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The Pennine Front zone in Savoie (western Alps), a review and new interpretations from the Zone Houillère Briançonnaise

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Key words: Pennine Front, Moûtiers region, Mesozoic, tectonic evolution, neotectonics, western Alps

ABSTRACT

What is the significance of the Pennine Front (PF) and where is it precisely located in the Savoie segment of the alpine chain between the Isère and Arc valleys? The only continuous guide to precisely locating the PF is the Zone Houillère Briançonnaise (ZHB), a lithological unit which may be followed over about 200 km, and outlined along its western side by a continuous belt of gypsum and cargneule, the Briançonnais Front (BF). The PF itself is defined as separating the Pennine domain from the Dauphinois domain i.e. the Mesozoic to Cenozoic parautochtonous to allochtonous cover of the external basement massifs (EBM). In Savoie, the Valaisan units, the most external units of the Pennine domain, die out with the Niélard sub-unit located south of Moûtiers. Toward the south, the Valaisan is relayed by the so-called Sub-Briançonnais units. A sharp contrast in stratigraphy and tectonic evolution seems to exist between Briançonnais (= Mesozoic to Early Cenozoic Pennine formations) and Dauphinois, with the Sub-Briançonnais showing an intermediate, poorly documented, structural evolution.

This paper attempts to fit existing map and structural data on both sides of the PF zone with the classical tectonic units which are, until now, mostly defined upon stratigraphical grounds and palaeogeographical interpretations. The apparent correlation of major seismic reflectors shown on the ECORS-CROP profile with gypsum and cargneule-outlined belts, especially in the BF case, pleads for a relatively simple structure, with two parallel east-dipping tectonic contacts corresponding respectively to the PF and the BF, with the Sub-Briançonnais units resting in between. The actual significance of these tectonic contacts, at least for the BF, is interpreted here as the result of a late extensional event. A structural study of the ZHB suggests a new interpretation of the contrast between dominantly gently west-dipping schistosities in the ZHB and east-dipping schistosities in the Sub-Briançonnais. A neoalpine event, including a late extension, leads to the broad refolding of earlier structures behind the BF and may explain the present geometry and the linearity of the seismic reflectors. Preliminary observations of the neotectonic behaviour in the PF zone provide a preliminary test of this interpretation.

RESUME

Quelle est la signification et la localisation précise du Front Pennique (PF) en Savoie, entre les vallées de l'Arc et de l'Isère? Le seul marqueur continu correspond à la Zone Houillère Briançonnaise (ZHB), une unité lithologique qui peut être suivie sur environ 200 km et qui est soulignée, sur sa bordure ouest, par une ceinture continue de gypses et de cargneules, le Front Briançonnais (BF). Le PF lui-même est défini comme marquant la limite entre les domaines pennique et dauphinois, ce dernier correspondant à la couverture mésozoïque et cénozoïque des Massifs Cristallins Externes. En Savoie, les unités valaisannes, partie la plus externe du domaine pennique, disparaissent avec l'unité du Niélard au sud de Moûtiers. Vers le sud, les unités valaisannes sont

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relayées par les unités dites sub-briançonnaises. Les formations briançonnaises (mésozoïque à cénozoïque inférieur du domaine pennique) contrastent fortement, par la stratigraphie et la tectonique, avec celles du domaine dauphinois, le Sub-Briançonnais présentant une évolution structurale intermédiaire, encore mal connue.

Cette note a pour but de confronter les données cartographiques et structurales existantes des deux côtés du PF avec les définitions classiques des unités tectoniques basées jusqu'à présent sur leur stratigraphie et sur des reconstitutions paléogéographiques. La corrélation apparente entre les principaux réflecteurs sismiques du profil ECORS-CROP et les ceintures de gypses et de cargneules, surtout dans le cas du BF, indique une structure relativement simple avec deux contacts tectoniques à pendage est correspondant respectivement au BF et au PF, qui encadrent les unités subbriançonnaises. En réalité, ces contacts tectoniques correspondraient, du moins pour le BF, à un évènement tardif en extension. L'étude structurale de la ZHB suggère une nouvelle interprétation du contraste entre les pendages à dominante ouest de la ZHB et ceux vers l'est des unités subbriançonnaises. Un évènement néoalpin responsable de l'enroulement des structures tectoniques précoces contre le BF, pourrait expliquer la géométrie actuelle et la linéarité des réflecteurs sismiques (BF et PF). Des observations néotectoniques préliminaires de la zone du PF fournissent un début de test pour cette interprétation.

1. Introduction

In the western Alps (Fig. 1), the Carboniferous to Permian "Zone Houillère Briançonnaise" (ZHB), the most external unit of the Briançonnais domain, is the only litho-tectonic unit that is continuous along-strike east of the External Basement Massifs (EBM). This observation provides a reference point, as the ZHB broadly follows the boundary zone between what is classically considered as external (i.e. strictly European) and internal (i.e. the Pennine domain, which may in part consist of exotic terranes; Stampfli 1993). The precise location of the genuine "Pennine Front" (PF) is somewhat obscured by the occurrence, west of the continuous belt of the ZHB, of several discontinuous tectonic units, whose attribution to internal or external domains has often been discussed (Fig. 2).

Actually, the most obvious tectonic break shown on existing maps is not the PF but the "Briançonnais Front" (BF), also called the première zone des gypses or nappe des gypses. This fault zone is outlined by a thick, almost continuous, gypsum and cargneule belt containing numerous pluri-hectometric to kilometric blocks (blocs-klippes) of Permo-Triassic quartzites, dolomites and even Cretaceous marbles (Barbier 1948, 1963). It corresponds to a dramatic geomorphological signature (the major passes of Galibier, Encombres and Petit Saint Bernard).

In contrast, the precise location of the PF (see discussion and references in Mugnier et al. 1993) is more difficult to assess and largely depends on the palaeogeographic attribution of the tectonic units. No clear structural break can be established either from the literature or from maps, except perhaps north of Moûtiers where the Valaisan domain (*i.e.* Pennine) is thrust upon the Dauphinois domain (*i.e.* Helvetic).

The aim of this paper is to briefly summarize some of the stratigraphical and structural features which characterize the PF zone in Savoie. The stratigraphical and sedimentological record of each of the defined units will not be detailed, but a short presentation is necessary in order to point out where the main problems lie. We rather insist on the, unfortunately still scattered, structural observations. As an example, a case study of a small part of the ZHB and its bearing on future tectonic modelling of the PF zone in Savoie is briefly presented and discussed. Numerous unsolved questions and shortcomings are highlighted as aims for future research.

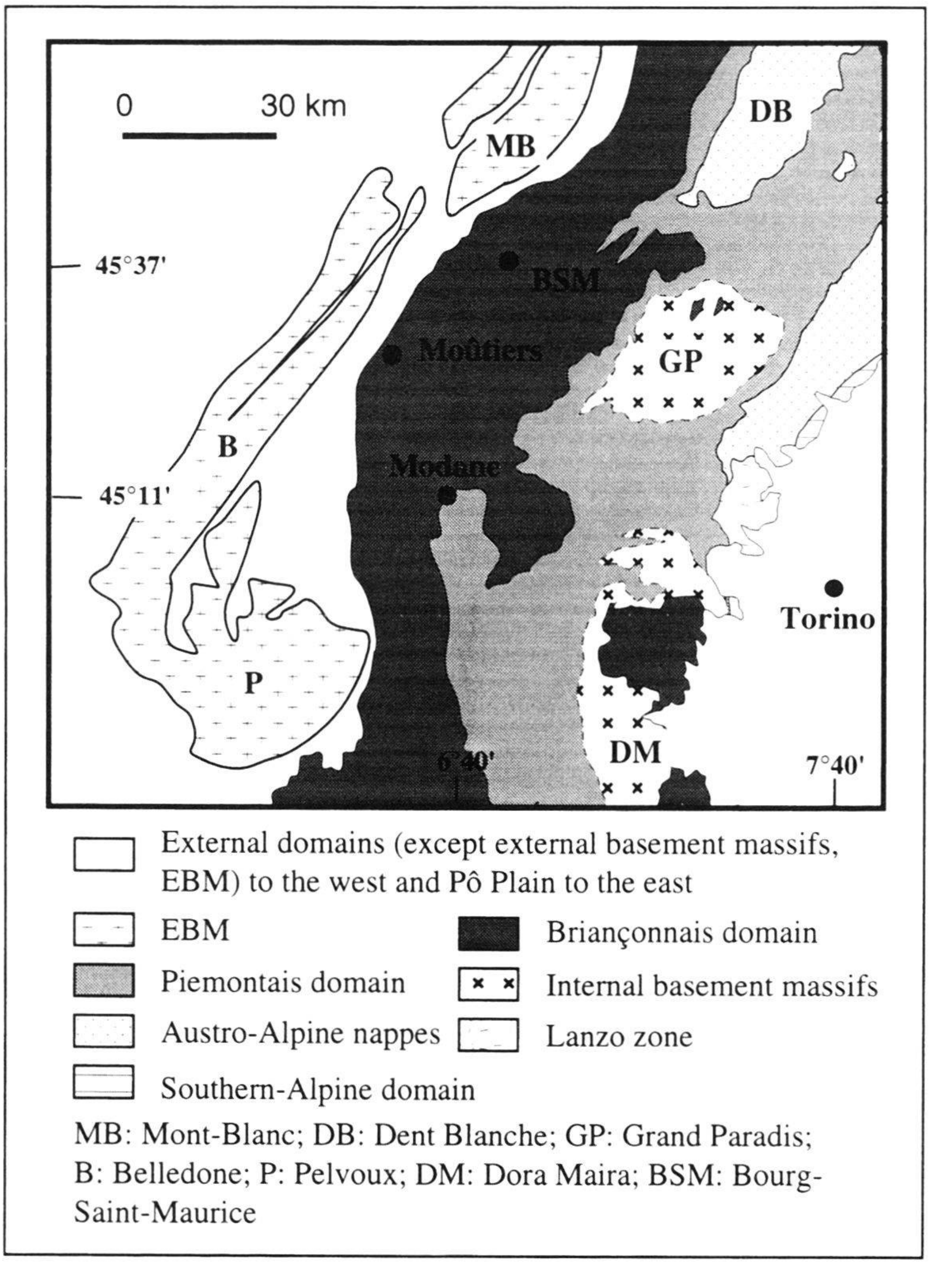


Fig. 1. Sketch map of the western Alps between Pelvoux and Mont-Blanc massifs.

2. Main stratigraphic features of the different domains

Many local investigations and previous reviews have dealt with the stratigraphy and palaeogeographical attribution of the numerous nappes or units defined in the PF zone (e.g. Barbier et al. 1963; Debelmas & Lemoine 1970). The definition of these classical units is mostly based upon the stratigraphy, palaeogeographical interpretations and map correlations and established continuity in the field. However, it is noteworthy that the structures are not cylindrical along the belt as suggested by the NNE-SSW oriented sketch of a longitudinal section as presented by Butler et al. (1986).

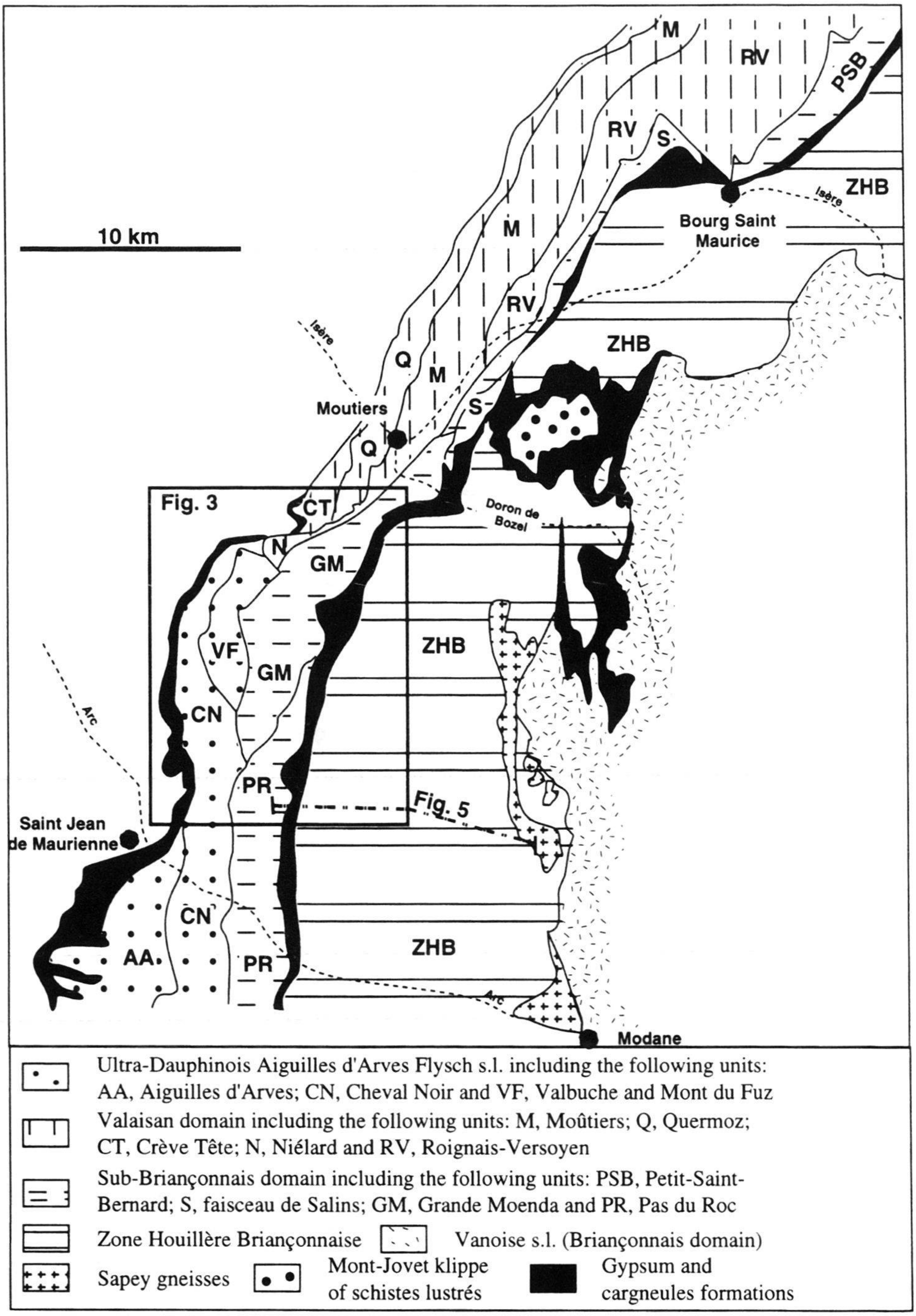


Fig. 2. Sketch paleogeographic and tectonic map of the region between the Petit-Saint-Bernard pass and Modane (modified from structural sketches of the 1/50,000 map sheets of Saint Jean de Maurienne, La Rochette, Bourg Saint Maurice, Modane et Moûtiers).

Even though the stratigraphical content of one tectonic unit may vary along strike, major palaeogeographic domains were parallelized with tectonic units in most of the literature. In the following we will briefly describe the main classical domains across a west to east composite section (see sketch maps on Fig. 2, 3).

a. Dauphinois (Helvetic) domain)

This domain constitutes the parautochtonous sedimentary cover of the EBM which is part of the European Variscan basement. A thin Permo-Triassic cover, often attached to the basement, is overlain by thick Lower to Middle Jurassic formations. Cretaceous units are also claimed in some places (Triboulet & Eltchaninoff 1980; Eltchaninoff et al. 1982). Most of these formations are involved in a nappe complex. The allochtonous or parautochtonous nature of the various units, including the Variscan basement, is discussed in many papers (e.g. Beach 1981; Eltchaninoff et al. 1982; Butler 1985; Butler et al. 1986; Epard 1990).

b. Ultra-Dauphinois (Ultra-Helvetic) domain

This domain tectonically rests on top of the Dauphinois units. According to the first definition by Barbier (1948), the Ultra-Dauphinois units are characterized by a Tertiary flysch unconformably overlying a Dauphinois substratum that was already deformed (the so-called Arvinche event). The thin pre-flysch formations are either tectonically fragmented or correspond to olistoliths according to Bravard et al. (1981). According to some authors, the composition of these Mesozoic formations suggests the possibility that two different flysch units are relaying from south to north: the Aiguilles d'Arves flysch, outcropping south of the Arc valley, has a Dauphinois substratum while the Cheval Noir flysch (in between Arc and Isère valleys) has a Briançonnais substratum (Martinez et al. 1979; Bravard et al. 1981; Serre et al. 1985). This discrepancy illustrates the urgent need to understand more clearly the relationships between the different flysch sub-units to locate precisely the PF south of Moûtiers.

The Valbuche and Mont du Fuz sub-units (Antoine et al. 1978; Martinez-Reyes 1980) are located east of the Cheval Noir flysch. They consist of basement (Valbuche) with overlying Carboniferous to Permo-Triassic and younger Mesozoic formations, and represent either tectonic slices or rather, mega-olistoliths within the flysch. Their stratigraphy suggests a Dauphinois origin. On the other hand, the Niélard sub-unit, also squeezed in between the Cheval Noir flysch and the Mesozoic formations of the Grande Moenda nappe (Sub-Briançonnais domain), is an olistostrom containing Jurassic breccias similar to those encountered in the Brèches de Tarentaise of the Valaisan domain. The Niélard sub-unit is considered to represent a major transversal break (Gély 1989) or a ridge separating the Sub-Briançonnais from the Valaisan domains (Antoine et al. 1978, Antoine et al. 1980).

c. Brèches de Tarentaise – Valaisan domain

This domain is composed of several tectonic units which are relaying from north to south and show a variable stratigraphical content. From west to east, the following units have been established (Fig. 2).

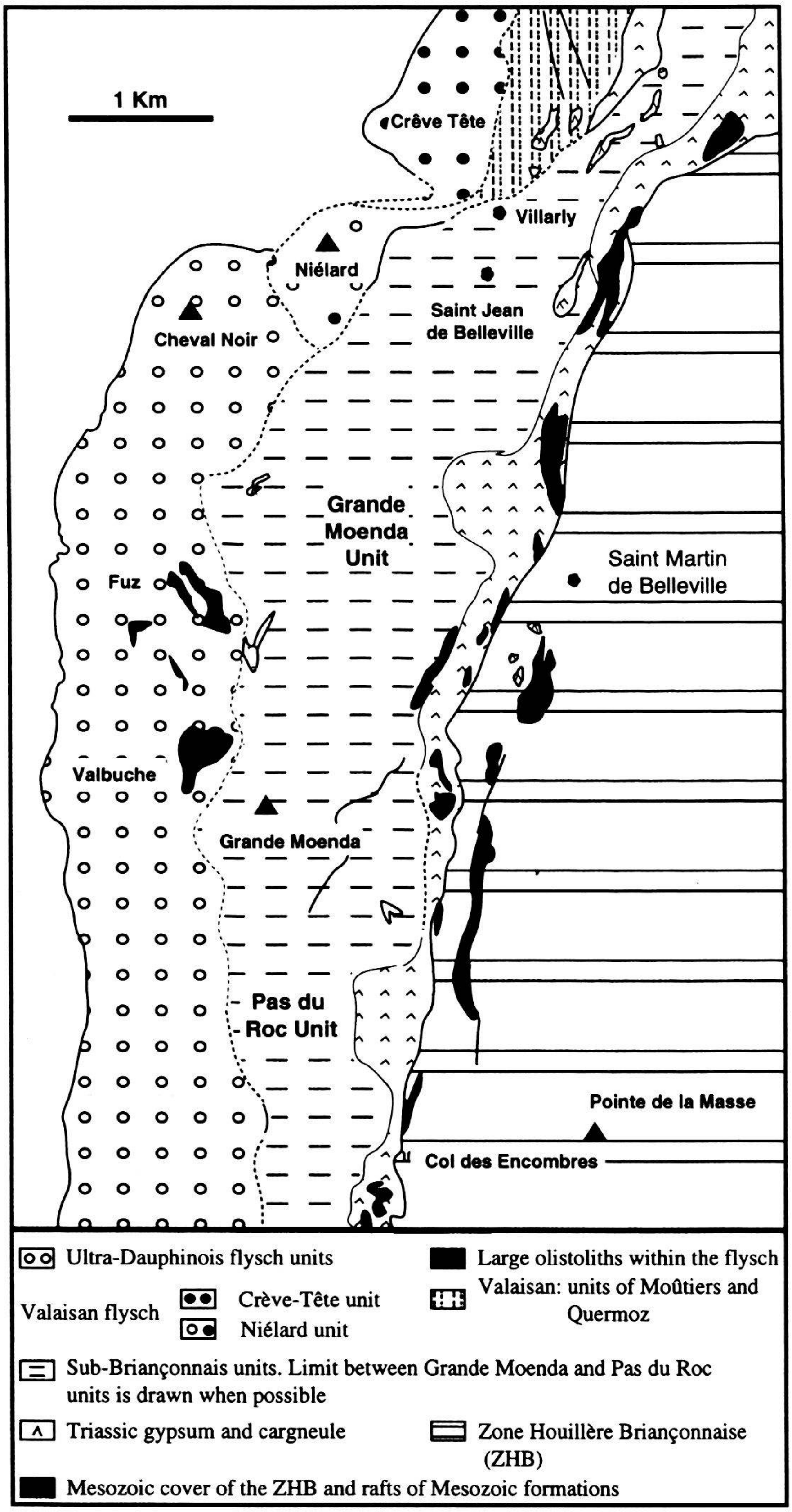


Fig. 3. Tentative sketch map of the key area, south of Moûtiers (adapted from 1/50,000 map sheets of Moûtiers, Modane, Saint Jean de Maurienne and La Rochette).

(a) The Quermoz unit (Antoine & Barbier 1978a) – in map view continuous with the Crève Tête unit of Gély (1989) south of Moûtiers: Lower breccias are attributed to the Jurassic while a clastic upper formation (flysch de Tarentaise) is of Late Cretaceous to Tertiary age. The Niélard sub-unit, south of Moûtiers (see above), may be also attributed to this unit according to Antoine & Barbier (1978b). To the west, the base of the Quermoz – Crève Tête unit is outlined by highly deformed slices of terranes of different ages. Near Moûtiers and toward the north this could represent the genuine PF, directly overlying the Dauphinois formations.

(b) The Moûtiers unit (Antoine & Barbier 1978b; Andrieux & Lancelot 1980) consists of crystalline basement (Hautecour), a Carboniferous to Early Jurassic cover (very similar to that of the Sub-Briançonnais domain) and a Cretaceous to Paleocene flysch. The Cretaceous to Paleocene flysch (flysch de Tarentaise) contains a formation characterized by black schists interlayered with green quartzite horizons (Marmontains beds), considered to be characteristic for the Valaisan domain (Antoine & Barbier 1978a).

(c) The Rognais-Versoyen unit consists either of a Carboniferous to Early Jurassic series of Sub-Briançonnais type or of black schists and mafic volcanics (Versoyen formation), both overlain by the Tarentaise flysch (Antoine 1971; Lancelot 1979; Lasserre & Laverne 1976; Andrieux & Lancelot 1980; Cannic et al. in press). The Versoyen formation contrasts with its surroundings by the presence of high-pressure metamorphic assemblages (ref in Cannic et al. 1996). The significance of the Punta Rossa granitoids is questionable: do they represent a Permian basement or a felsic body related to the Versoyen magmatism?

(d) The Salins unit (Faisceau de Salins) contains Carboniferous, Triassic and Early Jurassic series (Andrieux & Lancelot 1980). This unit may also be considered as the substratum of the unconformable Tarentaise flysch (Fudral 1980). According to Fudral (1980), block-bearing schists underlying the flysch conglomerates suggest a similarity with the Cheval Noir and Niélard sequences. This observation further outlines the ambiguity of the classical distinctions between Valaisan and Ultradauphinois units in the region.

d. Sub-Briançonnais domain (external Grande Moenda nappe and internal Pas du Roc nappe)

This domain is only known south of Moûtiers. The oldest formation is of Late Triassic age (Keuper) and contains gypsum, dolomites and violet schists. It is overlain by a thick Jurassic pile with some Cretaceous calcschists (marbres en plaquettes). This domain shows a strong stratigrahic contrast when compared with the Briançonnais domain, where the Jurassic formations are generally very thin. The Petit Saint Bernard unit and some isolated so-called blocs-klippes, contained within the "nappe des gypses" near Bourg-St Maurice, were attributed to the Sub-Briançonnais domain (Elter & Elter 1957). Fudral (1980) considers the Petit Saint Bernard unit as a tectonic unit, with no specific attribution, squeezed in between the ZHB and the Rognais-Versoyen unit while Cannic et al. (1996) suggest a Valaisan origin.

e. Briançonnais domain

East of the "nappe des gypses", the detrital and siliceous formations of the ZHB sharply contrast with the mainly calcareous and marly terranes outcropping to the west. Carboniferous and Permian formations are well-represented together with some Werfenian quartzites. A muscovite-chlorite greenschist facies metamorphic grade is characteristic. The classical Mesozoic Briançonnais series (e.g. Ellenberger 1958; Raoult 1980) with their thick Middle to Upper Triassic limestones and dolomites, only crop out further to the east. They are separated from the ZHB by a discontinuous strip consisting of the "Gneiss du Sapey", representing pre-Carboniferous basement according to Détraz (1984). The age of the Sapey gneisses is still unknown but the work of Guillot (1987) on the Mont Pourri basement in the Vanoise may suggest Variscan or even pre-Variscan ages (Guillot et al. 1991; Guillot et al. 1993).

In several places (e.g. Les Encombres, Saint Martin de Belleville, west of Mont Jovet and Petit Saint Bernard), the ZHB is bordered in the west by a strip consisting of lower grade, fossiliferous, Carboniferous to Permian formations (Mercier & Beaudouin 1987), locally separated from the main ZHB by discontinuous lenses of Trias (quartzites, dolomites and cargneules).

f. Discussion

This succession of domains, described above from west to east, is never complete in any particular section. It must be noted that south of Moûtiers, according to currently accepted (or proposed) correlations, the Valaisan domain is missing. The main change occurs immediately south of Moûtiers, where the Niélard sub-unit is exposed, the attribution of which is still in question (Martinez-Reyes 1980; Gély 1989). Towards the north, the Sub-Briançonnais domain is largely missing except for some discontinuous lenses of controversial attribution (near Bourg-Saint-Maurice and the Petit-Saint-Bernard unit). Thus, west of the BF, units are organized in relay, separated by tectonic contacts.

On the contrary, the Briançonnais domain is clearly non-cylindrical at map scale as evidenced by the patchy pattern shown on existing maps. However the Carboniferous formations of the ZHB and the slices of the Sapey gneisses are outcropping all along the studied strip, suggesting, together with the metamorphic contrast with the Vanoise, that this part of the Briançonnais domain had a specific behaviour, somewhat guided by the BF.

A strike-slip model has been proposed in order to explain the origin of the Sub-Briançonnais domain (Ricou 1980; Ricou & Siddans 1986) and the southward disappearance of the Valaisan domain. According to this model, the complexity of the Sub-Briançonnais, a stack of units of variable stratigraphic content, dragged below the PF, is the result of an Eocene strike-slip event (Ricou & Siddans 1986; Stampfli 1993). The Pennine domain has been emplaced as a nappe stack during Oligocene times, and hence after the strike-slip event which may have controlled parts of the flysch basins. According to Stampfli (1993), the Briançonnais domain may be interpreted as an exotic microplate. The time relationships between the evolution of the Valaisan trough and the emplacement of the Briançonnais domain, both comprising Eocene formations, may imply a large scale strike-slip event predating the Oligocene nappe emplacement.

g. Internal basement

Recent surprises concerning the Early Palaeozoic age of parts of the Mont Pourri basement (Guillot et al. 1991) also suggest the need for a closer look at the geochronology of pre-Mesozoic formations in the Vanoise and at the small pieces of basement occurring in the Valaisan, Sub-Briançonnais and Ultra-Dauphinois domains (Valbuche, Hautecour, Tête Rousse). In the Briançonnais domain the Sapey gneisses (basement slices according to Détraz 1984), outcropping along the eastern edge of the ZHB, are different in lithology from the Ruitor basement (Baudin 1987). Although strongly deformed and metamorphosed during Alpine events, these basement rocks may reveal significant differences in the provenance of the corresponding units. They may also help to place limits on the timing of the events of crustal thinning associated with the formation of both the Piemontese and Valaisan oceanic domains. At present, at least for precise U-Pb ages, the western internal Alps in France and Italy are almost terra incognita. This dating of the basement should also be complemented by attempts to decipher, using other geochronological methods, the precise timing of alpine metamorphic events within the several tectonic units to both sides of the PF zone.

3. Main structural features of the different domains

Only a few detailed structural studies are available in the key region of the Frontal Pennine Zone (FPZ) around Moûtiers (Andrieux & Lancelot 1980; Lu Chia 1986; Gély 1989; Spencer 1992). The most recent results (Spencer 1992) are summarized in Table 1 where two zones are distinguished in the FPZ according to this author: the North Frontal Pennine Zone (NFPZ) and the South Frontal Pennine Zone (SFPZ).

A major stage of NW-SE directed extension, especially well-preserved in the Lower Jurassic calcareous marls represents the oldest tectonic event, registered in both Dauphinois and Sub-Briançonnais domains. In these domains, two sets of calcite veins (respectively parallel and perpendicular to bedding) clearly predate all the folds and sets of cleavages (Spencer 1992). The veins are interpreted as resulting from a NW-SE extension (D_1 event of Spencer, Tab. 1) which predates the tectonic inversion of the Mesozoic basins, the formation of which was controlled by this extension. The Middle Tertiary collision, complicated by the lateral movements already quoted, produced the inversion of the basins. In the Valaisan domain (NFPZ – Valais and Brèche de Tarentaise zone), an extensional regime is still active until late Cretaceous to early Tertiary times. This extensional regime is broadly synchronous with the syntectonic (?) emplacement of the large Ultra-Dauphinois flysch units further south. However, from the available literature, the precise age of the different flysch units (Upper Cretaceous to Early Tertiary) is still discussed. Pre-Priabonian folds, sealed by an unconformity below Eocene flysch (Arvinche event of Barbier 1948), have also been reported by Gély (1989).

The age of the main collisional event is rather ill-constrained although considered by all authors to be post-Eocene (Middle to Late Oligocene for Eltchaninoff et al. 1982). According to Gély (1989) the first stage of this event is only recorded in the Brèches de Tarentaise but is lacking in the Dauphinois domain, an interpretation which is in disagreement with Epard's (1990) observations in the Dauphinois Mont Joly nappe to the north. This early stage, generally poorly preserved, is also described by Spencer (1992) in

Table 1. Structural evolution of the External, Frontal Pennine (FPZ) and Subbriançonnais zones according to S. Spencer (1992)
(1) NFPZ : North Frontal Pennine Zone – Valais or Brèche de Tarentaise zone.
(2) SFPZ: South Frontal Pennine Zone - Niélard, Valbuche, Mont du Fût and Aiguilles d'Arves zones.

	External	NFPZ (1)	SFPZ(2) S	N	Subbriançonnais
D6	*N-S extension.*	*N-S extension .*	*N-S extension.*		*N-S extension .*
D5	ESE facing F_3 backfolds. S3 cleavage. Locally, "en échelon" strike-slip faults.	ESE facing F_3 backfolds. S_4 cleavage linked backthrust system.	SE facing F_2 backfolds. Backthrusts with a SE movement.		SE facing F_2 backfolds. Locally downward facing structures. Backthrusts with a SE movement.
	Deformation and local thrusting associated with the arrival of the Subbriançonnais thrust sheet.	Deformation and local thrusting associated with the arrival of the Subbriançonnais thrust sheet.			
D3 et D4	Thrusting of the FPZ over the external zones with foreland directed duplex. S_1 and S_2 cleavages ; WNW vergent F_2 folds with along strike extension.	*Extensional faults trending N-S.* Main WNW compressional phase. F_2 folds and thrusting associated with along-strike extension. Development of S_2 and S_3 cleavages.	Main WNW compressional phase, with foreland directed duplex and F_1 folds. No along strike extension.	Development of NW-SE trending structures with strong along-strike extension. A lateral ramp?	
D2	Inversion of the external crystalline massifs.	Inversion of the basin leading to recumbent F_1 folds associated with a S_1 cleavage. *Development of a strike slip extensional basin.*			Thrusting of the Subbriançonnais on to the more external zones. F_1 folds back-steepening the faults.
D1	*NW-SE extension.*	*NW-SE extension .*	*NW-SE Extension.*		*NW-SE extension.*

the NFPZ but is lacking in the SFPZ (Niélard, Valbuche, Mont du Fuz and Aiguilles d'Arves areas). NW-verging F_1 folds (Late D_2 event, Tab. 1) and associated S_1 cleavage may be related to the emplacement of the Sub-Briançonnais nappe onto the more external regions.

During the D_3/D_4 events (Tab. 1), according to Spencer (1992), a strong cleavage related to WNW verging folds with along-strike extension and thrusting, developed in the NFPZ (F_2 folds and S_2/S_3 cleavage). Meanwhile, F_1 folds showing the same vergence developed in the SFPZ, associated with cleavage in the southern part of the zone, but not in the northern part of the zone where along-strike extension occurred. These events were followed by the thrusting of the FPZ over the external zones. The final emplacement of the Sub-Briançonnais thrust sheet took place after D_4 (Tab. 1). Also for Gély (1989), this stage is marked by a S_2 cleavage and by folds parallel to the strike of the zone and followed by later thrusts cutting these folds. Further north, in the Dauphinois domain near Megève, Epard (1990) describes kolometric- to decametric-size NW-verging F_2 folds with a S_2 cleavage.

The last recorded compressive event (Gély 1989; Spencer 1992; Epard 1990) corresponds to east-facing (locally ENE, ESE or SE) backfolds (D_5 in Tab. 1) which, according to Gély (1989) and Lu Chia (1986), may be associated with both sinistral and dextral strike-slip faults. It develops F_3/S_3, F_3/S_4 and F_2 structures respectively in the external, NFPZ and SFPZ (Spencer 1992).

The large-scale sinistral displacement postulated by Ricou (1980) is nowhere recorded in the deformation sequence as it corresponds to a pre-flysch and thus pre-D_2 event in the scheme of Table 1. The importance of strike-slip movements in the structural pattern of the EBM and Dauphinois domain, postulated by Barféty (1976), has not been confirmed by Beach (1981) in the Pelvoux region.

From this review, it appears very difficult to precisely correlate the deformation sequences in the different units as, except for the work of Spencer (1992) and Andrieux & Lancelot (1980), there is little data dealing with finite strain and kinematic indicators. Furthermore, the flysch units, both in the Ultra-Dauphinois and Valaisan domains, have not yet been well-studied structurally. They now appear as key-areas for deciphering the large-scale evolution of the FPZ. The existence of several periods of large-scale nappe emplacement is obvious at least in the Briançonnais domain where the base of the Mont Jovet-Schistes Lustrés nappe cuts across earlier structures. However, the precise chronology of these successive thrust events is not clear from the available literature.

4. Structure and kinematics of the Zone Houllière Briançonnaise

We will now focus on the tectonic evolution of the ZHB, studied in detail by Aillères et al. (1994, 1995a). The aim of this study was to determine the structure and kinematics of the ZHB in order to propose a new interpretation of the seismic ECORS-CROP-Alpes section crossing the PF zone (ECORS-CROP Gravity Group 1989; Nicolas et al. 1990; Mugnier et al. 1993).

a. Structural evolution of the ZHB

The ZHB is the easternmost unit of the Briançonnais domain. Its structural position, at the contact with the Sub-Briançonnais domain and on top of the BF, emphasizes its interest in locating the BF and understanding its kinematics. The structure of the ZHB has long been described as a fan structure (Favre 1861; Ellenberger 1958; Fabre 1961; Caby 1963; Fabre et al. 1982; Caby 1992). However, structural observations from the Vallée des Belleville (Savoie, France), north of the Arc valley, lead to a new kinematic model of the ZHB and of its western tectonic contact. The synthetic cross section (Fig. 4) shows the geometrical relationships between the different tectonic surfaces recognized within the ZHB just east of the so-called BF. The new proposed model (Fig. 5a) differs from those previously published by Debelmas et al. (1989b), Caby (1992) and also from a preliminary reinterpretation (Aillères et al. 1994). Three main tectonic events (still uncorrelated with the classifications given on Tab. 1) have been established and were followed by a late extensional stage.

The D_1 event is marked by strongly deformed thin layers alternating with thick layers of undeformed rocks. The strongly deformed layers show a penetrative S_1 schistosity, nearly parallel to S_0. The younging direction of S_0 remains identical in all undeformed layers. The D_1 event is interpreted to represent the piling up of tectonic units with an unknown transport direction.

The D_2 event develops the S_2 regional schistosity which is gently dipping to the west except close to the BF. The S_2 surfaces are axial planar to F_2 folds which correspond, in their present position, to km-size recumbent folds facing toward the east as evidenced by

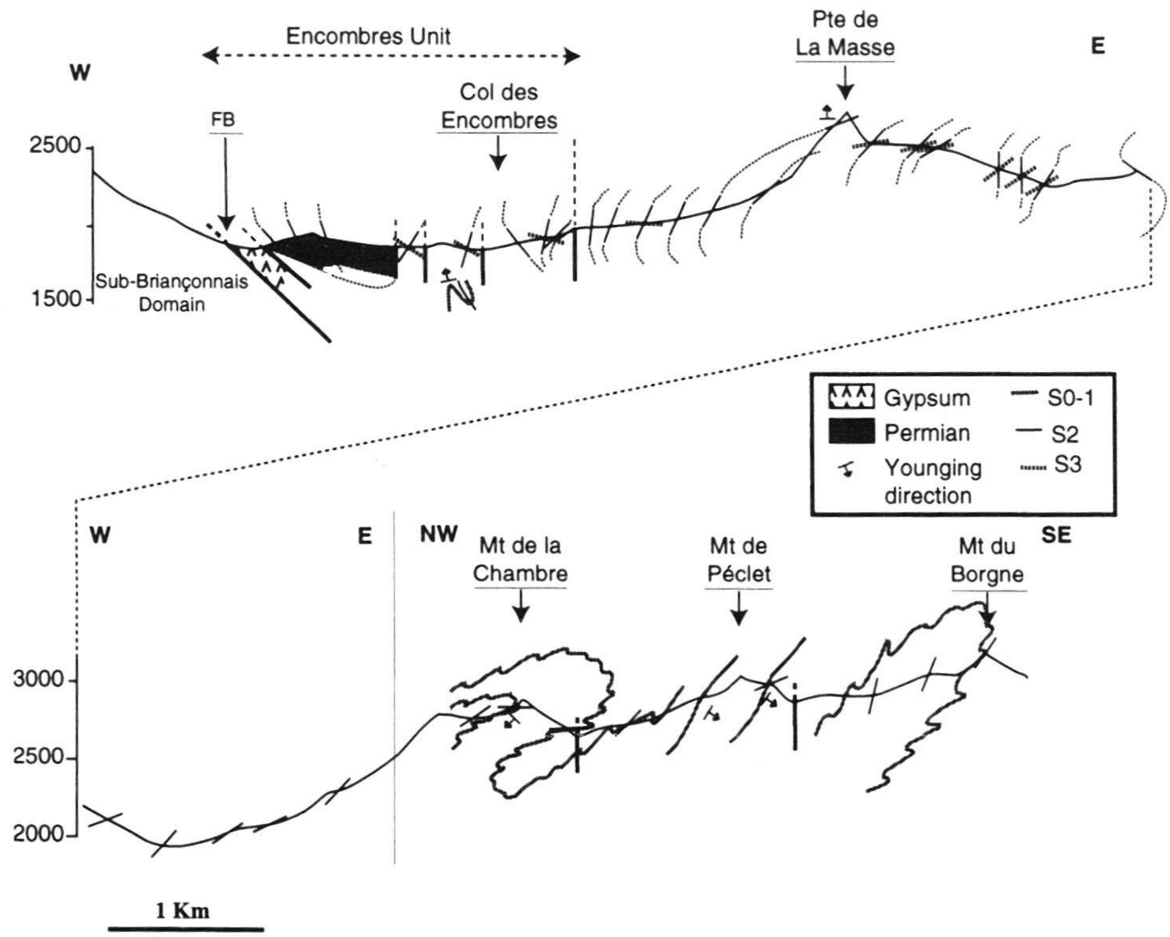
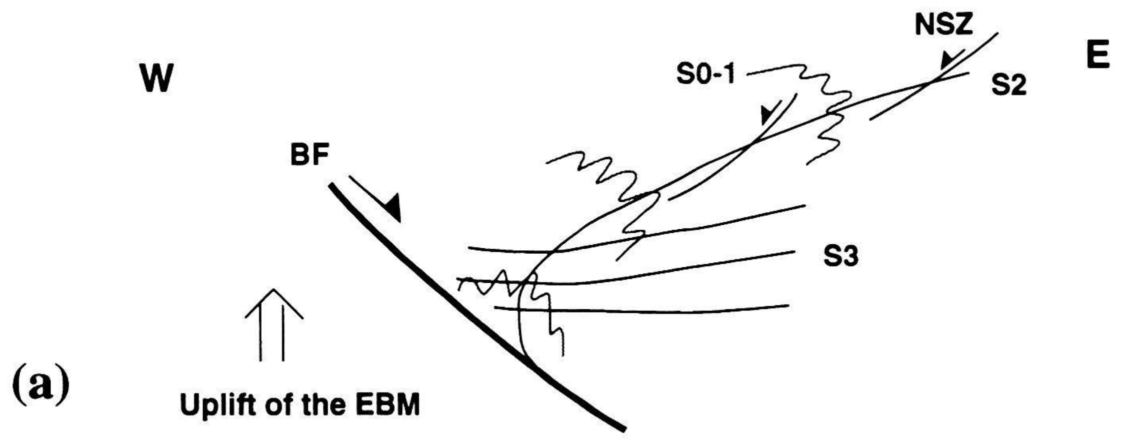


Fig. 4. Schematic cross-section of the ZHB stressing the attitude of the successive schistosities.

sedimentary younging and bedding-cleavage relationships. However, the original attitude of the F_2 folds cannot be determined with certainty since their gently-dipping attitude could be the result of later tectonic events.

The D_3 event corresponds to a large-scale bending of the S_2 schistosity around a km-size F_3 fold. This fold is partly responsible for the fan shape of the S_2 schistosity close to the Les Encombres pass (see discussion below). A S_3 schistosity, generally horizontal, develops only in the hinges of second order F_3 folds. Thus, the apparent eastward facing of the F_2 folds is probably due to the bending of D_2 structures around the large F_3 fold.

A late extensional stage, the time relationship relative to D_3 being still not clearly determined, is related to normal faulting along the so-called BF. Structural evidence is ambiguous as, on one hand, the geometrical relationships between the subhorizontal S_3 and the steeply east-dipping fault plane (BF) suggest synchronism but, on the other hand, S_3 appears slightly bended close to the BF, suggesting a downward movement of the eastern block. Unfortunately, no obvious kinematic criterion has been observed within the large gypsum belt outlining the BF.



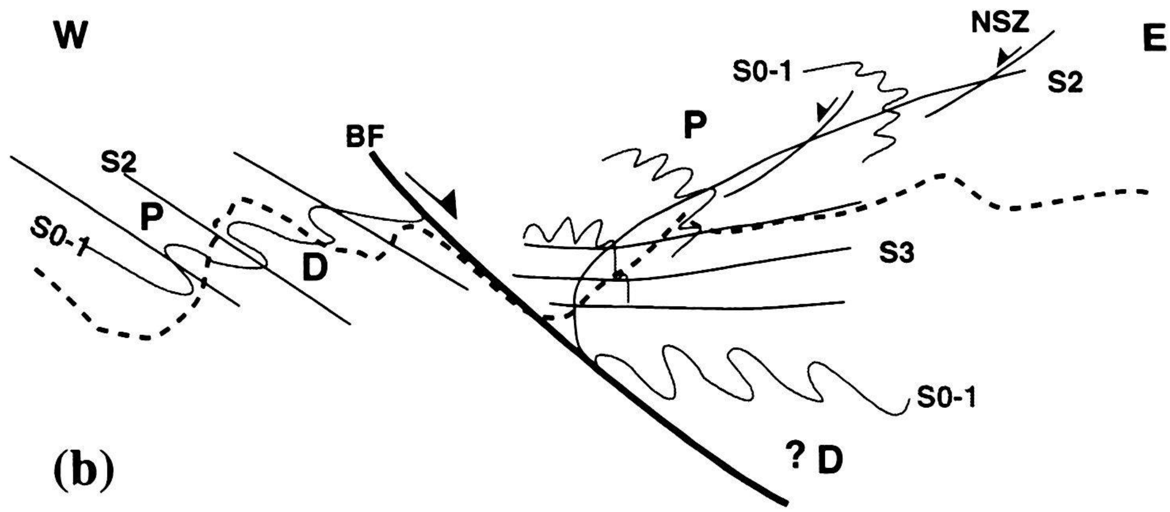


Fig. 5. (a) Structural evolution of the ZHB. NSZ: Normal shear zones. S_0 to S_3: see text and Fig. 4. (b) Enlarged model showing how the Sub-Briançonnais and Valaisan outcrops can be inverted at map scale. The dotted line corresponds to an average topography. P: Pennine domain s.l. including Valaisan terranes; D: Dauphinois, Ultra-Dauphinois and Sub-Briançonnais domains.

In a previous paper (Aillères et al. 1994), we interpreted the east-dipping penetrative schistosity (about 60° to 70° toward east), parallel to the BF observed in the "Les Encombres unit" as possibly related to a late normal faulting behaviour of the BF. Such interpretation is unlikely because the schistosity observed in this unit presents the same characteristics of our S_2 except that it is facing west, with Permian and Triassic formations overlying the Carboniferous. The "Les Encombres unit" (Fig. 4) is separated from the rest of the ZHB and from the larger F_3 fold described above by a vertical N30 trending fault. Could not such an east-dipping attitude of folds and main schistosity, rather be closer to the original attitude of D_2 folds?

West-dipping normal shear zones (NSZ) are developed especially in black schist layers in the central part of the studied area, far from the BF, and along the contact with the Sapey gneisses. These NSZ cross-cut both D_1 and D_2 structures but their direct relationships with D_3 or with the late extensional stage have never been observed. Baudin (1987) described similar structures in the Ruitor area (extensional crenulation cleavage, Platt & Vissers 1980) which here are immediately following his D_3 bending. This author interpreted the extensional crenulation cleavage as the result of the accomodation of his D_3 folding event and thus belonging to the same broad kinematic event.

b. Kinematic model

The sequence of events presented above does not differ significantly from those described in the Vanoise region (Platt et al. 1989), in the ZHB's Ruitor area (Baudin 1987) and in the Névache valley (Fabre et al. 1982), except for the vergence of the D_3 event and the interpretation of the backfolding and thrusting (Platt & Lister 1985; Platt et al. 1989). Our interpretation differs also from Détraz (1984) and from the recent synthesis by Caby (1992), who did not identify the D_1 non-penetrative deformation. We consider the D_1 event to be responsible (1) for the formation of the oldest nappe pile and (2) for the tectonic emplacement of the Sapey gneisses and easternmost units upon the ZHB. The dominant eastward younging direction observed in the Carboniferous formation of the eastern part of the ZHB suggests such an interpretation.

The D_2 event is responsible for early folding of the whole nappe pile formed during D_1, but its primary attitude is not yet clear. The most important new result is the evidence that the S_1 schistosity, where present, is always refolded. On the contrary, the S_2 schistosity which appears as the main regional feature in the ZHB is only affected by later folds in the vicinity of the BF. Assuming the identity of the main schistosities in the ZHB and in the Vanoise region (our S_2), it is possible that the D_3 folding is contemporaneous to Platt & Lister's (1985) backfolding. This possibility is still to be tested with a careful study of the critical Chavière fault zone which separates the ZHB from the Vanoise. Along the BF, on the western edge of the ZHB, the D_3 event produced the complete westward refolding of older structures, including early nappe contacts. Thus, the west-dipping S_2 schistosities in the ZHB and Vanoise could be equivalent, in time, to some of the east-dipping regional schistosities described in more external units. The problem raised by the west-dipping, post-S_2 NSZ may lead to two different interpretations for the D_3 event:

- (1) If the NSZ are interpreted as the progressive evolution of the D_3 event (Baudin 1987) which outlines a general westward movement during a compressional event, then, the observed tilting (Fig. 5a) of the ZHB and Vanoise is related to late normal faulting along the so-called BF (Cannic et al. in press; Aillères et al. 1995a). In that case, D_3 is related to a compressional event and is distinct from the late extension along the BF.
- (2) Another possible interpretation of the D_3-NSZ relationships could be that the NSZ represents antithetic shear zones with respect to the late normal faulting. In this case, the D_3 event may correspond to a roll-over style deformation induced by normal faulting along the BF. In other words, D_3, together with the extensional faulting, may be defined as corresponding to a late extensional event, most probably neoalpine in age.

5. Toward a new geological evolutionary model

The geometry and kinematics of the PF and BF zones may be interpreted in three different ways:

(1) the PF represents the genuine primary tectonic contact between Dauphinois (Helvetic *s.l.*) and Pennine domains. Some relatively well-preserved D_1 (in most cases D_1+D_2) tectonic contacts have been observed in the ZHB. Similarly, north of Moûtiers, there is a strong stratigraphic contrast between the Valaisan domain and the Dauphinois series and they are separated by a major tectonic contact.

(2) the large-scale D_3 structure identified close to the BF may be related to a post-collisional (Miocene?) westward movement of a subcrustal indenter similar to the one identified in the Central Alps (e.g. Schmid et al. in press). A similar indenter is also suggested by the crocodile imaged by the ECORS-CROP Profile below the Vanoise (Ménard & Thouvenot 1984; Mugnier et al. 1989; Roure et al. 1989; Thouvenot et al. 1990; Nicolas et al. 1990; Tardy et al. 1990). It must be noted that, in the Arc valley, the eastern edge of the ZHB (the contact with the Sapey gneisses) apparently shows a similar geometry to that of the western contact, with a subvertical S_0–S_1 and a subhorizontal S_2, but it is devoid of D_3 deformation (unpublished observations from 600 m-deep SNCF drilling).

(3) a late, large-scale crustal delamination occurring across the BF zone is suggested by (a) the existence of an east-dipping, thick and continuous gypsum and cargneule scar (b) well-marked seismic reflectors (see below) and (c) the contrasting geometry of the main tectonic surfaces (east-dipping west of the BF and west-dipping east of the BF). In this case, the western margin of the Pennine domain may have collapsed along the BF producing a roll-over style structure as subcrustal deformation moved from east to west, producing the uplift of the EBM (Aillères et al. 1995a).

Which of these three interpretations is pertinent? Or is it possible that along a unique map trace, the so-called PF, three distinctive mechanisms and/or successive events may have occurred? Model (1) tectonic contacts apparently occur west of the Sub-Briançonnais and Valaisan domains according to the literature (Mugnier et al. 1993) – the genuine PF – but are more difficult to assess across the BF. Regarding both models (2) and (3) a late event, Neoalpine in age, must be postulated to explain the present geometrical pattern of both sides of the BF. Figure 5b tentatively sketches such an interpretation and shows schematically how a primary, D_1-related thrust contact which could partly correspond also to a palaeogeographical break is folded by D_2 and is subsequently wrapped around a large D_3 fold. In this case, the more external position of the Valaisan domain with respect to the Sub-Briançonnais domain, close to Moûtiers, can be easily explained. Such a situation could be the result of the intersection of the topographic surface with a complex tectonic edifice, essentially resulting from a westward D_3-refolding of older structures – whatever the corresponding mechanism (indenter or collapse). Such an interpretation addresses the hypothesis of a major back-folding event proposed by most authors because the initial geometry of the D_2-related structures is unknown. However, such an emphasis on the role of the D_3 event does not signify that the backfolds and backthrusts observed further east, in Vanoise (Platt & Lister 1985), were initially foreland verging structures because they may also belong to the D_3 event. Is their present position, with often gently west-dipping axial surfaces, a primary feature? Would it be com-

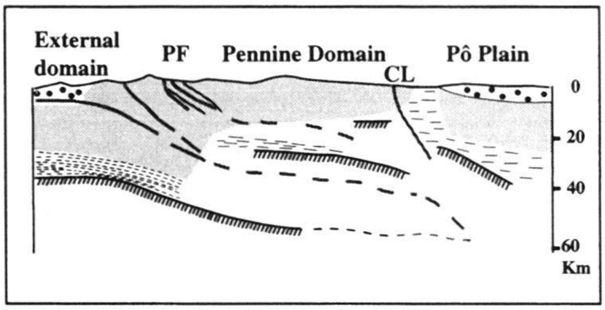


Fig. 6. Interpretative schematic cross-section from migrated vertical reflexion and refraction, wide-angle reflection (black lines with inclined barbs) data and gravity modelling. Grey is for upper crust, dotted lines represent the lower crust. Wide-angle data show the location of the Moho. CL: Canavese Line; PF: Pennine Front. Modified from ECORS-Crop Gravity Group (1989).

pared with ZHB's S_2 or NSZ? In the ZHB, the dominant flattening measured from finite strain analysis which dealt mostly with S_2 schistosity (Aillères et al. 1995b) suggests that D_2 structures were initially steep. However, the possibility that a large part of the Vanoise region could be upside down with respect to the early nappe structures is a provocative question (relative age of the megascopic Mont Pourri recumbent fold? Guillot 1987).

6. The seismic image under the PF zone

Is such an interpretation fitting with available geophysical data? Mapping of the Moho under the French-Italian Alps has been carried out by vertical seismic reflection, wide-angle reflection and gravity modelling (ECORS-CROP Deep Seismic Sounding Group 1989; Nicolas et al. 1990; Thouvenot et al. 1990). Data show (ECORS-CROP Gravity group 1989) two superposed reflective zones, both interpreted as the seismic signature of the Moho (Fig. 6). Under the EBM, the reflective zones, attributed to the European Moho, is at a depth of 37 km. Under the PF zone, it reaches a depth of 55 km and is relayed by a shallower (25–30 km) similar reflective zone which underlies the Pennine domain. This suggests crocodile structure (Meissner 1989) as proposed by Roure et al. (1989) and Nicolas et al. (1990). At the upper-crust level and just below the ZHB, time-migrated vertical reflection data (Mugnier & Marthelot 1991; Sénéchal & Thouvenot 1991) show two narrow and parallel bands of east-dipping reflectors which have been interpreted as the seismic signature of the PF s.l. (Mugnier et al. 1993). According to these authors, the external east-dipping band corresponds to the PF which separates the external Alps (Dauphinois and EBM) from the Valaisan domain (and Sub-Briançonnais?). The most internal band corresponds to the BF, separating the Valaisan domain from the Briançonnais domain. At depth the two bands cross-cut a series of poorly defined, west-dipping reflectors within the ZHB and the Vanoise further east. Tardy et al. (1990) proposed two different interpretations of these reflectors: they may correspond either to early alpine structures, subsequently tilted by the Grand Paradis massif exhumation or to late backthrusting.

Coming back to structural features, the west-dipping reflectors correlate well with the main D_2 pattern, especially east of the PF zone. The interpretation is less clear concerning the two east-dipping linear bands of reflectors as no easy correlation may be proposed with the D_3 event. However, the linearity of the two bands is the main evidence to suggest their relation with a late event, probably extensional according to structural observations (Seward & Mancktelow 1994; Cannic et al. in press; Aillères et al. 1995a).

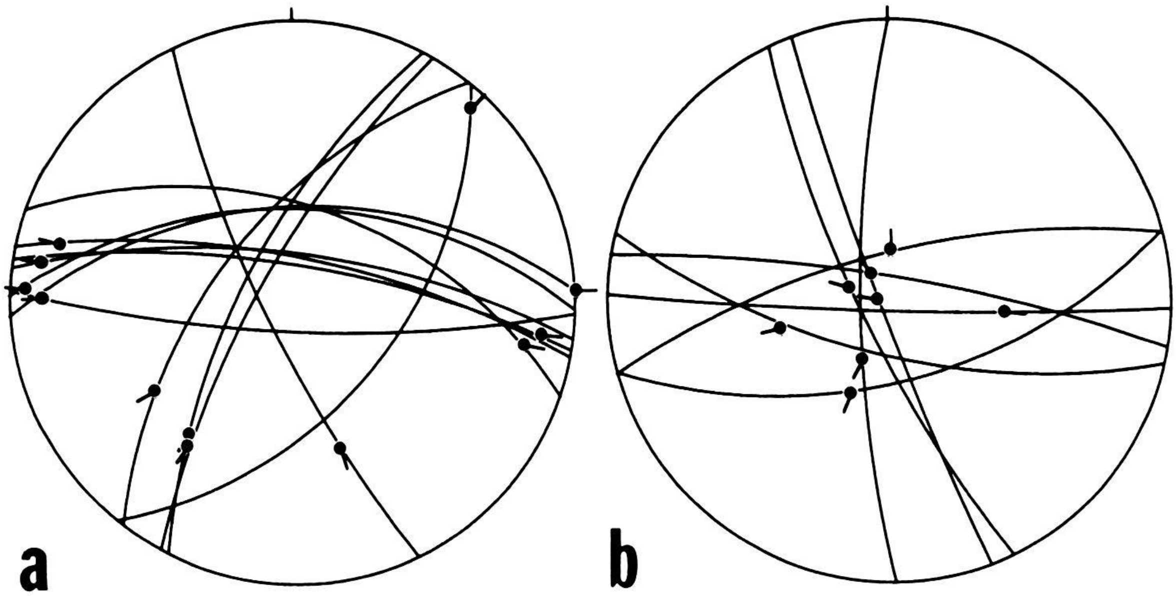


Fig. 7. Equal-area, lower-hemisphere stereographic representation of (a) strike-slip – mainly dextral – faults and (b) normal faults close to the PF zone near the Belleville valley.

7. A local test for the model of late extension: Neotectonic data in the ZHB

At least for the latest stages, the neotectonic data may be used as a test for the above model.

(a) Altimetry

Based on recent geodetic data Ménard (1988) and Jouanne & Ménard (1994) show a differential uplift of the EBM of up to 1.5 mm/yr with respect to the Internal Alps. The inflexion point of the uplift curve occurs close to the PF zone in the Arc valley. Lenotre et al. (1993) indicates an uplift of 2.5 mm/yr, not localized precisely, for the whole Alps. According to Ménard (1988), the maximum uplift is located along the easternmost part of the EBM.

(b) Seismic data

The Briançonnais zone is seismically active, with four significant events (with a magnitude > 4) during the last century (Thouvenot et al. 1991). Hypocenters are shallow (max. 10 km) and focal mechanisms indicate possible dextral movement with an EW extensional component. The 1993 La Plagne event, close to the BF is related to a normal fault mechanism with a probable fault plane N155/70 SW and a hypocenter at 7 km depth (Thouvenot, pers. comm).

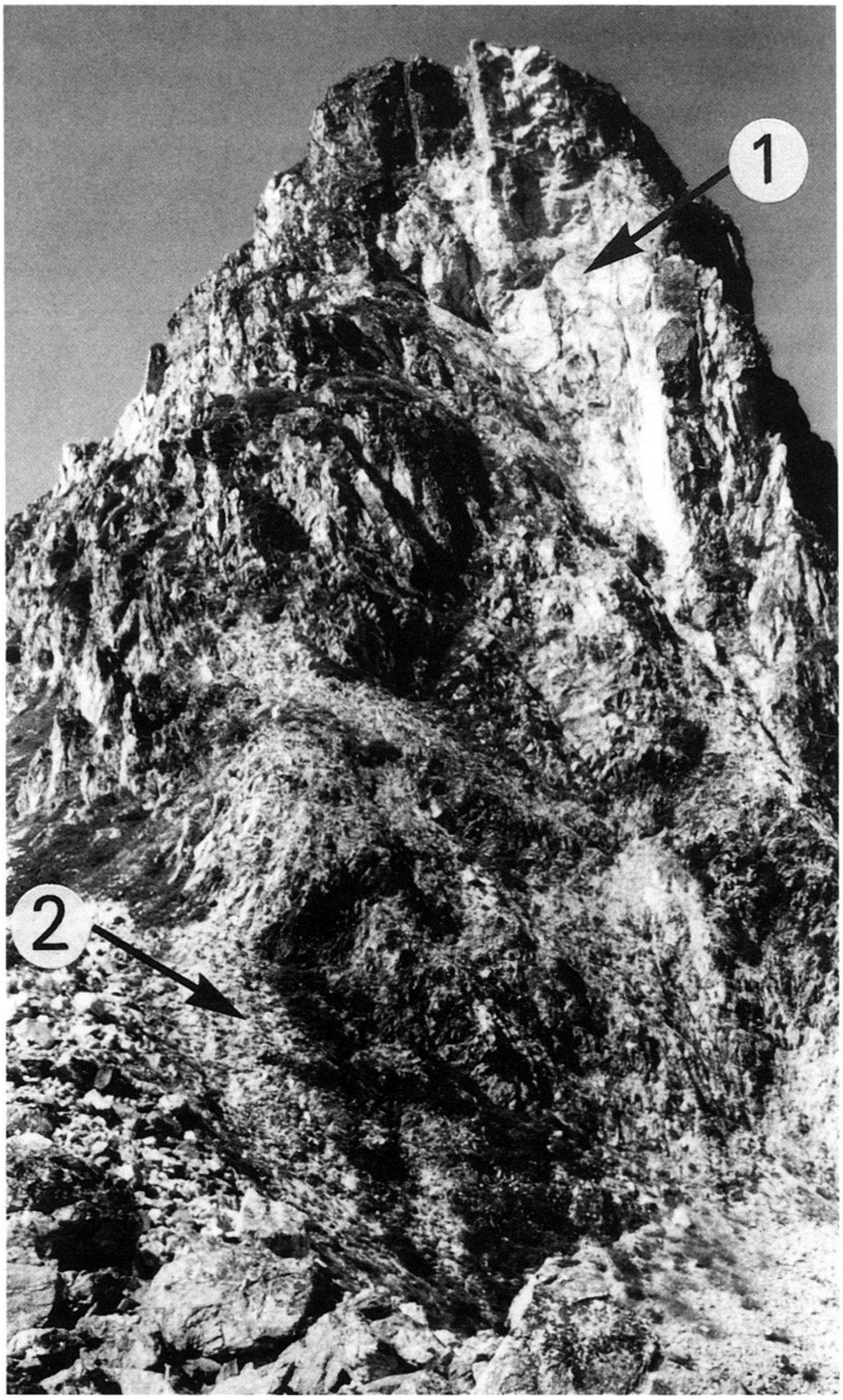


Fig. 8. Active fault from north of Pointe de Fenêtre (Belleville valley). The white cliff (see arrow 1) near the top of the peak corresponds to a very recent rockslide in the fault plane which forms a light grey tongue of unweathered screes (arrow 2).

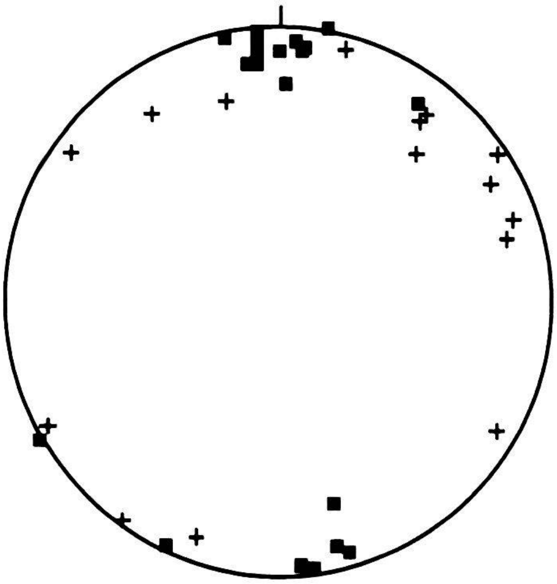


Fig. 9. Equal-area, lower-hemisphere stereographic representation of open joints from Pointe de Fenêtre (crosses) and north of Mont Brequin (squares).

(c) *Active faulting*

Ménard (1988) outlines the role of glacial abrasion to explain the fact that only neotectonic events younger than 10,000 years may be observed in the Alps. This may explain the relative paucity of published observations. Goguel (1969) and Blès et al. (1993) describe a N30, east-dipping normal fault with a dextral component near Peisey-Nancroix.

We have studied active faults near St Martin de Belleville. Fracture data show N40 and N90–100E strike-slip (mainly dextral) faults (Fig. 7a) and N75–N100E and N150–180E normal faults (Fig. 7b). These faults clearly reflect quaternary movements as underlined by rockslides and landslides (Fig. 8). Open joints have been observed in two main places: Mont Brequin and Pointe de Fenêtre – Geffriand. Close to the Mont Brequin, directions (Fig. 9) are well-defined at N80 to N100E. In the Pointe de Fenêtre – Geffriand area, they are scattered. The E-W joints (Mont-Brequin, Fig. 10) partly correspond to old quartz veins recently re-opened. This re-opening has not a topographical origin because their strikes are perpendicular to the slopes. All these data suggest one or two poorly-defined extensional events, parallel (NE-SW) to the local trend of the alpine belt.

(d) *Fission track dating*

Fission-track dating on zircons and apatites, on both sides of the PF and Simplon fault (Seward & Mancktelow 1994), shows a significant age difference with younger closure ages on the EBM side and thus, recent, and probably still active, exhumation.

7. Conclusions

There are still many unsolved questions concerning the structure of the PF and BF zones. This is primarily due to uncertainties still existing for the tectonic evolution of the ZHB, considered as the most continuous marker along the PF zone. Questions are (1) the

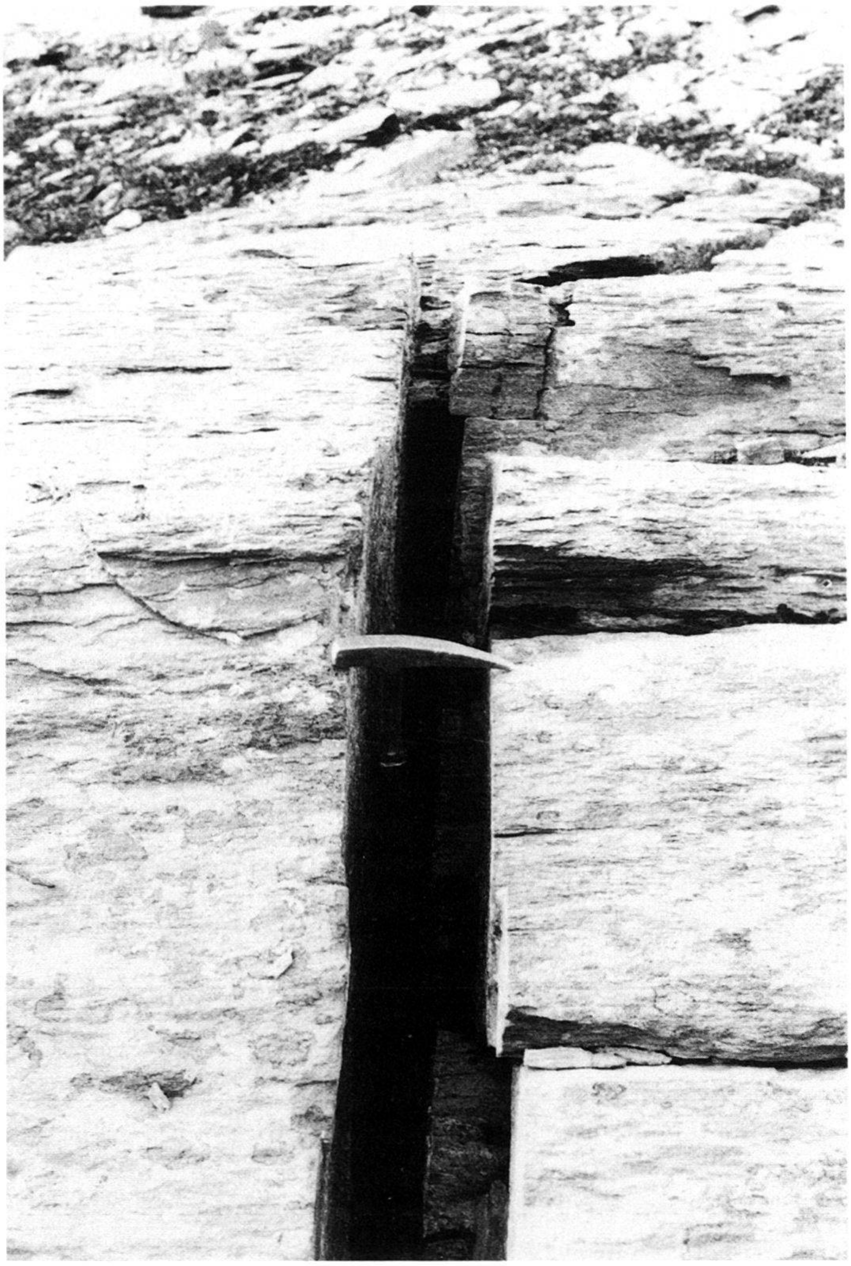


Fig. 10. E-W re-opened joint from Mont Brequin. The sharp edges of the joint indicate that the opening event occurs after the retreat of the last glaciers.

movement directions during D_1, (2) the primary attitude of D_2 structures and the reason why D_2 only records a dominant flattening (Aillères et al. 1995b), and (3) the scale and tectonic regime of the D_3 event (west-verging compression or extension-related roll-over structures).

The kinematic interpretation of S_1 and the geometry of the D_1 pile which shows little evidence for associated isoclinal folds are critical: is S_1, as we observed until now, always nearly parallel to S_0? Similarly, the primary relationships between ZHB and Sapey gneisses raises the same problem. In the present geometry, the Sapey gneisses outcrop below downward-facing formations of the ZHB. If we do not accept the previous interpretation of a Permian migmatization (Ellenberger 1958), highly dubious since Détraz's (1984) findings of obvious basement lithologies, the gneisses represent a tectonic unit resting above a formerly upward-facing D_1 pile. As this pile is now overturned, did it occur during D_2 or during the D_3 stage?

What are the time and/or kinematic relationships between extension along west-dipping fault described further south (Philippot 1990) and extension along the east-dipping PF?

An extrapolation of our preliminary model from the ZHB to the external tectonic units of the alpine belt is difficult because of the lack of good structural data for the Sub-Briançonnais and flyschs s.l. zones. A precise comparison of the relative chronologies of deformation of the Valaisan, Sub-Briançonnais and Ultra-Dauphinois units is a necessary prerequisite to any retrotectonic modelling and thus a testing the adequacy of the palaeogeographical interpretations. This approach is necessary to understand the relationships between deformation and sedimentation in the flysch units. Structural correlations should be extended toward the north (Val Ferret and Gd St Bernard) and the south (Briançon) to test the validity of the proposed model, whose main difference with respect to previous interpretations is the emphasis on the latest (Miocene to recent) events in the building of the present geometry of the Alpine belt. Knowing more about the neotectonic events may help to better understand the post-collisional evolution of the Alpine belt.

To conclude, keeping in mind the great number of available stratigraphic and map data, the geometric and kinematic data and the hypotheses outlined above, the need for a reassessment of the ECORS-CROP profile is only too clear. A special emphasis on linking seismic lines with a well-constrained 3D geometry may help to interpret the obvious major seismic reflectors apparently associated with the PF. An approach similar to that recently completed in the Central Alps (e.g. Schmid et al. in press) is now essential for the western Alps.

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