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Low-angle extrusion of high-pressure rocks and the balance between outward and inward displacements of Middle Penninic units in the western Alps

RENAUD CABY

Dedicated to Prof. François Ellenberger

Key words: Low-angle extrusions, synmetamorphic thinning, high pressure-low temperature metamorphism, Middle Penninic domain, Western Alps

ABSTRACT

The structures, the kinematics and the metamorphic evolution of units of the Middle Penninic domain are described in the Franco-Italian part of the western Alps. In the Hautes Alpes, the first deformation affecting most of the external Briançonnais zone with Carboniferous basement (zone Houillère) consists of east-verging folds. A west-dipping ductile normal/strike-slip fault delimits to the west an external sub-domain with N-S open folding which represents the shallowest crustal level (P = 4-5 kbar, T = 300°C). In the east, the frontal units of the Piemont zone *s.l.* obducted in post-Eocene times on the internal Briançonnais platform (internal Briançonnais) plunge westward beneath the external Briançonnais zone. Rocks of the Piemont-Liguria zone were intensely deformed under blueschist facies metamorphism (P = 7-9 kbar, T = 350-400°C) and record mainly early east-directed movements. The sharp tectonic contact between the Piemont zone *s.l.* and the external Briançonnais zone that dips outwards all along the Alpine arc, is interpreted as an extensional ductile fault that assisted exhumation of the blueschists. A deeper tectono-metamorphic evolution characterizes the internal Briançonnais zone (Acceglio zone) below (P = 10-12 kbar, T = 400-450°C) that was exhumed in the form of east-verging extrusions within overlying Piemonts units. North of the Savoy, east-verging extrusions also allowed the exhumation of the Ruitor Massif which represents the deepest parts of the inner Briançonnais zone with Alpine garnet-blueschist facies and eclogites (P≥ 12 kbar, T = 450-500°C). This massif is delimited from the zone Houillère to the west by a major extensional ductile fault, with associated syn-metamorphic thinning of the whole tectonic pile.

The east verging exhumation of both the continental and the oceanic high-pressure units imply their initial down-dragging in a west-dipping subduction complex. Farther north in the Val d'Aoste, the Grand Saint-Bernard nappe overlain by the Tsaté nappe with the Dent Blanche nappe on top cuts off the west-dipping tectonic edifice.

The mechanism of low-angle "forced" extrusions is discussed in the light of the rheological properties and the movement pattern of the deepest eclogitised Alpine crust attached to the lithospheric mantle and in the light of experimental models of subduction-type collisional belts.

RESUME

Les structures, la cinématique des déformations et l'évolution métamorphique des diverses unités de la zone pennique moyenne sont décrites dans les Alpes occidentales franco-italiennes sur l'exemple de trois transversales. Dans les Hautes-Alpes et le Queyras qui représentent le niveau crustal le moins profond, les plis à vergence interne intéressent la plus grande partie de la zone briançonnaise externe à socle permo-houiller (zone

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Houillère) et représentent la première déformation d'âge post-éocène. Une faille ductile à pendage ouest sépare ce sous-domaine des parties frontales plus superficielles de la zone houillère (P = 4-5 kbar, T = 300°C) affectée par des plis droits. A l'est, les unités frontales de la zone piémontaise *s.l.* à métamorphisme de HP (P = 7-9 kbar, T = 350-400°C) plongent régulièrement vers l'ouest sous la zone briançonnaise externe. A toutes échelles, les structures cisaillantes acquises à HP y indiquent globalement aussi des déplacements dirigés vers l'est. Le contact zone piémontaise *s.l.* / zone briançonnaise externe, qui est classiquement considéré comme un rétrocharriage tardif, est interprété sur la base de critères cinématiques et thermobarométriques comme une faille ductile majeure responsable de l'exhumation des schistes bleus tout au long de l'arc alpin. Les parties les plus internes de l'ancienne plateforme briançonnaise (Briançonnais interne) à couverture mésozoïque/tertiaire réduite (zone d'Acceglio) ont subi une évolution tectono-métamorphique alpine plus profonde (P = 10-12 kbar, T = 400-450°C) et émergent de sous la zone piémontaise externe à la faveur d'extrusions faiblement inclinées à vergence est. Au nord de la Savoie, les structures à vergence interne du massif de Ruitor, lui aussi recristallisé dans le faciès schiste bleu à grenat avec occurences éclogitiques, sont aussi interprétées comme des extrusions tangentielles mises en place vers l'est et séparées de la zone houillère par une faille normale ductile majeure, avec amincissement syn-métamorphique de l'ensemble de la pile tectonique. Un contexte de subduction d'âge éocène à pendage ouest est ainsi proposé pour l'acquisition des paragénèses de HP aussi bien dans les unités à matériel continental qu'océanique de la zone pennique moyenne. Au nord de la Savoie, l'avançée tardive vers le NW de la nappe du Grand Saint-Bernard, coiffée par la nappe du Tsaté avec au sommet la nappe de la Dent Blanche, a tronqué ces structures à pendage externe.

Le mécanisme de genèse de ces extrusions tangentielles est discuté, en prenant en compte la rhéologie et les déplacements de la croûte alpine profonde éclogitique, ainsi que les résultats de modèles expérimentaux.

1. Introduction

The traditional concept of outwards displacement of units of the Middle Penninic domain, followed by inward displacement or back-thrusting, has been inspired by the "fan" geometry of the Briançonnais zone (Kilian 1903; Argand 1916; Lemoine 1961; Fabre 1961; Gidon 1962). Unfortunately, only the outward thrusting of the frontal units of the Middle Penninic domain onto the Sub-Briançonnais domain or onto the parautochthonous cover of the external massifs in the French Alps is usually considered by geodynamic interpretations.

However, the overall westward dip of all units of the Middle Penninic domain in the Graie Alps and the Cottian Alps represents the main structural feature of the Middle Penninic domain in the western Alps and this geometry is inconsistent with the classical assumption of predominant outward displacements of units and nappes. Moreover, the distribution of metamorphic zones in the Middle Penninic domain is consistent with a normal polarity (higher pressure conditions always downward, Caby et al. 1978) unlike in the Central Alps.

New data on the geometry, metamorphic evolution and kinematic history of the several units now distinguished in the Middle Penninic domain have been gathered all along the Alpine arc between the Grand Saint Bernard pass and the Ligurian Alps, in order to clarify the balance of inward and outward displacements with respect to the Alpine arc and to establish their relationships in time and space. The structures and the related metamorphic evolution are described and evaluated in the inner Briançonnais domain and the western part of the Piemont zone *s.l.* at different crustal levels along the Alpine arc. Several synthetic and detailed profiles based on mapping at 1:20.000 performed in the Cottian Alps and in the Graie Alps are presented. Based on the evidence for early inward displacements in high-pressure conditions and on syn-metamorphic thinning, it is proposed that large parts of the inner Briançonnais platform in the Cottian Alps and the

Graie Alps were involved in a west-dipping subduction setting, as their oceanic counterparts. Their rapid exhumation occurred as low-angle forced extrusions directed towards the inner part of the arc during the main stage of late Eocene Alpine contraction.

2. Main characteristics and paleogeographic evolution of units derived from the Middle Penninic paleogeographic domain in the Western Alps

2.1 Pre-Triassic evolution of the composite basement

The zone Houillère is the basement of the external part of the Briançonnais zone (Fig. 1). This longitudinal domain may well represent a late-orogenic basin within the Variscan belt up to 300 km long and at least 40 km wide, taking into account an estimated shortening of about 50% at the latitude of Briançon. It comprises a >3-4 km thick continental terrigenous formation ranging in age from Namurian to Early Permian. Calc-alkaline magmatic activity initiated during the Stephanian, was followed by rhyolitic volcanism of Middle Permian age. In the Ligurian Alps, the zone Houillère was buried below the thick Permian volcanic cover and was also intruded by thick sills and laccoliths of porphyries and hypovolcanic granites, some of them with sub-alkaline affinity (Cortesogno et al. 1993). In contrast, the inner part of the Briançonnais zone is floored by pre-Permian metamorphic rocks subsequently affected by severe Alpine metamorphism (Ellenberger 1958; Fabre 1961). This pre-Permian basement exposed in the Ruitor, southern Vanoise, Ambin areas and in the Acceglio zone (Fig. 1) is composed of amphibolite facies metamorphics comprising Al-rich metapelites, amphibolites and various gneisses. $^{40}Ar/^{39}Ar$ dating of pre-Alpine metamorphic muscovite and biotite has given ages in the range of 340-360 Ma in both be Acceglio basement and in the Ambin massif (Monié 1990) whereas magmatic muscovite from granitoids of the Sapey massif at Modane indicates a Variscan age around 320 Ma (Monié, written communication, 1991). The more internal parts of the Briançonnais basement exposed in northern Vanoise comprise bimodal metavolcanics, black schists cut by sills of diabases and metamicrogranites with a granophyric structure. In the Aosta valley, black schists are intruded by the Cogne dioritic massif with subordinate gabbro, peripheral orthogneiss dikes and related aplites and pegmatites. The whole unit underwent greenschist facies Alpine metamorphism only. A Cambrian age of the protoliths is suggested by the U-Pb zircon age of 507 Ma obtained in Savoie on an intrusive granophyric sill (Guillot et al. 1991).

2.2 The Briançonnais zone: platform to passive continental margin evolution followed by Eocene syn-orogenic flysch

The Middle Penninic units are part of the former Mesozoic platform (Briançonnais zone) characterized by shallow marine deposits of Early and Middle Triassic age. The Late-Triassic to Early Jurassic rifting period responsible for normal faulting, tilted blocks and local unconformities, produced strong uplift of the inner parts of this platform, with the frequent erosion of Middle to Upper Triassic carbonates. Upper Jurassic rocks typically rest on quartzites and on pre-Permian basement rocks in the Acceglio zone and the Ambin and Ruitor massifs. Upper Cretaceous to Paleocene calcschists with fossiliferous hard grounds indicate a deep sea environment, ending with the deposition of a black Tertiary

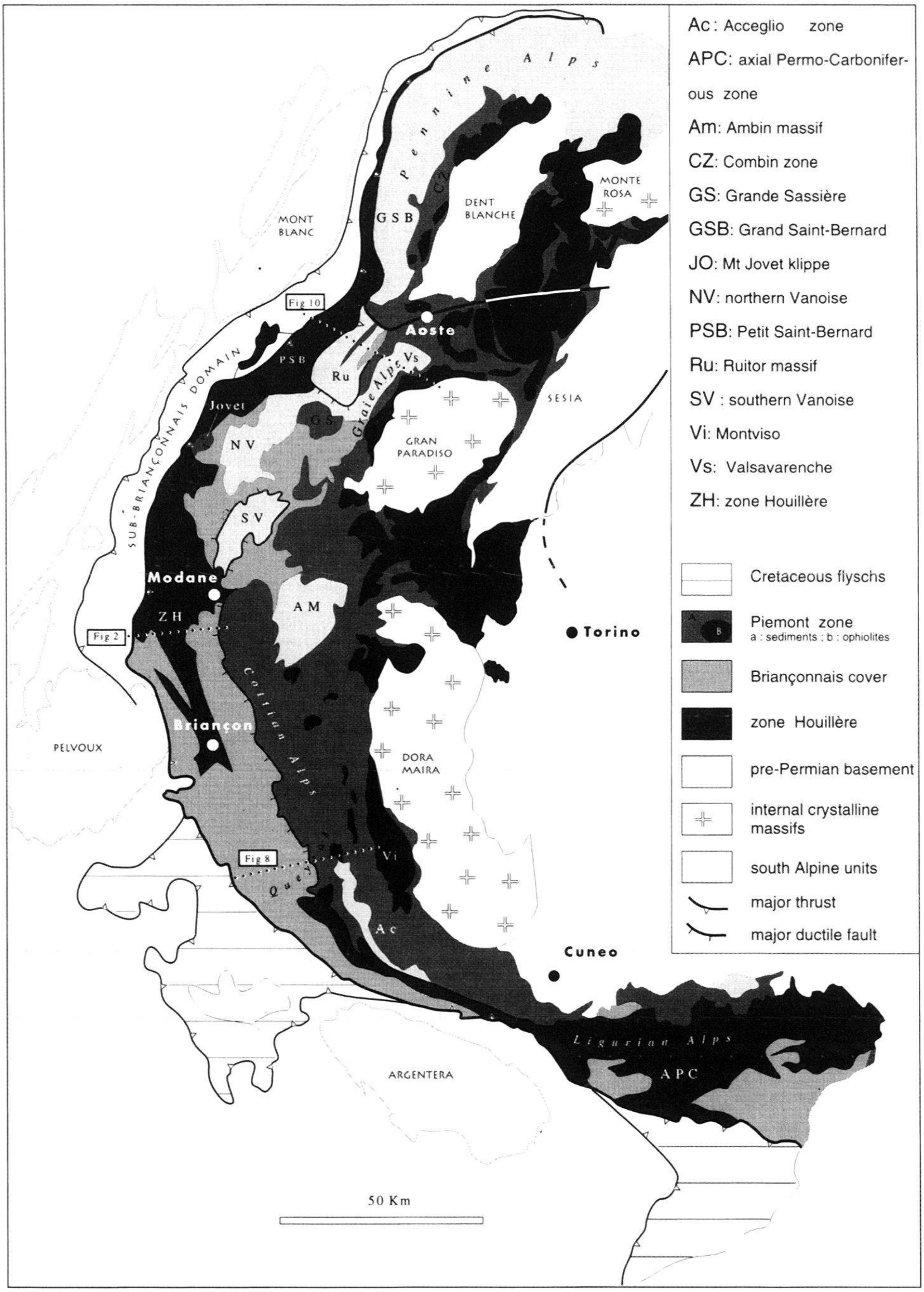


Fig. 1. Geological map of the western Alps. Only the Middle Penninic units are shown in detail.

flysch dated as Early Bartonian in age (around Briançon) into which olistostromes of crystalline rocks ("quatrième écaille", Barfety et al. 1992) and the Upper Cretaceous Helminthoid flyschs were emplaced. In the following sections, the term "external Briançonnaise zone" refers to its outer part with Carboniferous basement, complete Mesozoic to Tertiary cover and relatively weak Alpine metamorphism, whereas the "inner Briançonnaise zone" refers to its inner part with pre-Carboniferous basement, thin Mesozoic cover and blueschist facies metamorphism similar to that of the adjacent Piemont-Ligurian zone.

2.3 The Piemont zone s.l.

The Piemont zone *s.l.* includes the external "pre-Piemont" units deposited on thinned continental crust possibly adjacent to the inner Briançonnais zone, refered to as the external Piemont zone, and the Piemont-Liguria zone which was floored by pre-Jurassic oceanic crust and mantle (Lemoine 1971). The external Piemont units in the Cottian Alps comprises detached Carnian evaporites, Norian dolomites (800-1000 m), Liassic to Jurassic turbiditic slope facies and black shales of assumed Early Cretaceous age. Since this unit is mostly exposed along the external part of the Piemont zone, it has generally been regarded to represent the western passive margin of the Piemont oceanic basin. However, this unit is also exposed right in the middle of the Piemont-Liguria zone south of the Ambin massif (Lemoine 1971).

The Piemont-Liguria zone comprizes an oceanic basement made up of mantle peridotites mainly derived from lherzolites, gabbros and pillow basalts, both with MORB compositions, all capped by radiolarites of Kimmeridgian to early Cretaceous age. The Piemont-Liguria zone rests with a major tectonic contact onto the internal crystalline massifs in the east and on the various basement units in the west, caped with their Briançonnais cover and exposed as windows and half windows in the southern Vanoise, in the Ambin massif and in the Acceglio zone (Fig. 1).

3. Alpine structures, kinematics and metamorphic evolution of Middle Penninic units along the Alpine arc

Three crustal sections across the Middle Penninic domain are described in detail (Fig. 2, 8, 10). In agreement with the variable pressure/temperature conditions recorded along the Alpine arc in both the Briançonnaise zone and the Piemont-Liguria zone, these will be presented from shallower to increasingly deeper crustal levels, i.e. from the Cottian Alps in southern Savoie, to the Hautes-Alpes in the Queyras and then to the Graie Alps south of the Val d'Aoste (Fig. 1).

3.1 Southern Savoie/northern Hautes-Alpes (Fig. 2)

Here the Carboniferius basement (zone Houillère) emerges northwand from below its autochthonous cover and/or the Briançonnais nappes exposed south of Briançon. In the east, this zone is in direct contact with the Piemont zone *s.l.* which includes external Piemont units in its western part. North of Modane, the southern Vanoise massif, a large domal structure emerges from below the Piemont zone.

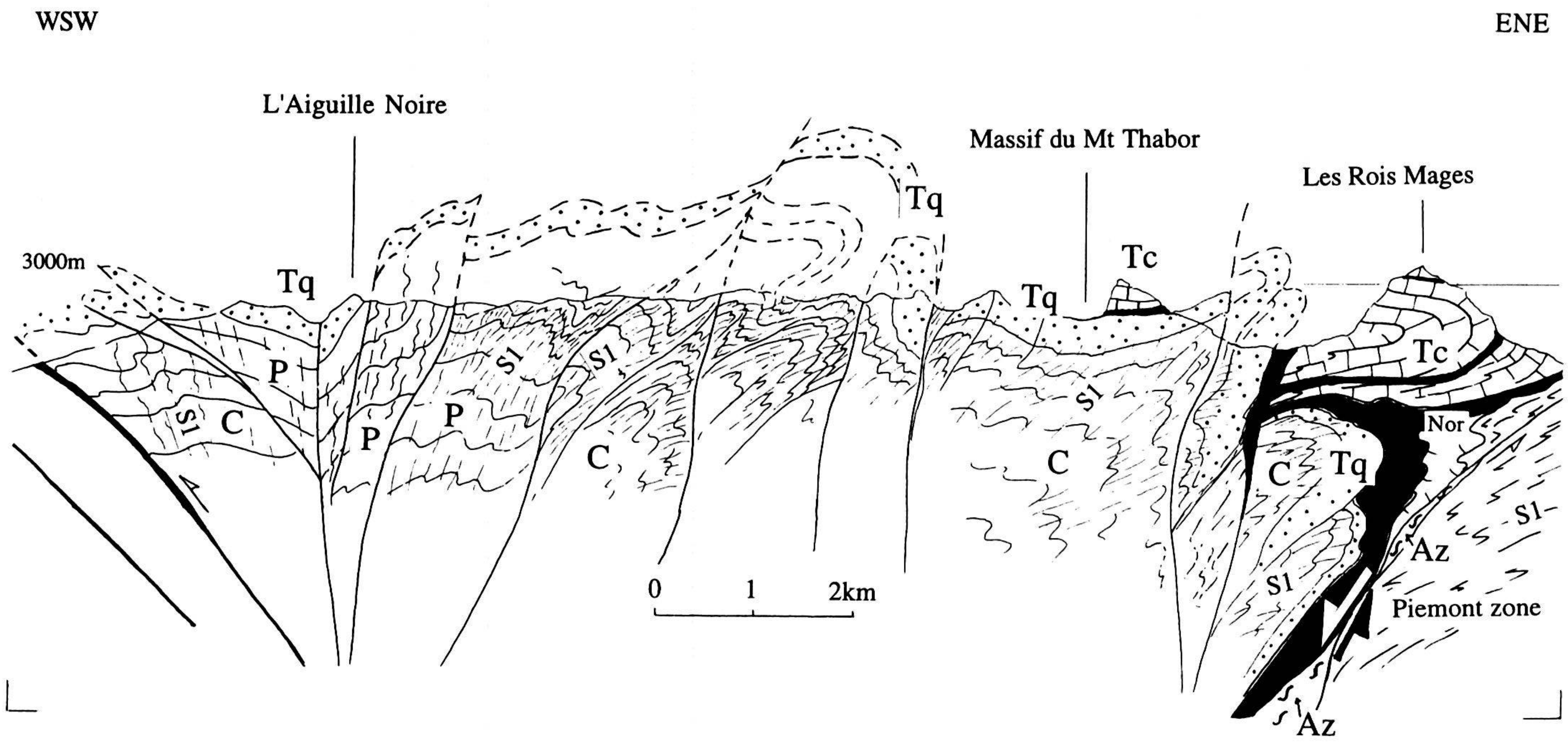


Fig. 2. Interpretative cross section of the Briançonnais zone in between Hautes Alpes and southern Savoie. Structures above the topographic surface as well as the deep structure of the eastern part of the section are projected from the north. Note how the steep S1 cleavage in the west becomes gradually recumbent going east (S2 not indicated). C: Carboniferous rocks; P: undifferentiated Permian rocks; Tq: Early Triassic quartzite and underlying latest Permian conglomerate; Tc: Middle to Late Triassic carbonates; Nor: Norian dolomite and fossiliferous Liassic sediments; AZ: slices of gneisses (jadeite-bearing) of the Acceglio zone. In black: Keuper evaporites.

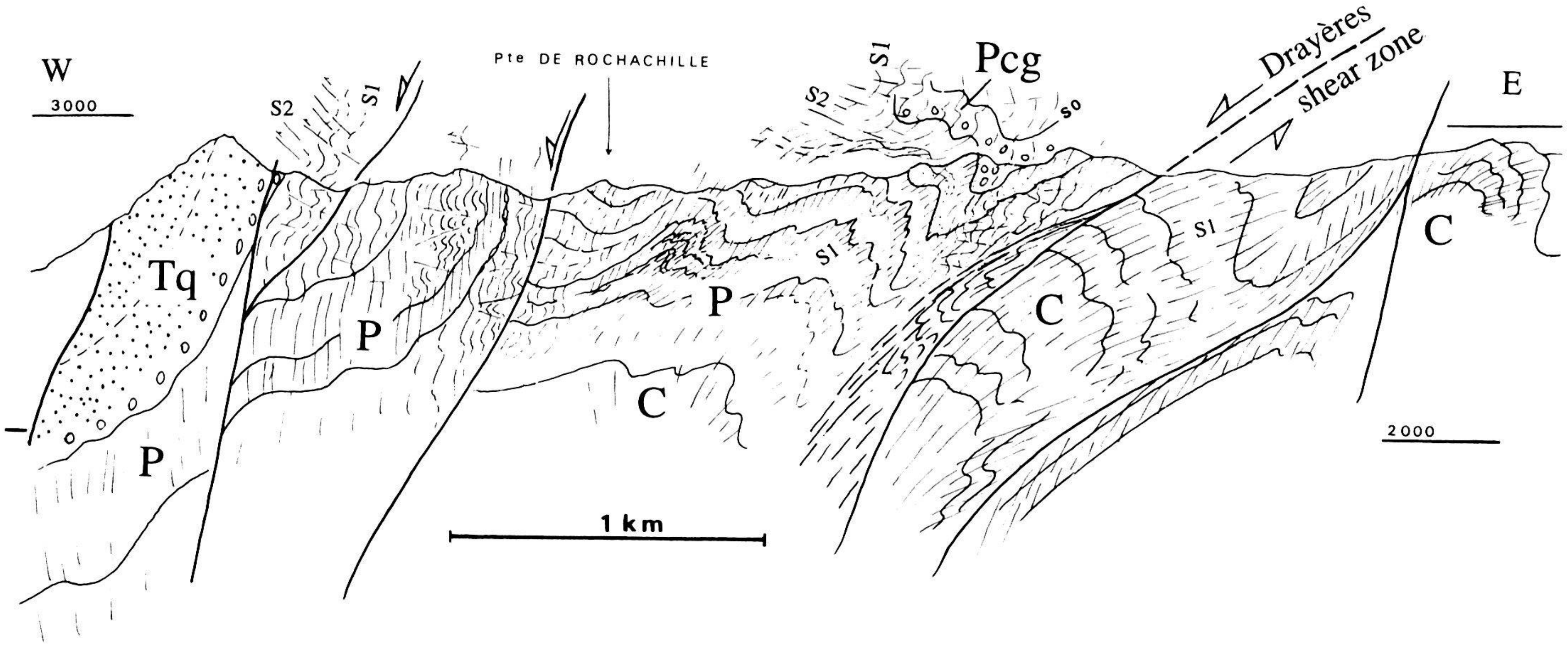


Fig. 3. Detailed cross-section of the Permian basin (enlarged part of Fig. 2) showing how S1 is folded by F2 folds and cut by the S2 cleavage (for more clarity, S2 is only represented in Permian rocks). C: Carboniferous rocks; P: Permian red beds; Pcg: Late Permian conglomerate.

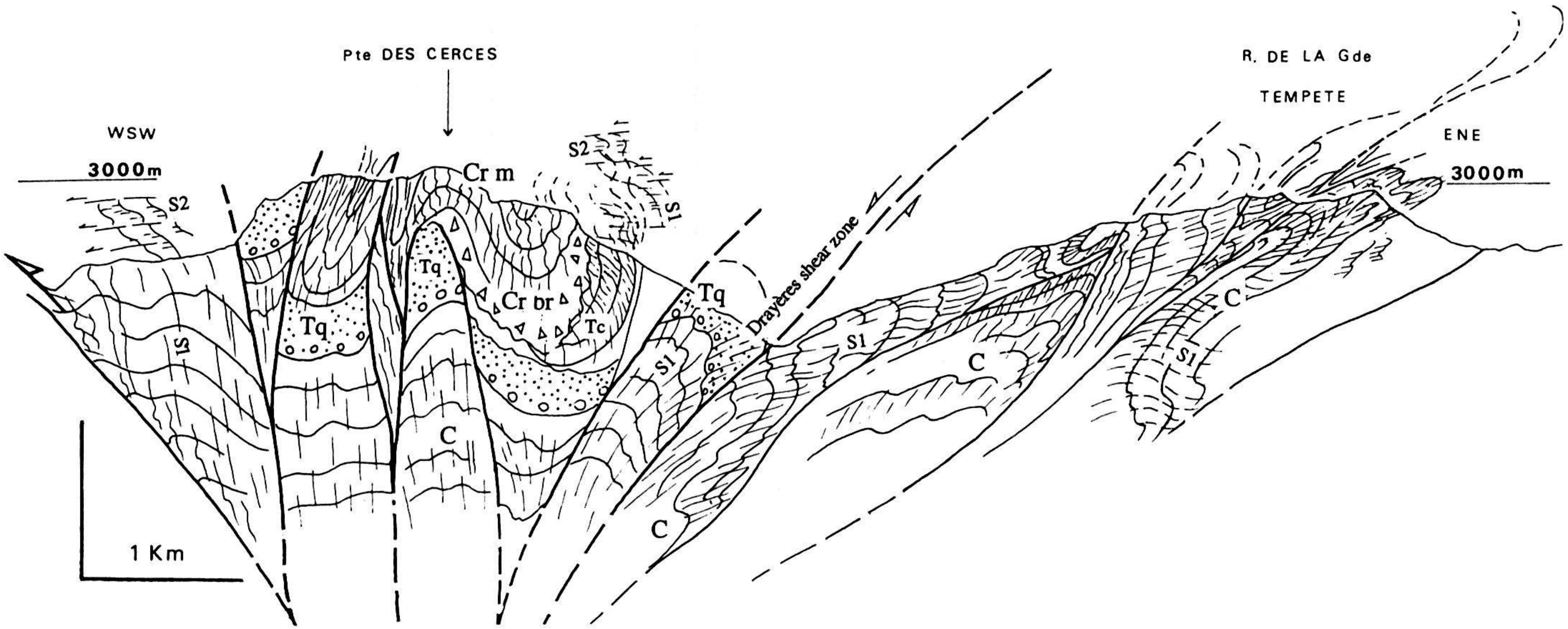


Fig. 4. Profile across the Massif des Cerces Mesozoic syncline, located 5 km south of Figure 2. Note the fan geometry of S1 cleavage and the subhorizontal S2 spaced cleavage associated with west-directed shear bands in Cretaceous rocks (S2 is not indicated in Carboniferous rocks). Some steep faults rework syn-sedimentary Mesozoic normal faults. C: Carboniferous rocks (fossiliferous Namurian in the west). Tq: Early Triassic quartzite; Tc: Middle to Late Triassic carbonates (the Late Jurassic marbles on top not represented); Cb: intraformational Late Cretaceous breccias; Cs: Late Cretaceous marls.

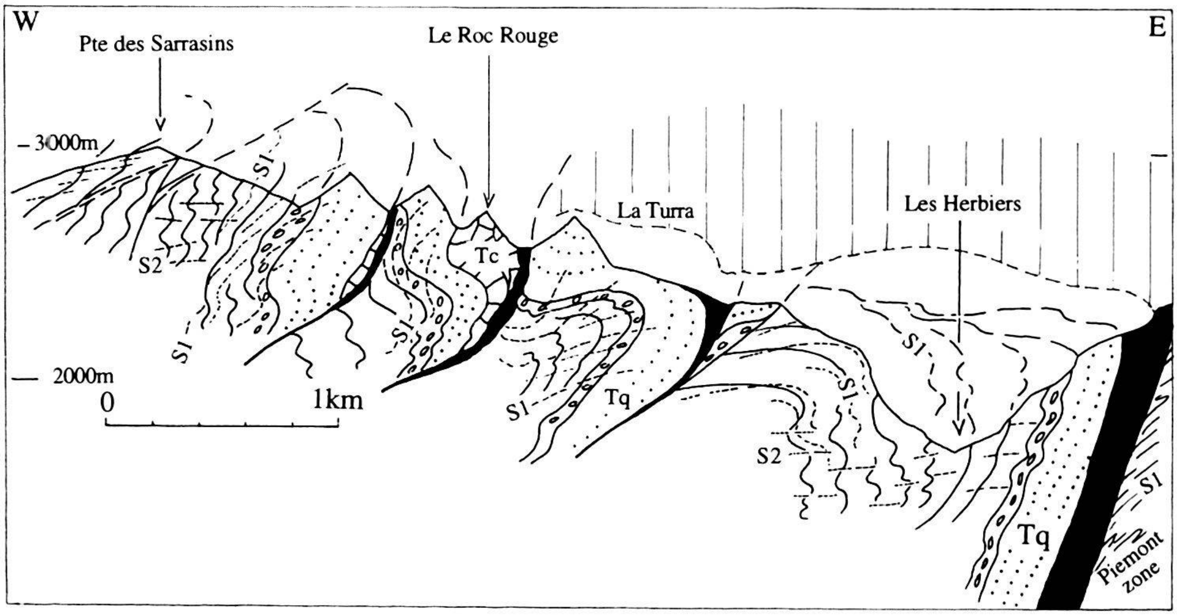


Fig. 5. Detailed profile of the eastern margin of the zone Houillère 10 km south of Modane (ca. 10 km north of the section Fig. 2). Early east-verging folds involving the Carboniferous rocks (C) and the Mesozoic cover (Triassic quartzite: Tq; Triassic carbonates: Tc) (F1) in the western part with S1 axial planar slaty cleavage are slightely redeformed. In the east, S1 related to a right way up section is itself passively deformed by a large F2 fold. Thrusts delineated by Middle Triassic anhydrite and cornieules may have been initiated synchronously with F1 folding and reactivated during F2 folding. The dashed area above the topography relates to the Rois Mages nappe (see Fig. 2) the northern edge of which is exposed 1 km south of the profile.

3.1.1 The zone Houillère and its Mesozoic cover

The fan structure of the zone Houillère is well established by the rather simple geometry of the undetached Lower Triassic quartzites. To the west, N-S trending open folds display a subvertical spaced cleavage (S1) grading to a slaty cleavage in Permian red shales and in volcanics (Fig. 2, 3). Matrix-supported conglomerates with andesite pebbles occasionaly display evidence of pure flattening, as demonstrated by the radial geometry of stretching lineations around rigid pebbles, some of them cut by veinlets of quartz+lawsonite+albite. Domains with vertical stretching lineations have also been observed. The original attitude of the steep S1 axial plane cleavage is also recorded in synclines of the undetached Jurassic to Tertiary cover (Fig. 4). The S1 cleavage reaches lower dips going eastward, with the development of a spectacular superposed spaced cleavage (S2) in the Permian beds related to open folds with horizontal axial planes (Fig. 3, 6c-d). Along the Drayères shear zone (Fig. 3, 4), stretching lineations and associated asymmetric shear bands dipping 30° to the southwest indicate an extensional regime with a sinistral strike-slip component. East of this ductile fault, early N-S-trending folds are overturned to the east, with well-developed inverted limbs (Fig. 2, 4). As pointed out by Fabre (1961) and Fabre et al. (1982), this regime of early east verging folds characterizes most of the zone Houillère even in the south around Briançon. Detailed investigations between 2500 and 3000 m altitude south of Modane (Fig. 5) have revealed the occurence of upsid-down Carboniferous strata related to east-verging, plurihectometric recumbent folds with a

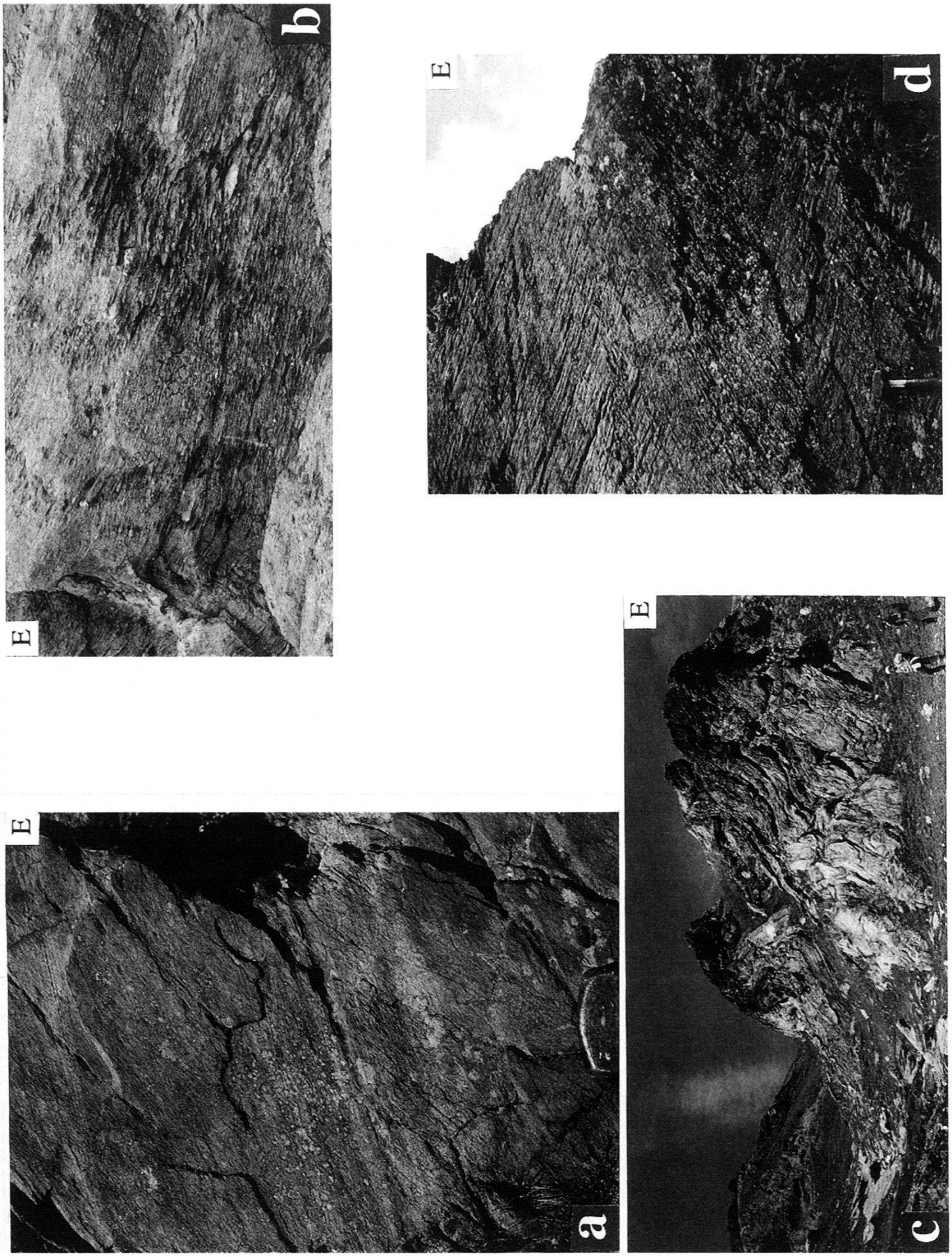
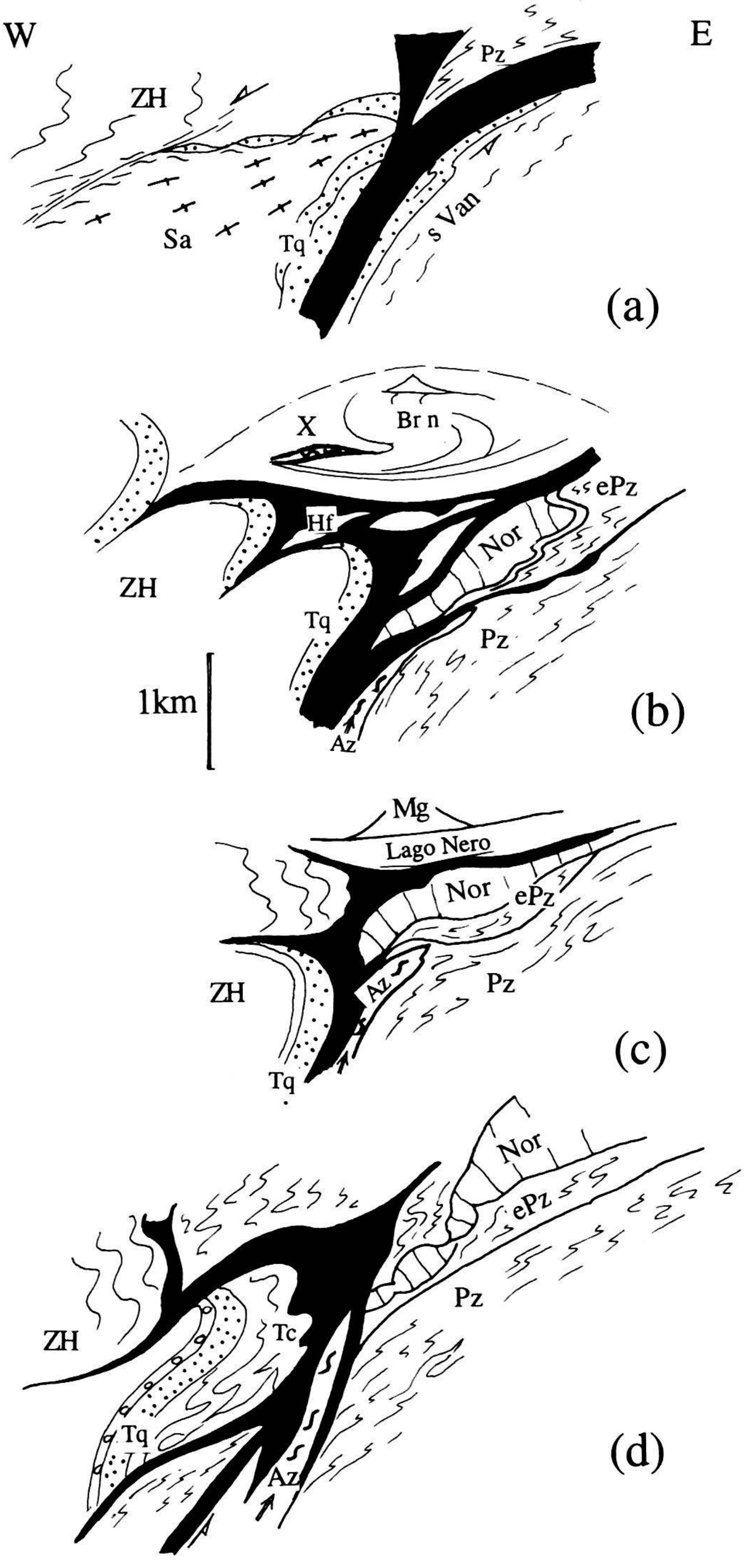


Fig. 6. Field aspect of the ductile deformation around the Drayères shear zone (see Fig. 3). (a) West dipping S1 cleavage in Carboniferous sandstone. (b) Hinge zone with subhorizontal S1 spaced cleavage in Carboniferous pebbly sandstone. (c) P2 folds with axes plunging 25° to N 160 affecting S0-S1 in mylonitic conglomerates, 2 km N of the Drayères refuge, 2450 m. (d) West-dipping S1 cleavage cut by east dipping S2 spaced cleavage in Permian coarse arkosic sandstone, 1,2 km NW of the Drayères refuge along the Clarée stream (looking north).

gently west-dipping slaty cleavage (Caby 1963). In impure sandstones (Fig. 6a-b), S1 is a spaced cleavage formed at high angles with bedding in normal limbs. Our interpretation differs from that of Fabre et al. (1982) and Bertrand et al. (1996) who regard the east-verging folds as post-dating an earlier cleavage parallel to bedding planes, which may have formed without associated folding. *Our* S1 indeed may parallel bedding in the inverted limbs, implying significant bedding plane parallel slip, especially in finely layered silts with a varve-like microstructure and enhanced by the coal horizons. In many cases, asymmetrical extensional shear bands that rework the S1 cleavage clearly indicate a top-to-the west extensional late movement. Bedding/S1 cleavage intersections measured preferentially in shaly horizons 10 to 20 km south of Modane strike between N50 and N90, implying the development of curved fold hinges. The Arc valley to the north also exposes a package of recumbent to isoclinal southeast-verging folds. These folds are curviplanar, with a mean fold axis trending between N50 and N120°. They formed under incipient blueschist facies conditions, as shown by the mineral assemblage glaucophane-lawsonite present in microdiorite sills (Fabre 1961; Saliot 1978) and the occurrence of lawsonite in Stephanian sandstones (Goffé, pers. communication). Variably oriented well-developed stretching lineations in protomylonitic sandstones and in matrix-supported conglomerates, as well as early slickensides defined by fibers of quartz and phengite are frequently oblique to S0/S1 intersections and display a rather high dispersion (from N50 to N120). The eastern margin of the zone Houillère is delineated by several imbricates of inverted limbs of Triassic quartzites with a gently west-dipping S1 slaty cleavage (Fig. 2, 5). The same east-verging structures are also recorded in the Sapey orthogneissic basement with its undetached Permo-Triassic quartzitic cover around Modane (Fig. 7a).

Along the eastern contact of the zone Houillère, a second generation of open to tight folds, displaying a subhorizontal axial-planar cleavage (S2) thoroughly overprinted early folds (Fig. 5). The original curvature of hinges of earlier folds has induced a considerable variation of F2 fold axes (from N10 to N110). S2 is a spaced pressure-solution cleavage sharply cutting and deforming S1. Most of the F2 folds are of metric to decametric amplitude. However, hectometric folds reworking the normal limb of earlier folds have also been identified (Les Herbiers, Fig. 5). The regular geometry of these second generation folds with subhorizontal axial planes is consistent with an eastern vergence caused by bulk vertical shortening. Part of the steep geometry of imbricates of Triassic quartzites therefore formed as a result of a combined effect of both deformations. In the deeper level exposed in the Arc valley (Fig. 7a), the Sapey basement orthogneiss and the Permian variegated shales exposed around Modane show the development of asymmetrical extensional shear bands, consistent with top-to-the-west extensional displacements. Such late extensional structures in this inner part of the zone Houillère, that are overgrown by random Fe glaucophane in mylonitic orthogneisses, may relate to the exhumation of the higher pressure rocks of the eastern compartment (southern Vanoise in the north, Piemont-Liguria zone + slices of Acceglio zone in the south, see section 3.2). It is also significant that the Mesozoic cover of the zone Houillère disappears north of Modane, indicating a gradually deeper crustal level in the north, in agreement with the southern axial plunge of both F1 and F2 folds. In the western part of the zone Houillère, the second generation of folds with horizontal axial planes (Fig. 4, 6c) are associated with top-to-the-west displacements linked to the westward thrusting of the Briançonnais zone onto the sub-Briançonnais domain.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3.1.2 The boundary between the external Briançonnais zone and the Piemontais zone *s.l.*

The profile provided by the Frejus tunnel constrains the geometry of this major tectonic contact (Fig. 5). Vertical sheets of Keuper anhydrite and vertical Triassic quartzites are in steep contact with the gently west-dipping main cleavage of the Piemont zone *s.l.* However, slices of jadeite-bearing orthogneiss (Fig. 2, 6c) occur close to fossiliferous Norian dolomites above 2300 m (Caby 1968; Saliot 1978). These slices are interpreted as steep extrusions representing the northernmost extension of the Acceglio zone (see sect. 3.2.4).

This complex boundary zone comprises several tectonic slices originating from different paleogeographic domains and from different crustal levels. They are continuously exposed between Modane and the profile described in a later section (Queyras area). Though several steep faults have overprinted the initial geometry of contacts, it is possible to restaure an ideal section, comprising shallow crustal units, with from the top to the base in the north (Fig. 7a, b):

i- a complex nappe pile with recumbent folds affecting rootless Middle Triassic carbonates with typical Briançonnais facies, ii- slices of non-metamorphic Helminthoid flysch; iii- slices of pre-Permian metamorphics, here only with a slight Alpine imprint; iv- the upside-down Norian dolomites and related Rhaeticto-Liassic series of the external Piemont zone, all detached from the Keuper anhydrites; the Sapey orthogneiss.

To the south the edifice comprises east of Briançon (Fig. 7c, d):

v- the non-metamorphic Montgenèvre ophiolite on top; vi- the Lago Nero oceanic unit, with glaucophane-lawsonite-carpholite mineral assemblages; vii- slices of jadeite-bearing gneiss similar to those from the Acceglio zone (see sect. 3.2). The entire geometry of the whole tectonic pile is reminiscent of a complex west-dipping flower structure overlain by allochthonous shallower units.

3.1.3 Implications from the metamorphic pattern

A significant pressure increase is evidenced from the external Briançonnais zone, in which the mineral assemblage lawsonite-albite-chlorite in mafic rocks suggests P = 4-5 kbar and T = 300°C, to the external Piemont zone in which the widespread occurrence of carpholite implies P>6 kbar, T = 300°C (Goffé & Chopin, 1986), and finally to the Piemont-Liguria zone, in which the mineral assemblages glaucophane-lawsonite-jadeite and jadeite-quartz recorded in mafic rocks are consistent with P~9-10 Kb, T = 400°C (Table 1). Therefore, the major west-dipping tectonic contact between the Briançonnais and the Piemont zones, which has been classically interpreted as a late back-thrust, does in fact represent a ductile extensional fault. Higher units with negligible Alpine metamorphism such as the Montgenèvre ophiolite and outliers of Helminthoid flysch (Fig. 7b) are only preserved along this major tectonic contact.

Fig. 7. Schematic profiles across the the Briançonnais-Piemont boundary in the Cottian Alps. (a): Arc valley, southern Savoie; (b): 15 km south of Modane; (c): Montgenèvre area (20 km east of Briançon); (d): Queyras. ZH: zone Houillère; s Van: southern Vanoise; Sa: Sapey orthogneiss; Br n: Briançonnais nappe; X: pre-Permian gneiss with negligible Alpine imprint; Pz: Piemont zone *s.l.* Az: Acceglio zone; Nor: Norian dolomite; Mg: Montgenèvre ophiolite. In black: Triassic anhydrite and cornieules.

Table 1. Critical metamorphic mineral assemblages (P max and related T) and pressure-temperature estimations for the main metamorphic zones in the Middle Penninic domain of the western Alps, with reference to type localities.

1 – laws, alb: P 4-5 kbar, T 300°C	Zone Houillère, Briançon
2 – car, ctd, laws (cross, Fe gl): P 4-6 kb, T 300->to 6-8 kb, T 300-350°C	ext. Piemont, Queyras
3 – gl, laws, jad (car out): P 9-10 kbar, T 350-400°C	Piemont zone, Queyras
4 – zois (laws), jd, rut, Mn gar: P>9-10 kbar, T 400°C	Piemont zone, inner Queyras
5 – laws, zois, alm-gro, jd, rut: P 10-12 kbar, T 400-450°C	Acceglio
6 – zois eclogites: P 12-14 kbar, T 450-500°C	Monviso

3.1.4 The structural link with the southern Vanoise

The southern Vanoise massif emerges north of Modane between the zone Houillère and the Piemont-Liguria zone (Fig. 1, 7a). This crystalline massif is delimited from overlying Piemont-Liguria units cropping out in the south by thick accumulations of Keuper anhydrite. Its Mesozoic Briançonnais cover with Paleocene- Eocene rocks on top is mostly detached from underlying Permo-Triassic rocks that overlie the pre-Permian basement. Post-Eocene metamorphism produced typical LT-HP, carpholite-bearing mineral assemblages in the cover (P around 8 kbar and T around 350°C, Goffé & Velde 1984) and blueschists with jadeite + quartz in the basement (Saliot 1978; Desmons 1992). The blueschist facies foliation generated during nappe formation in the basement (Platt & Lister 1985) was thoroughly deformed by tight folds. However, the apparent metamorphic gap between basement and cover (Platt & Lister 1985) may result from late-metamorphic thinning, as shown by the widespread development of an extensional crenulation cleavage associated with late growth and/or recrystallization of glaucophane. To the west, the west-dipping high-pressure foliation plunges below the west-dipping tectonic contact with the zone Houillère, as do the blueschists of the Piemont zone further to the south. The differences of P max recorded between the southern Vanoise massif and the zone Houillère implies that the west-dipping tectonic contact between both units also represents a major ductile extensional fault (Fig. 7a).

3.2 Queyras area (Cottian Alps, Fig. 8)

South of Briançon, the Carboniferous basement (zone Houillère) of the external Briançonnais zone progressively disappears below its autochthonous Briançonnais Mesozoic to Tertiary cover and below overlying Briançonnais nappes composed of Mesozoic to Tertiary cover (Fig. 1). The Acceglio zone which is part of the internal Briançonnais zone, outcrops as a half-window in a more internal position. Southeastward, the Acceglio zone will merge into the "Axial Permo-Carboniferous zone" of the Ligurian Alps.

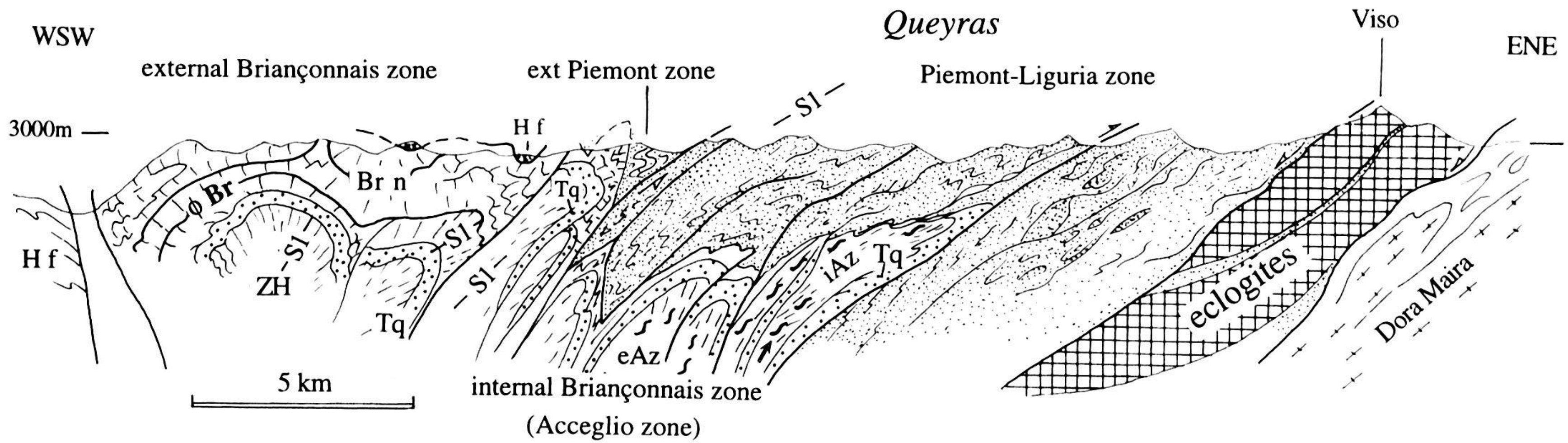


Fig. 8. Schematic cross-section of the Briançonnais and the Piemont zones in Queyras (Graie Alps). ZH: zone Houillère; Tq Triassic quartzite; Br ϕ: solethrust of the Briançonnais nappes (Br n); Hf: Helminthoid flysch; eAz and iAz: external and internal parts of the Acceglio zone, respectively (projected from the south). Br n: Briançonnais nappes; the geometry of S1 is represented only.

3.2.1 The external Briançonnais zone (Fig. 8)

In the west, the S1 slaty cleavage in Permian shales is axial-planar to NNE-trending open folds. This cleavage is incipient only within the underlying massive andesites which display syn-kinematic tension gashes with the paragenesis lawsonite-albite-chlorite in the Guil canyon. On top of the Triassic quartzites, the steeply inclined S1 is progressively bent over in order to reach the gently west-dipping orientation of the sheared rocks of the sole thrust of the lower Briançonnais nappe. Like north of Briançon, the inner part of the section corresponds to east-verging folds with well-preserved inverted limbs of the undetached Triassic cover. Incipient east-west elongation and associated flattening of quartz grains parallel to the west-dipping S1 attests minor ductile deformation in the Triassic quartzites. In contrast, middle Triassic limestones display spectacular recumbent folds with EW trending axes and associated strong boudinage as well as east-west trending stretching lineations. Shear indicators in impure marbles such as asymmetric clasts of micaceous layers, mica fish and small-scale asymmetrical extensional shear bands indicate initial top-to-the-NE directed displacement. The recumbent S1 cleavage is deformed by open folds displaying sub-horizontal axial planes.

3.2.2 The external Piemont zone

The same structural elements are found in the deformed Mesozoic calcschists of the external Piemont zone. Many isoclinal folds in Jurassic and Cretaceous calcschists are curviplanar and frequently reach the geometry of open sheaths to tongues (Fig. 9b). In limestones interlayered with black shales, many spectacular occurrences of carpholite fibres up to 10 cm long set up in calcite and quartz have been found. They attest higher pressures as compared to the adjacent external Briançonnais zone. Low-angle, west-dipping shear bands and asymmetric features indicate downthrow of the western compartiment. However, the initial geometry is obscured by a severe ductility contrast between calcschists and undeformed Norian dolomites up to 1000 m thick to the north (Fig. 7d). Moreover, the superposition of N-S steep faults (Barfety & Gidon 1975), some of them with a clear strike-slip component, have obscured the initial geometry.

3.2.3 The Piemont-Liguria zone

Oceanic rocks of the Piemont zone *s.l.* below display regularly west-dipping foliations (Fig. 8). Several ophiolitic massifs with their undetached post-ophiolitic cover are overturned (Lemoine 1971; Caby et al. 1987), analogous to the folds in the inner Briançonnais zone. This fact requires a global explanation. The whole zone has been deformed under blueschist facies conditions. Structures in the blueschists of the Queyras area have been interpreted as the result of several phases of folding (Tricart 1980; Tricart & Lemoine 1986). Progressive deformation under blueschist facies conditions followed by minor movements under retrogressive conditions better agrees with the widespread development of sheath folds frequently observed at all scales. Indeed, folds, shear zones and tension gashes filled with weakly retrogressed jadeite, lawsonite and glaucophane are widespread in the Queyras area and several examples of east directed shear have been observed (Philippot 1990; Fig. 9a, d). Carpholite in Cretaceous black shales is mostly replaced by prograde phengite but is preserved as voluminous fibres set up in the thicker

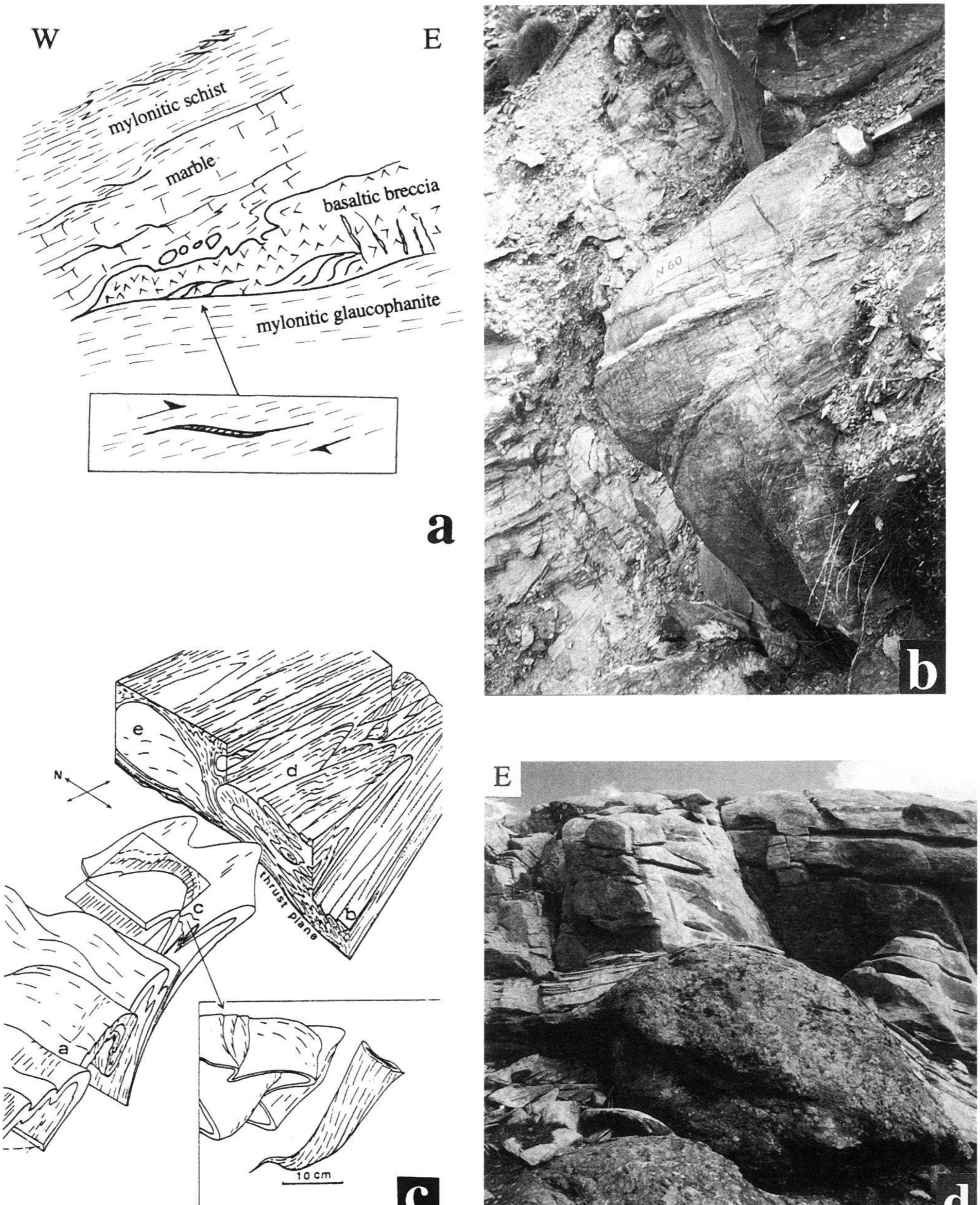


Fig. 9. Aspect of east-directed shear in the Piemont-Liguria zone (Queyras blueschists) (a) East-directed shear affecting a rigid slab of blueschist facies metabasaltic breccias, Peynin valley near Aiguilles. (b) Tongue-like east verging fold in Lower Cretaceous rocks of the pre-Piemont unit. (c) Schematic sketch of fold geometries observed at all scales and suggestive of progressive deformation leading to sheath folds. (d) Asymmetric boudin of gabbro enclosed in Jurassic marble, post-ophiolitic cover.

(>10 cm) quartz exsudates. Minute chloritoid (<50 mm) is also present in greenish Cretaceous schists, together with more or less retrogressed lawsonite. Inwards, the progressive replacement of lawsonite by zoisite in place of former plagioclase from metagabbros and dolerites clearly indicates a temperature increase. Mn-rich almandine has been found in equilibrium with glaucophane, jadeite and lawsonite-zoisite in massive metadolerites (Table 1). Metamorphic conditions of T around 300-400°C and P = 10-14 kbar have been estimated for such garnet occurrences by Ballèvre and Lagabrielle (1995). Therefore the apparent metamorphic gap between the Queyras blueschists and the Monviso eclogites, consistent with a ductile normal fault, is possibly less important than postulated (Ballèvre et al. 1990; Philippot 1990).

3.2.4 The Acceglio zone (internal Briançonnais zone)

The Acceglio half-window crops out as a west-dipping slice closing eastward (Fig. 1, 8), interleaved with rocks of the Piemont-Liguria zone above and below. This zone comprizes the pre-Permian basement and its undetached Mesozoic to Tertiary Briançonnais cover, both affected by a strong Alpine metamorphic imprint.

Hectometric- to kilometric-size folds, well defined by an undetached envelope of Mesozoic cover have been mapped (Houfflain, unpublished results; Houfflain & Caby 1987). Inverted limbs of Permian and Triassic quartzite with a well-marked horizontal slaty cleavage at a low angle to bedding and defined by phengite may reach the size of 1,5 km. Fold hinges are curviplanar and may reach the geometry of sheath folds, especially near the contact between the Acceglio zone and the overlying Piemont-Liguria zone. In the basement, jadeite-orthogneisses and associated porphyries were cleaved into augen to cigar-shaped bodies, representing relatively rigid lenses with E-W elongation, enclosed within retrogressed rocks. The enclosing more ductile schists with few relics of high-pressure minerals grade into white mica-chlorite-pumpellyite phyllonites. Early top-to-the-east shear indicators, such as asymmetric winged porphyroclasts of jadeite porphyroclasts and small-scale shear bands sealed by glaucophane are found especially within lenses and boudins of less retrogressed rocks. Many late small-scale shear bands in the retrogressive rocks however indicate top-to-the-west extensional displacements.

Metamorphism in the western part of the Acceglio zone is characterized by the occurrence of carpholite and chloritoid (Goffé & Chopin 1986). The eastern part is well known by its occurrences of jadeite (Lefèvre & Michard 1976) in basement rocks and in the Mesozoic cover. Lenses of sub-alkalic gneissic granites with associated metaaplites display the mineral assemblage jadeite (Jd 95 to 99) and quartz pseudomorphs after perthitic K feldspar phenocrysts in a retrogressed matrix. Early phengite clasts have a Si content of up to 3.40. Lenses of pre-Permian mafic sills, a few to 10 meters thick and with calcic leucocratic bands, were converted into garnet-glaucophanites. These display the early mineral assemblage glaucophane, garnet, rutile, jadeite (Jd 95 to 99), quartz, lawsonite/zoisite and phengite, with rare relics of brown amphibole. Garnet (alm 60-65, gro 25-65, pyr 3 to 13 in rims) occasionally displays intergrowths with jadeite, glaucophane and lawsonite, and contains rutile inclusions, suggesting its Alpine age. Inclusions of plagioclase (replaced by albite, lawsonite/zoisite) and of brown biotite have also been observed in larger garnets from granodioritic orthogneisses. The $^{39}Ar/^{40}Ar$ ages of around 340-360 Ma obtained on white micas from an orthogneiss, also document Variscan events (Monié

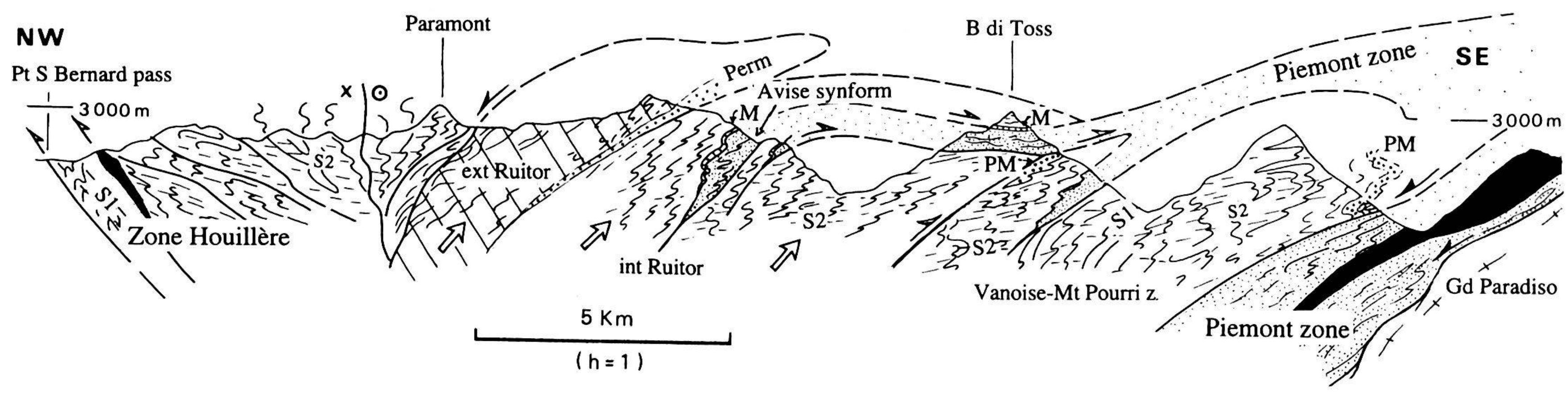


Fig. 10. Interpretative section across the Ruitor massif and adjacent zones. S1 and S2 schistosities are outlined. Large open arrows indicate the east-verging extrusions. PM: Permo-Mesozoic to Tertiary Acceglio-type cover; M: Late Jurassic marbles. In black: Triassic evaporites.

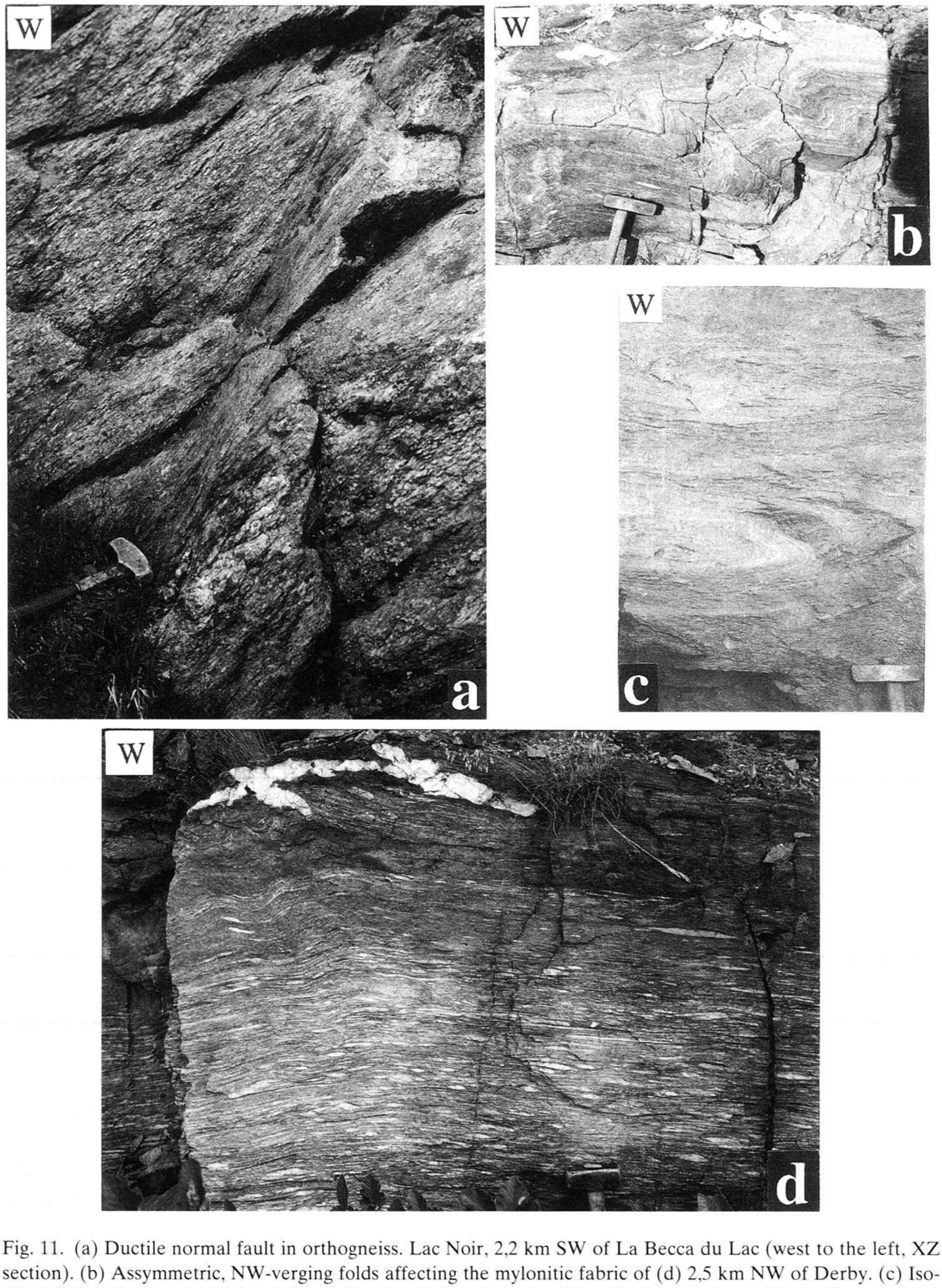


Fig. 11. (a) Ductile normal fault in orthogneiss. Lac Noir, 2,2 km SW of La Becca du Lac (west to the left, XZ section). (b) Assymmetric, NW-verging folds affecting the mylonitic fabric of (d) 2,5 km NW of Derby. (c) Isoclinal folds affecting the S1 fabric just below the Ruitor thrusting SE of Derby. (d) Mylonitic fabric parallel to bedding of a conglomeratic layer.

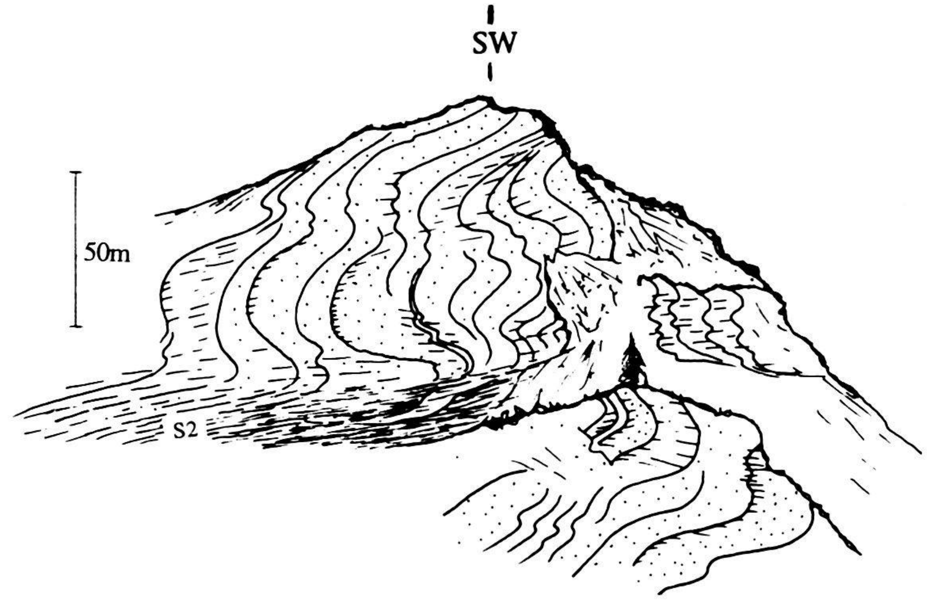


Fig. 12. F2 fold in Carboniferous sandstones and conglomerates near the front of the inner part of the zone Houillère, 3 km NE of the Petit St Bernard pass (drawing). S0 and S1 (not represented) are almost parallel.

1990). The occurrence of Alpine garnet in mafic rocks in equilibrium with jadeite and lawsonite/zoisite suggests metamorphic conditions of about 10-12 kbar and T around 400-450°C (Houfflain & Caby 1987).

3.3 Petit St. Bernard pass-Valsavaranche area (Graie Alps, Fig. 10 and 14)

This area comprises the zone Houillère, three different basement units to the east containing few relics of very thin Acceglio-type Mesozoic cover, and finally, thin imbricates of the Piemont zone *sl.*

3.3.1 The zone Houillère

The zone Houillère can be subdivided into two sub-units (Fig. 10). The external unit is affected by NE-trending upright folds with associated steeply dipping axial plane S1 slaty cleavage. A moderate ductile deformation is evidenced by the preservation of fossil plants in compact micaceous silts with incipient slaty cleavage near the Petit Saint Bernard pass. Immediately to the east, a continuous strip of cornieules and Triassic limestones delineates the contact with the internal sub-unit of the zone Houillère. At the front of the internal sub-unit, NNE trending open folds with horizontal axial planes and up to several hundreds of meters in size deform the S1 cleavage (Fig. 12). S2 is a spaced cleavage produced by pressure-solution and accompanied by the recrystallisation of minute white micas and chlorite and thus completely overprinting S1 in most rocks. The bulk geometry of such F2 folds with no clear asymmetry is consistent with vertical shortening. East of a steep fault displaying evidence for significant lateral dextral movement, all rocks display a much stronger penetrative deformation essentially related to the S1 cleav-

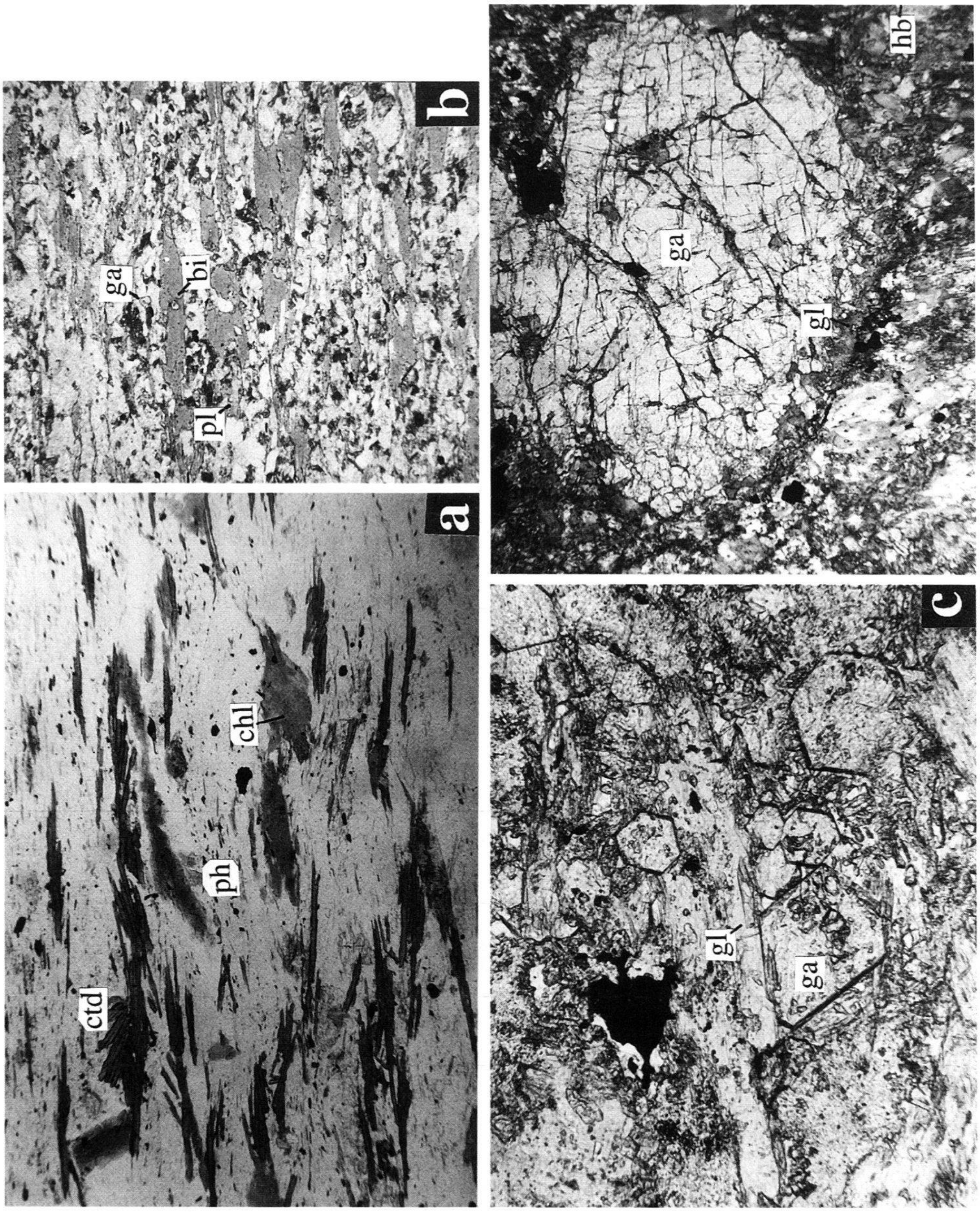


Fig. 13 (a) Syn-kinematic chloritoid (ctd) and chlorite (chl) pseudomorphs after possible glaucophane in Stephanian (?) phengite (ph) metashale: foot wall of the ductile fault between external Ruitor and the zone Houillère (western ridge of le Bec de l'Ane, 250 m west of le Lac Noir). (b) Pre-Alpine foliation defined by the planar disposition of brown biotite (bi) and the shape fabric of plagioclase (pl) and quartz, with significant Alpine recristallisation of zoisite and minute garnet (ga) in the site of oligoclase (western ridge of La Becca du Lac). (c) Textural equilibrium between euhedral garnet (ga) and pale glaucophane (gl). (d) Pre-Alpine garnet (ga) rimmed and cut by veinlets of glaucophane (gl) in a chlorite matrix with relics of retrogressed green hornblende (hb). (c and d) from the southern ridge of Le Bec de l'Ane.

age (Fig. 11d) and an associated strong L1 stretching lineation trending between N90 and N130. Due to the refolding of these structural elements (Fig. 11b, c; 12), early recumbent folds with S1 axial planar cleavage are only rarely found. Some isoclinal folds with transverse axes plunging to the ESE and up to several tens of meters in wave-length have been observed near La Thuile. However, in most cases S1 makes an angle$<10°$ to bedding planes. These early folds are considered to have formed parallel to the main elongation ("a" folds), as was the case in the Briançonnais Triassic limestones from Queyras described earlier. Metamorphism related to S1 in the inner part of the zone Houillère is essentially of greenschist grade. However, syn-kinematic Fe-chloritoid formed in Permian meta-shales, together with possible glaucophane relics (Fig. 13a). Phengite, chlorite, late albite and stilpnomelane are the ubiquitous minerals in shales and sandstones. The mineral assemblage biotite, phengite and minute garnet is restricted to pebbles of orthogneiss, whereas actinote, chlorite and tremolite occur in prasinites.

3.3.2 The external Ruitor

This western part of this massif represents an upside-down slab of polymetamorphic rocks capped in the south (Fig. 14) by the upside-down unconformable undetached Permian cover. This cover of bedded polygenic conglomerates reaches a thickness of some hundreds of metres southeast of the Valgrisanche lake, and can be continuously followed in the eastern cliffs of the massif to the Dora Baltea with a thickness < 20 m (Gouffon, pers. communication; Debelmas et al. 1991). It comprises (southeast of the Testa del Ruitor) about 50 m of quartz-schists, metaarenites with pink quartz gravels, and rhyolites and associated rhyolitic tuffs with ankerite layers and a few diabase sills.

Large volumes of basement rocks of the westernmost part of the massif are metapelites and semipelites displaying a relict pre-Permian foliation defined by biotite, muscovite and coarse-grain quartz (Fig. 13b), which is axial planar to isoclinal folds. Lenses of orthogneisses, amphibolites, and a few occurrences of impure marbles are also part of this pre-Alpine supracrustal sequence.

Pre-Alpine and Alpine metamorphism in the external Ruitor: Variably retrogressed biotite-plagioclase±garnet paragneisses alternate with metapelitic layers containing brown biotite, muscovite and garnet, locally up to 3 cm in diameter (Fig. 13d). Rare staurolite relics replaced by polycrystalline chloritoid, and kyanite overgrown by white micas are locally preserved (Desmons 1992). One sample with relict prismatic sillimanite armoured in large (1 cm) muscovite has been collected in the NW ridge of La Becca du Lac. These high-temperature mineral assemblages are clearly of pre-Alpine age. Discrete static blastesis of minute pale glaucophane in the site of biotite, and of zoisite and garnet in the site of plagioclase (Fig. 13b) have been observed in all samples of massive paragneisses which escaped hydration and fluid percolation, thus preventing significant late ductile Alpine shearing. Such massive rocks are mainly exposed above 2700 m in the western flank of the massif. The exceptional mineral assemblage jadeite, zoisite and quartz in the site of a former plagioclase has been observed in an massive metapegmatite collected from the same area. The pre-Alpine mineral assemblage of amphibolites includes brown and/or green hornblende, altered plagioclase and ilmenite. Pargasite, phlogopite and rutile are preserved in some mafic rocks, and relictual clinopyroxene is present in rare massive pyroxenite lenses. Pre-Alpine amphiboles are diversely replaced and/or overgrown by pale glaucophane, and the nucleation of minute garnet is observed in plagioclase.

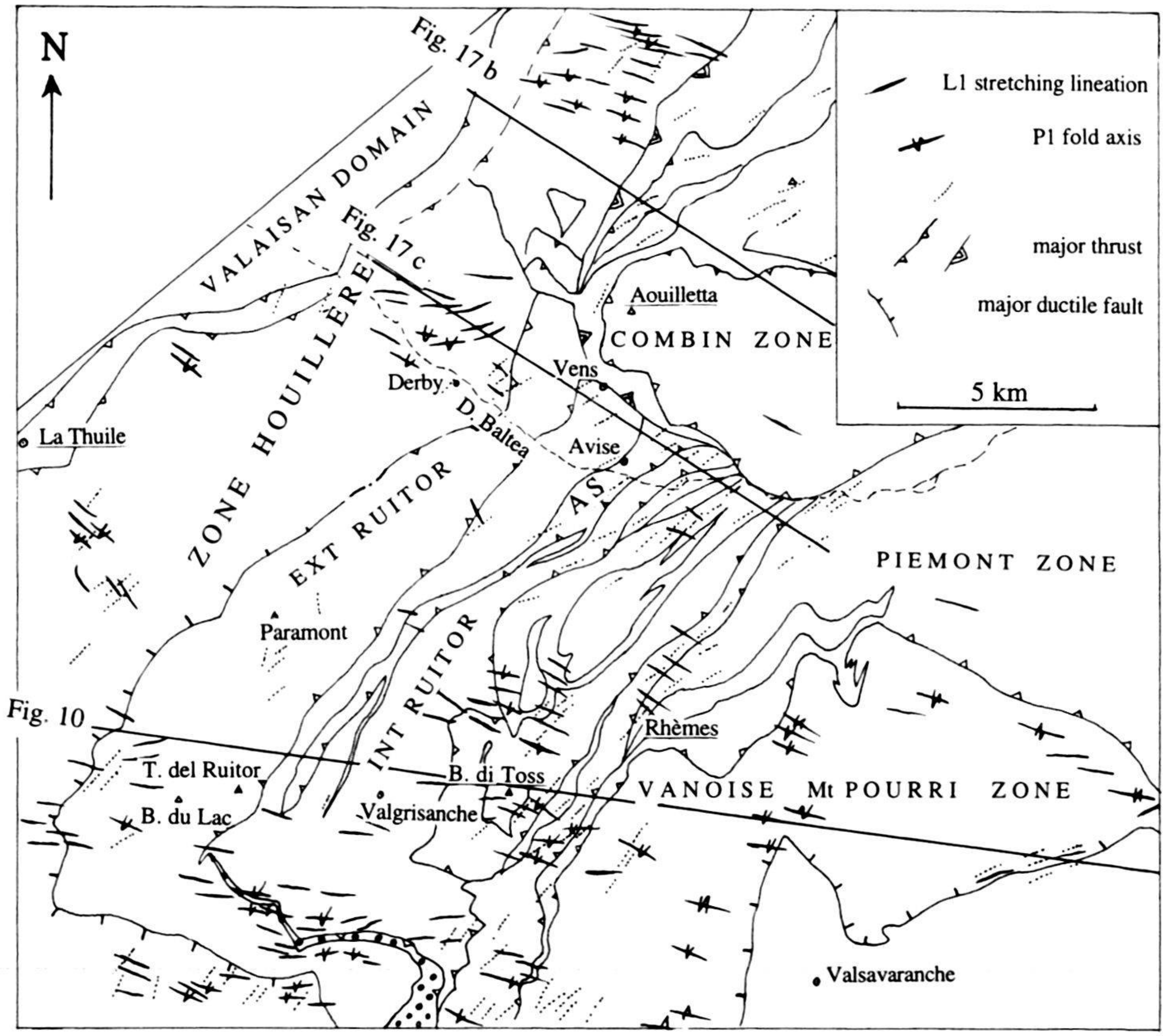


Fig. 14. Schematic map of the Ruitor massif and adjacent areas showing the structural patterns of F1 and F2 folds. A S: Avise synform.

Occurrence of garnet glaucophanites and eclogites: Detailed sampling of massive layers from the major amphibolite outcrops in the SW ridge of La Becca du Lac has revealed the occurrence of boudinaged layers of garnet-glaucophanites. Euhedral garnet is in textural equilibrium with pale glaucophane (Fig. 13c). In other samples, garnet with glaucophane and rutile inclusions is also rimmed and cut by glaucophane veinlets, suggesting a complex evolution. A few lenses of amphibolites and garnet glaucophanites at Derby and in the southern ridge of La Becca du Lac also preserve relics of an eclogitic paragenesis. These contain sub-euhedral garnet 2 to 5 mm in diameter, some occurring as a corona around a pre-Alpine amphibole which is variably replaced by pale glaucophane. A few relics of omphacite are essentially preserved in quartz, together with zoisite. Phengite is rimmed by pale brown biotite, and rutile is rimmed by sphene. The paragenesis omphacite, quartz, phengite and zoisite is also observed in associated leucocratic veins. Retro-eclogites linked with static hydration during late shearing of adjacent rocks are characterized by abundant green amphibole-albite symplectites formed around garnet as a contin-

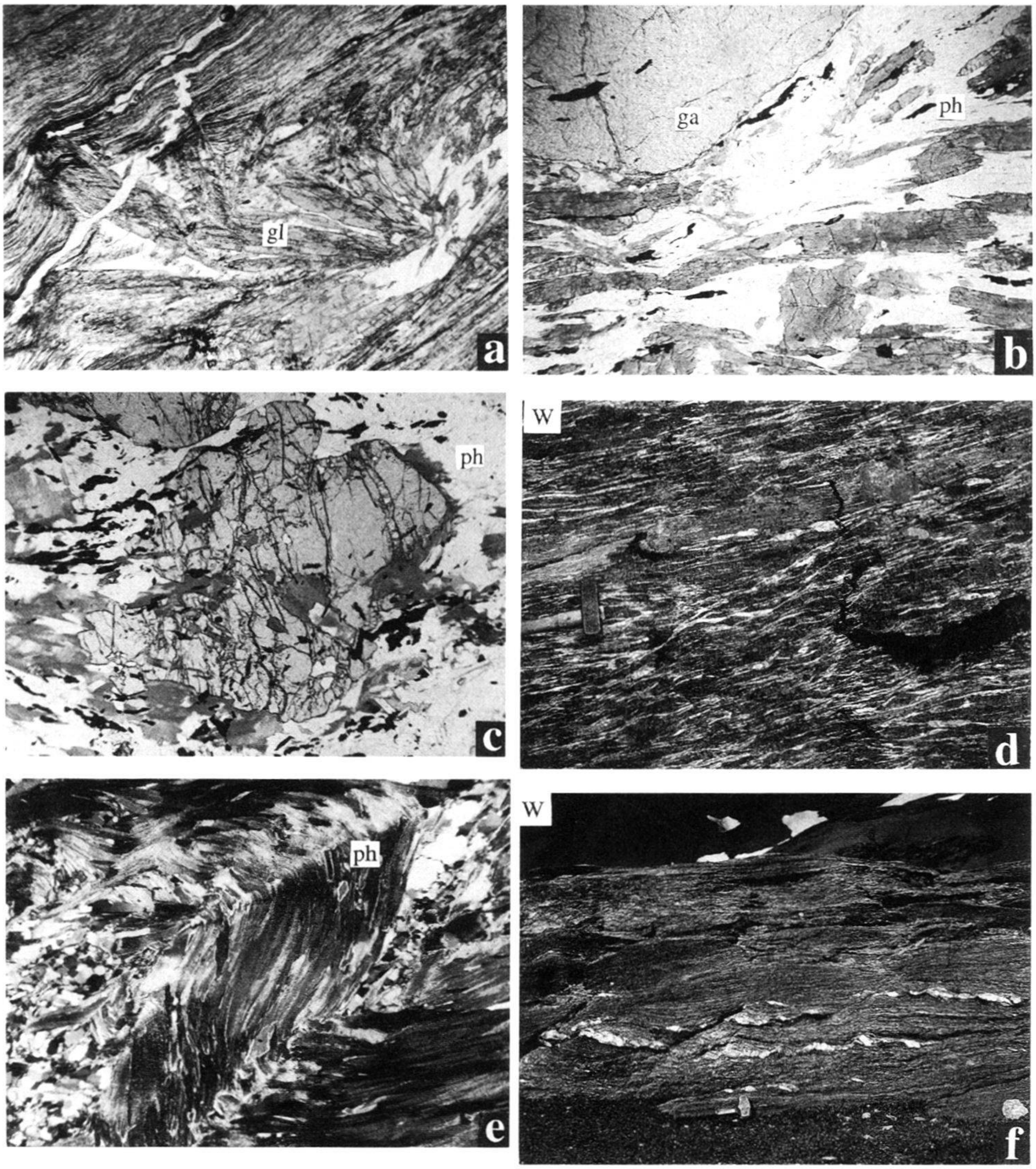


Fig. 15. (a) Undeformed spheroliths of pale glaucophane (gl) cutting the fine-grained ribbon fabric of an ultramylonite adjacent to Figure 11a. (b) Typical mineral assemblage of massive Al-Fe-Mg metapelite from internal Ruitor: the Alpine foliation is defined by phengite (ph), hematite (black) and Fe chloritoid (ctd) and syn-kinematic garnet (ga). (c) Idem, thoroughy retrogressed into a chlorite (chl) schist, chloritoid being only preserved in garnet cores. (d) Typical nodular texture of massiv chloritoid-rich metapelite near Valgrisanche. Note the development of syn-metamorphic shear bands consistent with top-to-the-west extensional shear. (e) Microfolded phengite (ph) in the hinge of NE trending late folds. (f) Top-to-the-west late metamorphic extensional shear in Mesozoic calcareous schist from the inner part of the Piemont-Liguria zone, Sources de l'Isère glacier, 500 m west of the contact with the Grand Paradiso massif.

uous reaction involving omphacite and garnet, in a matrix of green to pale-brown biotite, blue-green amphibole, clinozoisite, chlorite and albite. Since the pre-Alpine paragenesis of amphibolites around La Becca du Lac is free of garnet, an Alpine age is suggested for these eclogite occurrences consistent with P/T conditions around 12-14 kbar, 450°C (Caby & Kienast 1989).

Structures and kinematics: Alpine ductile deformation led to the progressive reactivation of the pre-Alpine foliation, initiating under high-pressure conditions, as evidenced by the crystallisation of tails of phengite, glaucophane, chloritoid, etc. from the pre-Alpine clasts. In a more advanced stage, thick horizons of the pile are free of pre-Alpine relics and look like monometamorphic Alpine schists. Mineral lineations with a WSW trend are defined by the shape fabric of tiny minerals among which unaltered chloritoid in equilibrium with phengite, as well as by relict glaucophane in garnet glaucophanites.

The external Ruitor/zone Houillère boundary: The contact between the pre-Permian rocks of the Ruitor basement and the Permo-Carboniferous strata of the zone Houillère to the west does not represent a deformed stratigraphic unconformity but a west-dipping ductile extensional shear zone several tens of meters in thickness and associated with small-scale ductile faults (Fig. 11a). The footwall is delineated by mylonites of orthogneiss and by banded mylonitic schists several tens of meters in thickness, affected by post-mylonitic asymmetric folds with horizontal axial planes. These display a mylonitic foliation marked by quartz ribbons interleaved with fine-grained micaceous layers chiefly made up of phengite and chlorite. Sigmoidal features and small-scale shear bands are consistent with top-to-the-west displacements. The mylonitic fabric of associated orthogneisses is post-kinematically overgrown by randomly distributed glaucophane needles (Fig. 15a), themselves partly destabilized and replaced by chlorite and albite. This implies that this extensional ductile deformation still initiated under elevated pressure conditions (following eclogitic conditions?). This implies severe syn-metamorphic thinning of the whole metamorphic pile. Further greenschist facies retrogression in these phyllites developed mainly under static conditions as a result of percolating fluids connected with younger brittle normal faults and related tension gashes. The Stephanian chloritoid schists of the hanging wall are also mylonitic, with highly stretched pebbles with a mean EW elongation.

The external Ruitor massif, therefore, does not represent the basement of the zone Houillère outcropping to the west, as classically considered, but a more internal terrane comprising solely an upside-down section of basement and its undetached Permian cover. It is therefore suggested that, prior to the exhumation of the massif along a major west-dipping ductile fault, east-directed movements were responsible for both the formation of the presently inverted section of basement and Permian cover and the eastward thrusting of the internal part of zone Houillère. The geometry and kinematics thus compares well with that of inverted limbs of east-werging folds with sheared normal limbs all along the eastern edge of the zone Houillère (Fig. 2).

3.3.3 Internal Ruitor

The architecture of the internal part of the massif is dominated by the Avise synform and the large inverted limb of the Becca di Toss isoclinal fold (Fig. 10), slightly deformed by open folds with horizontal axial planes (Baudin 1987). The upside-down Mesozoic cover of the Avise synform and Becca di Toss (30-50 m) starts with an impure, white tremolite marble layer (5-10 m) of assumed Upper Jurassic age. Its stratigraphic base is made up of sandy and pebbly marble with disseminated angular clasts of Triassic dolomites and marbles. This horizon is exposed 2,7 km NNW of the Valgrisanche village and below the pyramidal summit of the Becca di Toss. It is in contact with massive calcschists and black, non-calcareous chloritoid schists of assumed Lower Cretaceous age. Lenses of banded micaceous quartzite and phengite-rich quartz schists (resedimented Permotrias?) and of typical Triassic dolomites, tremolite- and talc-bearing outcropping around Avise are also part of this Mesozoic sequence and may represent olistoliths and/or part of an Alpine tectonic melange, as suggested by some lenses of cornieule and anhydrite. Several sections however suggest an apparent upward gradual passage into calcareous schists with lenses and boudins of serpentinites, metabasalts with garnet-blueschist facies and eclogites, all being part of the typical inner Piemont-Ligurian zone.

Massive basement rocks of this sub-unit have recently been correlated with the Siviez-Mischabel unit of the Valais (Gouffon 1993), although no pre-Alpine relics have yet been found. Albitic gneisses, phengite-rich orthogneisses, black tremolite-schists and amphibolites/prasinites represent a comprehensive sequence well distinct from the main monotonous formation of Fe-Mg metapelites with interlayered prasinitic layers. Metamorphism in Fe-Mg metapelites is characterized by the primary mineral assemblage quartz, phengite, garnet, Fe-glaucophane, Fe-chloritoid, ankerite and hematite (Fig. 15b). Inclusions of glaucophane, chloritoid and rutile are observed in garnet cores, within which they occasionally outline an internal cleavage. Fe-chlorite and green biotite grew in the tails and in the cracks of garnet clasts and therefore represent retrograde products. More severe retrogression converted the chloritoid rocks into chlorite schists with relict garnet, their cores still displaying chloritoid, inclusions (Fig. 15c). In prasinites, only a few relics of glaucophane, garnet, zoisite, and chloritoid are preserved owing to the severe overprinting by coarse-grained, frequently static blastesis of Fe-rich actinote to blue-green hornblende, green biotite, clinozoisite, albite, calcite and chlorite.

In spite of the large-scale east-directed folds, small-scale structures affecting the coarse-grained Alpine foliation in the basement evidence syn-metamorphic west-directed extensional shear (Fig. 15d). In domains where the foliation is thoroughly affected by NE trending open folds with NW dipping axial planes, no significant recrystallisation affected the fold hinges (Fig. 15e).

3.3.4 The Vanoise-Mont Pourri zone in the northern Vanoise massif and south of Aosta

This innermost basement unit exposed in northern Vanoise and south of Aosta in Valsavarenche-Val de Rhèmes mainly comprises black schists, metavolcanics and plutonic complexes of possible Cambrian to Ordovician age (Guillot et al. 1993). The cover starts with the basal Triassic quartzites overlain by Triassic marbles and dolomites. Unconformable black calcschists and limestones with breccias of probably Liassic age are overlain by Late Cretaceous calcschists containing lenses of polygenic breccias and olistoliths grading into the Paleocene and Eocene, as suggested in the Tsanteleina massif by the preservation of probable remnants of *Lithothamniae* in a phosphate-manganese-rich hardground converted into spessartine-apatite-carbonate (Caby 1968). The top of the sequence consists of black micaceous schists of assumed Eocene age.

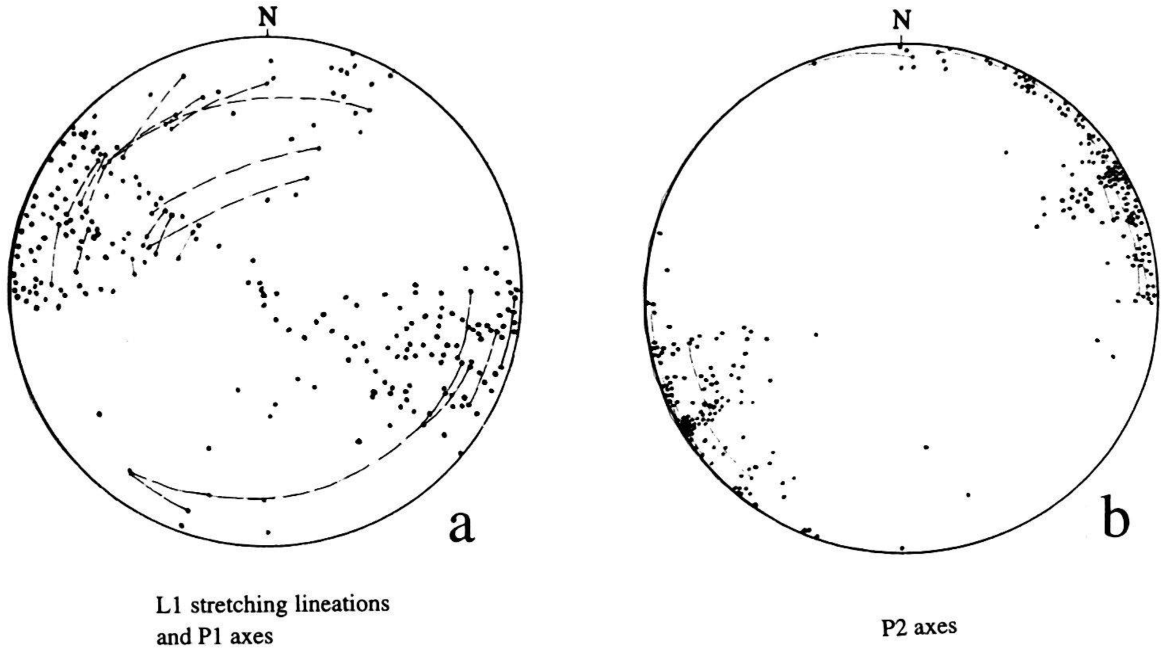


Fig. 16. Equal area, lower hemisphere stereographic representation of D1 and D2 structures, all structural units together.

Metamorphism. In Valsavaranche, relics of high-pressure metamorphism are rarely preserved, due to the intense green-schist facies retrogression. A unique glaucophane-chloritoid-garnet-rutile assemblage has been found in a metaquartzite and rare glaucophane relics are also observed in some massive mafic rocks. The common mineral assemblage of black schists comprises abundant poikilitic albite, phengite, chlorite and pale brown and/or green biotite in the easternmost part. Actinote to blue-green hornblende, epidote, albite green biotite and garnet are the ubiquitous minerals found in mafic rocks. Tremolite is present in dolomites of the cover. Early metamorphic conditions are compatible with garnet-blueschist facies, thus of higher pressure than in the northern Vanoise (Guillot et al. 1993). However, no jadeite relics have so far been found as in the southern Vanoise. The widespread occurrence of both pale brown and green biotite in equilibrium with garnet implies T≥ 400-420°C for the late green-schist facies imprint.

Structures. In the Aosta valley, the Vanoise-Mont Pourri zone is interleaved between the internal Ruitor and the Piemont-Liguria zone (Fig. 10, 14). The recumbent foliation is axial-planar to plurihectometric isoclinal folds. Fold axes are parallel to mineral and stretching lineations with a mean E-W trend. The Valsavaranche fold, classically regarded as a late back-fold, does, in fact, represent a kilometer size sheath fold with an E-W fold axis involving basement and the Mesozoic cover. The low-angle tectonic contact to the east with the underlying Piemont zone containing eclogites is therefore interpreted as a major extensional ductile fault. In Mesozoic calcschists, extensional shear bands cutting the west-dipping foliation (Fig. 15f) clearly indicate a considerable late-metamorphic thinning of the whole Piemont unit.

In the northern Vanoise, N-S chevron-type, assymmetric folds with sub-horizontal axial planes passively rework the early cleavage and related isoclinal folds, and the entire northern Vanoise unit rests with a flat tectonic contact on the zone Houillère (Fig. 1; Ellenberger, 1958). The late character of this thrusting is suggested by the truncation of folds of the zone Houillère.

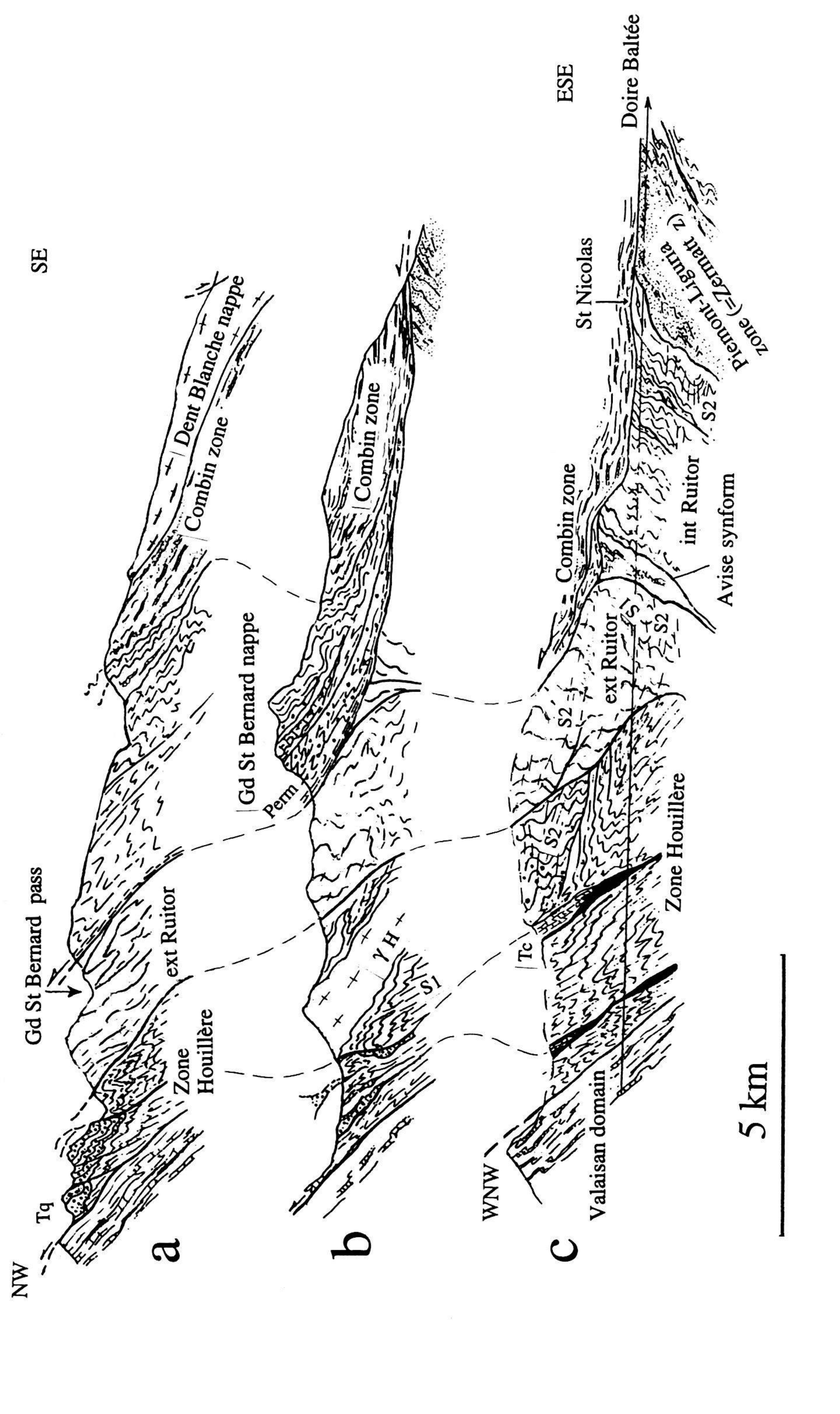
3.3.5 Large-scale infolding between Piemont *s.l.* units and basement units

Detailed mapping south of Aosta (Caby 1968; Debelmas et al. 1991) has revealed complex imbricated structures between rocks of the Piemont zone *s.l.* and basement units in Valgrisanche and in Val de Rhèmes (Fig. 14). Mesozoic calcschists and metaophiolites with garnet blueschist and eclogitic mineral assemblages pinched within the Avise synform of the inner Ruitor sub-unit, are petrographically similar to the nearby inner Piemont-Liguria unit (Zermatt zone) exposed around Aosta. In a more internal position, the val de Rhèmes imbricates of Mesozoic calcschists and metaophiolites which are infolded in Paleozoic black schists together with Cretaceous and Liassic (?) sediments of the inner Briançonnais zone (Caby 1968), are part of the Combin zone (the Tsaté zone in Switzerland), as evidenced by their green-schist facies mineral assemblages. These thin synforms thicken southward and merge to the Grande Sassière klippe (GS on Fig. 1) which only comprises green-schist facies rocks and is also considered as the major klippe of the Combin zone south of the Dora Baltea. Trajectories of stretching lineations and axes of recumbent to isoclinal folds in the surveyed domain (Fig. 14, 16) reveal a common pattern consistent with an homogeneous syn-to late-metamorphic ductile flow in all units. However, many shear criteria observed on the gently west-dipping foliations indicate a west-directed shear component, the relations of which are unclear with the large-scale east-verging folds recorded. Domains with steep foliations, in contrast, show the overall development of symmetric late folds with sub-horizontal axial planes and consistent with a main vertical shortening. The bulk of the syn- to late-metamorphic, NW-directed extensional shear and the late folds either with inward or with outward vergence is consistent with a global thinning of the whole tectonic pile.

3.4 The Aosta valley (Fig. 17)

The Dora Baltea section (Fig. 17c) illustrates the disappearance of the west-dipping structures described earlier beneath the Grand Saint Bernard nappe *s.s.* This higher nappe which thickens northward in the Valais, is characterized by continuously northward directed displacements of all the units (Escher 1988; Steck & Hunziker 1994).

Steeply west-dipping foliations of the lower edifice (Fig. 17c) are affected by decametric to hectometric open folds with associated low-angle axial planes and associated conjugate low-angle, mostly NW-directed reverse shears, the bulk displaying a large fan structure. This edifice is sharply cut by the gently southeast dipping basal sole thrust of the Grand Saint Bernard nappe (Fig. 17b, c), defined by thin imbricates of both Mesozoic and Paleozoic schists, lenses and boudins of anhydrite, of Triassic quartzite embedded in cornieules and cataclasites. The well exposed thrust zone at Vens (Fig. 14) is a 30 meter thick gently southeast dipping zone of gouge and cataclasites. This brittle contact shows evidence of late top-to-the-SE extensional shear, a reactivated feature possibly connected


NW
SE
a
Tq
Zone Houillère
Gd St Bernard pass
ext Ruitor
Combin zone
Dent Blanche nappe
b
S1
γH
Perm
Gd St Bernard nappe
Combin zone
WNW
ESE
c
Valaisan domain
Zone Houillère
Tc
S2
ext Ruitor
S2
S1
Avise synform
int Ruitor
Combin zone
S2
St Nicolas
Piemont-Liguria zone (=Zermatt ?)
Doire Baltée
5 km

with the western prolongation of the EW trending normal/sinistral strike-slip fault of the Aosta valley, a counterpart of the Simplon Fault (Gouffon 1993). To the north, this thrust contact is either rather sharp or defined by a narrow zone of gently east dipping phyllonites and mylonites made up of Permian rocks. The basal sole thrust of the overlying Combin zone is also defined by lenses and boudins of Triassic quartzite, limestones and anhydrite, all with typical Briançonnais affinities (Caby 1981).

The gross structure of the Grand Saint Bernard nappe in its southern part is that of regularly southeast dipping imbricates of pre-Permian basement units and Permian cover. In this domain, Gouffon (1993) has recognized the different units defined in the Valais area by Escher (1988). NW-verging, asymmetric open folds of all sizes with horizontal axial planes affect both the foliation and some of the thrust contacts. The geometry of the lower edifice also differs from that of Figure 10 by the northwestward thrusting of the external Ruitor zone onto the zone Houillère. Thus the west-dipping extensional ductile fault zone between the external Ruitor and the zone Houillère (Fig. 10) gradually steepens northward and is progressively bent in order to be transformed into a NW-directed thrust. Passive folding of this major contact is a consequence of the late thrusting of the Grand Saint Bernard nappe, itself overlain by the Combin zone and overlying Dent Blanche nappe (Fig. 17a). Though similar in lithology (but not in metamorphic grade), the different units of the Grand Saint Bernard nappe match with those of the lower edifice (Gouffon 1993).

4. Synthesis and implications for the tectonic evolution of the Middle Penninic domain: deepening crustal levels from Briançon to the Aosta valley

4.1 Gross geometry, vergence of structures and thinning of the pile of Middle Penninic units

Middle Penninic units between Briançon and the Aosta valley display a regular westerly dip, the deeper crustal levels being exposed towards the internal parts of the Alpine arc. The situation is just the opposite of that in the Valais, where deeper units are thrust northwestward and overlie the less metamorphic zone Houillère (Escher 1988).

The shollower crustal section of the outer part of the zone Houillère around Briançon (western part of Fig. 2) shows that the first post-Eocene deformation resulted from moderate E-W horizontal shortening responsible for upright folding with a pronounced fanning axial-plane cleavage. The upright attitude of F1 folds indicates that this shortening event was apparently not related to initial outward thrusting of the Briançonnais zone onto the sub-Briançonnais domain. The syn-kinematic mineral assemblage lawsonite-albite-chlorite suggests metamorphic conditions of P around 4 kbar (Goffé & Chopin

Fig. 17. Three cross-sections between the Aosta valley and the Grand Saint Bernard pass showing the geometric relationship between the Grand Saint Bernard nappe and the underlying west-dipping edifice. γH: Carboniferous granite (See Fig. 1 and 14 for location of sections).

1986). This is consistent with a tectonic burial ≤12 km below the now eroded Briançonnais nappes and overriding Helminthoid flyschs. The sharp boundary between the outer (shallower) and the inner (deeper) sub-domains of the zone Houillère (the Drayères shear zone, Fig. 3) is a continuous outward-dipping ductile fault with a normal/sinistral strike-slip component indicating a stronger uplift of the eastern compartment. This tectonic contact, frequently outlined in the north by a narrow strip of Mesozoic Briançonnais cover, can be continuously observed from Briançon to the Petit St. Bernard pass: it marks the sharp limit between upright to west-verging folds (in northern Savoie, Fig. 10) in the outer sub-domain, and east-verging folds with well-preserved inverted limbs in the eastern sub-domain. In southern Savoie (the eastern part of Fig. 2), the inner part of the zone Houillère indeed exposes a deeper crustal level which suffered incipient blueschist facies conditions (P around 6 kbar) thus implying a tectonic burial in excess of 20 km. This inner sub-domain of the zone Houillère (and related Briançonnais Mesozoic to Tertiary cover southeast of Briançon) shows clear evidence for the initial generation of east-verging folds and reverse faults and thrusts, the recumbent folds generally displaying well-preserved inverted limbs and sheared normal limbs (Fig. 6). No earlier cleavage nor folds that hypothetically may have formed during "the oldest nappe pile" (Betrand et al. 1996) have been identified. The Queyras section (Fig. 8) shows the development of isoclinal folds with axes perpendicular to the Alpine arc in the more ductilely deformed Triassic marbles of the inner part of the external Briançonnais zone. This regime of transverse folds parallel to stretching lineations ("a" folds) perpendicular to the Alpine arc progressively affects the entire inner part of the zone Houillère in northern Savoie, as a result of increasing strain under a similar global EW horizontal stretching.

According to the classical interpretation, the tectonic contact between the zone Houillère (or external Briançonnais zone) and the Piemont zone *s.l.* formed as the result of late back thrusting (Lemoine 1961; Tricart 1984; Tricart & Lemoine 1986). In other words, the Piemont schistes lustrés and ophiolites, previously affected by tectonometamorphic events of assumed Cretaceous age, would have first overthrusted the entire Briançonnais zone to the west before being backthrusted to the east. This is valid for the southern Vanoise massif, but is precluded for the zone Houillère. Indeed, the only outlier of the Piemont zone (Mont Jovet, Savoie) lying on the Briançonnais zone did not experience blueschist facies metamorphism, and outliers of Helminthoid flyschs overlying the Eocene flysch southeast of Briançon are anchizonal. The geometry of structures, the numerous kinematic indicators and the estimates of P max. recorded in the different units (Table 1) clearly indicate that the boundary between the external Briançonnais zone and the Piemont zone in fact represents a continuous west-dipping ductile, normal fault in the Cottian Alps, which was reworked by normal and strikeslip brittle faults. This implies that both the internal Briançonnais zone and the external parts of the Piemont zone *s.l.* must have been subducted westward below the external Briançonnais zone during an early stage.

South of Briançon, the occurrence of preserved carpholite is restricted to the external Piemont zone, considered to represent the passive margin to the Piemont domain with thinned continental crust, adjacent to the Piemont-Liguria zone with oceanic crust and mantle. In the Queyras area, however, the jadeite+quartz blueschists of the Piemont-Liguria zone (P about 9 kbar) are in direct contact with the overlying Briançonnais zone (P about 4 kbar). Southward, the appearance of carpholite coincides with the tectonic contact between the external and the internal Briançonnais subdomains (Goffé & Chopin 1986), the latter outcropping as a half-window (= Acceglio zone) below the blueschist facies Piemont-Liguria zone. The inner part of the Acceglio zone suffered garnet-blueschist facies metamorphism (P max ≥10-12 kbar). Thus, a metamorphic omission of about 10-15 km in the Briançon area and of about 20 km south of Queyras necessarily occurs in the Cottian Alps along the Briançonnais/Piemont tectonic boundary.

North of the Arc valley, the zone Houillère is in direct contact with underlying high-pressure rocks of the southern Vanoise, which have been exhumed as a domal structure from below the Piemont zone (Fig. 7a) exposed in the south. This large crystalline massif exposes a thinned section of rocks affected by high-pressure, low-temperature metamorphism of post Middle Eocene age, with mineral assemblages similar to those from the Piemont-Liguria zone in Queyras and characterized in the basement by blueschists with the rarely observed coexistence of jadeite+quartz and by carpholite in the Mesozoic cover. The Ambin window also exposes pre-Permian basement rocks in a more internal position with higher grade metamorphism (jadeite-garnet-blueschist facies metamorphism similar to that from the Acceglio basement).

It is therefore concluded that the inner Briançonnais basement exposed east of the zone Houillère (Acceglio zone, southern Vanoise (P max ca 10 kbar) and in the Ruitor massif (P max about 12-14 kbar)) had been previously tectonically buried at depths of about 40-45 km under a low geothermal gradient of about 10-12°C/km typical of subduction-obduction contexts involving oceanic lithosphere. However, the major structures in the Acceglio and the Ruitor basement are characterized by recumbent to isoclinal folds with well-preserved inverted limbs, in agreement with syn-metamorphic east-directed displacement postdating the emplacement of the Piemont zone. This implies that initial prograde fabrics formed during the post-Eocene overriding of the Piemont zone during this subduction-obduction event may have been totally overprinted by the syn- to late-blueschist facies ductile deformation related to their exhumation. Paradoxically, most of the small-scale structures related to the late incremental ductile deformation show the development of top-to-the-west shearing. Synmetamorphic thinning is documented by the growth of glaucophane associated with, and even postdating, extensional mylonitic structures in the Ruitor basement (Fig. 15a).

Exhumation of the variably buried pre-Permian basement which implies up to 20 km of differential uplift with respect to the zone Houillère, was accompanied by tectonic denudation and unroofing of overlying units, allowing the outward emplacement of the Briançonnais nappes onto the external Briançonnais zone, as suggested by Gidon (1962) and Michard & Henry (1988). This overriding of nappes postdates the early emplacement of Cretaceous Helminthoid flyschs on top of the terrigeneous nummulitic flysch deposited in the Eocene Briançonnais sea.

4.2 The formation of syn-collisional low angle extrusions

Several authors have recently pointed to the rolo of extensional faults in adjacent areas, considered to represent post-orogenic collapse (Platt 1987; Philippot 1990; Ballèvre et al. 1990; Wheeler & Butler 1993). The Piemont-Liguria zone with blueschist facies metamorphism in the Queyras area is separated from the more internal counterparts (the Monviso Fig. 8) characterized by eclogitic metamorphism dated around 50 Ma (Monié &

Philippot 1989) by a late normal fault causing >10 km of metamorphic omission (Philippot 1990; Ballèvre et al. 1990). The western tectonic contact between the internal crystalline massifs and the eclogitic ophiolites and related Mesozoic cover also shows the existence of a significant extensional component. Moreover, the Monviso/Rocciavre massifs with eclogitic metamorphism are reduced to a narrow strip of prasinites and calcschists towards the north, all affected by late top-to-the-west extensional shear bands (Fig. 15f), thus in an opposite direction with that reported in the southern Vanoise (Platt & Lister 1985).

The cristallisation of HP/LT mineral assemblages in both sialic and oceanic units during post Middle Eocene times is consistent with a low geothermal gradient ob about 10 to 12°C/km typical for subduction-obduction scenarios (Schreyer 1988; Michard et al. 1995). Indeed, the innermost portions of the former Briançonnais platform (southern Vanoise, Ambin, Acceglio massifs) had been tectonically buried below the "Géosynclinal de nappes" of Ellenberger, (1958) (in other words the obduction of oceanic crust and mantle+abundant pelagic and terrigeneous sediments of the Piemont zone *s.l.*).

In the case of Oman (Michard et al. 1993), high-pressure, low-temperature metamorphism strikingly similar to that in the western Alps is entirely the result of obduction, and this scenario is also tentatively proposed for the western Alps (Michard et al. 1996). However, the east-verging structures described in the inner zone Houillère, the Acceglio and the Ruitor zones are exhumed from below the external Briançonnais zone and these east-verging structures do not fit with the classical assumption of a west-directed obduction. Alternatively, the attainment of a low geothermal gradient may have been reached through the refrigeration from below by initial west-directed subduction of the Piemont oceanic crust and mantle, as already suggested by Caby et al. (1978).

The structures reported in the Briançonnais zone show the development of east-directed thrusts and associated large-scale, mostly "a" type folds at deep crustal levels, and ductile extensional faults, both roughly time-equivalent, initiated under high-pressure conditions and still active under decreasing pressure. Geometries, kinematics and petrological data suggest that these structures did not form through a complex interaction in space and time between compression and extension, but rather represent low-angle east-verging extrusions of deeper rocks through shallower crustal levels. The generation of such "forced" extrusion during continuous convergence has already been proposed for exhumation of the ultra-high-pressure unit of Dora-Maira (Michard et al. 1993). The Figure 18 summarizes different stages of exhumation of high-pressure rocks of the Briançonnais basement in the form of extrusive anticlines. This sketch is based on the similarity of geometries and kinematics from mid-crustal levels (15 km in the Briançon area, A) to much deeper levels (ca. 45 km in the Ruitor basement, D with the overall formation of "a" folds and sheath folds). Continuous simple shear affecting an anticline may account for such thinning and for the preservation of the autochthonous cover in inverted limbs of east-verging folds.

Chemenda et al. (1995), based on physical modelling, stress that syn-collisional rock exhumation unvariably takes place following subduction of the continental lithosphere in the Himmalayan-type collisional ranges. In the experiments presented by these authors, the subducted crustal sheet moves back up to the surface at a critical stage of the subduction and forms relief, while continuing underthrusting of the denser lithosphere. Erosional unloading induces further rise of the crustal slice, as a result of buoyancy forces. If this

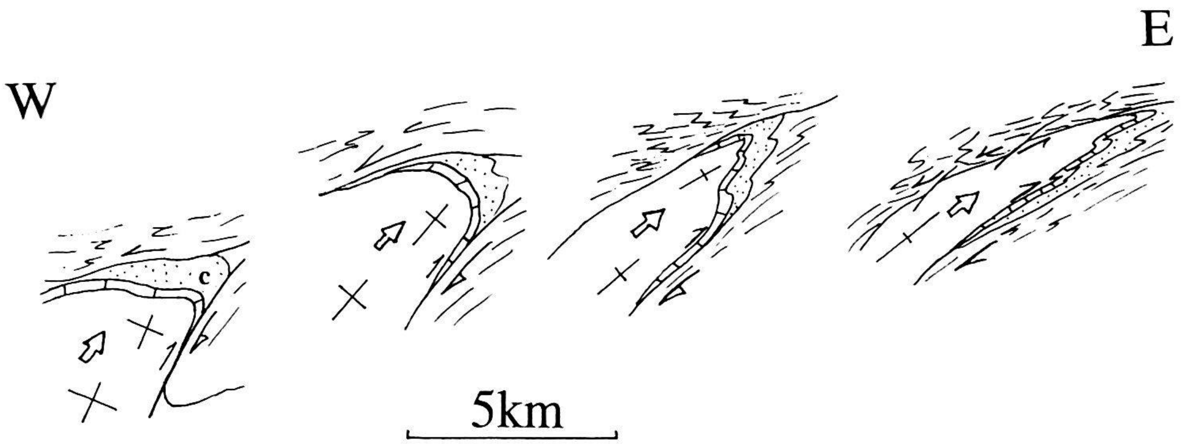


Fig. 18. Sketch showing the possible formation of east-verging "forced" extrusions of pre-Permian basement and autochthonous Mesozoic cover (c) burried below allochthonous units. Explanations in text.

model is applied to the western Alps, a west-dipping subduction zone may have been active between the Briançonnais passive margin and the Piemont ocean in Eocene times, as already proposed by Caby et al. (1978). However, since the western continental mass (paleo-Europe) had a thin crust resulting from Mesozoic rifting, it could not behave as a rigid buttress as in the Asian paleocontinent for the Himalayas and was affected by east-directed thrusts and east-verging folds.

4.3 Continuous convergence: the late emplacement of the Grand Saint-Bernard nappe

In the Aosta valley, the basal thrust of the Grand Saint Bernard nappe truncates the west-dipping structures and the root zone of east-verging extrusions (Fig. 17). This clearly demonstrates that outward directed displacements postdate inward directed displacements. The outward emplacement of the Grand Saint Bernard nappe followed the metamorphic peak dated around 41-36 Ma (Barnicoat et al. 1995). However the occurrence of gouge in the basal sole thrust implies an overprint by extensional movement at shallow crustal level, possibly connected with the Simplon fault, as proposed by Gouffon (1993).

The east-verging extrusions described in the Cottian Alps and in the Graie Alps may thus have formed both as a direct consequence of Eocene west-directed subduction and also as a response to permanent underthrusting at depths and indenting of the internal crystalline massifs, in line with Argand's concepts (1916): *"l'avancée en profondeur (Unterschiebung), vers l'extérieur des Alpes du pli V (Grand Paradis-Mont Rose) sous une partie du pli IV (zone du Grand St Bernard sl) qui a été contraint à se plisser en retour au-dessus de l'objet perturbateur"*. Roure et al. (1990) also stress the major role of wedging of the south Alpine dense and rigid lithosphere and its indentation at depth with the deeper continental eclogitic Alpine root, part of which is exposed in the inner part of the Piemont-Liguria zone and in the internal crystalline massifs.

5. Conclusions

The early east-verging structures recorded in the basement units from the Middle Penninic domain in the western Alps formed during global horizontal E-W contraction of the growing Alpine range. However, the radiating trajectories of deformation are globally E-W in the Cottian Alps, NW-SE in the Graie Alps, N-S in the Pennine Alps, but also N-S in the Ligurian Alps and with opposite vergence (Vanosi et al. 1984). This has not yet been taken into account by paleogeodynamic reconstructions (Platt et al. 1989). We suggest that the Alpine arc is entirely an Alpine feature resulting from wedging of the south Alpine lithosphere at depth and indentation of the internal crystalline massifs during the late Eocene and Oligocene. The latter include ultra high-pressure rocks which were subducted at depths exceeding 100 km below the inner Piemont-Ligurian ocean itself subducted beneath the south Alpine continent. However, the kinematics related to this subduction event are largely overprinted by kinematics linked with exhumation (Henry et al. 1993; Barnicoat et al. 1995).

The distribution of metamorphic zones and the inward-directed structures described from the western Alps suggest that an outward-dipping subduction zone may have been active in post Middle Eocene time along the boundary between the external Briançonnais zone and the Piemont zone *s.l.* This tectonic setting is distinct from the eastward-dipping subduction/obduction setting of the inner Piemont-Ligurian ocean below Adria Plate, the Upper Cretaceous age of which is controversial (Tilton et al. 1989; Barnicoat et al. 1995).

The geometry of the regularly west dipping middle Penninic units at the scale of the crust reminds the lamellae or "crocodiles", as already pointed out by Meissner (1989). The conclusions of Chemenda et al. (1995) strongly suggest that the eastward emplacement of the continental units with higher pressure metamorphism in the form of low-angle extrusive slices is the result of back up rise, while continuous convergence along a west-dipping subduction. This allowed the high-pressure crustal rocks to pierce the shallower crustal levels.

The younger outward-directed displacements which represent the most spectacular feature (i.e. the Penninic Front) are clearly younger features in respect to those related to inward displacements: they necessarily cut at depth the west-dipping structures described in the internal zones, as does the Grand Saint Bernard nappe in the Aosta valley at the surface. This is indeed suggested by the interpretation of seismic reflectors revealed by the ECORS CROP seismic profile (Damotte et al. 1990; Mugnier et al. 1990; Roure et al. 1990).

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