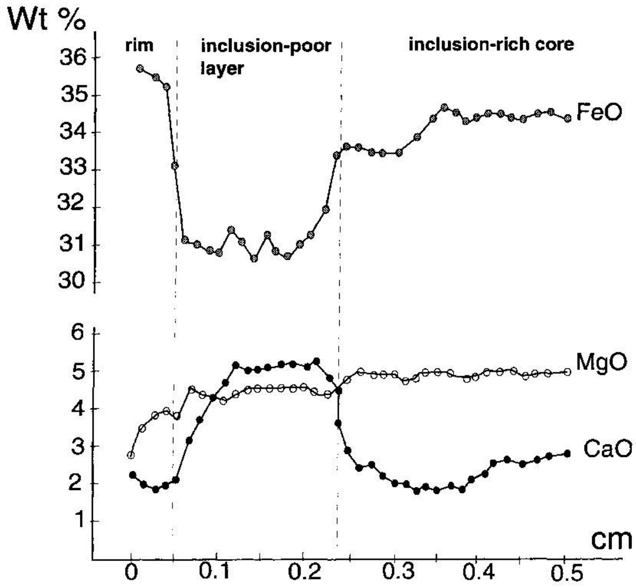


Fig. 3 Plot of garnet compositions versus radius showing the variation in wt% of calcium (Ca), magnesium (Mg) and iron (Fe) in a porphyritic garnet from the Valpelline paragneisses.

Garnet: Representative garnet analyses are given in table 1. There is a large compositional range between the different samples but within a single sample the composition is homogeneous. Garnets porphyroblast (analyses 1 to 14 in Tab. 1) are very well zoned and the zonation consist in a sharp transition between the core and the rim of the garnet for the Ca, Fe and Mg contents. An example of a zoning profile for a selected garnet (Fig. 3) shows a break in the zoning pattern from a plateau like core to a sharply zoned rim where Ca increases and Fe decreases. The core composition is $Alm_{73-78}Pyr_{15-19}Gros_{5-7}And_{1-3}$, the rim composition is $Alm_{66-68}Pyr_{18}Gros_{15-18}And_{4-6}$ (analyses 1 to 10 Tab. 1). The very external rim shows a Fe increase coupled with a Mg + Ca decrease. In some gneisses we observe only one generation of garnet, in this case the composition range between $Alm_{79-83}Pyr_{9-15}Gros_{1-4}Spe_1$ (analyses 1 to 3 in Tab. 2) the inclusions of kyanite were founded in the core of this garnets which correspond to the first generation. Some garnets are also totally homogeneous with a constant composition Alm_{62-66} $Pyr_{29-33}Gros_{2.4-3}Spe_{1.5-2}$ (analyses 4 to 6 in Tab. 2) surrounded by a narrow rim where Fe/Mg increases. This increase in the Fe/Mg ratio at the edge of garnet is interpreted as an effect of retrograde exchange with the biotites in the matrix during cooling.

Biotite: There is not a large compositional range for the biotites between the different samples, representative biotite analyses are given in table 3 together with muscovite analyses. In gneiss with only the first generation of garnets, biotites in inclusion within garnet (analyses 1 to 3 in Tab. 3) have a Fe/Fe + Mg ratio about 0.60 and the TiO_2 at about 1.7 to 3 wt%. Biotites in the matrix (analyses 4 and 5 in Tab. 3) have a Fe/Fe + Mg ratio of 0.55 to 0.60 and the TiO_2 content range from 3 tom 5 wt%. When the two generations of garnets are present in the gneiss, the biotites in inclusion within garnets have a Fe/Fe + Mg ratio of 0.37 to 0.40 and the TiO_2 contents is very high from 5 to 6 wt% (analyses 6 to 8 in Tab. 3). The biotites in the matrix associated with sillimanite have an Fe/Fe + Mg ratios of 0.55 and a TiO_2 content of 2.5 to 4 wt% similar to the analyses 4 and 5 in table 3.

Feldspar: Representative analyses of feldspars and ilmenite are given in table 4. When plagioclases are in inclusion within garnet they contain 39 to 40 wt% of anorthite (analyses 1 and 2 Tab. 4), and 30 wt% of anorthite when they are in the matrix of the gneiss (analyses 3 and 4 in Tab. 4). Rare alkali feldspars in the matrix are very rich in orthoclase (88 to 92 wt%) and contain 11 wt% of (analyses 5 and 6 in Tab. 4).

Metamorphic reactions

The cores of garnet porphyroblasts preserve relics of earlier structures and parageneses as oriented inclusions of biotite, plagioclase alkali feldspar, some rutile and rare kyanite. The rims of garnet porphyroblasts contain inclusions of quartz, sillimanite and ilmenite. The presence of rutile as inclusion in the core of garnet suggests the transgression of the following reaction:

Alm (Gar 1) + Rut = Ilm + Ky + Qtz (Bohlen et al., 1983).

The presence of alkali feldspar and kyanite as primary phases in rocks suggests that the following reactions have been exceeded.

Mus + Qtz = Ksp 1 + Als + Liq (Chatterjee and Johannes, 1974)

Ky = Sil (Robie and Hemingway, 1984).

The reactions described below are slightly prior to the development of the second generation of garnet and in some localities to the development of stromatitic migmatites in where garnet leucosomes are interlayered with unmigmatized gneisses. The growth of the second generation of garnet after sillimanite is supported by the inclusions of fibrolite in the rim of garnet.

Biol + Sil + Qtz = Gar2 + Ksp2 + Liq (Le

Tab. 2 Selected microprobe analyses of garnet from gneisses with only one generation of garnet (analyses 1 to 3) and in totally reequilibrated gneisses (analyses 4 to 6). Structural formulae are calculated on the basis of 7 cations and 24 charges.

	1	2	3	4	5	6
SiO_2	36.93	36.55	36.36	38.47	39.17	38.64
TiO_2	0.03	0.02	0.04	0.04	0.03	0.02
Al_2O_3	22.13	21.45	21.51	22.14	21.54	22.43
Fe_2O_3	0.14	0.67	1.33	0	0.82	0
FeO	36.46	36.60	35.76	24.59	28.85	29.19
MnO	0.56	0.54	0.46	0.60	0.79	0.69
MgO	2.48	3.03	3.13	6.14	8.63	8.31
CaO	1.58	1.79	1.89	0.83	1.08	1.10
Na_2O	0.09	0.01	0.09	0	0.06	0
K_2O	0.10	0.01	0.03	0.03	0.01	0.04
Total	100.53	100.66	100.62	100.46	100.19	100.61
			Endmembers			
Gros	0.04	0.03	0.012	0.026	0.028	0.024
Alm	0.838	0.816	0.808	0.66	0.621	0.633
Pyr	0.102	0.120	0.126	0.294	0.331	0.321
Spes	0.013	0.012	0.010	0.016	0.017	0.015
And	0.004	0.020	0.041	0	0	0.004

Tab. 3 Selected microprobe analyses of biotites.

	Biotite								Muscovite	
	1	2	3	4	5	6	7	8	9	10
SiO_2	34.55	35.05	34.88	34.95	35.5	36.62	36.95	36.55	45.56	45.59
TiO_2	1.7	2.96	3.29	4.14	4.47	5.63	5.71	6.12	1.68	1.23
Al_2O_3	19.19	19.34	18.8	18.24	15.15	15.41	16.4	16.7	33.90	34.74
Cr_2O_3	0.02	0.08	0.04	0	0.02	0.08	0.1	0.08	0	0.03
FeO	22.16	21.45	21.39	21.94	21.49	14.79	14	14.71	1.45	1.37
MnO	0.04	0.03	0.02	0.04	0.13	0.02	0.02	0.03	0.0	0.01
MgO	8.05	7.25	7.22	7.01	10.3	13.7	13.56	12.95	0.76	0.52
CaO	0.02	0.03	0.01	0.1	0.01	0	0.02	0.01	0.02	0
Na_2O	0.25	0.12	0.16	0.11	0.02	0.11	0.09	0.1	0.31	0.38
K_2O	9.45	9.41	9.47	9.7	9.52	9.5	9.45	9.26	10.83	10.17
H_2O	3.81	3.81	3.78	3.79	3.84	3.94	3.97	3.97	4.82	4.79
Total	99.24	99.53	99.04	99.94	100.4	99.83	100.3	100.5	99.33	98.8
	Cations calculated on the basis of 11 ox									
Si	2.72	2.76	2.77	2.77	2.77	2.79	2.79	2.76	3.17	3.13
Ti	0.1	0.18	0.2	0.25	0.22	0.32	0.32	0.39	0.1	0.07
Al^{IV}	1.3	1.5	1.35	1.23	1.23	1.21	1.21	1.24	0.42	0.47
Al^{VI}	0.38	0.33	0.45	0.55	0.07	0.17	0.25	0.25	2.71	2.77
Fe^{2+}	1.46	1.41	1.42	1.45	1.4	0.94	0.88	0.99	0.09	0.09
Mg	0.95	0.85	0.86	0.83	1.2	1.55	1.53	1.46	0.09	0.06
K	0.95	0.95	0.96	0.98	0.95	0.92	0.91	0.89	0.98	1.02

BRETON and THOMPSON, 1988; VIELZEUF and HOLLOWAY, 1988).

The biotite-sillimanite coronas around garnet and the few occurrence of alkali feldspar in the matrix of the gneiss show that garnet and feldspar represent reactants to the biotite + sillimanite producing reaction. This stage is contemporaneous to the main mylonitic foliation because both

Tab. 4 Selected microprobe analyses of plagioclase and alkali feldspar and ilmenite. Structural formulae are calculated on the basis of 5 cations and 16 charges for the feldspar and 2 cations and 6 charges for ilmenite.

	Feldspars							Ilmenite		
	1	2	3	4	5	6		1	2	3
SiO_2	60.83	61.53	61.11	60.94	63.71	63.7		0	0	0
TiO_2	0.01	0.03	0.03	0.01	0.03	0.02		52.58	52.80	53.05
Al_2O_3	22.29	24.5	24.67	24.61	18.53	18.62		0.02	0.14	0.15
Cr_2O_3	0.03	0.2	0	0.03	0.6	0.02		0.03	0	0.05
Fe_2O_3	0.02	0.24	0.02	0	0.17	0.21		0.05	0	0
FeO	0.01	0.02	0.12	0.07	0.05	0.06		46.25	46.77	46.57
MnO	0.03	0.04	0.02	0.01	0.02	0.01		0.84	0.15	0.33
MgO	0.03	0.01	0.01	0.3	0.5	0.4		0.06	0.18	0.08
CaO	5.85	5.91	6.17	6.16	0.04	0.66		0	0.02	0.01
Na_2O	8.38	8.43	7.94	7.96	1.29	0.89		0.01	0	0.02
K_2O	0.26	0.15	0.21	0.21	14.95	15.37		0	0.02	0
Total	99.71	100.8	100.3	100	99.7	99.6		99.86	100.09	100.27
					Endmembers					
Ab	71	71	69	69	11.3	7.6	Ilm	0.99	0.99	0.99
An	27.5	28	30	30	0	0				
Or	1.5	1	1	1	88.5	92.2				

fibrous sillimanite and biotite 2 are elongated in the foliation plane, according to the reaction:

Gar2 + Ksp2 + Liq = Bio2 + Sil + Qtz (LE BRETON and THOMPSON, 1988; VIELZEUF and HOLLOWAY, 1988).

Later a migmatitic imprint gives rise to the development of patchy migmatites in which cordierite occurs as poikiloblastic mineral including quartz, biotite and sillimanite according to the reactions:

Alm + Sil + Qtz = Fe–Cd (MYKHOPADHAYA and HOLDAWAY, 1994).

The latest reactions producing hydrous minerals (biotite, cordierite) from an anhydrous assemblage (garnet + alkali feldspar) require H_2O to progress, also supported by the occurrence of retromorphic amphibole around biotites in the paragneisses. The source of the fluid is not yet clear.

The later stage of this evolution is characterized by the occurrence of chlorite at the expense of biotite and garnet, whereas alkali feldspar is destabilized into white micas.

Bio + Gar + Kya = Chl + Mus + Qtz (HIRSCHBERG and WINKLER, 1968)
Alm + V = Fe–Chl + Qtz and,
Spe + V = Mn–Chl + Qtz (HSU, 1968).

Metamorphic conditions

Metamorphic conditions can be obtained using petrographic evidence as described above. Two approaches have been undertaken in an attempt to quantify the P-T conditions during the metamorphic evolution of this pelitic rocks, different thermobarometers, and petrogenetic grids for pelitic rocks.

Using the biotite-garnet geothermometer of FERRY and SPEAR (1978) on garnet core composition and compositions of included biotites, a temperature of approximately 650–700 °C is obtained. Only minerals that lie within the compositional limits defined by FERRY and SPEAR (1978). (Ca + Mn / Ca + Mn + Fe + Mg < 0.2 in garnet and biotites Al^{VI} + Ti/Al^{VI} + Ti + Fe + Mg < 0.15 in biotites) where used for the calculations.

The pressure for the granulitic stage is obtained using the formulation of NEWTON and HASELTON (1981) and the formula of BOHLEN et al. (1983) indicate a pressure of 7.5 to 10.5 kbar. The garnet-plagioclase-Al-silicate-quartz of GHENT (1976) geobarometer of garnet core composition and the composition of included plagioclases, yields estimated early granulitic conditions of about 8 to 10 kbar. Both results are in agreement with the stability field of kyanite (ROBIE and HEMINGWAY, 1984) for the obtained temperature estimates (Fig. 4, box 1). This result should be treated with circumspection because it is possible that

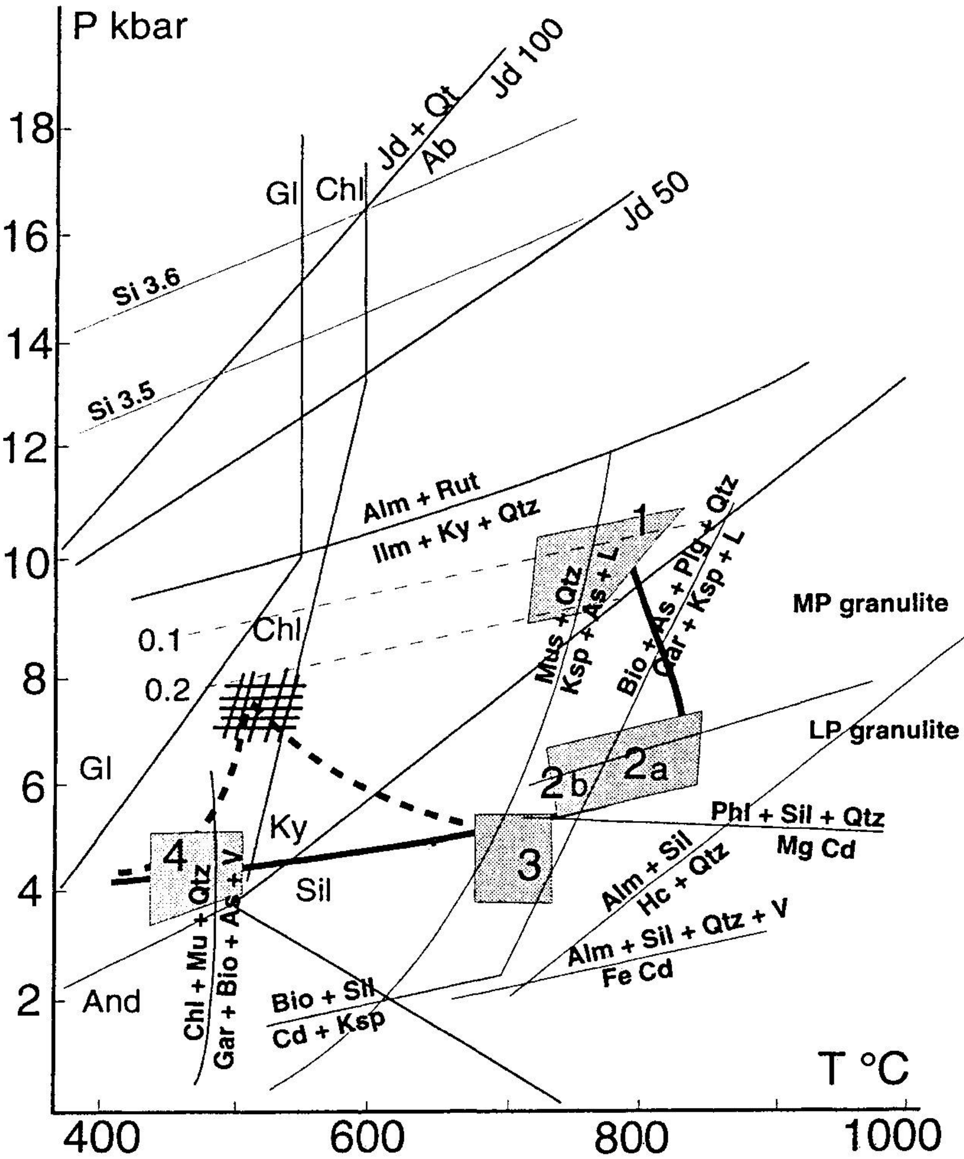


Fig. 4 P-T path of the Valpelline paragneisses. 1, 2, 3, 4 represent P-T conditions for the successive mineral assemblages. The background reaction curves is explained in the text. Stability field of glaucophane from MARESH (1977) and of choritoide from LAIRD (1982) are given. The reaction Ab = Jd + Qtz is from HOLLAND (1980) the Si content in phengite is from MASSONNE and SCHREYER (1987).

retrograde Fe–Mg exchange has occurred between garnet and biotite. Then the calculated values for the temperature represent a minimum. Furthermore, to use the garnet-plagioclase-Al-silicate-quartz barometer, these phases must have been saturated with quartz and Al-silicate. This is possibly realistic for garnet edges and recrystallized plagioclase in the matrix but it is difficult to demonstrate this latter point for garnet cores and plagioclase inclusions even in presence of kyanite and quartz as inclusions in garnet.

The Fe–Mg exchange equilibrium of FERRY and SPEAR (1978) is used for temperature estimates during growth of biotite and sillimanite from the assemblage garnet + alkali feldspar. Determined from garnet II interior and the core composition of the biotite in the matrix the temperature of about 750 to 800 °C (Fig. 4, box 2a) is in agreement with the location of the reaction curve Bio + Sil + Qtz = Ksp + Gar + H_2O (LE BRETON and THOMPSON, 1988; VIELZEUF and HOLLOWAY, 1988). The absence of spinel in the gneiss allows to estimate the upper temperature of this stage at about 850 °C using the experimental curve for the reaction:

Alm + Sil = Hc + Qtz (BOHLEN et al., 1986).

The absence of cordierite in the oldest generation of migmatites gives the lower pressure value for this stage at 5.5 kbar using the experimental curve Phl + Sil + Qtz = Mg–Cd which crosscuts at 6 kbar the experimental curve between medium pressure and low pressure granulites calibrated by GREEN and RINGWOOD (1967). Similar values of the temperature obtained using the biotite included within the core of the garnet II are interpreted as the P-T condition at the onset of deformation. This is supported by microstructures which indicates that mineral growth occurred during the main stage of deformation as they underline both foliation plane and extensional crenulation cleavages (Fig. 4, box 2b).

The following stage corresponds to the occurrence of poikiloblastic cordierite. The thermobarometer based on the Fe–Mg exchange between garnet and cordierite cannot be used since all the cordierite observed in the samples are more or less altered into pinite. The cordierites present in our samples are not pure iron or magnesium-end members. The upper pressure is given by the reaction Phl + Sil + Qtz = Mg–Cd but the lower pressure is not very well defined. An approximate value at about 700 ± 50 °C for the temperature can be proposed by the experimental curves Mus + Qtz = Ksp + Als + Liq (CHATTERJEE and JOHANNES, 1974) and Bio + Als + Plg + Qtz = Gar + Ksp + Liq (LE BRETON and THOMPSON, 1988; VIELZEUF and HOLLOWAY, 1988) (Fig. 4, box 3). The temperature around 620–650 °C calculated from the garnet rim and the rim of the biotite in matrix gives an indication of the last continuous cooling equilibration.

The alkali feldspar and cordierite breakdown into white micas and the development of chlorite at the rim of biotite and garnet correspond to temperature values lower than 500 °C and the absence of andalusite after sillimanite suggests a pressure of about 3.5 kbar (box 4, Fig. 4) supported by the pseudomorphose of kyanite after sillimanite (PENNACCHIONI and GUERMANI, 1993).

Discussion and conclusions

Because of the high temperature re-equilibration, little petrologic and textural evidence of the earlier history of the rocks is preserved. The petrographic study of the samples from the Valpelline gneisses has led to the recognition of parageneses which characterize a complex tectono-metamorphic history. The occurrence of kyanite-rutile-alkali feldspar relics led to recognition of earlier metamorphic granulite facies conditions (box 1, Fig. 4), characterized by a pressure at around 9–10 kbar and a temperature about 700–750 °C. The breakdown of kyanite into sillimanite and the occurrence of migmatites indicate that the retrograde evolution is associated with a decrease in pressure to 4–6 kbar and a small increase in temperature to 750–800 °C (box 2a, Fig. 4). The destabilization of the garnet-alkali feldspar assemblage into biotite-sillimanite indicates a decrease in temperature, this stage is contemporaneous with the main deformation event because biotite and sillimanite underline the structures (box 2b, Fig. 4). Locally the development of cordierite indicates pressure at about 3.5 to 4.5 kbar for a temperature range between 650 to 700 °C (box 3, Fig. 4). The final stage of the evolution took place under greenschists facies conditions preferentially well developed in narrows shear zones indicating temperature lower than 500 °C (box 4, Fig. 4) for a pressure at about 3–4 kbar. The squared area in figure 4, figures the relative HP eo-Alpine stage (PENNACCHIONI and GUERMANI, 1993; CANEPA et al., 1990; AYRTON et al., 1982; DE LEO et al., 1986; DAL PIAZ and MARTIN, 1986; KIÉNAST and NICOT, 1971) estimated at 7–8 kbar and 550 °C. This stage was not observed in our samples and one could argue that the absence of the assemblage Jd + Qtz is not consistent with the Si content (3.5 to 3.6) in white micas (Fig. 4).

Lot of field studies have shown the close relationship between low-P granulites, migmatites and mafic or ultramafic rocks. From a structural point of view such areas are also deformed and show the development of mylonitic foliation often associated with extensional structures as extensional crenulation cleavages. Moreover, kinematic indicators (S-C relationship, asymmetric pressure shadows, asymmetric tails around porphyroclast, asymmetric quartz C-axis fabric, ...) are all in agreement with the development of normal ductile faults (DAVIS, 1983; PASSCHIER and SIMPSON, 1986). Thus, it was suggested to relate low P / high T metamorphism to extension (VIELZEUF, 1984, BRODIE et al., 1987, 1989). Reactions and textures demonstrate that the Valpelline gneisses equilibrated at about 4–6 kbar and 750–800 °C. This pressure corresponds to a depth of about 18 km, i. e., mid to lower crustal level in a crust of normal thickness. The associated temperature (750–800 °C) is unusually high for this depth and is associated with the development of both foliation plane and extensional crenulation cleavages. From a thermal point of view, the temperature reached by granulites in the Valpelline gneisses exceeds the maximum value of a relaxed geotherme even during post-collisional uplift (THOMPSON and ENGLAND, 1984). The heat supply which produces the high thermal regime must be related to the intrusion of basic and ultrabasic

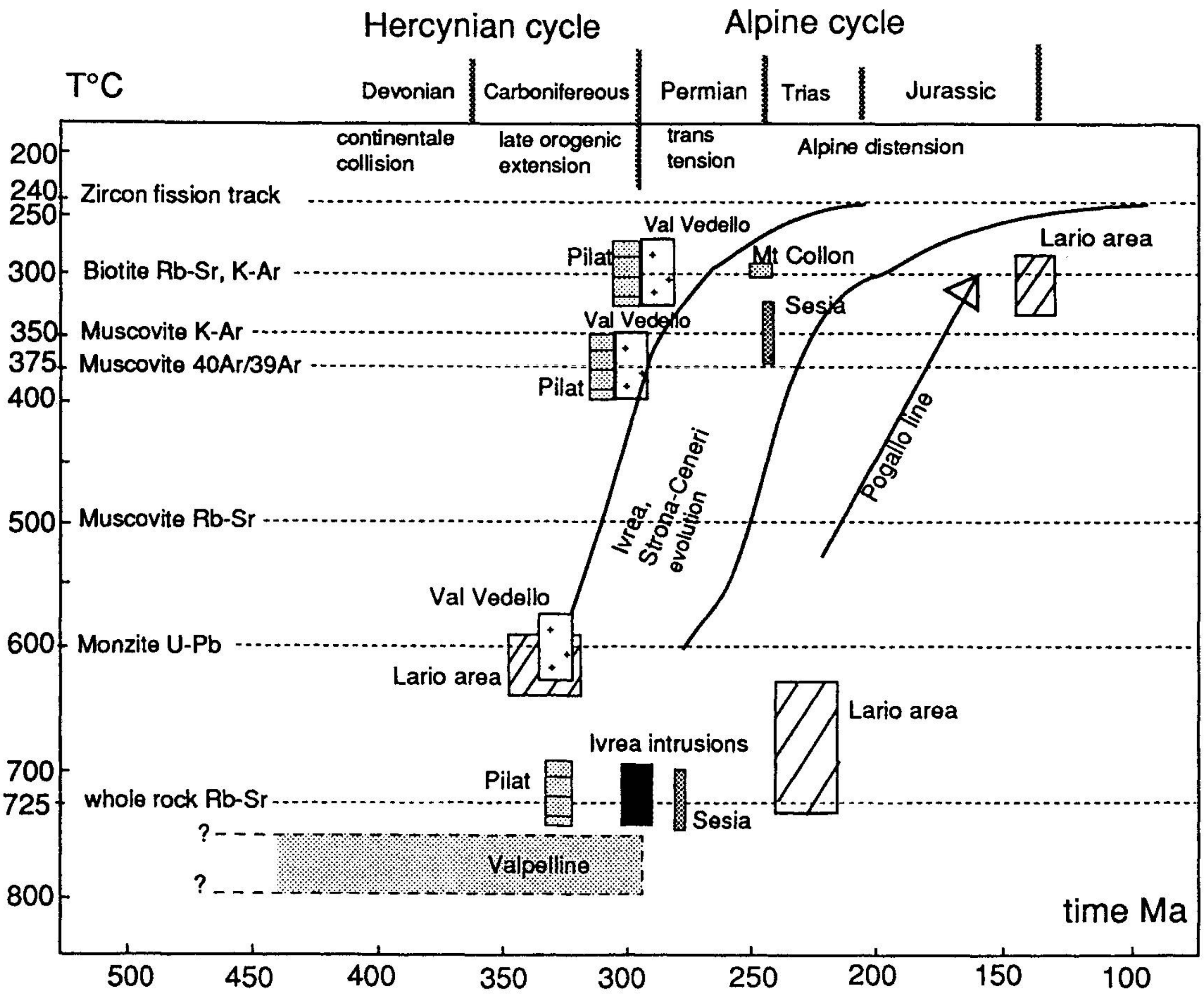


Fig. 5 Modified after ZINGG et al. (1990). Calculated temperature-time evolutions for the Ivrea Zone and Pogallo line (dark curves), Sesia-Lanzo zone (dark grey), Pilat unit (light grey with horizontal lines). Estimated T-time evolutions for the Valpelline area (light grey) and the Val Vedello area (crosses) and the Lario area (oblique lines) in the Southern Orobic Alps. See explanations and references in the text.

rocks (Mont Collon gabbros and peridotites). Thus, the P-T evolution of the Valpelline gneisses could be related to the development of a low angle normal ductile fault during crustal thinning.

So far, few geochronological dates are available in the Dent Blanche nappe. The Mont Collon gabbro masses located in the northern Arolla series gives cooling ages between 242 and 250 Ma with both K–Ar and Rb–Sr methods on biotite (DAL PIAZ et al., 1977). Some biotites and muscovites at the base of the Valpelline series have been dated at 240–140 Ma, and they are interpreted as cooling ages of Variscan metamorphism (HUNZIKER, 1974). But the age of the granulite metamorphism is still unknown and the Valpelline granulites can be related either to a late Variscan or Permo-Jurassic period.

To discuss these two hypothesis, we will compare temperature-time evolutions from different segments of Variscan crust in this part of the Alps (Fig. 5). In the Ivrea-Strona Ceneri zone, which shows similar lithologies and pre-Alpine imprint on the Valpelline and the II DK series, radiometrics ages range from 418 to 275 Ma for the peak of metamorphism (HUNZIKER and ZINGG, 1980; KÖPPEL, 1974). Young ages have been obtained in individual minerals, extending to ca 190 Ma and thought to record the cooling history of the unit. The interpretation is that HP/HT conditions are maintained in the rocks from Ordovician through Carboniferous to Permian times. A normal extensional shear zone is inferred to have occurred at 30 km depth during Permo-Carboniferous times or earlier (BRODIE and RUTTER, 1987, 1989).

In the Dent Blanche nappe some radiometric dates (HUNZIKER, 1974) on the Mont Collon meta-gabbro and biotites from the Valpelline gneisses agree extremely well with the temperature-time evolution of the Ivrea-Strona Ceneri zone. If we consider the Dent Blanche nappe as a coherent part of the southern Alpine basement, we should obtain similar temperature-time evolution, with Carboniferous ages for the granulite-amphibolite metamorphism (750–800 °C) in the Valpelline series. In this case stages 1, 2 and 3 in the figure 5 might be attributed to the late-Variscan cycle and only the stage 4 of the evolution corresponding to the narrow shear zones under greenschists facies conditions might be attributed to the Permo-Jurassic extension. Following this hypothesis the Valpelline low-P granulites must be the result of post thickening extensional tectonics, for instance well described in the Mont Pilat area (eastern French Massif Central, MALAVIEILLE et al., 1991) where this event is dated late Carboniferous (CAEN-VACHETTE et al., 1984). But it is important to note that the granulitic stage in the Valpelline gneisses (Fig. 5) is about 50 to 100 °C hotter than the high temperature stage in the Mont Pilat area (GARDIEN, 1990). Such difference in temperature can be attributed to the late Carboniferous-Permian activity and a much higher geothermal gradient.

The south Alpine Tectonic domain is considered as a segment of the Adria plate separated from the Alpine domain by the Insubric Line. In this domain, the Pogallo ductile fault zone is a major tectonic contact which affects the southern paragneisses within the Ivrea zone and the northern gneissic unit of the Strona-Cenri zone. The Pogallo shearing took place under amphibolite (500 °C) facies conditions in the early stage and greenschists facies conditions (300 °C) in the later stage (HANDY, 1987) and is interpreted as the result of continuous extension under retrograde conditions during the early Mesozoic (ZINGG et al., 1990). The minerals growing in both sides of the contact and the mechanisms of deformation prevailing in the minerals affected by the deformation allow characteristization of the P-T conditions of the tectonic contact. Moreover, the radiometric ages of minerals in the tectonic zone and the different units crosscut by the tectonic line give absolute and relative ages for the activity of the tectonic zone; T-t evolutions can be draw and compared to the T-t evolutions of the units related to this tectonic contact.

In the South Alpine domain, from the Como Lake to the Adamello Massif (Orobic Southern Alps) the main metamorphic imprint is considered to be Variscan. Recent studies (DIELLA et al., 1992; SILETTO et al., 1993) have demonstrated different P-T evolutions from west to east. By comparison with radiometric dates obtained on similar lithologies from the same area, the authors suggest an intermediate temperature-time evolutions for the most Eastern part of the series (Val Vedello and Passo St Marco area) similar to the temperature-time evolution of the Pilat unit (Fig. 5). Moreover the evolution of the Val Vedello and Passo St Marco area is interpreted as an uplift controlled by isostatic/erosion processes (DIELLA et al., 1992). On the contrary (DIELLA et al., 1992) suggest a temperature-time evolution for the Lario area in the western part of the series (Fig. 5) identical to the temperature-time evolution of the Pogallo line. Such evolutions also proposed by LARDEAUX and SPALLA (1992) for the Sesia-Lanzo zone, are related to an extensional episode corresponding to the opening of the Permo-Jurassic basins (BERTOTTI et al., 1993; TROMMSDORFF et al., 1993). This suggests that some part of the Variscan basement are unaffected during the Alpine extension and they record only the late Variscan orogeny (Val Vedello and Passo St Marco area). Some parts are affected and record a Permo-Jurassic extensional episode (Lario area, Sesia-Lanzo zone) and intermediate situations are also possible (Ivrea-Strona Ceneri zone). The acquisition of more petrological, structural and geochronological data from the Valpelline and Arolla series is necessary to better understand the behavior of the Dent Blanche unit during the Permo-Jurassic extensional episode and to choose among the different hypotheses.

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