1661-8726/07/020227-16
DOI 10.1007/s00015-007-1222-4
Birkhäuser Verlag, Basel, 2007

Swiss j. geosci. 100 (2007) 227–242

Metamorphic evolution of the Briançonnais units along the ECORS-CROP profile (Western Alps): new data on metasedimentary rocks

STEFAN BUCHER[1,*] & ROMAIN BOUSQUET[2]

Key words: metasediments, Western Alps, HP metamorphism, chloritoid

ABSTRACT

Briançonnais units are squeezed between two Mesozoic eclogitic belts (Piemont-Ligurian ocean and Valaisan ocean) along the ECORS-CROP seismic line in the Italian-French Western Alps (France, Italy). The metamorphic evolution of this area plays a key role for understanding the evolution of the Western Alps and is discussed on the basis of detailed petrographic investigations carried out on weathered sediments issued from the erosion of the Hercynian belt, especially on lower Permian to Mesozoic sediments. In the Zone Houillère, as well in the Permo-Triassic cover of the Briançonnais basement, the index metamorphic mineral assemblage is mainly composed of white micas with varying chemical composition, chloritoid and garnet. This same assemblage occurs within different lithologies (metaarkose, metapelite, metasandstone). Consequently, equilibrium phase diagrams were computed for different whole rock compositions using DOMINO software. The results of the P-T investigations clearly show that each unit underwent a different sequence of metamorphic reactions. An increase in metamorphic grade from greenschist facies conditions in the Northwest (Zone Houillère) to the transition between blueschist and eclogite facies conditions in the Southeast (Internal Briançonnais) is observed. A major discontinuity in metamorphic grade is located at the contact between Zone Houillère and Ruitor unit, as documented by a pressure gap of ~ 7 kbar. In general, the observed metamorphic field gradient is inverted and is interpreted to represent different depths of burial during subduction, which correlates with the paleogeographic position of the different units.

Introduction

At first sight one is tempted to think that the knowledge of the overall structure of the Alps did not evolve much since the well-known synthesis of Argand (1916). However, new data presented in subsequent studies forced researchers to revise some key points concerning the structure and evolution of the Alpine chain. Particularly seismic investigations along transects over the Alps (NFP 20, Pfiffner et al. 1997; ECORS-CROP, Roure et al. 1990) allow a better understanding of the deep structure of the Alpine belt (see for example Polino et al. 1990; Schmid et al. 1996; Schmid & Kissling 2000). In addition, significant progress has been made in the understanding of the tectono-metamorphic history of the Alps (see review in Oberhänsli et al. 2004, Schmid et al. 2004). Surprisingly, combined metamorphic and structural data are still lacking in some key areas, although they are crucial for the understanding of the evolution of the Alps. Many of these areas are composed of basement rocks that underwent several metamorphic events. In such rocks, it is not always easy to relate metamorphic assemblages and events to the hercynian or alpine orogenesis. One of these areas is the Briançonnais domain of the Northwestern Alps. While in the southern part of the Western Alps, composed mainly of sediments, abundant evidence has been found for an Alpine high-pressure overprint (Goffé 1977; Goffé & Velde 1984), the alpine metamorphic evolution of the northern part, composed mainly of basement rocks, is still subject to debate.

In this paper, we present a new metamorphic evolution for the whole area from a careful study of the petrology in the post-Hercynian metasediments occurring scarcely in the Briançonnais units along the trace of ECORS-CROP seismic line. These new PT-path data will provide new constrains for the geodynamic evolution of an area that plays a key role for the understanding of the evolution of the Western Alps.

[1] Department of Earth Sciences, Universität Basel, Bernoullistrasse 32 CH-4056 Basel, Switzerland
[*]Present address: Muséum d'histoire naturelle de Neuchâtel 14, rue des Terreaux CH-2000 Neuchâtel, Switzerland
[2] Institut für Geowissenschaften, Universität Potsdam, Karl Liebknecht Str. 24 D-14476 Potsdam, Germany
Correspondence to: R. Bousquet. E-mail: romain@geo.uni-potsdam.de

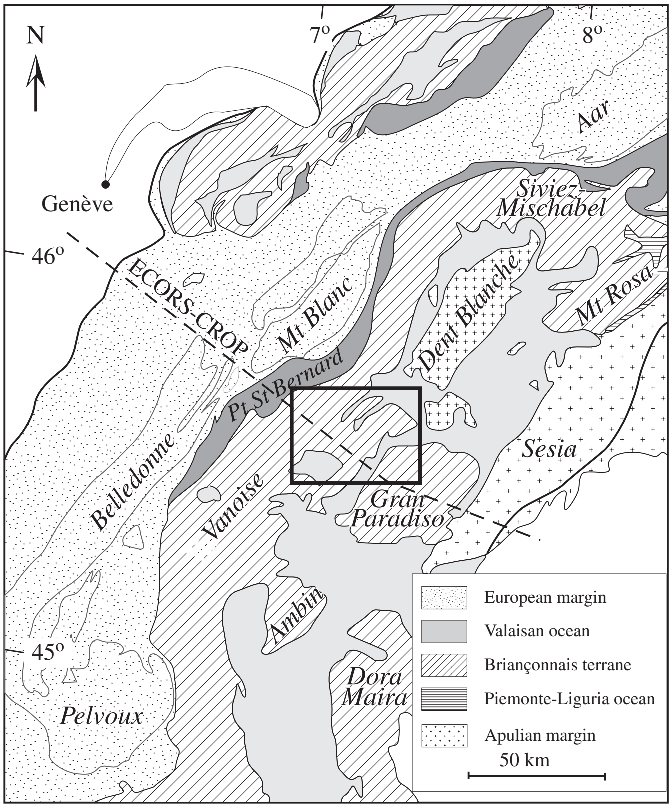


Fig. 1. Paleogeographic domains of the Western Alps. The rectangle is indicating the study area.

Alpine HP in the Briançonnais area along the ECORS-CROP profile?

In the area along the ECORS-CROP seismic line in the Italian-French Western Alps the Briançonnais units appear squeezed between two Mesozoic oceanic units that both underwent high-pressure (HP) metamorphic overprinting. Eclogitic rocks are known from the Piemont-Ligurian domain ("Grivola", Dal Piaz 1928; Droop et al. 1990) in the southeast and as well from the Valaisan in the northwest (Schürch 1987; Oberhänsli 1994; Goffé & Bousquet 1997). The most internal part of the Briançonnais domain, the Gran Paradiso massif that underlies the Schistes Lustrés, also evidences a HP history (Compagnoni and Lombardo 1974; Dal Piaz & Lombardo 1986; Ballèvre 1990). The Briançonnais domain s.str. is located in between these eclogitic units but its metamorphic evolution is not well constrained in the northwestern part of the Alps, while in the south a significant pressure increase is evidenced from the external to internal Briançonnais zones (Goffé & Chopin 1986; Goffé et al. 2004). Although some petrological studies were carried out in these units (Baudin 1987; Cigolini 1981; Boquet 1974, 1999; Caby & Kienast 1989), its metamorphic history during the alpine orogenesis is still a matter of debate (see Monié 1990). For example, in the Ruitor unit while all authors agree about the presence of Barrovian type metamorphism of pre-Alpine age (e.g. Boquet 1974, Baudin 1987; Caby 1968, 1996; Gouffon 1993), the grade of the Alpine metamorphic imprint is still in discussion. Baudin (1987) ascribed epidote-blueschist facies conditions to a first alpine metamorphic stage and postulated pressures around 5–7 kbar at temperatures between 350 °C and 400 °C. Boquet (1974) extensively studied mineral compositions and described large amounts of pre-Alpine garnet, besides a minor amount of Alpine garnet. This author also inferred Alpine epidote blueschist conditions for the Ruitor unit. Caby & Kienast (1989) and Caby (1996), however, interpreted eclogite facies conditions to have prevailed during the peak of the Alpine evolution in the Ruitor unit. The debate is largely about the distinction between minerals of Alpine and pre-Alpine age, due to the fact that all these studies only investigated pre-alpine basement rocks. In the Internal unit Cigolini (1995) evidenced pre-Alpine relics in basement rocks, but he also evidenced a HP metamorphic event in the post-Variscan rocks of the most internal part: Na-amphibole overgrowing relic magmatic hornblende in the Cogne-Savarenche pluton (360 Ma, Bertrand et al. 2000) and pseudomorphs after jadeite in Permian metasediments.

Geological setting

The investigated area extends along the ECORS-CROP seismic line from the Pt. St. Bernard pass in the NW to the border of the Gran Paradiso massif in the SE (Fig.1) and it covers most of the Briançonnais units of the northern Western Alps. In the NW the Zone Houillère unit represents the most external part of the Briançonnais paleogeographic domain, which is separated from the Valaisan units by the Houiller Front (Nicolas et al. 1990; Fügenschuh et al. 1999). Towards the SE follows the more internal Ruitor unit, which is classically divided into an external ("Ruitor externe") and an internal part ("Ruitor interne"), respectively (Caby 1996). The Internal unit, still further to the SE, is separated from the underlying Piemont-Liguria (P–L) oceanic unit by a refolded former thrust, referred to as the "Enigmatic tectonic contact" (ETC) by Bucher et al. (2003). In this area, the Briançonnais unit is composed of three different zones:

Zone Houillère unit

This unit is characterised by a Paleozoic sequence of continental deposits (Fabre 1961). The lower part of this sequence consists of black schists with anthracitic lenses and arkoses (Namurien to Stefanien in age; Feys 1963; Gerber 1965). The upper part is dominated by arkoses and conglomerates, probably of Stefano-Autunien age (Fabre 1961). The clasts mainly consist of polycrystalline quartz, micaschists and paragneisses. The latter display a poly-phase metamorphic imprint (Desmons & Mercier 1993). A Permo-Triassic sequence discordantly overlies this Carboniferous sequence (Ellenberger 1958; Elter 1960). During the Alpine deformation the Zone

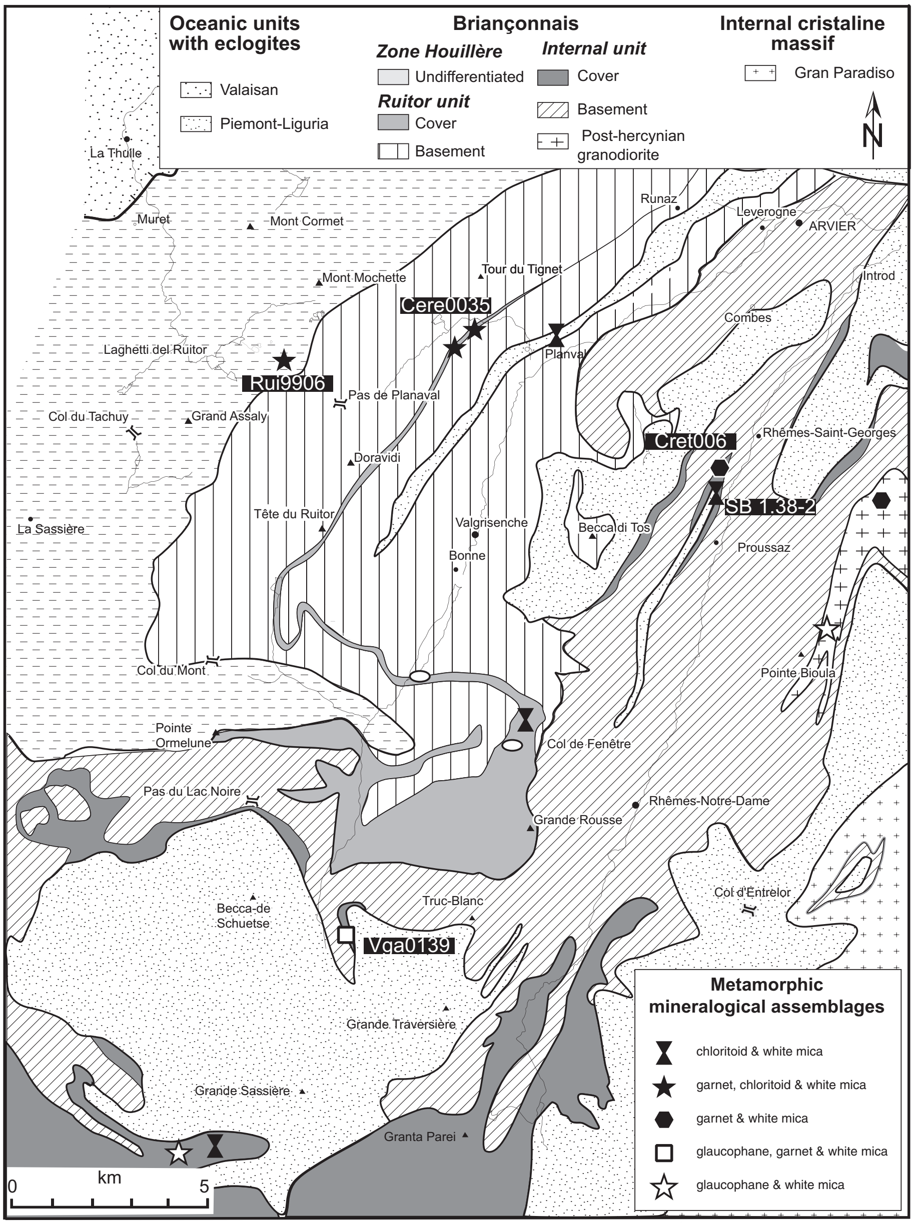


Fig. 2. Geological map of the study area after Bucher et al. (2003) indicating occurrences of the metamorphic minerals in post-Hercynian rocks of the Briançonnais (data from Polino & Dal Piaz 1978; Cigolini 1995; this study). Studied samples are also located.

Table 1. Bulk rock compositions of the investigated samples.

	Rui9906	**Cere0035**	**Vga0139**	**SB 1.38-2**	**Cret006**
SiO_2	69.67	57.81	76.96	91.51	92.8
TiO_2	0.57	0.86	0.47	0.16	0.18
Al_2O_3	14.94	20.67	8.53	3.95	3.59
FeO	5.06	7.98	4.41	1.17	0.77
MnO	0.08	0.07	0.03	0.02	0.01
MgO	1.01	1.70	2.48	0.23	0.21
CaO	0.33	0.26	0.74	0.14	0.1
Na_2O	1.65	0.45	2.71	0.15	0.2
K_2O	4.4	5.05	0.61	1.23	0.98
P_2O_5	0.17	0.20	0.11	0.04	0.03
Total	**97.88**	**95.05**	**97.05**	**98.60**	**98.87**

Houillère was decoupled from its former basement, whose present-day position remains unknown, since it does not outcrop at the earth's surface (Desmons & Mercier 1993).

Ruitor unit

The Ruitor unit dominantly consists of pre-Permian garnet micaschists and paragneisses with abundant intercalated metabasites (Baudin 1987). There is definitely an Alpine metamorphic overprint (Caby 1996), but some relicts of pre-alpine metamorphism survived the alpine cycle (Boquet 1974). Its sedimentary cover is made up by a thin Permo-Triassic se-

Table 2. Representatives microprobe analyses.

	Rui9906				Cere0035				Vga0139			Cret006		
Sample *Mineral*	*Phe*	*Grt core*	*Grt rim*	*Ctd*	*Phe*	*Grt*	*Chl*	*Ctd*	*Phe*	*Grt*	*Gln*	*Phe*	*Grt*	*Ctd*
SiO_2	47.14	36.62	36.91	27.66	50.12	36.52	25.65	24.11	49.81	36.56	58.31	44.55	37.97	23.55
TiO_2	0.39	0.26	0.00	0.15	0.26	0.00	0.01	0.04	0.35	0.11	0.08	0.14	0.05	0.05
Al_2O_3	30.96	20.28	19.83	30.44	26.57	19.54	19.53	37.71	25.66	19.50	10.43	34.03	18.23	36.74
FeO	4.90	21.03	22.01	21.93	3.50	35.17	31.85	26.46	3.70	30.53	13.45	2.25	28.30	26.57
MnO	0.18	18.22	16.63	9.44	0.06	3.08	0.22	0.58	0.05	4.68	0.04	0.00	5.52	0.71
MgO	1.33	0.64	0.70	1.66	2.38	2.05	10.98	1.95	3.13	0.88	8.85	0.31	0.55	1.44
CaO	0.01	3.15	3.99	1.54	0.00	4.78	0.01	0.05	0.00	7.46	0.17	0.00	7.95	0.02
Na_2O	0.24	0.04	0.00	0.03	0.40	0.02	0.04	0.12	0.38	0.02	6.90	0.85	0.02	0.00
K_2O	8.20	0.04	0.04	0.04	10.59	0.00	0.00	0.00	11.15	0.00	0.02	10.44	0.06	0.00
Total	**93.35**	**100.28**	**100.11**	**92.89**	**93.88**	**101.16**	**88.15**	**91.02**	**94.23**	**99.74**	**98.25**	**92.57**	**98.65**	**89.16**
Si	3.21	2.99	3.02	2.31	3.42	2.97	2.78	2.04	3.41	2.99	7.97	3.08	3.12	2.04
Ti	0.02	0.02	0.00	0.01	0.01	0.00	0.00	0.00	0.02	0.01	0.01	0.01	0.00	0.00
Al	2.49	1.95	1.91	3.00	2.14	1.87	2.49	3.76	2.07	1.88	1.68	2.77	1.77	3.76
$*Fe^{3+}$	–	0.06	0.09	0.61	–	0.17	–	0.19	–	0.13	0.49	–	0.23	0.19
Fe^{2+}	0.28	1.38	1.42	0.93	0.20	2.22	2.85	1.69	0.21	1.96	1.05	0.13	1.71	1.74
Mn	0.01	1.26	1.15	0.67	0.00	0.21	0.01	0.04	0.00	0.32	0.00	0.00	0.38	0.05
Mg	0.14	0.08	0.09	0.21	0.24	0.25	1.83	0.25	0.32	0.11	1.80	0.03	0.07	0.19
Ca	0.00	0.28	0.35	0.14	0.00	0.42	0.00	0.00	0.00	0.65	0.02	0.00	0.70	0.00
Na	0.03	0.01	0.00	0.00	0.05	0.00	0.00	0.02	0.05	0.00	1.83	0.11	0.00	0.00
K	0.71	0.01	0.00	0.00	0.92	0.00	0.00	0.00	0.97	0.00	0.00	0.92	0.01	0.00

* estimated

quence (Debelmas et al. 1991b), consisting of "Verrucano"-type conglomerates (Trümpy 1966) at the base, followed by lower Triassic meta-arkoses, which are stratigraphically overlain by quartz-phyllites and ankerite-bearing micaschists (Baudin 1987; Gouffon 1993; Ulardic 2001). This sequence crops out throughout the entire Valgrisenche (Fig. 2).

The existence of a separation of the Ruitor unit into an external and an internal part is debated, since there is no unequivocal tectonic contact. Desmons & Mercier (1993) question this separation. Some authors made a separation based on the dominant mineral assemblages (alpine vs. pre-alpine, Debelmas et al. 1991a), while others used the intensity of alpine deformation as a criterion (i.e. Gouffon 1993) for defining a boundary between two parts of the Ruitor unit. Bucher et al. (2004) showed that the used criteria are questionable and thus, based on structural and stratigraphic correlations, the Ruitor unit can be viewed as only one consistent unit.

Internal unit

The Internal unit ("Zona Interna" or the "Briançonnais interne") corresponds to the Vanoise-Mont Pourri unit found further south (Elter 1972). Northwards this Internal unit was correlated with the Mont Fort unit (Gouffon 1993). The Internal unit is made up of a lower part, formed by paragneisses and micaschists with a polymetamorphic history (Boquet 1974, Cigolini 1992), and of a mono-metamorphic upper part that consists of lower Permian to Mesozoic formations. According to Amstutz (1955, 1962), the lower part is mainly of volcanoclastic origin. This succession is intruded by Paleozoic granitic and granodioritic bodies dated from 507 to 270 Ma (Bertrand et al. 2000).

Leucocratic gneisses define the basis of the mono-metamorphic upper part. These are followed by a typical Permo-Triassic sequence, consisting of conglomerates ("Verrucano"), quartzitic meta-sandstones, impure quartzites and ankerite-bearing micaschists. The younger Mesozoic cover is only preserved in the southern part of the study area (Adatte et al. 1992, Saadi 1992).

Mineral and whole rock chemistry

Methods of investigation

The mineral compositions were determined with a JEOL JXA-8600 electron microprobe at the University of Basel (15 kV, 10 nA, PROZA correction procedure) using wollastonite (Si,Ca), albite (Na, Al), graftonite (Mn, Fe), rutile (Ti), albite (Na), orthoclase (K), olivine (Mg) as standards. The structural formulae were calculated for chlorite on 14 oxygens, for phengite on 11 oxygens, for chloritoid on 12 oxygens following Chopin et al. (1992), for Na-amphibole on 13 cations and on 23 oxygens, for garnet on 12 oxygens, and Fe^{3+} is calculated from the deficit in Al into octahedral site.

Bulk rock compositions were determined on melted pellets by XRF using a Brucker AXS SRS-3400 at the Geochemical Laboratory in Basel. No major layering was observed in thin sections and therefore bulk rock chemistries were taken from adjoining parts of the rock sample without a further volume reduction, except for sample Vga0139.

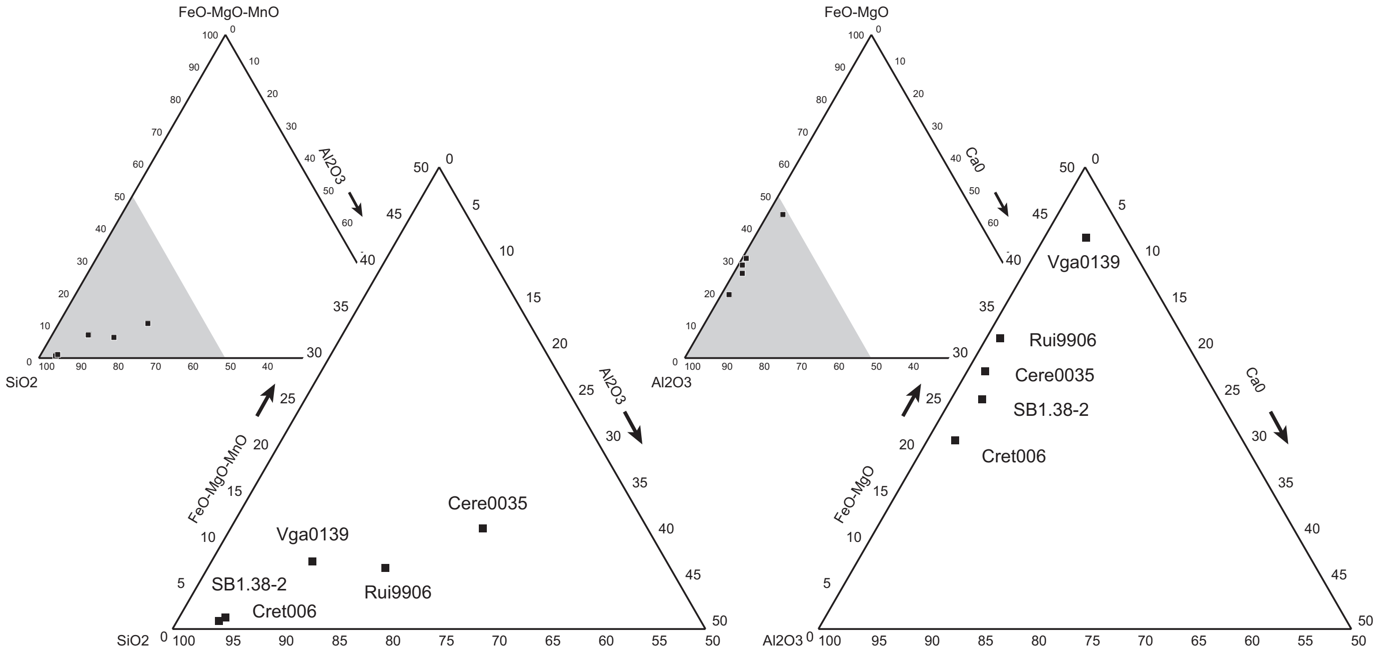


Fig. 3. Ternary diagrams (SFA and ACF) for the bulk rock compositions of studied samples. See text for details.

Sample selection and whole rock chemistry

In the whole area, e.g. in the Zone Houillère as well as in the Permo-Triassic cover, the index metamorphic mineral assemblage is composed of chloritoid, garnet and white micas (± chlorite) (Fig. 2). Only few samples contain Na-amphiboles.

Four samples, one of the Zone Houillère unit, one of the Ruitor unit and two of the Internal unit show well preserved microstructures and early metamorphic stage mineral assemblage and were selected for detailed P-T investigations. In parallel, a microstructural study was carried out in order to constrain the tectonic evolution proposed by Bucher et al. (2004). We present a detailed study of five different samples coming from metasediments of each zone. The bulk rock data of the studied samples are summarized in Table 1 and representative microprobe analyses are given in Table 2.

The first sample Rui9906, collected in the internal Zone Houillère unit near the tectonic contact to the Ruitor unit, is a highly deformed metaarkose from the Stefano-Autunien, i.e. the upper sequence of the Carboniferous sediments. This Alrich (20–25% Al_2O_3) metaarkose contains 5 to 10 % of ferro-magnesian (FeO+MgO+MnO) and alkaline (K_2O+Na_2O) elements, indicating bulk rock chemistry intermediate between pure sandstone and pelite (Fig. 3). Sample Cere0035 is from the Permo-Triassic cover pinched in the Ruitor unit, which crops out between Planaval and the Tour de Tignet (Fig. 2). It has a bulk-rock composition typical for metapelite, i.e. poorer in SiO_2 compared to sample Rui9906 (Fig. 3). The third sample Vga0139 derives from the Permo-Triassic cover sequence of the Internal unit in the area of the uppermost Valgrisenche. The fourth one (Cret006 & SB 1.38-2) comes from upper Permian quartzite cropping out in the Val di Rhêmes (Fig. 2).

Note that although samples Cere0035, Vga0139, Cret006 and SB 1.38-2 all derive from the Permo-Triassic sequence, they show different whole rock compositions (Fig. 3) due to their different stratigraphic age. Whereas sample Cere0035 is a lower Triassic quartz phyllite with a metapelitic whole rock composition, sample Vag0139 belongs to the upper Permian "Verrucano" facies and is of an intermediate whole rock composition between metapelite and metasandstone (Fig 3). Sample Cret006 has a typical quartzite composition (Fig. 3).

Sample description and microstructures

Sample Rui9906

Petrology. Sample Rui9901 is a highly deformed metaconglomerate from the Zone Houillère unit (Fig. 2*)*. Minerals are phengite, chlorite, garnet, chloritoid and quartz, the main foliation being mainly defined by quartz, phengite and chlorite (Fig. 4a). Relics of Mn-rich garnet, phengite, chlorite and chloritoid occur in the main foliation (Fig. 4b). Garnet shows no zoning and the Mn-rich composition (X_{Sps}~0.4, X_{Alm}~0.45, X_{Prp}<0.1, X_{Grs}~0.15; Fig. 5) is typical for low-grade metamorphic conditions (i.e. Spear 1993). In these small garnets (~150 µm) inclusions of chloritoid can be observed (X_{Mg}~0.12; X_{Mn}>0.16, Tab. 2). Chloritoid has a high Mn-content, indicating a strong interaction with the host garnet. Two mineralogical assemblages can be distinguished in this sample: the first one {1} is composed of garnet, chloritoid, phengite, chlorite and quartz

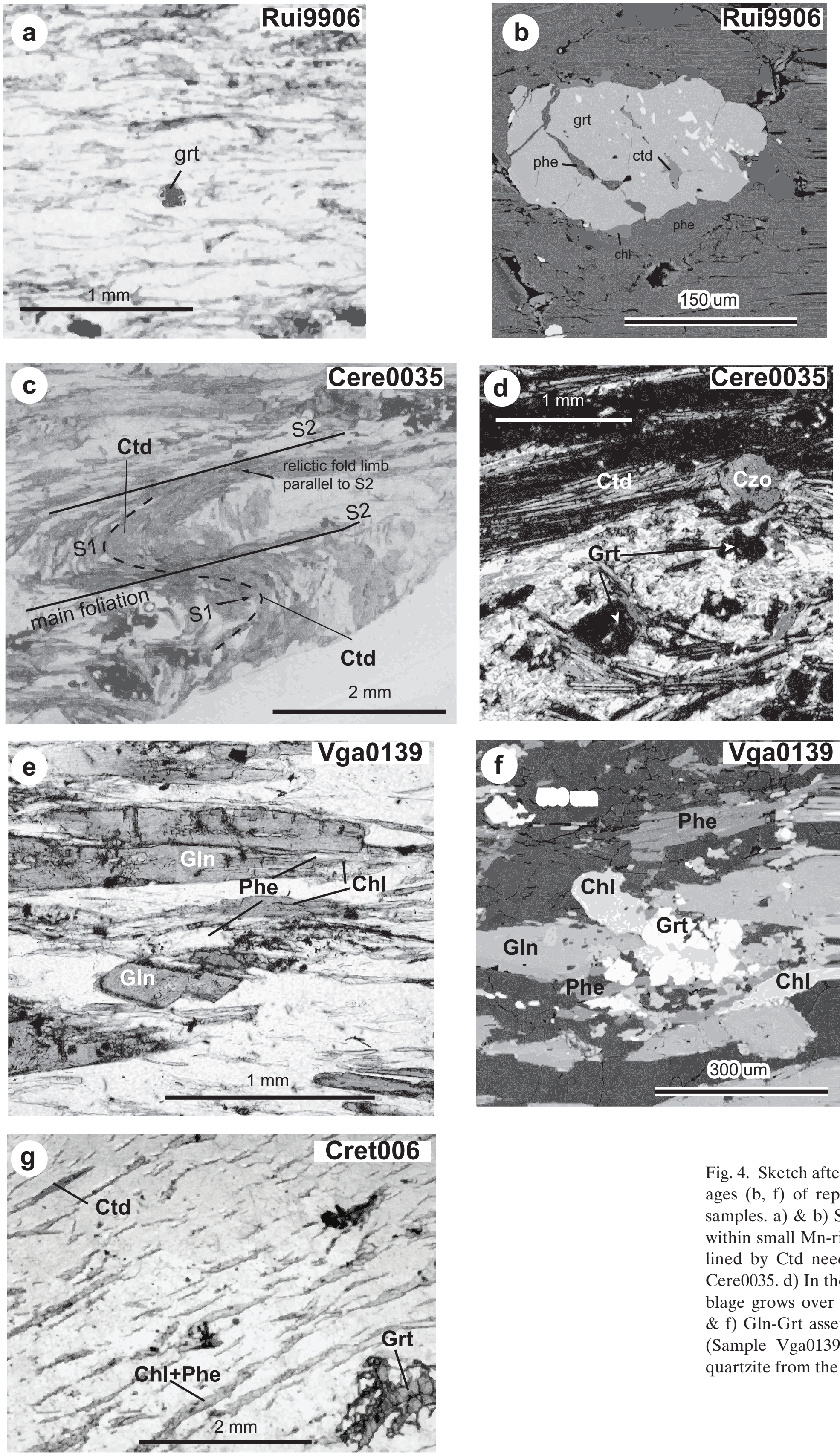
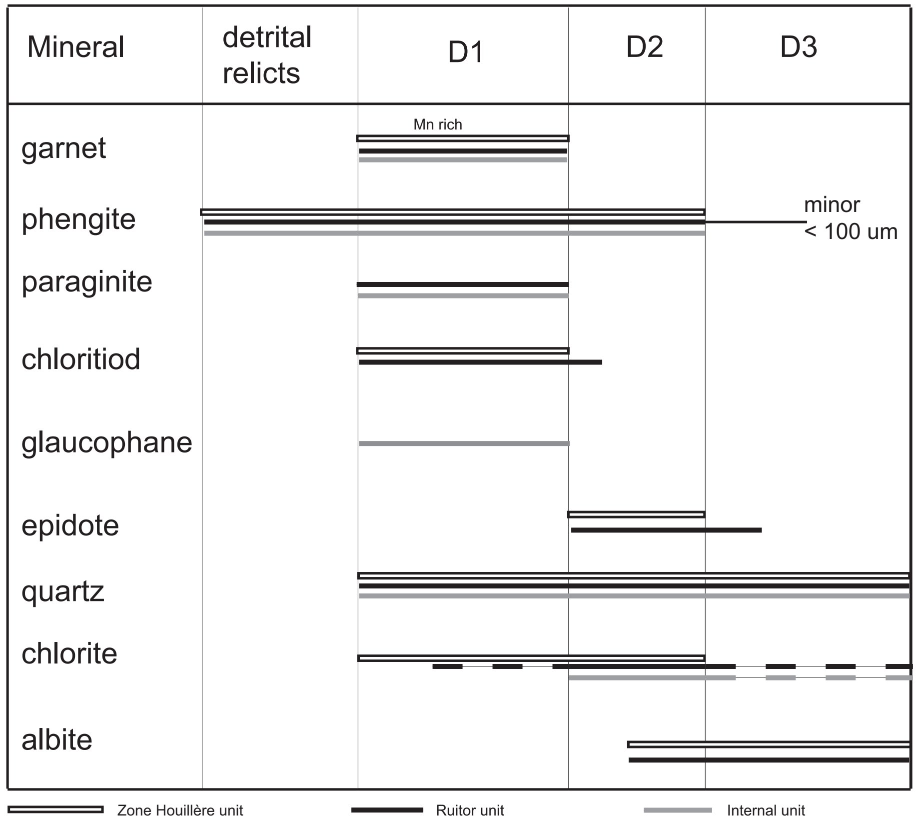


Fig. 4. Sketch after photomicrographs (a, c, d, e, g) or REM images (b, f) of representative mineralogy observed in studied samples. a) & b) Sample Rui990 shows inclusions of chloritoid within small Mn-rich garnets. c) Earlier schistosity (S1) underlined by Ctd needles preserved in S2 fold hinges in sample Cere0035. d) In the same sample, Czo-Phe2-Chl mineral assemblage grows over the former one formed by Ctd-Grt-Phe1 e) & f) Gln-Grt assemblages occurring in Na-rich metasediments (Sample Vga0139). g) Relics of Ctd and Grt preserved in quartzite from the Internal unit (sample Cret006).

Table 3. Relationship between petrology and deformation in metasedimentary rocks of the Briançonnais domain.



while a second one {2} is only composed of a second generation of phengite, chlorite and quartz. Additionally, albite overgrows the main foliation during a late stage. Such late albite growth is a common observation in the northern western Alps (Desmons et al. 1999c).

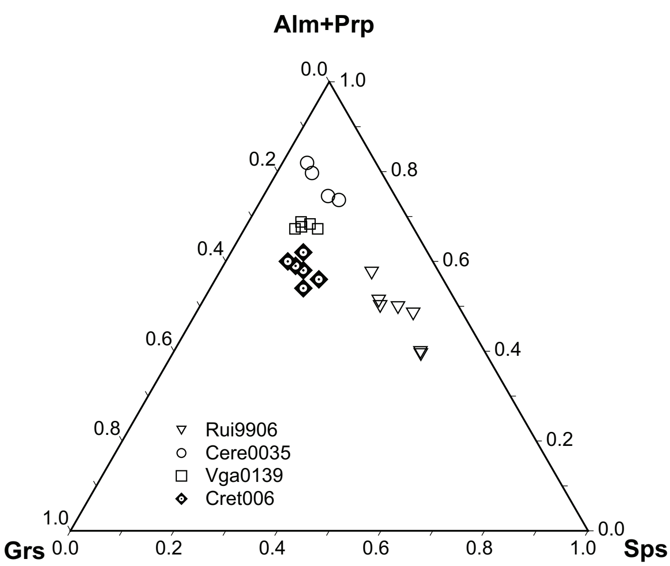


Fig. 5. Chemical compositions of garnet occurring in the Briançonnais metasediments. Each zone shows a specific range of garnet composition. Only sample from the Houillère zone (Rui9906) shows enrichment in Mn.

Microstructures. Figure 4a shows the intense main foliation S2 mainly defined by quartz and chlorite. Garnet appears as porphyroclasts within the S2 foliation. Metastability of garnet in S2 foliation is indicated by the overgrowth of chlorite and phengite (Fig. 4b). Furthermore, irregular grain boundaries of garnet indicate that this mineral predates the main deformation event D2. Chloritoid is only observed as inclusions in garnet and is therefore also attributed to assemblage {1}. In summary, these clear relationships allow for attributing mineral assemblage {1}, composed of phengite, chloritoid, garnet, chlorite and phengite to the first deformation phase D1 (Tab. 3). In contrast, assemblage {2}, only consisting of phengite and chlorite, defines the main foliation S2 and is therefore ascribed to D2 (Tab. 3).

Sample Cere0035

Petrology. This sample was collected in an intermediate structural position of the Ruitor unit from the Permo-Triassic cover (Fig. 2). Occurring minerals are chloritoid, garnet, phengite, paragonite, chlorite, clinozoisite, quartz and accessory opaque minerals. Chloritoid is overprinted by the main foliation defined by phengite, chlorite and clinozoisite and forms relic fold hinges (Fig. 4c). Furthermore, overgrowth of chloritoid by clinozoisite indicates that the main foliation postdates chloritoid growth (Fig. 4d). Two phengite populations are microstructurally and chemically distinguishable. A detailed combined EMP and microstructural analysis of the different phengite populations from this sample is carried out. The first population (D1), preserved as microlithons, is characterized by high Si-contents (>3.3 p.f.u.) while the Si-content of the second population formed during D2 ranges from 3.2 to 3.3 p.f.u. Although not always easy to detect, a third population of phengite can be interpreted as detrital grains which survived the alpine metamorphic cycle (Bucher 2003).

Chloritoid and garnet show rather constant compositions with a high Fe-content. For chloritoid, X_{Mg} varies between 0.09 and 0.13, while garnet is almandine–rich (≥ 70%) with around 10% of grossular, spessartine and pyrope component (Fig. 5). From these observations, two metamorphic stages can be distinguished in thin sections: the first one {1} characterised by association of Grt + Phe (1) + Pg + Ctd, and the second one {2} with Phe (2) + Chl + Czo.

Microstructures. As shown in Figure 4c chloritoid is aligned within a first foliation (S1), preserved in relic fold hinges formed during D2, i.e. when the main foliation (S2) formed. The main foliation S2 is defined by phengite, chlorite and clinozoisite. Figure d shows a top-to-the-W shear band associated with synkinematical growth of chlorite. Note that the shear plane dissects chloritoid. These observations allow attributing the assemblage {1} to the first deformation phase D1 and assemblage {2} to the D2 event (Tab. 3).

Sample Vga0139

Petrology. Sample Vga0139 is derived from the cover of an external part of the Internal unit (Fig. 1). Occurring minerals are glaucophane, phengite, paragonite, garnet, chlorite, quartz and minor amounts of opaque phases. Glaucophane, garnet, paragonite are associated with a first generation of phengite and represent peak pressure conditions. Abundant chlorite overgrows glaucophane, which has a rather constant X_{Fe} of 0.3–0.4. Garnets show no zoning in their chemical composition (X_{Alm}~0.65; X_{Grs}~0.20; X_{Prp}~0.05 and X_{Sps}~0.10, see Fig. 5) but are strongly retrogressed to chlorites that define the main foliation in association with a second generation of phengite. Despite the presence of chlorite, the HP-mineral assemblage is dominating in this sample. The same mineral assemblage, but without garnet occurs also south of the Grand Sassière klippe within white quartzites (Fig. 2).

Microstructures. Figure 4e shows that chlorite grows in expense of glaucophane, suggesting that chlorite is the stable mineral in the main foliation. In many cases, due to intense transposition during D2 glaucophane also appears to be aligned in the main foliation although it formed earlier: Backscatter images (Figs. 4f) show that chlorite is the stable mineral in the main foliation, growing in expense of glaucophane (Fig. 4e) and garnet (Fig. 4f). Hence, only chlorite is stable in the main foliation. In summary, mineral assemblage garnet, glaucophane, phengite (1), and paragonite predates the main foliation and is therefore attributed to D1 (Tab. 3). During the second deformation phase D2 only chlorite and phengite appear to be stable.

Samples Cret006 and SB 1.38-2

Petrology. These two samples are derived from the same outcrop. Stratigraphically, they belong to a late Permian to Early Miocene, reddish quartzite cropping out in Val di Rhêmes (Cigolini 1992, 1995). In this quartzite, two different mineralogical assemblages occur. In sample Cret006, the mineral assemblage only consists of white mica, garnet, quartz and ± chlorite, while in the second sample SB 1.38-2 only chloritoid, white mica, quartz and ± chlorite is found.

In both samples the MgO content of the bulk rock is low (Table 1), and therefore garnet and chloritoid have Mg-poor compositions. Hence garnets have a mean composition of X_{Alm}~0.60; X_{Gro}~0.30; X_{Prp}~0.02 and X_{Spe}~0.18 (Fig. 5) and X_{Mg} in chloritoid never exceed 0.10.

Microstructures. The assemblage garnet – white mica, and chloritoid – white mica, respectively, occur as thin layers in the quartzitic matrix. However, chloritoid and garnet were never observed together in the same thin section although they occur in the same microstructural context. Both, chloritoid and garnet seem to predate the main foliation S2, underlined by chlorite and white micas. Often chloritoid is crosscut by S2, while dismembered garnet is often replaced by chlorite.

P-T estimates

Methods used

Equilibrium phase diagrams of natural samples, as well as model compositions were calculated with the computer program DOMINO (De Capitani 1994) for the NaCaKFMASH system. These diagrams visualise stable assemblages, including mode and composition of solution phases, for specific bulk rock compositions. The independent variables may be any combination of temperature, pressure, activity of a particular phase or compositional vectors. In order to include highly non-ideal solution models for minerals with potential miscibility gaps, stable mineral assemblages are computed using a Gibbs free energy minimization (De Capitani & Brown, 1987).

Main advantage of such equilibrium phase diagrams is that all phases are considered for each point and that the diagrams are very easy to interpret, if attention focuses on assemblages. Each field represents the predicted stability-field of a particular assemblage. However, interpretation of the diagrams is limited by the accuracy of thermodynamic data, and additionally, by the degree of equilibrium reached in that portion of a rock that was used for determining the bulk composition. The database of Berman (1988) was used for all calculations. However, the latter was completed by following recent thermodynamic data: Mg-chloritoid data of B. Patrick (listed in Goffé & Bousquet 1997), Fe-chloritoid data of Vidal et al. (1994), chlorite data of Vidal et al. (2001), glaucophane data of Holland and Powell (1998) and alumino-celadonite data from Massonne and Szpurka (1997). Solid-solution models for phengite are from Keller et al. (2004), for chlorite from Vidal et al. (2001) and for glaucophane from Holland and Powell (1998).

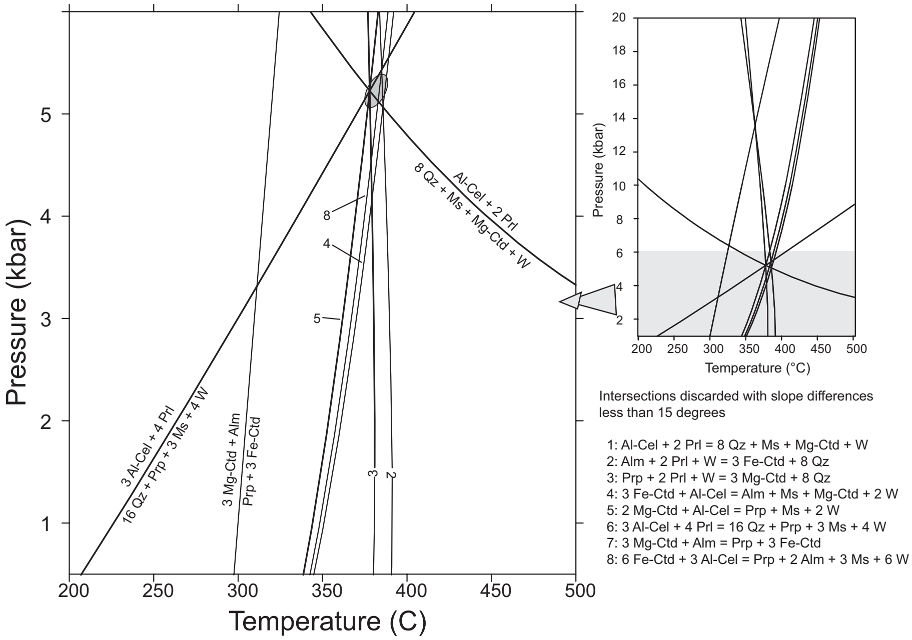


Fig. 6. Multi-equilibria calculations for the sample Rui9906. The observed mineral assemblage Ctd-Grt-Phe is stable for P-T conditions around 5.2 kbar and 375°C.

Because of the high Mn-content found in metamorphic minerals (garnet, chloritoid, see Table 1) of sample Rui9906, whose whole rock composition does not indicate any Mn-enrichment (Table 1), P-T estimates for this sample from the Zone Houillère unit were calculated by using the TWQ software package of Berman (1991). Calculations were done with the same database presented above, except for white micas. Atom site repartition for white micas is calculated after Bousquet et al. (2002), and thermodynamic data are from Vidal and Parra (2000). The water activity was kept constant at one and no other fluid components were added.

Sample Rui9906 (Zone Houillère unit)

P-T estimates using the phase diagram equilibrium was not possible due to the lack of thermodynamic data for many Mn-rich phases. A multi-equilibrium (TWQ) approach taking into account the activity of minerals and the Mn-content of each mineral was applied to this sample in order to compute P-T estimates. Calculated equilibrium are done in the KFMASH system with the following phases: chlorite, garnet, phengite chloritoid and quartz. P-T estimates evidence greenschist metamorphic conditions around 5 kbar and 375 °C (Fig 6). These estimates are consistent with evidences for incipient metamorphism in Mn-poor rocks, in which Mn-rich minerals such as spessartine-rich garnets often grow first (see for example Spear 1993).

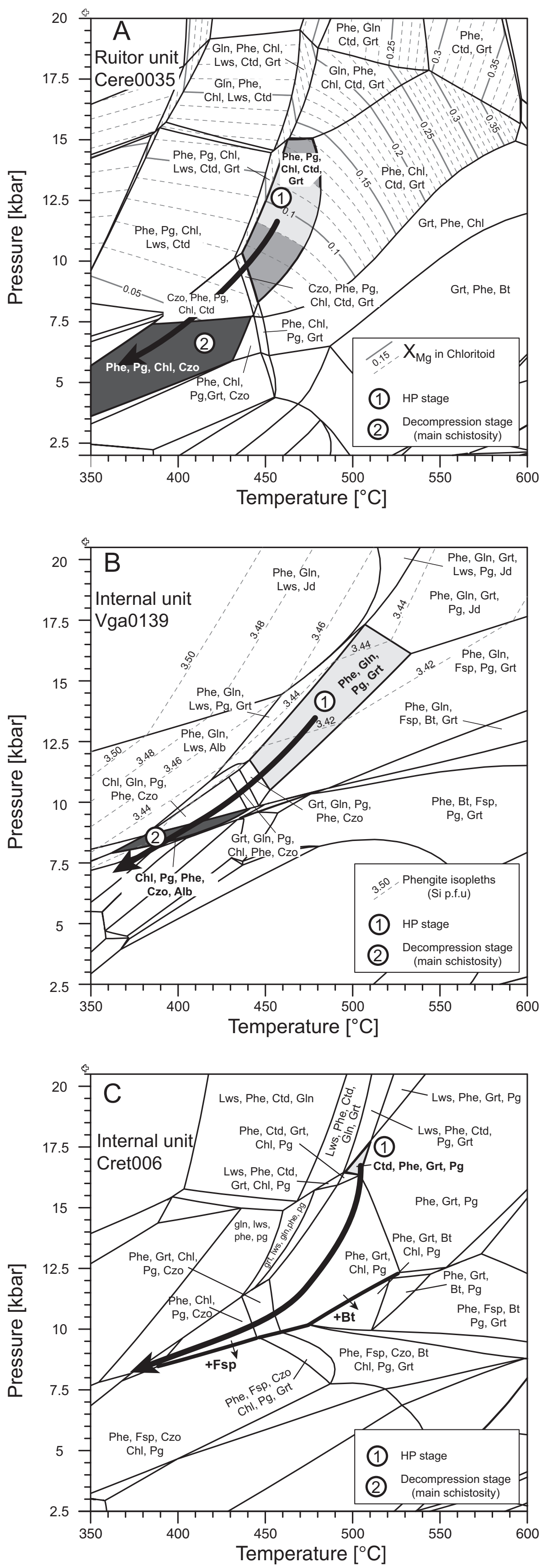
Sample Cere0035 (Ruitor unit)

Figure 7a shows the resulting equilibrium phase diagram, calculated in the K_2O-Na_2O-CaO-FeO-MgO-Al_2O_3-SiO_2-H_2O system and water activity of one for the measured bulk rock composition of sample Cere0035. Stability field of the first mineralogical assemblage {1} composed of Grt, Pg, Phe, Chl and Ctd ranges from 440 to 480°C for pressures between 8.5 kbar and 15kbar (Fig. 7a). The temperature interval is constrained by the appearance of Lws towards lower temperatures, and by disappearance of Pg towards higher temperatures. Appearance of Gln towards higher and appearance of Czo towards lower pressures delimits the stability field. Calculation of the isopleths for X_{Mg} in chloritoid, which vary between 0.9 and 0.12 in this sample, allow for a further restriction of the pressure between 11 and 13.5 kbar for temperatures ranging form 450 to 480°C (Fig. 7a).

The retrograde path is constrained by the assemblage Czo, Chl, Phe that forms the main foliation and is stable for pressure conditions below 7 kbar and temperature below 450°C.

Sample Vga0139 (external part of the Internal unit)

Figure 7b shows the equilibrium phase diagram calculated in the K_2O-Na_2O-CaO-FeO-MgO-Al_2O_3-SiO_2-H_2O system for the bulk rock composition of sample Vga0139, which is an intermediate between metapelite and sandstone. The dominant mineral assemblage stable at HP stage is formed by Gln-Grt-Phe-Pg. The overgrowth of garnet and glaucophane by chlorite documents metastability of theses mineral during the retrograde path. The equilibrium diagram predicts that the HP mineral assemblage is stable from 10 kbar to 17 kbar and from 440° C to 540° C. Temperature is, as in the case of the previously discussed sample, confined by absence of lawsonite and disappearance of paragonite towards lower and higher temperatures, respectively. Pressure limits are given by appearance of



jadeite towards higher pressures, and by growth of clinozoisite and feldspar towards lower pressures. Absence of jadeite in this sample indicates that pressures did not exceed 17 kbar in this part of the Internal unit. In contrast, the absence of Czo and Fsp, expected to form at lower pressures, is seen as an indication that this sample escaped intense retrogression. Although chlorite is clearly a retrograde product, its presence alone is not sufficient for further constraining retrograde P-T conditions. Analogous to sample Cere0035, further restrictions on pressures and temperatures within the stability field by the composition of phengite are not possible, due to the small variations (only ~4 %) predicted by phengite isopleths (Fig. 7b).

Sample Cret006 (Internal unit)

Figure 7c shows the equilibrium phase diagram calculated in the K_2O-Na_2O-CaO-FeO-MgO-Al_2O_3-SiO_2-H_2O system for sample Cret006. In this sample, the HP mineral assemblage is composed of Ctd, Grt, Phe, Qz. This assemblage is only stable in a small field between 16 and 17.5 kbar at 500 ± 10° C (Fig. 7c), which is limited by the same reactions as described for the previous sample. Appearance of Lws delimits the stability field towards lower temperatures, while breakdown of Ctd delimits it towards higher temperature. Maximum in pressure is constrained by disappearance of Chl at higher pressure. Because no biotite occurs in this sample, and since Chl is the only retrograde mineral, rather cooling then isothermal decompression characterises the retrograde path of this sample.

Interpretation

Peak metamorphic conditions

P-T estimates for the Zone Houillère unit indicate pressures of ~5 kbar at temperatures of ~375° C (Fig. 8) for internal parts of the Zone Houillère unit situated near the contact with the Ruitor unit. Slightly lower metamorphic conditions of 2.5 to 4 kbar at 300° C are observed (Ceriani et al. 2003) for the external part of the Zone Houillère unit further to the south. In this area, zircon fission tracks are only partially annealed (Fügenschuh & Schmid, 2003; Malusà et al. 2005) indicating the observed temperature to be below the full annealing temperature of 320°C. These small differences within the Zone Houillère unit might be considered to be, taking into account

Fig. 7. Equilibrium phases diagrams and P-T paths computed with DOMINO for different kind of metasediments of the Briançonnais terrane. All these rocks [a) Cere0035, b) Vga0136, c) Cret006] display an HP metamorphic imprint and a cold retrograd path. a) For the sample Cere0035, peak pressure (~13 kbar, 460°C) is constrained by Grt-Phe-Pg-Ctd-Chl assemblage stability field and by the Ctd compostion and retrograd path (at ~6kbar, 400°C) by Phe2-Chl-Czo assemblage. b) Phengite isopleths and occurrence of Gln together with Grt-Phe1-Pg (sample Vga0139) define an HP stability field (~13 kbar, 480°C), and appearance of Czo at ~9kbar, 430°C documents a cold retrogression. c) In quartzite (sample Cret006) in which metamorphic minerals are scarce stability field of Ctd-Grt-Phe1-Pg is well constrain at 16 kbar, 500°C.

the uncertainty of measurements and the different used methods, as an increasing metamorphic grade towards internal parts of the Zone Houillère unit. Disappearance of fossil plants, and the appearance of Mn-rich garnet, towards the SE (internal) are excellent arguments supporting an increase of the metamorphic grade towards the SE, where spessartine-rich garnet are occurring (Desmons et al. 1999a).

In the Ruitor unit the P-T estimates evidence peak pressures ranging between 11-13.5 kbar at temperatures between 450–480°C, typical for epidote-blueschist conditions (Fig. 8). These data clarify the Alpine metamorphic history of the Ruitor unit and indicate a HP imprint for this unit. So far, two different interpretations for the P-T evolution exist in the literature for the Ruitor unit. While several authors inferred only elevated greenschist facies conditions (~7 kbar/400°C; e.g. Baudin 1987; Desmons et al. 1999c) others, mainly Caby (1996), postulated eclogite facies conditions (12–14 kbar, 450°C). The debate regarding the P-T conditions was mainly about the attribution of specific minerals to either Alpine or pre-Alpine assemblages in the basement.

Within the third investigated unit, the Internal unit, P-T estimates indicate even higher metamorphic conditions when compared to other units. P-T conditions range from 10 to 17 kbar and 440 to 540°C in the external part of this unit near the contact to the Ruitor unit (Fig. 8, Vga0139), and from 16 to 17.5 kbar and 490 to 510°C (eclogite facies) in a structural position which is one kilometre further to the SE (Fig. 8, Cret006, Fig. 9). The pressure range from 10 kbar to 17 kbar at temperatures of 440°C to 540°C inferred from the external part of the internal unit (Vga0139) is very large. This large uncertainty is given by the stability of glaucophane. Unfortunately, with the observed mineralogical assemblages it is not possible to better constrain peak metamorphic conditions. Because sample Vag0139 and sample Cere006 are collected within a distance of only about one kilometre when projected along strike (Fig. 2), it is assumed that they underwent identical peak P-T conditions. Therefore the overlap of the stability fields of samples with different rock compositions (Vga0139, Cret006) represents the best estimate for the external part of the Internal unit, giving P-T estimates around 16 kbar and 500°C. At the contact with the Schistes Lustrés, Cigolini (1995) estimated pressures are higher than 12 kbar at temperatures around 500°C, based on observation of pseudomorphs after jadeite in Permian quartzites of the Internal unit.

Correlation between petrology and deformation

Regionally, three main deformation phases (D1–D3) have been observed in the studied area and have been described in previous work (Bucher et al. 2004). The main foliation underlined by the mineral assemblages Phe-Chl-Czo or by late growth of chlorite, is connected with the development of a second deformation phase D_2 (Caby 1968; Cigolini 1995; Bucher et al. 2004). HP mineral assemblages, preserved as microlithons or inclusions in investigated samples, indicate that higher

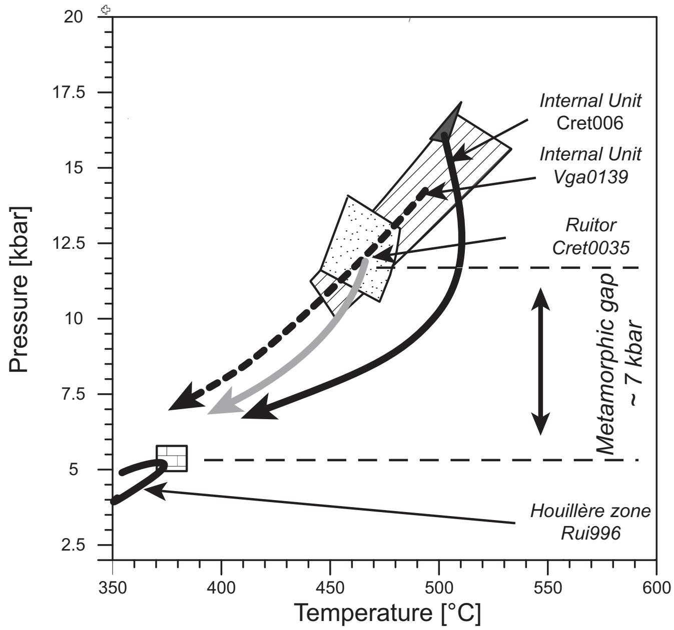


Fig. 8. Summary of P-T estimates for all studied samples. We note two kind metamorphic histories: a deep evolution for the Ruitor massif and the Internal unit and a shallow one for the Houillère zone with a pressure gap of about 7 kbar.

metamorphic conditions predate the main foliation in all units. Hence, as shown by microstructural analysis the metamorphic peak can be attributed to a first deformation phase D_1.

In the P-T diagram peak pressure conditions for different tectonic units define a linear trend indicating a continuous metamorphic gradient during D1. An estimated geotherm of 8° C/ km is typical for subduction. Furthermore, assumption that the presently stacked tectonic units once represented a lateral continuity is also confirmed by the occurring gradient. However, stacking of internal units over external units during exhumation (D2), following peak pressure conditions generated metamorphic discontinuities at the tectonic contacts. For example the Ruitor unit was thrust over the Zone Houillère unit during a late stage of D2 (Bucher et al. 2004). Between these two units, a difference in peak pressures of about 7 kbar is found. This large difference of 7 kbar can hardly be explained by a metamorphic gradient corresponding to about 25 km difference in depth. Presently, localities of sample Rui9906 (Zone Houillère unit) and Cere0035 (Ruitor unit) are at a distance of only 2.5 km (Fig. 9). Because the composite S1/S2 main foliation was refolded by open parasitic folds (D3), which are generally NE-SW oriented plunging moderately either to the NE or to the SW and axial planes gently dipping to the SE with 5 to 20° (Bucher et al. 2004), the present day distance does not exactly correspond to the original distance in the undeformed nappe stack. However a reduction of the thickness by a factor ten seems unlikely. Hence we exclude that the internal metamorphic gradient of the Ruitor unit has

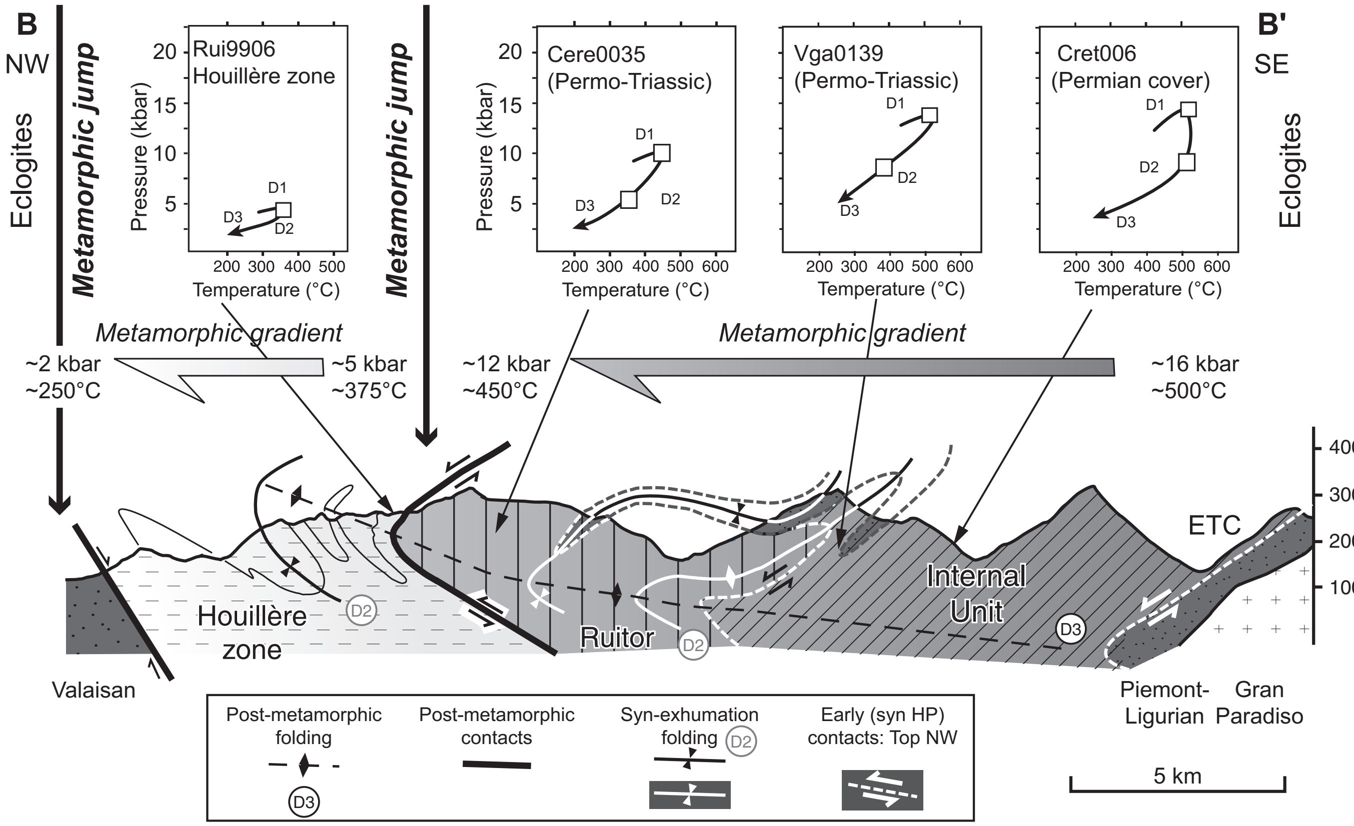


Fig. 9. Schematic cross section (modified after Bucher et al. 2003) in which metamorphic evolution of each unit has been reported. Retrodeforming of the late deformation phase (D3) documents an apparent inverse metamorphic field gradient results from the stacking of the internal units (Internal & Ruitor) over the more external one (Houillère zone) during exhumation (D2).

caused the observed pressure difference of ~7 kbar. Instead, we interpret the difference of ~7 kbar in peak pressure between the Ruitor unit and the Zone Houillère unit to represent a metamorphic discontinuity at the tectonic contact created during D2 nappe stacking.

D3 is characterized by open parasitic folds that refold the composite S1/S2 main foliation. The fold axes related to D3 are generally NE-SW oriented and plunge moderately either to the NE or to the SW. In general, the D3 axial planes gently dip to the SE with 5 to 20°, but dips to the SW or NE are also observed locally (D3 in Fig. 9). An axial plane pressure solution cleavage is only locally established and only some fine chlorite has grown in this cleavage.

P-T-d paths

While in all studied samples HP mineral assemblages, preserved as microlithons or inclusions are contemporaneous to the first phase of deformation D1, the main foliation attributed to D2 is underlined by the mineral assemblages Phe-Chl-Czo in the Permo-Triassic cover of the Ruitor unit (Cere0035) and by growth of chlorite after garnet, glaucophane or chloritoid in the Internal unit (Vga0139, Cret006) (Table 3). P-T estimates for D2 mineral assemblage indicate pressures lower than 7 kbar and temperatures lower than 450°C in the Ruitor unit (Fig. 9), resulting in a decompression of at least 4 kbar and a cooling of ~50° C during D2 exhumation. This contrasts with interpretations of Bucher et al. (2003), who found evidences for isothermal decompression, although estimates for D1 and D2 differ only slightly. This is due to the resulting stability fields in the calculated P-T diagrams, which excludes an isothermal decompression by the presence of Czo (Fig. 7a).

The retrograde path of the Internal unit is not well constrained, however, some observations allow for some restrictions at least. The absence of biotite in sample Cret006 excludes isothermal decompression below 11 kbar (at temperatures around 500° C, Figs. 8, 9).

All tectonic contacts between Internal unit and Ruitor unit are clearly refolded by D2 folds. Hence, the contacts must have been previously formed, namely at the end of D1, or alternatively, during early stages of D2. Note, however, that top-NW shearing was still active during D2 folding, particularly at the tectonic contact between the Ruitor- and Zone Houillère unit, where top-NW shearing is still active during final stages of nappe stacking (D2). Therefore Ruitor unit and Internal unit share a common P-T evolution from an early stage during D2 on. Consequently P-T path of these two units must join in the stability field of D2 from the Ruitor unit (Fig. 9). Combining all these arguments suggests that the Internal unit came in contact with the Ruitor unit at around 8 kbar for temperatures around 420° C, resulting in a cooling of ~100° C and a decompression of ~7 kbar. It seems that all units share a common late P-T history (Fig. 9) at least from temperature around 300°C as has been shown by fission track studies (Fügenschuh & Schmid, 2003; Malusà et al. 2005).

Discussion-Conclusion

In summary, P-T investigations on the post-Hercynian sediments of the Briançonnais terrane along the ECORS-CROP profile clearly show that each tectonic unit recorded a different metamorphic history (Fig. 9). An increase in metamorphic grade from greenschist facies conditions in the Northwest (Zone Houillère) to the transition between blueschist and eclogite facies conditions in the Southeast (Internal Briançonnais) is observed. A major discontinuity in metamorphic grade is located at the contact between Zone Houillère and Ruitor units, as documented by a pressure gap of ~ 7 kbar (Fig. 9).

In the Western Alps, paleogeographic significance and metamorphic evolution of the Briançonnais microcontinent were always in debate (Stampfli 1993; Monié 1990). In the southwestern Alps, a HP imprint is well documented by occurrences of Fe,Mg-carpholite (Goffé 1977, 1984; Goffé et al. 1973, 2004; Goffé & Chopin 1986), aragonite (Goffé & Velde 1984) or relatively high graphite crystallinity (Beyssac et al. 2002) in metasediments and by occurrences of lawsonite and jadeite in metabasites (Lefèvre & Michard 1976; Schwartz et al. 2000). Paradoxically in the northwestern Alps, only the upper most units of the Briançonnais domain (the Mont Fort nappe) display deep burial indicated by HP metamorphic overprint in epidote-blueschist facies conditions (Schaer 1959; Bearth 1963; Bousquet et al. 2004).

We show that in the central part of the Western Alps along the trace of the ECORS-CROP seismic line, petrology of post-Hercynian metasediments clearly indicate a deep burial evidenced by blueschist-eclogite facies condition (BET, Oberhänsli et al. 2004) for the internal (eastern) part. From studies of microstructures, we can correlate that peak pressure conditions occur during the first deformation phase (D1), which predates the main stage of nappe stacking (Bucher et al. 2004). Exhumation of HP rocks took place during nappe stacking (D2) of more internal units overthrusted northwestwards over external ones. The external (western) area displays a metamorphic evolution within greenschist condtions. Pressures of ~5 kbar found for the Zone Houillère unit allow to conclude that this unit was never deeply subducted and therefore only incorporated into the nappe stack at a late stage and during the exhumation of the higher pressure Ruitor unit and Internal unit. Along the ECORS-CROP profile, the major metamorphic gap (~7 kbar) is occurring at the contact between Ruitor unit (~12 kbar) and Houillère zone (~4.5 kbar), as it was already proposed by Caby et al. (1978). Estimated differences in peak pressure is interpreted as the result of the late D_2 activity of the tectonic contact between both units by overthrusting the higher metamorphic Ruitor unit over the low metamorphic Zone Houillère unit during the exhumation of the HP units.

The present work, together with geochronological data (Agard et al. 2002; Bucher 2003) suggests the following evolution of tectonic units of the Briançonnais domain. During D1 (50–43 Ma) all units reached peak pressure conditions resulting from southward subduction. Clear relationships between original paleogeographic position and depth can be observed, with the internal units having been subducted deeper than the external units. The external parts of the Zone Houillère unit remained within sub-greenschist facies conditions. Exhumation and nappe stacking took place during D2 (43–35 Ma). We emphasize that, in contrast to common belief (Caby 1996; Rolland et al. 2000), extension played no significant role during the exhumation from HP to greenschist facies conditions, but it has a major significance for the late alpine to present-day tectonics of the Western Alps, in relation to the propagation of thrusts in the outer zones during Neogene times (Sue & Tricart 2003). Instead, we propose ascent by extrusion within and parallel to a subduction channel. Ongoing deformation refolded these contacts during the late stages of D2 deformation, while top-NW to -NNW shearing was still going on. Finally, the Ruitor unit was thrust onto the Zone Houillère unit at a latest stage during D2. Large-scale nappe refolding (D3; 35–31 Ma) post-dated early exhumation of the tectono-metamorphic units.

These results argue for two tectonic groups, according to the metamorphic evolution, within the Briançonnais terrane during the alpine orogenesis. A deep burial (around 50 km) for rocks located in the East (Ruitor and Internal units) similar to the neighbouring rocks of the Gran Paradiso (60 km, Le Bayon et al. 2006) and of the Piemont-Ligurian ocean (50–60 km, Bousquet 2007) and a shallow burial (around 10 km) for rocks located in the East, in contrast to the rocks of the Valaisan ocean that were buried at great depths (50 km, Bousquet et al. 2002). A major tectonic contact, acting top-to-the-northwest during exhumation of HP rocks has separated the two groups. The resulting apparent inverse metamorphic field gradient can be interpreted as representing different depths of subduction due to the paleogeographic position of the different units.

Acknowledgements

Substantial funding by the Swiss National Science Foundation (projects 20-55559.98 and 2000-63391.00). S.M. Schmid is thanked for fruitful discussions and for its enthusiasm for the alpine geology. Geological and petrological knowledge of C. Cigolini were useful to improve this work. We feel grateful to him for his help. This work has benefited from comments, help and support by K. Waite, S.M. Schmid and C. de Capitani. W. Stern, H. Hürlimann and R. Milke from the geochemical laboratory of the Basel University are thanked for performing the chemical analyses. P. Tricart and M. Engi are thanked for their useful comments that greatly improved the manuscript.

REFERENCES

Adatte P., Dubas A., Tache E. & Strauss F. (1992) Géologie et minéralogie du haut Val di Rhêmes (Vallée d'Aoste), Université de Lausanne, 134 pp.

Amstutz A. (1955) Rocher du ravin de Lessert dans la Val D'Aoste. Les Archives des Sciences, Genève 8, 6–9.

Amstutz A. (1962) Notice pour une carte géologique de la Vallée de Cogne et de quelques autres espaces au Sud d'Aoste. Les Archives des Sciences, Genève 15, 1–104.

Ballèvre M. (1988) Collision continentale et chemins P-T: l'unité pennique du Grand Paradis, Alpes Occidentales. Centre Armoricain d'études structurale des socles, 332 pp.

Baudin T. (1987) Étude géologique du Massif du Ruitor (Alpes franco-italiennes): évolution structurale d'un socle briançonnais. Thèse du 3ième cycle, Grenoble, 243 pp.

Bearth P. (1963) Contribution à la subdivision tectonique et stratigraphique du cristallin de la nappe du Grand Saint-Bernard dans le Valais (Suisse). In: Livre à la mémoire du Professeur Fallot, Vol. 2 (ed. M. Durand Delga), pp. 407–418. Mémoire de la Société géologique de France.

Berman R. G. (1988) Internally-Consistent Thermodynamic Data for Minerals in the system Na_2O-K_2O-Ca-MgO-FeO-Fe_2O_3-Al_2O_3-SiO_2-TiO_2-H_2O-CO_2. Journal of Petrology 29, 445–522.

Berman R. G. (1991) Thermobarometry using multiequilibrium calculations: a new technique, with petrological applications. Canadian Mineralogist 29, 833–855.

Bertrand J. M., Pidgeon R. T., Leterrier J., Guillot F., Gasquet D. & Gattiglio M. (2000) SHRIMP and IDTIMS U-Pb zircon ages of the pre-Alpine basement in the Internal Western Alps (Savoy amd Piemont). Schweizerische Mineralogische und Petrographische Mitteilungen 80, 225–248.

Beyssac O., Goffé B., Chopin C. & Rouzaud J.-N. (2002) Raman spectra of carbonaceous material in metasediments: a new geothermometer. Journal of Metamorphic Geology 20, 859–872.

Bocquet J. (1974) Le socle briançonnais de Vanoise (Savoie): arguments en faveur de son âge anté-alpin et de son polymétamorphisme. Comptes Rendus de l'academie de Sciences, Paris, 278, 2601–2604.

Bocquet J. (1974) Études minéralogiques et pétrographiques sur les métamorphismes d'âge alpine dans les Alpes françaises. Thèse d'État, Grenoble, 490 pp.

Bousquet, R., 2007. Metamorphic heterogeneities within a same HP unit: overprint effect or metamorphic mix? Lithos, in press.

Bousquet R., Goffé B., Henry P., Le Pichon X. & Chopin C. (1997) Kinematic, Thermal and Petrological model of the Central Alps: Lepontine Metamorphism in the Upper Crust and Eclogitisation of the Lower Crust. Tectonophysics 273, 105–127.

Bousquet R., Goffé B., Vidal O., R. O. & Patriat M. (2002) The tectono-metamorphic history of the Valaisan domain from the Western to the Central Alps: New constraints on the evolution of the Alps. Geological Society of America, Bulletin 114, 207–225.

Bousquet R., Engi M., Gosso G., Oberhänsli R., Berger A., Spalla M. I., Zucali M. & Goffé B. (2004) Transition from the Western to the Central Alps. In: Explanatory note to the map "Metamorphic structure of the Alps", (ed. R. Oberhänsli), Mitteilungen Österreichische Mineralogischen Gesellschaft 149, 145–156.

Bucher S. (2003) The Briançonnais units along the ECORS-CROP transect (Italian-French Western Alps): structures, metamorphism and geochronology. Ph.D Thesis, Universität Basel.

Bucher S., Schmid S. M., Bousquet R. & Fügenschuh B. (2003) Late-stage deformation in a collisional orogen (Western Alps): nappe refolding, back-thrusting or normal faulting? Terra Nova 15, 109–117.

Bucher S., Ulardic C., Bousquet R., Ceriani S., Fügenschuh B., Gouffon Y. & Schmid S. M. (2004) Tectonic evolution of the Briançonnais units along a transect (ECORS-CROP) trough the Western Alps. Eclogae Geologicae Helvetiae 97, 321–346.

Caby R. (1968) Contribution à l'étude structurale des Alpes Occidentales: Subdivisions stratigraphiques et structure de la zone du Grand-Saint-Bernard dans la partie sud du Val d'Aoste. Géologie Alpine 44, 95–111.

Caby R. (1996) Low-angle extrusion of high-pressure rocks and the balance between outward and inward displacements of Middle Penninic units in the western Alps. Eclogae Geologicae Helvetiae 89, 229–267.

Caby R. and Kienast J.-R. (1989) Meso-Alpine high-pressure assemblages and excavaction of the Ruitor Briançonnais basement (Savoie, Val d'Aoste, Graie Alps). Terra Abstracts 1, 266.

Caby R., Kienast J.-R. & Saliot P. (1978) Structure, métamorphisme et modèle d'évolution tectonique des Alpes Occidentales. Revue de Géographie physique et de Géologie dynamique, 307–322.

Ceriani S. and Schmid S. M. (2004) From N-S collision to WNW-directed post-collisional thrusting and folding: Structural study of the Frontal Penninic Units in Savoie (Western Alps, France). Eclogae Geologicae Helvetiae 97, 347–369.

Chopin C., Seidel E., Theye T., Ferraris G., Ivaldi G. & Catti M. (1992) Magnesiochloritoid and the Fe-Mg series in the chloritoid group. European Journal of Mineralogy 4, 67–76.

Cigolini C. (1981) Garnet chemistry and zonation in the Italian sector of the Grand Saint Bernard nappe. Atti della Reale Accademia di Scienze di Torino 115, 331–344.

Cigolini C. (1992) Note Illustrative alla Carta Geologica del Ricoprimento del Gran San Bernardo tra la Valsavarenche e la Val di Rhêmes (Valle d'Aosta), Regione Autonoma della Valle d'Aosta.

Cigolini C. (1995) Geology of the Internal Zone of the Grand Saint Bernard Nappe: a metamorphic Late Paleozoic volcano-sedimentary sequence in South-Western Aosta Valley (Western Alps). In: Studies on metamorphic rocks and minerals of the western Alps. A Volume in Memory of Ugo Pognante., Vol. 13, n°2 (ed. B. Lombardo), pp. 293–328. Bollettino del Museo Regionale di Scienze Naturali (supplementary).

Compagnoni R., Elter G. & Lombardo B. (1974) Eterogeneità stratigrafica del compleso degli "Gneiss Minuti" nel massicci cristallino del Gran Paradiso. Memorie della Società di Geologia Italiana 13, 227–239.

Dal Piaz G. (1928) Carta Geologica della catena Gran Nomenon-Grivola-Herbetet. Memorie degli Instituti di Geologia e Mineralogia dell'Università di Padova 7, 1–83.

Dal Piaz G. V. and Lombardo B. (1986) Early Alpine eclogite metamorphism in the Pennine Monte Rosa – Grand Paradiso basement nappes of the northwestern Alps. Geological Society of America, Memoirs 164, 249–265.

De Capitani C. and Brown T. H. (1987) The computation of chemical equilibrium in complex systems containing non-ideal solutions. Geochimica and Cosmochimica Acta 51, 2639–2652.

Debelmas J., Elter, G., Antonie, P., Elter, M., Caby R., Mercier, D., marion, R. & Jaillard, E. (1991) Carte Géologique de la France à 1/50000 Feuille Ste-Foy-Tarentaise, Bureau de Recherches Géologique et Minière.

Debelmas J., Caby R. & Desmons J. (1991) Notice explicative, Carte géologique de la France à 1/50000, Feuille Ste-Foy-Tarentaise. Bureau de Recherches Géologique et Minière, Orléans 728, 43pp.

Desmons J., Aprahamian J., Compagnoni R., Cortesogno L. & Frey M. (1999) Alpine Metamorphism of the Western Alps: I. Middle to highT/P metamorphism. Schweizerische Mineralogische und Petrographische Mitteilungen 79, 89–110.

Desmons J., Aprahamian J., Compagnoni R., Cortesogno L., Frey M. & Gaggero L. (1999) Pre-Alpine metamorphism of the Internal zones of the Western Alps. Schweizerische Mineralogische und Petrographische Mitteilungen 79, 23–39.

Desmons J., Aprahamian J., Compagnoni R., Cortesogno L., Frey M., Gaggero L., Dallagiovanna G., Seno S. & Radelli L. (1999) Alpine metamorphism of the Western Alps: II. High-P/T and related pre-greenschist metamorphism. Schweizerische Mineralogische und Petrographische Mitteilungen 79, 111–134.

Desmons J. and Mercier D. (1993) Passing through the Briançon Zone. In: Pre-Mesozoic Geology in the Alps (ed. J. F. v. R. F. Neubauer), 279–295. Springer-Verlag.

Droop G. T. R., Lombardo B. & Pognante U. (1990) Formation and distribution of eclogite facies rocks in the Alps. In: Eclogite facies rocks (ed. D. A. Carswell), 225–259. Blackie.

Ellenberger F. (1958) Étude géologique du pays de Vanoise. Mémoires pour servir à l'explication de la carte géologique détaillée de la France, 561 pp.

Elter G. (1960) La zona pennidica dell'alta e media Val d'Aosta e le unità limitrofe. Memorie degli Istituti die Geologia e Mineralogia dell'Universita di Padova 22, 113.

Elter G. (1972) Contribution à la connaissance du Briançonnais interne et de la bordure piémontaise dans les Alpes Graies nord-orientales et considérations sur les rapports entre les zones du Briançonnais et des Schistes lustrés. Memorie degli Istituti die Geologia e Mineralogia dell'Universita di Padova 26, 1–19.

Fabre J. (1961) Contribution à l'étude de la Zone Houillère Briançonnaise en Maurienne et en Tarantaise (Alpes de Savoie). Bureau de Recherches Géologique et Minière 2.

Feys R. (1963) Etude géologique du Carbonifère brinaçonnais (Hautes-Alpes). Bureau de Recherches Géologique et Minière 6, 387 pp.

Fügenschuh B., Loprieno A., Ceriani S. & Schmid S. (1999) Structural analysis of the Subbriançonnais and Valais units in the area of Moûtiers (Savoy, Western Alps): paleogeographic and tectonic consequences. International Journal of Earth Sciences 88, 201–218.

Fügenschuh B. and Schmid S. M. (2003) Late stages of deformation and exhumation of an orogen constrained by fission-track: A case study in the Western Alps. Geological Society of America, Bulletin 115, 1425–1440.

Gerber C. (1965) Flore et stratigraphie du Carbonifère des Alpes françaises, 380 pp.

Goffé B. (1977) Succession de subfacies métamorphiques en Vanoise méridionale (Savoie). Contributions to Mineralogy and Petrology 62, 23–41.

Goffé B. (1984) Le facies à carpholite-chloritoide dans la couverture briançonnaise des Alpes Ligures: un témoin de l'histoire tectono-metamorphique régionale. Memorie della Società di Geologia Italiana 28, 461–479.

Goffé B. and Bousquet R. (1997) Ferrocarpholite, chloritoïde et lawsonite dans les métapélites des unités du Versoyen et du Petit St. Bernard (zone valaisanne, Alpes occidentales). Schweizerische Mineralogische und Petrographische Mitteilungen 77, 137–147.

Goffé B. and Chopin C. (1986) High-pressure metamorphism in the Western Alps: zoneography of metapelites, chronology and consequences. Schweizerische Mineralogische und Petrographische Mitteilungen 66, 41–52.

Goffé B., Goffé-Urbano G. & Saliot P. (1973) Sur la présence d'une variété magnésienne de la ferrocarpholite en Vanoise (Alpes françaises): sa signification probable dans le métamorphisme alpin. Comptes rendues de l'Académie des sciences, Paris, 277, 1965–1968.

Goffé B., Goffé-Urbano G. & Saliot P. (1973) Sur la présence d'une variété magnésienne de la ferrocarpholite en Vanoise (Alpes françaises): sa signification probable dans le métamorphisme alpin. Comptes rendues de l'Académie des sciences, Paris, 277, 1965–1968.

Goffé B., Schwartz S., Lardeaux J.-M. & Bousquet R. (2004) Metamorphic structure of the Western and Ligurian Alps. In: Explanatory note to the map "Metamorphic structure of the Alps", (ed. R. Oberhänsli), Mitteilungen der Österreichischen Mineralogischen Gesellschaft 149, 125–144.

Goffé B. and Velde B. (1984) Contrasted metamorphic evolution in thrusted cover units of the Briançonnais zone (french Alps): a model for the conservation of HP-BT metamorphic mineral assemblages. Earth and Planetary Science Letters 68, 351–360.

Gouffon Y. (1993) Géologie de la "nappe" du Grand St-Bernard entre la Doire Baltée et la frontière Suisse (Vallée d'Aoste- Italie. Mémories de Géologie, Lausanne 12, 147 pp.

Holland T. J. B. and Powell R. (1998) An internally consistent thermodynamic data setfor phases of petrological interest. Journal of Metamorphic Geology 16, 309–343.

Keller L. M., Abart R., Schmid S. M. & De Capitani C. (2005) Phase Relations and Chemical Composition of Phengite and Paragonite in Pelitic Schists During Decompression: a Case Study from the Monte Rosa Nappe and Camughera-Moncucco Unit, Western Alps. Journal of Petrology in press, doi:10.1093/petrology/egi051.

Le Bayon, B., Pitra, P., Ballevre, M. and Bohn, M., 2006. Reconstructing P-T paths during continental collision using multi-stage garnet (Gran Paradiso nappe, Western Alps). Journal of Metamorphic Geology 24, 477–496.

Lefèvre R. and Michard A. (1976) Les nappes briançonnaises internes et ultra-briançonnaises de la bande d'Acceglio (Alpes franco-italiennes). Une étude structurale et pétrographique dans le faciès des schistes bleus à jadéite. Sciences Géologiques Bulletin, Strasbourg 29, 183–222.

Loprieno A. (2001) A combined structural and sedimentological approach to decipher the evolution of the Valaisan domain in Savoy (Western Alps) Unpublished PhD thesis, Universität Basel, 285 pp.

Malusà M. G., Polino R., Zattin M., Bigazzi G., Martin S. & Piana F. (2005) Miocene to Present differential exhumation in the Western Alps: Insights from fission track thermochronology. Tectonics 24, doi:10.1029/2004TC001782.

Massonne H.-J. and Szpurka Z. (1997) Thermodynamic properties of white micas on the basis of high-pressure experiments in the systems K_2O-MgO-Al_2O_3-SiO_2-H_2O and K_2O-FeO-Al_2O_3-SiO_2-H_2O. Lithos 41, 229–250.

Monié P. (1990) Preservation of Hercynian Ar-40/Ar-39 Ages Through High-Pressure Low-Temperature Alpine Metamorphism In The Western Alps. European Journal of Mineralogy 2, 343–361.

Nagel T., de Capitani C. & Frey M. (2002) Isograds and PT evolution in the eastern Lepontine Alps, Switzerland. Journal of Metamorphic Geology 20, 309–324.

Nicolas A., Polino R., Hirn A., Nicolich R. & group E.-C. w. (1990) ECORS-CROP traverse and deep structure of the Western Alps: a synthesis. In: Deep structure of the Alps, (ed. F. Roure, P. Heitzmann & R. Polino). Mémoire de la Société géologique de France 156, 15–28

Oberhänsli R. (1994) Sudbucted and obducted ophiolites of the Central Alps: Paleotectonic implications deducted by their distribution and metamorphism overprint. Lithos 33, 109–118.

Oberhänsli, R., Bousquet, R., Engi, M., Goffé, B., Gosso, G., Handy, M., Höck, V., Koller, F., Lardeaux, J.-M., Polino, R., Rossi, P., Schuster, R., Schwartz, S. and Spalla, M. I. (2004) Metamorphic structure of the Alps, Commission for the Geological Map of the World (CCGM-CGMW), UNESCO, Paris.

Pfiffner O. A., Lehner P., Heitzmann P. & Mueller S. (1997) Deep Structures of the Alps: Results from NRP 20 (ed. O. A. e. a. Pfiffner), pp. 73–114. Birkhäuser.

Polino R. and Dal Piaz G. V. (1978) Geologia dell'Alta Val d'Isère e del Bacino del lago Serrù. Memorie degli Instituti di Geologia e Mineralogia dell'Università di Padova 22, 1–20.

Polino R., Dal Piaz G. V. & Gosso G. (1990) The alpine cretaceous orogeny: an accretionary wedge model based on integred statigraphic, petrologic and radiometric data. In: Deep structure of the Alps, Vol. 156 (ed. F. Roure, P. Heitzmann & R. Polino), pp. 345–367. Mémoire de la Société géologique de France, 156, 345–367.

Roure F., Heitzmann P. & Polino R. (1990) Deep structure of the Alps. Mémoires de la société géologique de France, 367 pp.

Saadi M. (1992) Géologie du haut Val di Rhêmes (Vallée d'Aoste), Genève, 120 pp.

Schaer J.-P. (1959) Géologie de la partie septentrionale de l'éventail de Bagnes (entre le Val d'Hérémence et le Vaal de Bagnes, Valais, Suisse). Les Archives des Sciences, Genève 12, 473–620.

Schmid S. M., Fugenschuh B., Kissling E. & Schuster R. (2004) Tectonic map and overall architecture of the Alpine orogen. Eclogae Geologicae Helvetiae 97, 93–117.

Schmid S. M. and Kissling E. (2000) The arc of the Western Alps in the light of new data on deep crustal structure. Tectonics 19, 62–85.

Schmid S. M., Pfiffner O. A., Froitzheim N., Schönborn G. & Kissling E. (1996) Geophysical-geological transect and tectonic evolution of the Swiss-Italian Alps. Tectonics 15, 1036–1064.

Schürch M. L. (1987) Les ophiolites de la zone du Versoyen: témoin d'un bassin à évolution métamorphique complexe. PhD thesis, Genève, 157 pp.

Schwartz S., Lardeaux J.-M. & Tricart P. (2000) La zone d'Acceglio (Alpes cottiennes): un nouvel exemple de croûte continentale éclogitisée dans les Alpes occidentales. Comptes rendues de l'Académie des sciences, Paris 320, 859–866.

Spear F. S. (1993) Metamorphic Phase Equilibria and Pressure-Temperature-Time Paths. Mineralogical Society of America, 799 pp.

Stampfli G. M. (1993) Le Briançonnais, terrain exotique dans les Alpes? Eclogae Geologiae Helvetiae 86, 1–45.

Trümpy R. (1966) Considérations générales sur le "Verrucano" des Alpes Suisses. In: Atti del simposio sul Verrucano. Pisa 1966. Atti della Società Toscana di Scienze Naturali, Pisa, 212–232.
Ulardic C. (2001) Strukturgeologische und petrographische Untersuchungen im Valgrisenche (Briançonnais der italienischen Alpen), Universität Freiburg, Germany, 100 pp.
Vidal O. and Parra T. (2000) Exhumation of high-pressure metapelites obtained from local equilibria for chlorite phengite assemblage. Geological Magazine 35, 139–161.
Vidal O., Parra T. & Trotet F. (2001) A thermodynamic model for Fe-Mg aluminous chlorite using data from phase equilibrium experiments and natural pelitic assemblages in the 100–600°C, 1–25 kbar range. American Journal of Science 301, 557–592.
Vidal O., Theye T. & Chopin C. (1994) Experimental study of chloritoid stability at high pressure and various fO_2 conditions. Contributions to Mineralogy and Petrology 118, 256–270.

Manuscript received 24 August 2005
Revision accepted 23 November 2006
Published Online First August 31, 2007
Editorial handling: Martin Engi, Edwin Gnos