Zeitschrift: Eclogae Geologicae Helvetiae

Herausgeber: Schweizerische Geologische Gesellschaft

Band: 89 (1996)

Heft: 1

Artikel: Tectono-metamorphic evolution of the Roignais-Versoyen Unit (Valaisan domain, France)

Autor: Cannic, Sébastien / Lardeaux, Jean-Marc / Mugnier, Jean-Louis

DOI: https://doi.org/10.5169/seals-167904

Nutzungsbedingungen

Die ETH-Bibliothek ist die Anbieterin der digitalisierten Zeitschriften auf E-Periodica. Sie besitzt keine Urheberrechte an den Zeitschriften und ist nicht verantwortlich für deren Inhalte. Die Rechte liegen in der Regel bei den Herausgebern beziehungsweise den externen Rechteinhabern. Das Veröffentlichen von Bildern in Print- und Online-Publikationen sowie auf Social Media-Kanälen oder Webseiten ist nur mit vorheriger Genehmigung der Rechteinhaber erlaubt. Mehr erfahren

Conditions d'utilisation

L'ETH Library est le fournisseur des revues numérisées. Elle ne détient aucun droit d'auteur sur les revues et n'est pas responsable de leur contenu. En règle générale, les droits sont détenus par les éditeurs ou les détenteurs de droits externes. La reproduction d'images dans des publications imprimées ou en ligne ainsi que sur des canaux de médias sociaux ou des sites web n'est autorisée qu'avec l'accord préalable des détenteurs des droits. En savoir plus

Terms of use

The ETH Library is the provider of the digitised journals. It does not own any copyrights to the journals and is not responsible for their content. The rights usually lie with the publishers or the external rights holders. Publishing images in print and online publications, as well as on social media channels or websites, is only permitted with the prior consent of the rights holders. Find out more

Download PDF: 07.08.2025

ETH-Bibliothek Zürich, E-Periodica, https://www.e-periodica.ch

Eclogae geol. Helv. 89/1: 321–343 (1996)

0012-9402/96/010321-23 $1.50 + 0.20/0
Birkhäuser Verlag, Basel

Tectono-metamorphic evolution of the Roignais-Versoyen Unit (Valaisan domain, France)

SÉBASTIEN CANNIC[1], JEAN-MARC LARDEAUX[2],
JEAN-LOUIS MUGNIER[1] & JEAN HERNANDEZ[3]

Key words: Eclogitic metamorphism, P-T path, normal ductile fault, Roignais-Versoyen Unit, Valaisan domain, Western Alps

ABSTRACT

The Roignais-Versoyen Unit (Western Alps, France) offers the best preserved example of ultramafic-mafic rocks affected by eclogitic metamorphism in the Valaisan domain during the Alpine orogenesis. The Roignais-Versoyen unit is composed of the Valaisan flysch and the igneous sedimentary pile of the Versoyen (Versoyen complex).

The Versoyen complex shows three metamorphic stages which are characterized by: (1) A high-pressure – low-temperature (HP-LT) eclogitic stage giving rise to the development of omphacite ± Fe-garnet ± glaucophane 1 ± zoisite ± rutile ± quartz in the metagabbros and Fe-garnet ± jadeite ± chloritoid in the metasediments. (2) A blueschist stage producing the development of glaucophane 2 ± phengite ± zoisite-clinozoisite in the metagabbros and glaucophane 2 ± zoisite-clinozoisite ± lawsonite in the metasediments. (3) A greenschist stage corresponding to the growth of actinolite ± albite ± chlorite ± Mn-garnet ± stilpnomelane ± quartz ± tourmaline and of prehnite ± pumpellyite. Petrographical study allows to estimate the P-T condition of the eclogitic stage and the retromorphic evolution under blueschist and greenschist facies conditions.

New structural data allow to precise a part of the tectonic evolution of the Roignais-Versoyen unit. Stretching lineation, extensional crenulation cleavage and drag folds verging to the SE indicate a top to the SE shearing under greenschist facies conditions. The location of the deformation allows to interpret the Versoyen complex as a normal ductile shear zone. In the Versoyen complex, earlier (under pre-greenschist facies conditions) deformation has been observed: the distribution of the textures within the laccoliths indicates a succession of normal and inverted limbs. This succession is explained by the presence of isoclinal folds verging to the NW.

We outline the relationships between the post-eclogitic evolution and the exhumation processes and we discuss the significance of the eclogitic facies metamorphism in the metamorphic zoneography of the Western Alps.

RESUME

L'unité du Roignais-Versoyen (Alpes occidentales, France) représente le meilleur exemple de métamorphisme éclogitique ayant affecté le domaine valaisan au cours de l'orogénèse alpine. Cette unité est constituée du flysch valaisan et de la série volcano-sédimentaire du Versoyen.

La série volcano-sédimentaire du Versoyen est affectée par un métamorphisme polyphasé de type éclogitique, puis schiste bleu et schiste vert. Les paragénèses observées sont: (1) omphacite ± grenat ± glaucophane 1 ± épidote ± rutile ± quartz dans les méta-gabbros et grenat ± jadeïte ± chloritoïde dans les méta-sédiments pour

[1] ERS CNRS 129, Institut Dolomieu, 15 rue M. Gignoux, F-38031 Grenoble CEDEX
[2] URA CNRS 726, Université C. Bernard, Lyon I, F-69324 Villeurbanne CEDEX 07
[3] UNIL Sciences de la Terre, Lab. de Micro Analyse Electronique, BFSH 12, CH-1015 Lausanne

le façiès éclogitique, (2) glaucophane 2 ± phengite ± épidote ± albite dans les méta-gabbros et glaucophane 2 ± épidote ± lawsonite dans les méta-sédiments pour le façiès schiste bleu et (3) actinote ± albite ± chlorite ± grenat magnésien ± stilpnomélane ± quartz ± tourmaline et prehnite ± pumpellyite pour le façiès schiste vert. Une étude pétrographique a permis d'évaluer les conditions P-T du stade éclogitique et de préciser l'évolution rétrograde des métamorphismes schiste bleu et schiste vert.

De nouvelles données structurales ont permis de préciser l'évolution tectonique de l'unité du Roignais-Versoyen. Une linéation d'étirement, des plans d'ECC (extensional crenulation cleavage) et des plis d'entraînement indiquent une déformation en cisaillement contemporaine du métamorphisme schiste vert. La déformation localisée essentiellement au sein de la série du Versoyen, correspond à un jeu normal vers le SE. D'autre part, au sein de la série du Versoyen, une déformation antérieure à cette déformation syn-schiste vert a été mise en évidence: la répartition des textures magmatiques au sein des laccolithes de la série volcano-sédimentaire du Versoyen démontre une alternance de polarité au sein de la série. Cette alternance pourrait être expliquée par un plissement isoclinal affectant la série.

Le jeu en faille normale de la zone du Versoyen permet ainsi d'expliquer une partie des processus d'exhumation responsables de l'évolution P-T de la série du Versoyen. Cependant, l'existence d'un métamorphisme éclogitique remet en cause les schémas métamorphiques classiques établis pour les Alpes occidentales.

1. Introduction

Occurrences of eclogites are known for a long time in the Alpine belt (see for references Droop et al. 1990). In the internal zone of the western Alps, eclogites and jadeite-bearing rocks have been studied in details. Their formation is directly related to southwards and eastwards subduction of an oceanic domain and to a collision between Eurasia and Africa (Ernst 1971; Dal Piaz et al. 1972, Caby et al. 1978, Lardeaux et al. 1982, Selverstone 1985, Goffé & Chopin 1986, Pognante 1989a, Polino et al. 1990, Miller 1990). This oceanic closure led to the development of high-pressure (HP) assemblages in both oceanic and continental crusts and related sediments (Chopin 1987, Ballèvre 1986, Pognante 1989b, Lardeaux & Spalla 1991). This stage of the tectono-metamorphic evolution was achieved during early Alpine times (Cretaceous to Eocene age; Dal Piaz 1974, Desmons 1977, Rubie 1984, Oberhänsli et al. 1985, Carpéna et al. 1986, Guillet et al. 1986, Hurford & Hunziker 1989). The suture of the oceanic domain is exposed along the Piemont-Ligurian domain as dismembered meta-ophiolitic suites i.e. Monviso and Rocciavré massifs, Suza, Lanzo and Aosta valleys, Zermatt-Saas zone (Ernst & Dal Piaz 1978, Lombardo et al. 1978, Pognante 1979, 1984, Barnicoat & Fry 1986, Colombi & Pfeifer 1986, Lardeaux et al. 1987, Reinecke 1991, Messiga & Scamballeri 1991).

At the scale of the belt, eclogite-facies rocks including locally coesite-bearing assemblages, occur in the axial internal domain of the Alpine chain (i.e. Austroalpine and Penninic nappe systems). However, it must be underlined that eclogitized ultramafic-mafic igneous rocks are not restricted to the Piemont-Ligurian domain but are also exposed in the Valaisan domain (Schürch 1986). The largest mafic body in this domain forms the Roignais-Versoyen Unit (RVU, Mugnier et al. 1993).

The aim of this paper is to precise (i) the location and the characteristics of the different metamorphic parageneses of the RVU and (ii) the tectonic evolution of this unit (particularly the part of tectonics in the exhumation processes of the eclogitic rocks). We discuss the assemblages in terms of pressure-temperature (P-T) path of the RVU and the tectonic implications at the scale of the Alpine belt.

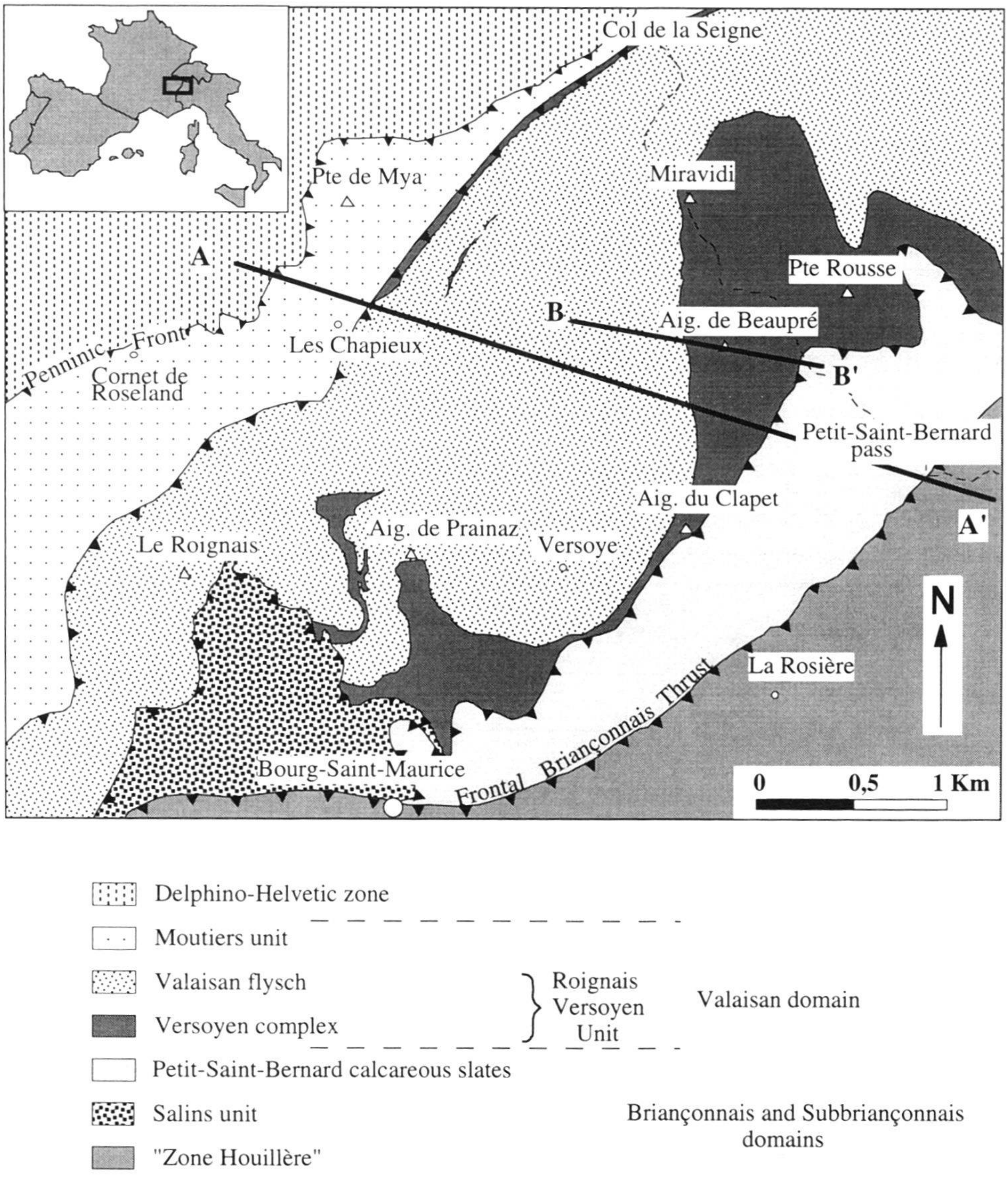

Fig. 1. Geological sketch map of the boundary of the Delphino-Helvetic zone, the Valaisan and Briançonnais domains in the Western Alps. The "Aiguille du Clapet", "Aiguille de Beaupré", "Miravidi" and West of the "Pointe Rousse" are the sampling localities of the studied rocks. The locations of the geological sections represented in Figures 2 and 8 are shown by the lines A-A' and B-B' respectively.

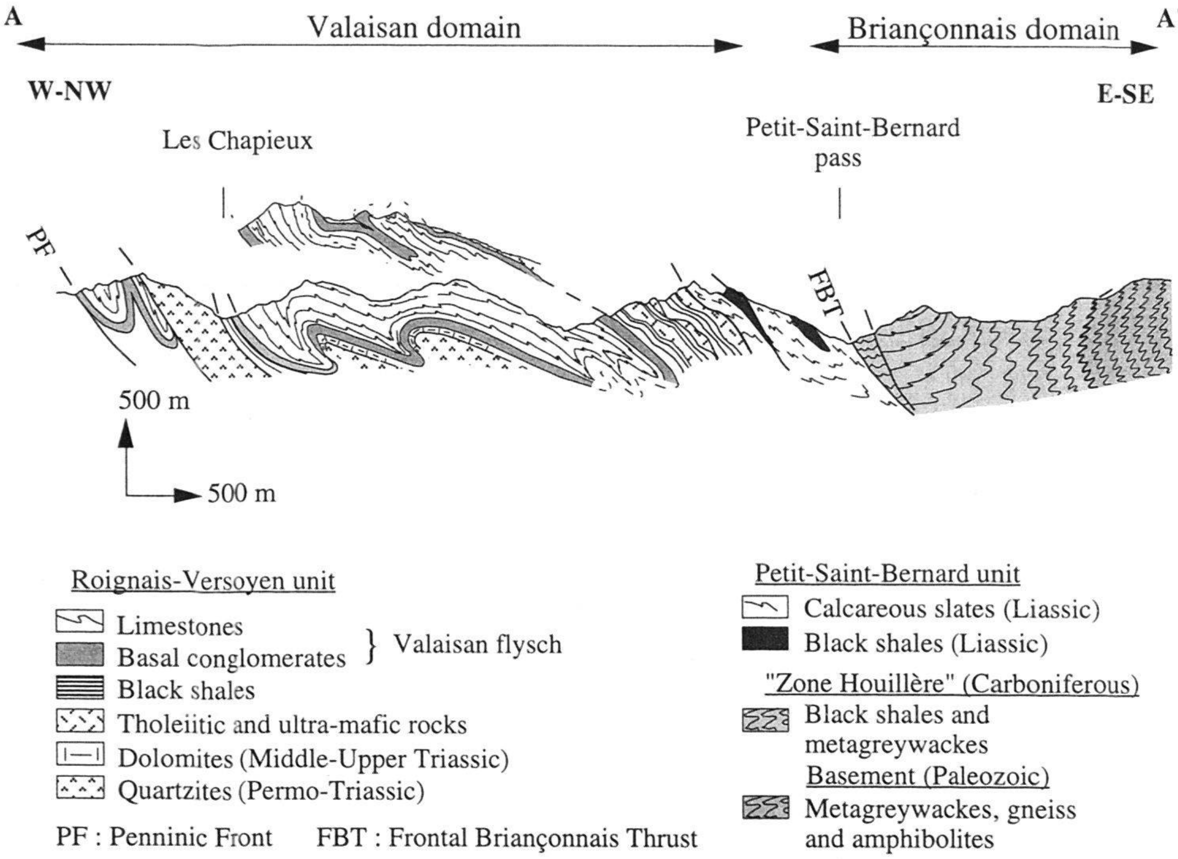

Fig. 2. WNW-ESE geological cross section through the Valaisan domain modified after Antoine (1971), Lancelot (1979) and Baudin (1987).

2. Geological setting

In the Western Alps, the southern boundary of the Valaisan domain forms a thin belt bounded to the east and to the west by two major thrusts which are the Frontal Briançonnais Thrust (FBT) and the Penninic Front (FP) respectively (Fig. 1).

The RVU is located in the vicinity of Bourg-Saint-Maurice (Savoie, France) across the border between France and Italy. This unit is composed of the Valaisan series i.e., the Valaisan flysch (or "flysch de Tarentaise") and the igneous-sedimentary pile of the Versoyen. The Valaisan flysch is characterized by the following succession from bottom to top: The "Couche de l'Aroley", the "Couche des Marmontains" and the "Couches de Saint-Christophe" (Trümpy 1955, Antoine 1971, Fudral 1973). The age of the Valaisan flysch is still debated, it could be Senonian to Campanian (Antoine 1971) or Priabonian (Gely 1989). The Versoyen complex is composed of a succession of igneous rocks interbedded with sediments or exceptionally intruded within a metamorphic basement (Pointe Rousse area). This complex consists of mafic sills and laccoliths, basaltic dikelets, pillow-basalts, mafic tuffs, serpentinized ultramafic rocks, black shales and gneisses (Loubat 1968, Lasserre & Laverne 1976, Cannic et al. 1995). The age of the Versoyen complex is not determined. Near the Petit-Saint-Bernard pass, the RVU is bordered by the Petit-

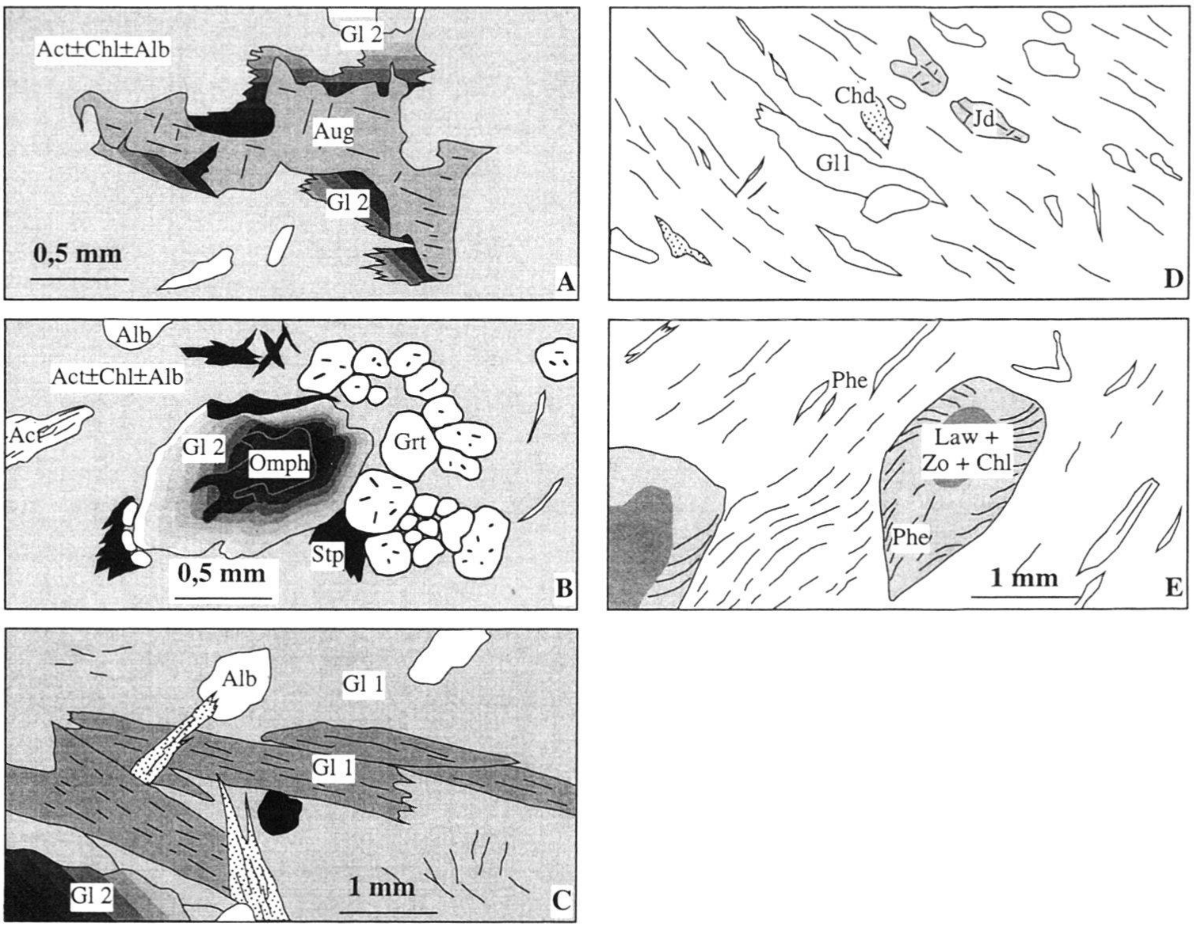

Fig. 3. Magmatic (A) and eclogitic assemblages in the meta-igneous rocks (A, B and C) and in the metasediments (D and E). (A) Relic of augitic pyroxene (Aug) pseudomorphosed in glaucophane 2 (Gl 2). (B) High-P assemblages in gabbros from group 1 with garnet (Grt) in equilibrium with sodic pyroxene (Omph) within an actinolite (Act), chlorite (Chl), stilpnomelane (Stp) and albite (Alb) matrix corresponding to the greenschist facies; porphyroblast of glaucophane 2 grows after sodic pyroxene. (C) high-P assemblage in the gabbros from group 2 with automorph and fine-grained glaucophane 1 (Gl 1). (D) Chloritoid (Chd), glaucophane 1 (Gl 1) and jadeite (Jd) in the glaucophanitic schist. (E) Euhedral relictual lawsonite retromorphosed in phengite (Phe) and chlorite (Chl).

Saint-Bernard unit. This unit is composed of Liassic calcareous slates and black shales (Antoine 1971) wich are attributed to the Subbriançonnais domain (Fudral 1980).

At the scale of the belt, in the classical zonations of the Alpine metamorphism (see Frey et al. 1974, BRGM 1980, Goffé & Chopin 1988, Hunziker et al. 1992), the metamorphism of the RVU is usually considered as greenschist facies. However, previous mineralogical investigations have shown the polyphased character of the metamorphic evolution (Lasserre & Laverne 1976, Schürch 1986). Blueschist and eclogite facies were identified in various exposures of the Versoyen complex, especially in the "Aiguille du Clapet" and West of the "Pointe Rousse" areas (Schürch 1986).

The RVU forms an imbricated thrust sheet within a SE dipping stack of nappes (Barbier 1951, Trümpy 1955, Butler 1984). The most prominent compressional features are

(Fig. 2): (i) numerous SE dipping planes (Antoine 1971) leading to the thrusting of the calcareous slates of the Petit-Saint-Bernard above the Versoyen complex, (ii) N 40° isoclinal folds verging to the NW (Lancelot 1979), (iii) foliation plane dipping to the SE (from 20 to 45°) which corresponds to axial plane cleavage in the Valaisan flysch and in the calcareous slates of the Petit-Saint-Bernard.

3. Petrography and bulk-rock chemistry

Different lithologies located in the Versoyen complex, have been studied. They are the meta-igneous rocks (metagabbros, metadolerites, metabasalts) and the metasediments. The metagabbros show good preservation of the primary gabbroic textures, but the magmatic assemblage is generally completely replaced with the exception of some augitic pyroxene (Fig. 3a). Average bulk-rock compositions of the studied rocks are given in table 1. Although chemical redistribution may have affected these lithologies during the different metamorphic stages, the compositional characteristics tend to reflect the magmatic origin for the protoliths of the igneous rocks (tholeiitic affinities, similar to T-MORB, Lasserre & Laverne 1976, Schürch 1986, Cannic et al. 1993). Chemical data allow two groups of metagabbros to be separated. The group 1 rocks are depleted in Si and Al and enriched in Fe, Ti and Ca with respect to the group 2 rocks. These features are consistent

Tab. 1. Representative bulk-rock analyses of the tholeiitic rocks and the metasediments.

	Tholeiitic rocks		Metasediments	
	Group 1	Group 2	Black shales (1)	Glaucophanitic schists (2)
SiO2	49.81	51.06	55.42	49.52
Al2O3	13.51	14.86	20.92	18.58
TiO2	2.75	1.95	0.97	0.76
FeO tot	13.28	10.05	6.23	5.52
MnO	0.20	0.28	0.19	0.26
MgO	4.97	7.59	3.08	2.88
CaO	8.53	4.49	1.63	4.55
Na2O	4.44	5.54	1.26	7.19
K2O	traces	traces	5.13	0.31
P2O5	0.34	0.26	-	0.14
H2O	-	-	-	3.19
CO2	-	-	-	2.44

1: Lasserre & Laverne, 1976
2: Schürch, 1987

with the petrographic evidence which suggests that the group 1 rocks contain more rutile and ferrostilpnomelane and are richer in Ti-augite relicts. On the other hand, the higher Na values can be explained by differentiation processes and/or metamorphism in oceanic environment (Lasserre & Laverne 1976).

The eclogitized mafic rocks crop out in several places in the Versoyen complex. Most frequently, the eclogitic assemblages are observed in the largest mafic bodies (metagabbros in the thickest sills located in the "Aiguille du Clapet", in the "Haut vallon de Beaupré" near the "Aiguille du Beaupré", in the "Miravidi" or in the "Pointe Rousse", refer to figure 1 for location). These HP assemblages have been recognized in glaucophanitic schists (in the "Aiguille du Clapet", Schürch 1986) and in the black shales (in the "Haut vallon du Beaupré"). In the small mafic bodies (metabasalts and metadolerites), the observed parageneses correspond to blueschist and greenschist facies.

3.1 Eclogitic stage

The metagabbros are the most suitable to describe the development of the HP minerals in the tholeiitic rocks of the Versoyen complex. Omphacite ± garnet ± glaucophane 1 ± zoisite-clinozoisite ± rutile ± quartz are the common minerals in eclogitic metagabbros of the group 1 (Fig. 3b). The main pseudomorphic replacements are (i) omphacite after augite, (ii) Ca-Fe rich garnet after plagioclase and (iii) rutile after Fe-Ti ores. The average grain size of omphacite is 1–2 mm. Some of these have conserved the blasto-ophitic structure of the augitic pyroxene. Garnet appears as cracked crystal, very rich in small inclusions of quartz, amphiboles, phengites. The grain size of glaucophane 1 is 2–4 mm. The eclogitic paragenesis in the metagabbros of the group 2, is characterized by the assemblage omphacite ± glaucophane 1 ± zoisite-clinozoisite ± quartz-rich. The large porphyroblasts of omphacite (3-5 mm) grow after the magmatic pyroxene and are generally pseudomorphosed in glaucophane 2. Zoisite and small (<3 mm) glaucophane 1 are present in the finely-recrystallized matrix (Fig. 3c).

The eclogitic paragenesis recognized in the glaucophanitic schists (metasediments), see table 1 for the bulk rock composition (Schürch 1986), is characterized by the assemblage garnet ± jadeite ± chloritoid surrounded by a fine-grained matrix (Fig. 3d). The black shales exceptionally show some relicts of euhedral lawsonite pseudomorphosed in phengite (Fig. 3e).

3.2 Retromorphic stages

The earliest retromorphic assemblage, identified in the meta-igneous rocks, is: glaucophane 2 ± zoisite-clinozoisite ± phengite ± paragonite ± albite. Glaucophane 2 is different from glaucophane 1: (i) glaucophane 2 grows at the expense of omphacite while the association of glaucophane 1 and omphacite is observed exceptionally, (ii) its grain size (5–8 mm) is longer than the grain size of glaucophane 1, (iii) optically, glaucophane 2 is strongly zoned, with dark cores showing opaque oxide inclusions. The cores usually evolve into blue and pale-blue margins. Glaucophane 2 may correspond to the low-pressure (LP) glaucophane after Ernst (1968). In the metasediments, the retromorphic assemblage is glaucophane 2 ± zoisite-clinozoisite ± phengite ± paragonite. Small (less than 1 mm) zoisite-clinozoisite grows at the expense of relictual lawsonite.

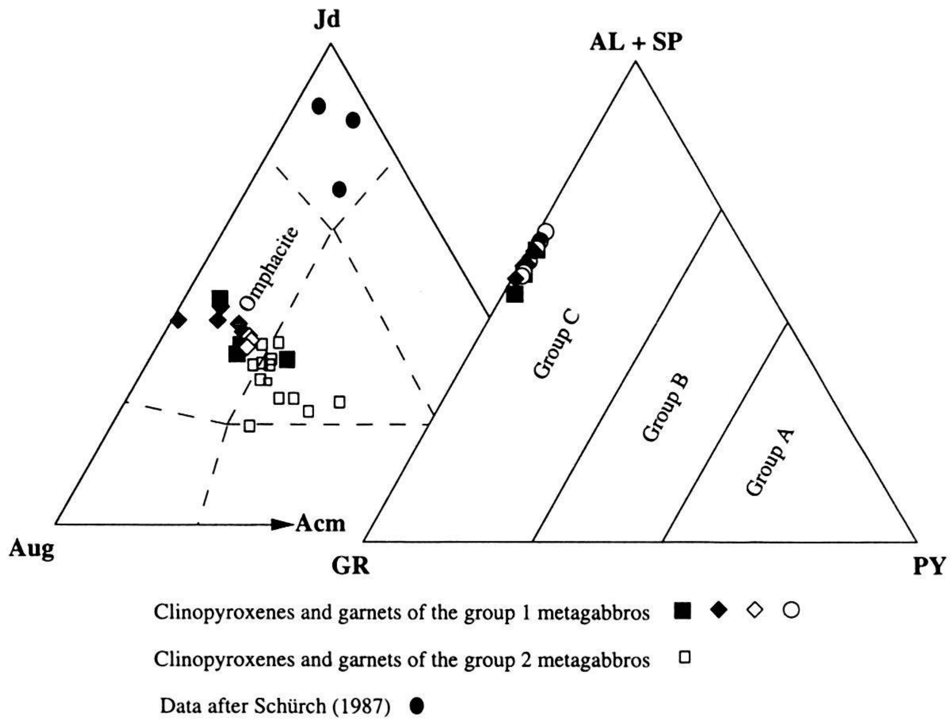

Fig. 4. Average pyroxene and garnet compositions plotted after Essene & Fyfe (1967) and Coleman et al. (1965), respectively. Pyroxene end-members are jadeite (Jd), augite (Aug) and acmite (Acm); garnet end-members are almandine + spessartine (AL + SP), grossular (GR) and pyrope (PY). Also shown are the composition fields (after Coleman et al. 1965) of garnets from eclogites associated with kimberlites and garnet peridotites (group A), of garnets from eclogites associated with gneisses and migmatites (group B), and of garnets from eclogites associated with blueschist (group C).

The end of the retromorphic evolution is characterized by the LP recrystallization under greenschist facies conditions and finally, in very lower grade. The common assemblages are green-amphibole (actinolite-tremolite) ± albite ± chlorite ± Mn-garnet ± Fe-epidote ± stilpnomelane ± quartz ± tourmaline and prehnite ± pumpellyite. Large porphyroblasts of actinolite grow after glaucophane 2 and small euhedral actinolites grow at the expense of glaucophane 1 in the fine-grained matrix. The other retromorphic replacements are: chlorite after actinolite and pumpellyite after clinozoisite and/or lawsonite.

In summary, considering the well preserved relictual assemblages, the metamorphic history of the Versoyen complex is characterized by an eclogitic event followed by retrogression under blueschist and greenschist facies conditions.

4. Mineral chemistry and P-T path

The mineral chemistry has been studied in order to estimate the P-T conditions from the metamorphic assemblages. Composition of the metamorphic phases were determined in the Laboratoire de Micro Analyse Electronique, Université de Lausanne, with a CAMEBAX microprobe operating at 15 KV, 15 nA and using natural minerals as standards. The integration time was 20 s. Representative mineral compositions are listed in tables 2 to 6.

Tab. 2. Representative analyses of clinopyroxene in the metagabbros and the glaucophanitic shists (formula based on 6 oxygens).

	Chloromelanite	Omphacite			Jadeite
	93-43	94-82	94-90	94-90	740
SiO2	54.53	55.53	53.78	53.90	56.97
Al2O3	5.89	11.08	9.25	9.87	19.68
TiO2	0.09	0.09	0.04	0.00	0.15
FeO	15.01	6.95	13.40	11.26	5.59
MgO	5.42	5.91	2.96	4.33	0.72
CaO	9.03	11.89	11.67	12.61	1.20
MnO	0.30	0.19	1.07	0.14	0.04
Cr2O3	0.00	0.03	0.00	0.00	–
NiO	0.00	0.01	0.45	0.00	–
Na2O	9.08	7.64	7.35	7.13	13.91
Σ	99.36	99.33	99.97	99.24	98.26
Si	1.99	2.00	1.98	1.98	1.99
ALIV	0.01	0.00	0.01	0.02	0.01
AlVI	0.24	0.47	0.39	0.41	0.80
Ti	0.00	0.00	0.00	0.00	0.00
Mg	0.29	0.32	0.16	0.24	0.04
Fe 3+	0.41	0.06	0.15	0.12	0.14
Fe 2+	0.05	0.15	0.26	0.23	0.03
Ca	0.35	0.46	0.46	0.50	0.04
Mn	0.01	0.01	0.03	0.00	0.00
Cr	0.00	0.00	0.00	0.00	–
Ni	0.00	0.00	0.01	0.00	–
Na	0.64	0.53	0.53	0.51	0.94
Jadeite	23.97	47.21	39.13	40.07	79.94
Augite	36.31	46.47	46.95	50.04	6.29
Acmite	39.72	6.31	13.93	9.88	13.77

4.1 Clinopyroxene

Mineral compositions are given in table 2 and plotted in the Jd-Aug-Ac diagram (Fig. 4) of Essene and Fyfe (1967). Generally, the analyzed clinopyroxenes are omphacite in metagabbros of the group 1 and chloromelanite in metagabbros of the group 2. Jadeite contents in omphacite, calculated according the method of Cawthorn and Collerson (1974), range from Jd_{32} to Jd_{47}. Acmite contents range between 0 to 24% in the metagabbros of the group 1 and between 19 to 34% in the more retromorphosed sample (metagabbros of the group 2, 93-43). Chemical analyses of jadeite in metasediments studied by Schürch (1986), are presented in the same diagram.

Tab. 3. Representative analyses of garnet in the metagabbros (formula based on 6 oxygens).

	Grt 1 94-90.18				Grt 2 94-89.05			
	Cores		Rims		Cores		Rims	
SiO2	36.74	37.28	37.05	37.26	37.85	37.02	37.20	37.55
Al2O3	20.34	20.59	20.53	20.63	21.46	20.31	20.88	20.79
TiO2	0.08	0.13	0.17	0.20	0.22	0.31	0.16	0.15
FeO	22.44	22.21	19.91	20.16	17.82	17.87	19.44	20.17
MgO	0.15	0.15	0.16	0.12	0.34	0.17	0.24	0.27
CaO	13.41	14.29	15.64	15.63	16.96	17.18	15.80	15.38
MnO	6.82	5.92	5.93	6.03	6.58	7.12	6.29	5.89
Cr2O3	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.00
NiO	0.00	0.00	0.04	0.00	0.06	0.14	0.03	0.03
Na2O	0.00	0.01	0.02	0.01	0.02	0.03	0.04	0.00
K2O	0.00	0.01	0.01	0.00	0.00	0.01	0.03	0.00
Σ	100.00	100.60	99.46	100.05	101.33	100.18	100.12	100.24
Si	2.96	2.98	2.98	2.98	2.96	2.96	2.96	2.99
Al IV	0.03	0.02	0.02	0.02	0.04	0.04	0.03	0.01
Al VI	1.90	1.91	1.92	1.92	1.95	1.87	1.93	1.94
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ti	0.00	0.01	0.01	0.01	0.01	0.02	0.01	0.01
Mg	0.02	0.02	0.02	0.01	0.04	0.02	0.03	0.03
Fe 3+	0.09	0.08	0.07	0.07	0.04	0.11	0.06	0.05
Fe 2+	1.42	1.40	1.27	1.28	1.13	1.08	1.23	1.29
Mn	0.47	0.40	0.40	0.41	0.44	0.48	0.42	0.40
Ni	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00
Ca	1.16	1.22	1.35	1.34	1.42	1.47	1.35	1.31
Na	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00
K	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Z	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
Y	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
X	3.06	3.05	3.04	3.04	3.03	3.07	3.05	3.03
% Alm	47.95	47.47	43.06	43.36	38.07	37.69	41.83	43.54
% Spe	14.76	12.83	12.98	13.13	14.24	15.21	13.72	12.88
% Gros	36.73	39.13	43.32	43.05	46.40	46.43	43.54	42.53
% Pyr	0.56	0.56	0.64	0.46	1.30	0.66	0.92	1.04

4.2 Garnet

Average garnet compositions are given in table 3 (according to the method of Rickwood 1968) and plotted in terms of mole per cent pyrope, almandine + spessartine and grossular in figure 4. The garnet compositions correspond to eclogitic garnets associated with glaucophanitic schist (Coleman et al. 1965).

The garnets in the igneous rocks are almandine-pyrope grossular-spessartine solid solutions with 37 to 47% almandine and 38 to 47% grossular. The chemical compositions of the garnets allow to distinguish two types of garnets: the garnet 1 (94-90) is almandine rich (Alm > 44%) with respect to garnet 2. Occasionally, the garnets 1 are zoned with al-

Tab. 4. Representative analyses of sodic (formula based on 15 = total cations less (Ca+Na+K) and Fe^{3+} = 46 - sum of all cation charge assuming all iron as ferrous) and calcic amphiboles (formula based on 13 = total cations less Ca, Na and K).

	Metagabbros			Metasediments		Metagabbros
	Glauco 1	Glauco 2				
		Cores	Rims	Cores	Rims	
		Crossite	Glauco	Glauco	Riebeckite	Actinolite
SiO2	52.21	53.23	54.03	56.09	55.64	53.48
Al2O3	10.87	8.18	10.17	11.14	1.43	2.05
TiO2	0.05	0.07	0.07	0.17	0.05	0.04
FeO	20.93	25.46	21.43	14.63	17.34	13.82
MgO	3.535	2.54	3.56	7.40	13.23	14.98
CaO	2.02	0.70	0.58	0.63	3.62	10.03
MnO	0.23	0.15	0.38	0.10	0.10	0.26
Cr2O3	0.00	0.00	0.01	0.02	0.02	0.02
NiO	0.07	0.05	0.02	0.05	0.00	0.00
Na2O	6.12	6.47	6.61	6.92	5.81	2.01
K2O	0.10	0.03	0.01	0.02	0.00	0.10
Σ	96.15	96.89	96.87	97.17	97.24	96.79
Si	7.66	7.87	7.86	7.87	7.64	7.72
Al IV	0.34	0.13	0.14	0.13	0.36	0.28
Al VI	1.54	1.29	1.61	1.71	0.39	0.07
Cr	0.00	0.00	0.00	0.00	0.01	0.00
Ti	0.00	0.01	0.01	0.00	0.01	0.00
Fe 3+	0.55	0.69	0.38	0.26	1.57	0.51
Mg	0.77	0.56	0.77	1.55	1.98	3.22
Mn	0.03	0.02	0.05	0.01	0.04	0.03
Fe 2+	2.10	2.44	2.18	1.44	1.00	1.15
Fe 2+	0.00	0.00	0.04	0.01	0.00	0.00
Ca	0.32	0.11	0.09	0.09	0.54	1.55
Na	1.68	1.85	1.86	1.88	1.46	0.45
Na	0.06	0.00	0.00	0.00	0.15	0.11
K	0.02	0.00	0.00	0.00	0.00	0.02

mandine enrichment towards their cores and grossular enrichment towards their rims (sample 94-90.18), then almandine and grossular display an antithetic pattern in the garnet 2 (sample 94-89.05).

4.3 Amphiboles

Alkali amphiboles, which are present in the igneous rocks and glaucophanitic schists show a compositional evolution (Tab. 4 and Fig. 5).

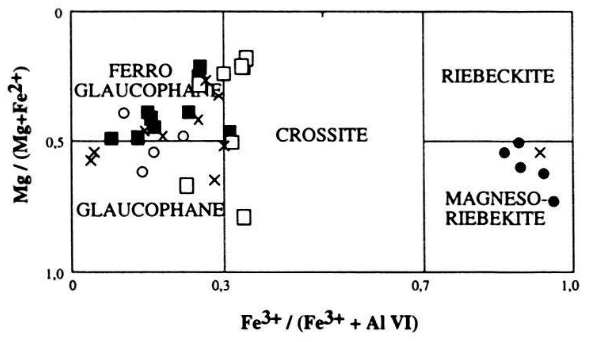

Fig. 5. Composition of the alkali amphiboles from the metagabbros and the metasediments in the Miyashiro-type diagram. Metagabbros: glaucophane 1 (cross symbols), cores and rims of glaucophane 2 (open and full squares respectively). Metasediments: cores of glaucophane 2 (open circles) and rims of glaucophane 2 (full circles).

Tab. 5. Representative analyses of mica (formula based on 12 oxygens with 6 = total cation less Ca+Na+K).

	Phengite			
	Metagabbros		Metasediments	
	93-34	93-21	93-09	94-94
SiO2	55.58	54.19	50.74	51.11
Al2O3	25.92	28.80	35.68	27.95
TiO2	0.14	0.06	0.21	0.17
FeO	2.75	2.87	0.79	2.42
MgO	4.01	2.89	0.91	3.10
CaO	0.00	0.00	0.02	0.02
MnO	0.00	0.00	0.00	0.02
Na2O	0.04	0.31	0.92	0.25
K2O	8.71	9.02	8.18	9.81
Σ	97.15	98.15	97.45	94.85
Si	3.51	3.43	3.21	3.37
Al IV	0.47	0.57	0.79	0.62
Al VI	1.47	1.57	1.86	1.55
Fe	0.15	0.15	0.04	0.13
Mg	0.38	0.27	0.09	0.30
Ti	0.01	0.00	0.01	0.01
Mn	0.00	0.00	0.00	0.00
Ca	0.00	0.00	0.00	0.00
Na	0.00	0.04	0.11	0.03
K	0.70	0.73	0.66	0.83
Z	4.00	4.00	4.00	4.00
Y	2.00	2.00	2.00	2.00
X	0.71	0.77	0.77	0.86

Tab. 6. Representative analyses of Lawsonite (formula based on 8 oxygens).

	Lawsonite 93-07	
SiO2	38.52	38.71
Al2O3	31.92	32.04
TiO2	0.10	0.00
FeO	0.51	0.47
MgO	0.04	0.00
CaO	17.77	18.09
MnO	0.0	0.00
Na2O	0.03	0.06
K2O	0.00	0.00
Σ	88.89	89.37
Si	2.01	2.01
Al IV	0.00	0.00
Al VI	1.96	1.96
Fe2+	0.02	0.20
Mg	0.00	0.00
Ti	0.00	0.00
Mn	0.00	0.00
Ca	0.99	1.01
Na	0.00	0.01
K	0.00	0.00
Σ	5.00	5.01

According to the classification of Leake (1978), the cores of the amphiboles are glaucophane and/or Fe-glaucophane in the schists and their rims show a range of composition from riebekite to Mg-riebekite. The alkali amphiboles in the metagabbros are crossite in the cores and glaucophane and/or Fe-glaucophane in the rims. The latter chemical evolution could result from the retrogressive evolution during blueschist metamorphism.

Calcic amphiboles (actinolite and actinolite-hornblende) grow at the expense of the alkali amphiboles. The replacement of Na by Ca within the B site of the amphiboles corresponds to the retrogressive evolution under greenschist facies conditions.

4.4 White mica

Phengite and paragonite are the most common micas observed in the RVU. Representative analyses are given in table 5. Large grain size (2–4 mm) porphyroblasts of paragonite coexist with phengites which generally underline the foliation plane. The celadonite substitution in the analyzed phengites from the metasediments and from the metagabbros, ranges between 3.08 and 3.61, with higher values for phengites from tholeiites ($3.40 < Si^{4}+ < 3.56$). In the black shales, phengites occurring as pseudomorphic crystals show lower $Si^{4}+$ values (3.08 to 3.40). These lower values can be the result of the particular chemistry of the black shales which are alumina-rich (chloritoid and chlorite occurrences). The association chloritoid-chlorite limits the celadonite substitution (Chopin 1981).

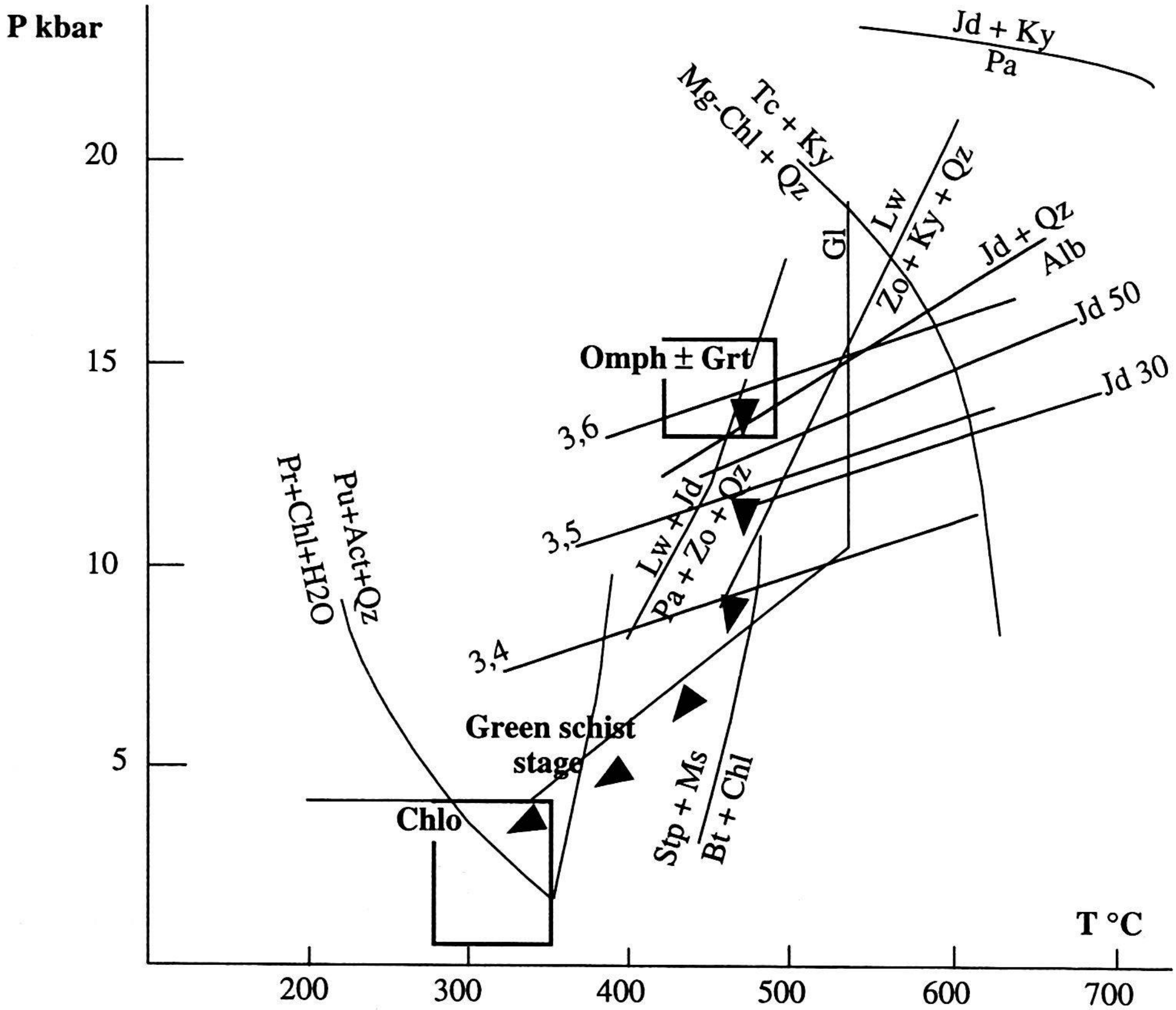

Fig. 6. P-T path of the studied rocks. Glaucophane (Gl) stability after Maresch (1977). Pump+Act+Qz –>Pr+Chl+H_2O and Pump+Chl+Qz—>Czo+Tr+H_2O after Nitsch (1971). Biotite (Bt) stability after Nitsch (1970). Isopleths of Si^4+ content in phengite barometer after Massone & Schreyer (1987), Alb—>Jd+Qz and stability of the omphacite (Jd_{50}) after Holland (1980). Lawsonite-zoisite transition after Heinrich & Althaus (1980) and Newton & Kennedy (1963). Jd+Ky—>Pa after Holland (1979). Tc+Ky—>Mg-Chl+Qz after Massone et al. (1981).

4.5 Lawsonite

Some relicts of lawsonite occur in the black shales. Representative analyses are given in table 6. Two types of occurrences are distinguished: (1) fine-grained (less than 0.2 mm) lawsonite with phengite in the matrix, (2) largest grain size (2–4 mm) euhedral relicts of lawsonite which generally show their cores retromorphosed in zoisite and their rims retromorphosed in phengite.

4.6 P-T path of the Versoyen complex (Fig. 6)

In the meta-igneous rocks, the development of glaucophane in the eclogitic parageneses suggests temperatures lower than 550°C. The eclogitic assemblage sodic clinopyroxene ± garnet ± quartz allows the jadeite content in Na-pyroxene (Holland 1980, 1983) and the Fe-Mg exchange equilibria between coexisting garnet-pyroxene pairs (Raheim & Green 1974, Ellis & Green 1979, Ganguli 1979, Saxena 1979, Powel 1985, Krogh 1988) to be used for pressure and temperature determination respectively. The maximal jadeite content of omphacite indicates a minimal pressure of about 13 kb (Holland 1980). The contemporaneous development of garnet and omphacite porphyroblasts within the metagabbros allows the temperature of the eclogitic stage to be calculated. The range of X^{Gt}_{Ca} = 0.43–0.45 implies to choose the Krogh (1988) thermometer, which considers the partitioning of Fe^{2+} and Mg^{2+} between garnet and clinopyroxene for the calculation of K_d. Using this approach, the temperature estimates range between 425°C and 470°C. According to the experimental works of Massonne (1981) and Massonne and Schreyer (1987), the Si^{4+} content of phengites found in the metagabbros (3.4–3.6) indicates a minimal pressure range between 10 and 15 kb for a temperature lower than 500°C. This value is consistent with the occurrence of chloritoid instead of straurolite in the metasediments.

The early transition from lawsonite to zoisite (Heinrich & Althaus 1980) suggests that the decompression is accompanied by a temperature higher than 400 °C. The transition from glaucophane 2 to actinolite indicates a pressure decreasing from 7–8 kb to lower than 4 kb. Using the Na (M4) contents in calcic amphiboles (Shido & Miyashiro 1959, Brown 1977), the compositions of the actinolites suggest a pressure range between 6 to 2.5 kb and the assemblage prehnite ± pumpellyite ± actinolite ± quartz indicates a temperature range between 375° to 200°C (Nitsch 1971). The cation site occupancy thermometer for chlorite and illite (Cathelineau & Nieva 1985, Cathelineau 1988, Schiffman & Fridleifsson 1991) yields a temperature between 275 to 350°C for a pressure lower than 4 kb.

In summary for the eclogitic stage, the minimal pressure is estimated about 13–15 kb for a temperature ranging between 425°C and 470°C. After a decompression without significant temperature decrease, the P-T conditions are estimated 6–2.5 kb and lower than 375 °C for the greenschist stage and lower than 4 kb and 275°–350 °C for the lower grade stage.

5. Tectonic evolution

This section focuses on finite strain markers corresponding to the normal ductile shearing and to the earliest folding of the Versoyen complex.

5.1 Normal shearing in the Roignais-Versoyen unit

In the Roignais-Versoyen unit, the foliation plane dipping 20–45° towards the SE, is distorted by a later planar fabric (Fig. 7). This SW-NE fabric dips about 40 to 60° towards the SE and took place during the greenschist condition. This planar fabric corresponds to an extensional crenulation cleavage ("ECC"; Platt & Vissers 1980). These ECC represent the ductile microscale shear bands produced by a shearing strain along the axial plane cleavage.

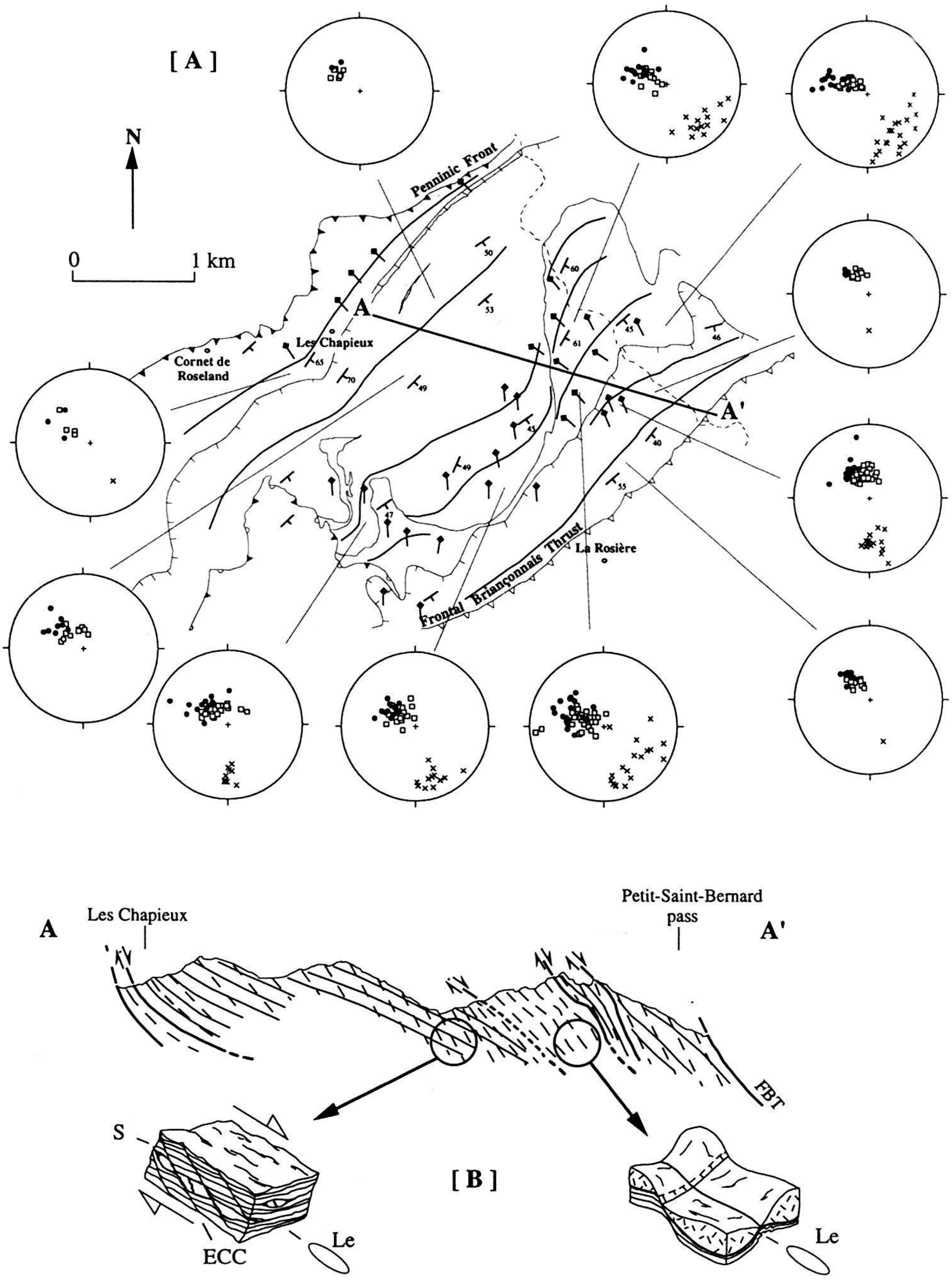

Fig. 7. [A] Trajectories map of the extensional crenulation cleavage and orientation of the streching lineation in the Roignais-Versoyen Unit. Stereogram of streching lineation (cross symbols), axial plane cleavage (open squares) and extensional crenulation cleavage (full circles), lower hemisphere (equal area projection). [B] Structural section showing the relation between the axial plane cleavage (S, full line) dipping 20–45° towards the SE and the extensional crenulation cleavage (ECC, dashed lines) dipping 45–75° towards the SE.

A stretching lineation striking N140 to N160° is marked by actinolite, chlorite and phengite. Those minerals correspond to the retrograde greenschist facies metamorphism. The stretching lineation occurs in the Versoyen complex, in the inverted limb of the Valaisan flysch synform, in the black shales of the "Petit-Saint-Bernard" unit (in the "Roc de Belleface") and in the Carboniferous schist in the "vallée des Chapieux" (Fig. 7a). The observation of the ECC in a plane oriented perpendicularly to the foliation plane and parallel to the stretching lineation, allows to interpret this lineation as the direction of movement during the shearing strain in greenschist condition.

The dip of the ECC is steeper than the foliation plane (Fig. 7b). The ECC reveal a regional shearing corresponding to the displacement of the upper units towards the SE. The displacement marks a normal movement along a shear plane dipping towards the SE. The deformation, very strong inside the Versoyen complex, decreases in the Valaisan flysch and in the Petit-Saint-Bernard unit. This finite strain gradient explains the development of the stretching lineation inside the Versoyen complex and the tectonic transposition of the meta-igneous-sedimentary pile. Actually, the Versoyen complex can be considered as a normal ductile shear zone. This movement also generates some N 20–40° drag folds verging to the SE.

The meta-igneous rocks of the Versoyen, the sandstone beds in the Valaisan flysch and the limestone beds in the calcareous slates of the "Petit-Saint-Bernard" are affected by a "chocolate tablet boudinage" (Ramsay & Huber 1987). This bed-thinning is compatible with the normal shearing strain.

The ECC presents the same orientation in normal and inverted limbs of the isoclinal folds. This structural relationship between the ECC and the axial plane cleavage indicates that the top to the SE shearing postdates the thrusting movement towards the NW. A later brittle deformation is characterized by normal faults dipping towards the SE. This brittle deformation succeeds the normal ductile shearing.

5.2 Isoclinal folds in the Versoyen complex

In spite of the tectonic transposition of the Versoyen complex, it is possible to recognize earlier structural features: a NW-SE cross section through the Versoyen complex shows a succession of laccoliths and black shales dipping to the SE. This succession although apparently expressing the original sedimentary and magmatic pattern (Loubat 1984, Schürch 1986) is more complex (Fig. 8a). The polarity of the stratigraphic succession in the Versoyen complex has been established using the distribution of textures within the doleritic-gabbroic ultramafic-mafic laccolith and the shape of the pillows in the basaltic flows. Where the undeformed laccoliths are thick enough to show gabbroic or ultramafic composition, the polarity of the sequence is determined by the presence of cumulate ultramafic-mafic rocks and/or intersertal gabbros located at the base of laccolith, just above the lower chilled margin, while the uppermost part of the laccolith is composed of dolerite with ophitic texture, located immediately beneath the upper chilled margin. This distribution of textures reflects the evolution of bulk-rocks compositions within the thickest laccoliths (Lasserre & Laverne 1976). Using this approach, the meta-igneous rocks present a succession of normal and inverted stratigraphic polarity (Fig. 8b). These sequences suggest the presence of 10 m to 100 m scale isoclinal folds verging to the NW whose limbs and axes are difficult to observe. Nevertheless, an isoclinal fold is well ex-

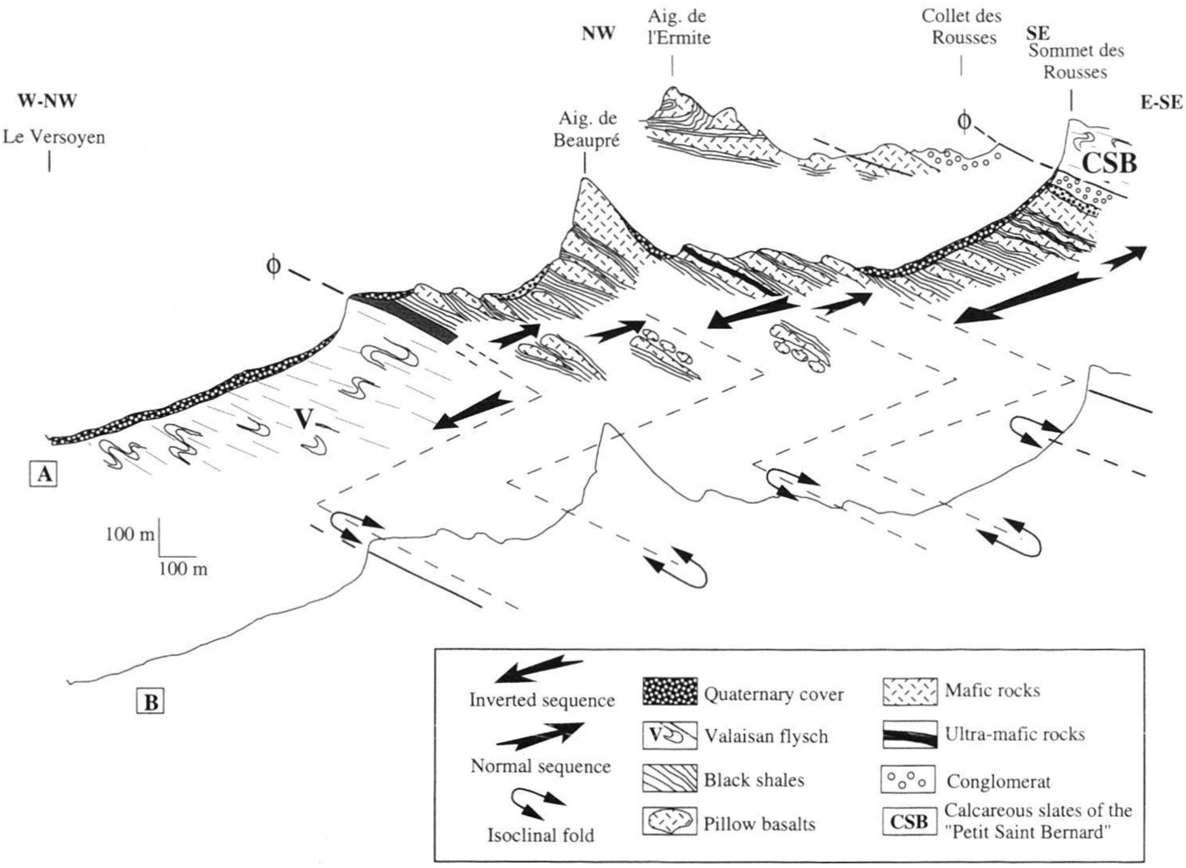

Fig. 8. [A] WNW-ESE cross section through the "Haut vallon du Beaupré" (Versoyen complex). [B] Sketch across section showing the inferred fold axes.

posed at the "Pointe de l'Ermitte" (Lasserre & Laverne 1976), and numerous centimeters to hectometers scale isoclinal folds have been observed within the adjacent Valaisan flysch. The foliation plane dipping towards the SE observed in the black shales can be interpreted as the axial plane cleavage of the isoclinal folds.

The lateral terminal tips of the laccoliths are intrusive within the sediments. Nonetheless, faults (or shear zones) parallel to the laccoliths cannot be precluded, as intense cleavage is frequently observed, and as thrust contact is also observed (Lasserre & Laverne 1976).

6. Discussion and conclusions

6.1 Characteristics of the HP metamorphism

The HP assemblages observed in the tholeiitic rocks (metagabbros, metabasalts) and in the metasediments (black shales, glaucophanitic schists) indicate that the eclogitic metamorphism was widespread in the different lithologies of the Versoyen complex. These eclogites have recrystallized under high pressure (> 13 kb) and very low temperature (< 425–470°C). In the Western Alps, such characteristics are similar to the HP conditions observed in some ophiolitic units and Penninic basement nappes (Rocciavré massif, Pognante & Kienast 1987, Bouffette 1993; Monviso, Lardeaux et al. 1987; Vanoise massif, Platt & Lister 1985; Ruitor, Caby & Kienast 1989; Val Campiglia; Benciolini et al. 1984). The eclogite presents a lower temperature than the Zermatt-Saas ophiolitic suites (Meyer 1983, Fry & Barnicoat 1987, Reinecke 1991). However, the age of the HP metamorphism of the Versoyen complex is still not determined.

6.2 Post-eclogitic evolution and exhumation processes

The post-eclogitic evolution is very well preserved in the Versoyen complex and suggests a decompressional path without significant temperature decrease. The HP event has affected the totality of the Versoyen complex; however, the later deformation under greenschist facies conditions is very strong and the HP parageneses are only preserved in the less deformed domains (i.e. the core of the thickest sills). The deformation under greenschist facies conditions indicates a normal movement of the units towards the SE. This normal fault is compatible with the distribution of fission-track ages in the external crystalline massifs and the northern Penninic nappes that suggests an important normal fault component during the Neogene (Seward & Mancktelow 1994). Such a tectonic denudation could explain a part of the exhumation processes under greenschist and lower grade conditions. However, the deformation under eclogitic and blueschist conditions have never been observed. In that case, the mechanism responsible for the pre-greenschist exhumation of the HP rocks remains unknown.

Several models consider the Versoyen complex as a klippe of Piemont units (Schoeller 1929, Bocquet 1974). These models suggest (1) an early eclogitic metamorphism of the Piemont units, (2) a tectonic emplacement of the Piemont units above the Briançonnais and the Valaisan domains and (3) the thrusting of the Briançonnais and Subbriançonnais domains above the Versoyen complex. These models appear incompatible with the retrotectonic evolution of the RVU as discussed here. Accordingly, the SE-dipping normal fault and the burial of the Versoyen complex (from 50 to 60 km depth), may indicate that the Versoyen complex was located below the Briançonnais domain before the extension. South of Moutier, the FBT (so called "Faille des Encombres"), could correspond to a normal fault (Aillères et al. 1995). The F3 kilometer-scale folds observed in the "zone Houillère" (Baudin 1987), could represent a roll-over structure induced by the normal faulting (Aillères et al. 1995). However, the roll-over style deformation can not induce an important overtilting of the unit. In this case, the RVU can not correspond to the inverted limb of the megascopic folds.

6.3 Significance of the HP metamorphism and the structural evolution

The Versoyen complex is bounded by the Valaisan flysch and the Calcareous slates of the Petit-Saint-Bernard which are metamorphosed under very low P-T conditions. This reflects a strong metamorphic gap within the RVU. Two hypotheses can explain this P-T "jump": (i) HP assemblages are also present in the bounded series, but they have never been observed due to a strong retromorphic imprint. (ii) The Versoyen complex and the other series have recorded different P-T histories. However, the External Crystalline massifs and the "Zone Houillère" are also metamorphosed under very low grade condition in Alpine time. In any case, the Versoyen complex, represents an eclogitic unit imbricated within a very low grade nappes system. The eclogite of the Versoyen complex located just near the Penninic front, cannot be explained by the classical metamorphic zoneography of the Western Alps which suggests a decrease in metamorphic intensity from the internal to the external zones. Finite strain markers together with the metamorphic gaps suggest that the transitions RVU-"Zone Houillère" and RVU-"External Crystalline massifs" could correspond to a major SE-dipping normal fault and a NW-directed thrust respectively.

The late structural evolution and the metamorphic characteristics of the RVU underline the coexistence of SE dipping thrust and SE dipping normal faulting during the late stage of the continental collision in the western Alps.

Acknowledgement

The authors express their sincere gratitude to J.M. Bertrand, H. Loubat and R. Chessex for critical reading of the manuscript.

The data presented in this paper were supported by a scientific collaboration between the universities of Grenoble 1, Lyon 1 and Lausanne. We would like to give our special thanks to H. Lapierre who developed this international project. We thank J.M. Bertrand and L. Aillère for fruitful discussions in the field. Thanks to F. Bussy for providing assistance during microprobe analyses and J.C. Hunziker for his kind hospitality in Lausanne. Working period in Lausanne (S. Cannic) was supported by Erasmus program and a "Bourse Régionale" for international exchange are gratefully acknowledged.

REFERENCES

Aillères, L. , Bertrand, J. M. , Macaudière, J. & Champenois, M. 1995: Structure de la Zone Houillère Briançonnaise (Alpes françaises), tectonique néoalpine et conséquences sur l'interprétation des Zones Penniques Frontales. C.R. Acad. Sci. (Paris) 321, 247–254.

Antoine, P. 1971: La zone des brèches de Tarentaise entre Bourg-Saint-Maurice (vallée de l'Isère) et la frontière italo-suisse. PhD thesis Univ. Grenoble.

Ballèvre, M. 1986: Collision continentale et chemin P-T: L'unité pennique du Grand Paradis. Mém. Doc. Centre Arm. Et. Struct. Socle 19, Rennes.

Barbier, R. 1951: La prolongation de la zone subbriançonnaise de France en Italie et en Suisse. Les conséquences pour une corrélation d'ensemble des zones penniques de ces trois pays. Trav. Lab. géol. Grenoble 29, 3–46.

Barnicoat, A. C. & Fry, N. 1986: High-pressure metamorphism of the Zermatt-Saas ophiolite, Switzerland. Geol. Soc. London 143, 607–618.

Baudin, T. 1987: Etude géologique du massif du Ruitor (Alpes franco-italiennes): Evolution structurale d'un socle briançonnais. PhD thesis Univ. Grenoble.

Benciolini, L., Martin, S. & Tartarotti, P. 1984: Il metamorfismo eclogitico nel basamento del Gran Paradiso ed in Unità Piemontesi della Valle di Campiglia. Mem. Soc. geol. ital. 29, 121–157.

Bocquet, J. 1974: Etudes minéralogiques et pétrographiques sur les métasédiments d'âge alpin dans les Alpes françaises. PhD thesis Univ. Grenoble.

Bouffette, J. 1993: Evolution tectonométamorphique des unités océaniques et continentales au Nord du massif Dora-Maira (Alpes Occidentales). PhD thesis Univ. Claude Bernard Lyon I.

BRGM 1980: Carte Géologique de la France au 1:250 000^e, feuille Annecy. Bur. Rech. géol. min.

Brown, E. H. 1977: The crossite content of Ca-amphiboles as a guide to pressure of metamorphism. J. Petrol. 18, 229–250.

BUTLER, R. W. H. 1984: Balanced cross-section and their implications for the deep structure of the northwest Alps: discussion. J. struct. Geol. 6, 603–606.
CABY, R., KIENAST, J. R. & SALIOT, O. 1978: Structure, métamorphisme et modèle d'évolution tectonique des Alpes occidentales. Rev. Géogr. phys. Géol. dyn. 20, 307–322.
CANNIC, S., LAPIERRE, H. & MUGNIER, J. L. 1993: The Versoyen: an intriguing metamorphic basaltic complex at the boundary between internal and external domains of the western Alps. Terra Abstr. 5: 423.
CANNIC, S., MUGNIER, J. L., LAPIERRE, H., LARDEAUX, J. M., HUNZIKER, J. C. & HERNANDEZ, J. 1995: The lower Penninic nappes in the Western Alps: the link between Helvetic and Penninic. Discussion. J. struct. Geol. 17, 1481–1484.
CARPÉNA, J., POGNANTE, U. & LOMBARDO, B. 1986: New constraints for the timing of the Alpine metamorphism in the internal ophiolitic nappes from the Western Alps as inferred from fission track data. Tectonophysics 127, 117–127.
CATHELINEAU, M. 1988: Cation site occupency in chlorites and illites as a function of temperature. Clay Miner. (Bull.) 23, 471–485.
CATHELINEAU, M. & NIEVA, D. 1985: A chlorite solid solution geothermometer. The Los Azufres geothermal system. Contr. Mineral. Petrol. 91, 235–244.
CAWTHORN, R. G. & COLLERSON, K. D. 1974: The recalculation of pyroxene end-member parameters and the estimation of ferrous and ferric iron content from electron microprobe analyses. Amer. Mineralogist 59, 1203–1208.
CHOPIN, C. 1981: Talc-phengite: a widespread assemblage in high-grade pelitic blueschist of the Western Alps. J. Petrol. 22, 628–650.
– 1987: Very-high-pressure metamorphism in the western Alps: implications for subduction of continental crust. Phil. Trans. r. Soc. London 321, 183–197.
COLEMAN, R. G., BEATTY, L. B. & BRANNOCK, W. W. 1965: Eclogites and eclogites: their differences and similarities. Bull. geol. Soc. Amer. 76, 483–508.
COLOMBI, A. & PFEIFER, H. R. 1986: Ferrogabbroic and basaltic meta-eclogites from the Antrona mafic-ultramafic complex and the Centovalli-Locarno region (Italy and Southern Switzerland) – first results. Schweiz. mineral. petrogr. Mitt. 66, 99–110.
DAL PIAZ, G. V. 1974: Le métamorphisme de haute pression et basse température dans l'évolution structurale du bassin ophiolitique alpino appenninique. Schweiz. mineral. petrogr. Mitt. 54, 399–424.
DAL PIAZ, G. V., HUNZIKER, J. C. & MARTINOTTI, G. 1972: La zona Sezia-Lanzo e l'evoluzione tettonico metamorfica delle Alpi nord-occidentali interne. Mem. Soc. geol. ital. 11, 433–460.
DESMONS, J. 1977: Mineralogical and petrological investigations of Alpine metamorphism in the internal French Western Alps. Amer. J. Sci. 277, 1045–1066.
DROOP, G. T. R., LOMBARDO, B. & POGNANTE, U. 1990: Formation and distribution of eclogitic facies rocks in the Alps. In: Eclogite facies rocks (Ed. by CARSWELL, D. A.). Glasgow, 225–259.
ELLIS, D. J. & GREEN, D. H. 1979: An experimental study on the effect of the Ca upon garnet-clinopyroxene Fe-Mg exchange equilibria. Contr. Mineral. Petrol. 71, 13–22.
ERNST, W. G. 1968: Amphiboles. Springer Verlag, New-York, 125.
– 1971: Metamorphic zonation on presumably subducted lithospheric plates from Japan, California and the Alps. Contr. Mineral. Petrol. 34, 43–59.
ERNST, W. G. & DAL PIAZ, G. V. 1978: Mineral parageneses of eclogitic and related mafics schists of the Piemonte ophiolite nappe, Breuil-St Jacques area, Italian Western Alps. Amer. Mineralogist 63, 621–640.
ESSENE, E. J. & FYFE, W. S. 1967: Omphacite in California metamorphic rocks. Contr. Mineral. Petrol. 15, 1–23.
FREY, M., HUNZIKER, J. C., BOCQUET, J., DAL PIAZ, G. V., JÄGER, E. & NIGGLI, E. 1974: Alpine metamorphism of the Alps. A review. Schweiz. mineral. petrogr. Mitt. 54, 247–290.
FRY, N. & BARNICOAT, A. C. 1987: The tectonic implications of high-pressure metamorphism in the Western Alps. J. geol. Soc. (London) 144, 653–659.
FUDRAL, S. 1973: Contribution à l'étude de l'unité de Moutiers entre le torrent du Cormet d'Arêches et le hameau des Chapieux. PhD thesis Univ. Grenoble.
– 1980: Une nouvelle interprétation de l'unité des Salins (zone des brèches de Tarentaise) au nord de Bourg-Saint-Maurice (Savoie). Conséquences structurales. C.R. Acad. Sci. (Paris) 290, 1333–1336.
GANGULI, J. 1979: Garnet and clinopyroxene solid solutions and geothermometry based on Fe-Mg distribution coefficient. Geochim. cosmochim. Acta 43, 1021–1029.
GELY, J. P. 1989: Stratigraphie, tectonique et métamorphisme comparés de part et d'autre du Front pennique en Tarentaise (Alpes de Savoie, France). PhD thesis Univ. Chambéry.

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

GUILLET, P., CHOUKROUNE, P., BALLÈVRE, M. & DAVY, P. 1986: Thickening history of the Western Alps. Earth and planet. Sci. Lett. 78, 44–52.

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

HOLLAND, T. J. B. 1979: Experimental determination of the reaction paragonite: jadeite + kyanite + H2O and internally consistent thermodynamic data for part of the system Na_2O-Al_2O_3-SiO_2-H_2O with applications to eclogites and blueschist. Contr. Mineral. Petrol. 68, 293–301.

– 1980: The reaction albite = jadeite + quartz determined experimentally in the range 600°–1200°C. Amer. Mineralogist 64, 129–134.

– 1983: The experimental determination of activities in disordered and short-range ordered jadeitic pyroxenes. Contr. Mineral. Petrol. 82, 214–220.

HUNZIKER, J. C., DESMONS, J. & HURFORD, A. J. 1992: Thirty-two years of geochronological work in the Central and Western Alps: a review on seven maps. Mem. Géol. Lausanne 13, 59.

HURFORD, A. J. & HUNZIKER, J. C. 1989: A revised thermal history for the Grand Paradiso Massifs. Schweiz. mineral. petrogr. Mitt. 69, 319–329.

KROGH, E. J. 1988: The garnet-clinopyroxene Fe-Mg geothermometer – a reinterpretation of existing experimental data. Contr. Mineral. Petrol. 99, 44–48.

LANCELOT, J. C. 1979: Etude tectonique de la zone des brèches de Tarentaise dans la région de Bourg-Saint-Maurice, Savoie. PhD thesis Univ. Paris VII.

LARDEAUX, J. M., GOSSO, G., KIENAST, J. R. & LOMBARDO, B. 1982: Relations entre le métamorphisme et la déformation dans la zone de Sézia-Lanzo (Alpes occidentales) et le problème de l'éclogitisation de la croûte continentale. Bull. Soc. géol. France 24, 793–800.

LARDEAUX, J. M., NISIO, P. & BOUDEULLE, M. 1987: Deformational and metamorphic history at the Lago Superiore area of the Monviso ophiolitic complex (Italian Western Alps): a record of subduction-collision cycle? Ofioliti 12, 479–502.

LARDEAUX, J. M. & SPALLA, M. I. 1991: From granulites to eclogites in the Sesia zone (Italian Western Alps): a record of the opening and closure of the Piemont ocean. J. metamorph. Geol. 9, 35–59.

LASSERRE, J. L. & LAVERNE, C. 1976: Le volcanisme tholeiitique de la zone du Versoyen (Alpes franco–italiennes): minéralogie, pétrographie et géochimie. PhD thesis Univ. Grenoble.

LEAKE, B. E. 1978: Nomenclature of amphiboles. Amer. Mineralogist 63, 1023–1052.

LOMBARDO, B., NERVO, R., COMPAGNONI, R., MESSIGA, B., KIENAST, J. R., MEVEL, C., FIORA, L., PICCARDO, G. B. & LANZA, R. 1978: Osservazioni preliminari sulle ofioliti metamorfiche del Monviso (Alpi occidentali). Rend. Soc. ital. Mineral. Petrol. 34, 253–305.

LOUBAT, H. 1968: Etude pétrographique des ophiolites de la "zone du Versoyen" Savoie (France). Province d'Aoste (Italie). Arch. Sci. (Genève) 28.

– 1984: Considérations préliminaires sur la configuration horizontale de l'édifice subvolcanique du Versoyen (Alpes franco-italiennes) analogue aux bassins du type Golfe de Californie. Géol. alp. (Grenoble) 60, 37–44.

MARESCH, W. V. 1977: Experimental studies of glaucophane: an analysis of present knowledge. Tectonophysics 43, 109–125.

MASSONNE, H. J. 1981: Phengite: Eine experimentelle Untersuchung ihres Druck-Temperatur-Verhaltens im System K_2O–MgO-Al_2O_3-SiO_2. PhD thesis Univ. Bochum.

MASSONE, H. J., MIRWALD, P. W. & SCHREYER, W. 1981: Experimentelle Überprüfung der Reaktionskurve Chlorit + Quartz = Talk + Disthen im System MgO-Al_2O_3-SiO_2-H_2O. Fortschr. Mineral. 59, 122–123.

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

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

MILLER, C. 1990: Petrology of the type locality eclogites from the Koralpe and Saualpe (Eastern Alps), Austria. Schweiz. mineral. petrogr. Mitt. 70, 287–300.

MUGNIER, J. L., LOUBAT, H. & CANNIC, S. 1993: Correlation of seismic images and geology at the boundary between internal and external domains of the western alps. Bull. Soc. géol. France 164, 697–708.

NEWTON, R. C. & KENNEDY, G. C. 1963: Some equilibrium reactions in the join $CaAl_2Si_2O_8$-H_2O. J. geophys. Res. 68, 2967–2983.

NITSCH, K. H. 1970: Experimental-Bestimmung der oberen Stabilitätsgrenze von Stilpnomelan. Fortschr. Mineral. 47, 47–49.
– 1971: Stabilitätsbeziehungen von Prehnit und Pumpellyit-haltigen Paragenesen. Contr. Mineral. Petrol. 30, 240–260.
OBERHÄNSLI, R., HUNZIKER, J. C., MARTINOTTI, G. & STERN, W. 1985: Geochemistry, geochronology and petrology of Monte Mucrone: an example of eoalpine eclogitisation of Permian granitoids in the Sezia-Lanzo zone, Western Alps, Italy. Chem. Geol. 52, 165–184.
PLATT, J. P. & VISSERS, R. L. M. 1980: Extensional structures in anisotropic rocks. J. struct. Geol. 2, 397–410.
POGNANTE, U. 1984: Eclogitic versus blueschist metamorphism in the internal Western Alps along the Susa Valley traverse. Sci. géol. (Strasbourg) 37, 29–36.
– 1989a: Tectonic implications of lawsonite formation in the Sezia zone (Western Alps). Tectonophysics 162, 219–227.
– 1989b: Lawsonite, blueschist and eclogite formation in the southern Sezia zone (western Alps, Italy). Europ. J. Mineral. 1, 89–104.
POGNANTE, U. & KIENAST, J. R. 1987: Blueschist and eclogite transformation in Fe-Ti gabbros: A case from the Western Alps ophiolites. J. Petrol. 28, 2, 271–292.
POLINO, R. , DAL PIAZ, G. V. & GOSSO, G. 1990: The alpine cretaceous orogeny: an accretionary wedge model based on integred stratigraphic, petrologic and radiometric data. Mem. Soc. géol. France 156, 345–367.
POWEL, R. 1985: Regression diagnostics and robust regression in geothermometer/geobarometer calibration: the garnet-clinopyroxene geothermometer revised. J. metamorph. Geol. 3, 231–243.
RAHEIM, A. & GREEN, D. H. 1974: Experimental determination of the temperature and pressure dependence of the Fe-Mg partition coefficient for coexisting garnet and clinopyroxene. Contr. Mineral. Petrol. 48, 179–203.
RAMSAY, J. G. & HUBER, M. I. 1987: The technique of modern structural geology, 2. Academic press, London.
REINECKE, T. 1991: Very high pressure metamorphism and uplift of coesite-bearing metasediments from the Zermatt-Saas Zone, Western Alps. Europ. J. Mineral. 10, 7–17.
RICKWOOD, P. C. 1968: On recasting analyses of garnet into and-member molecules. Contr. Mineral. Petrol. 18, 175–198.
RUBIE, D. C. 1984: A thermal-tectonic model for high-pressure metamorphism and deformation in the Sesia zone, Western Alps. J. Geol. 92, 21–36.
SAXENA, S. K. 1979: Garnet-clinopyroxene geothermometer. Contr. Mineral. Petrol. 70, 151–158.
SELVERSTONE, J. 1985: Petrologic constraints on imbrication, metamorphism and uplift in the SW Tauern window, Eastern Alps. Tectonics 4, 687–704.
SEWARD, D. & MANCKTELOW, N. S. 1994: Neogene kinematics of the central and western Alps: Evidence from fission-track dating. Geology 22, 803–806.
SCHIFFMAN, P. & FRIDLEIFSSON, G. O. 1991: The smectite-chlorite transition in drillhole NJ 15. Nesjavellir geothermal field, Iceland: XRD, BSE and electron microprobe investigation. J. metamorph. Geol. 9, 679–696.
SCHOELLER, H. 1929: La nappe de l'Embrunais au nord de l'Isère. Bull. Carte géol. France 175, 422.
SCHÜRCH, M. L. 1987: Les ophiolites de la zone du Versoyen: témoin d'un bassin à évolution métamorphique complexe. PhD thesis Univ. Genève.
SHIDO, F. & MIYASHIRO, A. 1959: Hornblendes of basic metamorphic rocks. J. Fac. Sci. Tokyo Univ. sec. II, 12, 85–102.
TRÜMPY, R. 1955: Remarques sur la corrélation des unités penniques externes entre la Savoie et le Valais et sur l'origine des nappes préalpines. Bull. Soc. géol. France 6, 217–231.

Manuscript received May 7, 1995
Revision accepted August 10, 1995