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Late Alpine brittle extension above the Frontal Pennine Thrust near Briançon, Western Alps

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Key words: Western Alps, Briançonnais zone, Frontal Pennine Thrust, extensionally reactivated thrust, late orogenic extension, extensional tilted blocks, brittle deformation

Mots clés: Alpes occidentales, zone briançonnaise, Chevauchement Pennique Frontal, chevauchement réactivé en extension, extension tardi-orogénique, bloc basculé, déformation cassante

ABSTRACT

The internal HP-LT metamorphic nappe pile SE of the Pelvoux massif, built during the Eocene, was subsequently thrust onto the external zone during the Oligocene. This resulted in the shearing of the Subbriançonnais domain, reduced to some tectonic lenses along the Frontal Pennine Thrust. We propose that this major thrust zone was subsequently reactivated as a normal fault, controlling the collapse of the Briançonnais zone with respect to the external zone. The collapsed zones underwent important synchronous NNW-SSE and ENE-WSW normal faulting and strike-slip faulting. A major associated structure is the High Durance fault zone, inferred to branch onto the inverted Frontal Pennine Thrust at depth. Brittle extension is particularly well developed between this fault zone and the Frontal Pennine Thrust (FPT), while strike-slip reactivation of normal faults is more important to the east. This "late" brittle deformation everywhere postdates schistosities associated with Alpine folding and thrusting. Its onset cannot be dated but the corresponding tectonic regime seems to be still active. To discuss its Alpine significance new geophysical data are needed.

RESUME

Au SE du Pelvoux, la pile des nappes internes métamorphiques HP-BT éocènes chevauche depuis l'Oligocène la zone externe suivant le Chevauchement Pennique Frontal, que jalonnent des écailles subbriançonnaises. Nous proposons que ce chevauchement majeur ait rejoué tardivement en extension, contrôlant l'effondrement de la zone briançonnaise relativement à la zone externe. Corrélativement les zones effondrées ont elles-même été sujettes à une importante fracturation NNW-SSE et ENE-WSW distensive et coulissante à laquelle participe le couloir de failles de haute Durance, supposé se brancher en profondeur sur le Chevauchement Pennique Frontal. L'extension est particulièrement développée entre ce couloir de failles et le Chevauchement Pennique Frontal tandis que les rejeux coulissants se développent plus à l'Est. Cette déformation cassante «tardive», qui se superpose à toutes les structures alpines synschisteuses, n'est pas datée mais resterait active actuellement. Sa signification alpine reste à discuter en l'absence de données géophysiques suffisantes.

1. Introduction

The Western Alps consist in a pile of nappes and units derived from the Tethyan ocean and from the European passive margin (Lemoine et al. 1986). After rifting and drifting in the Jurassic, the various units were assembled during the Europe-Africa collision from the Late Cretaceous onwards (e.g. de Graciansky et al. 1989). Models for the inversion of Tethyan extensional structures during Eocene-Oligocene Alpine compression have been proposed for the western Alps (e.g. Tricart & Lemoine 1986). Between the Pelvoux and Viso massifs, tectonic analyses have investigated late Alpine brittle extension within the HP-LT metamorphic internal nappes, in the Briançonnais (Virlouvet et al. 1996) and Queyras (Lazarre et al. 1994) areas (Fig. 1). Here we examine the front of these nappes (Frontal Pennine Thrust), at the SE corner of the Pelvoux massif (Fig. 2). We present new structural field data constraining its tectonic evolution during late Alpine regional scale extension.

2. The Frontal Pennine Thrust (*FPT*), SE of the Pelvoux massif

All along the Alpine arc, the main boundary between external and internal zones corresponds to the *FPT*. At the SE corner of the Pelvoux massif, Alpine structures trend N-S and the surface of this west-directed thrust dips eastward (Fig. 2); its hangingwall consists mainly of Briançonnais sedimentary cover thrust sheets, bearing a HP-LT metamorphic imprint; the footwall consists of Dauphiné sedimentary cover units which were partly detached and deformed under low grade to very low grade metamorphic conditions ("Ultra-Dauphiné zone" of Debelmas 1974). This cover is mainly represented by the Tertiary Champsaur Sandstones, the equivalent of the so-called Annot and Taveyannaz Sandstones (Debelmas 1980; Waibel 1990). The Subbriançonnais zone is reduced to tectonic slices, a few tens or hundred metres thick (Debelmas 1955) between the *FPT* and the so-called Frontal Briançonnais Thrust (*FBT*). As

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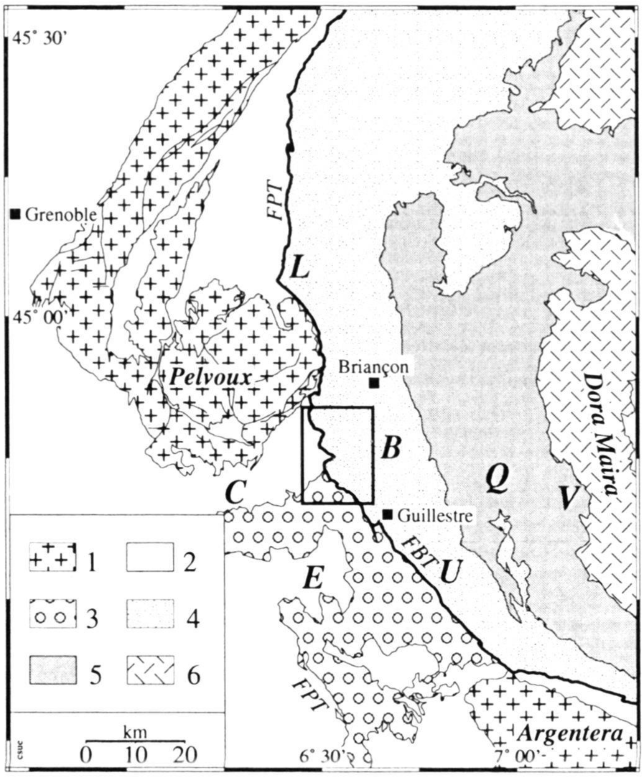

Fig. 1. Location map (western Alpine arc).
1, external (Dauphiné) crystalline massifs
2, external (Dauphiné) Meso-Cenozoic sedimentary cover
3, Helminthoid flysch nappes and associated tectonic lenses
4, Valais, Subbriançonnais and Briançonnais zones
5, Piémont Schistes lustrés
6, internal (Piémont) crystalline massifs
Main geographic areas: B, Briançonnais; C, Champsaur; E, Embrunais; Q, Queyras; U, Ubaye; L, Lautaret pass; V, Viso.
FPT, Frontal Pennine Thrust; *FBT*, Frontal Briançonnais Thrust at the rear of the Helminthoid flysch nappes, between Pelvoux and Argentera massifs. The bold line indicates the main crustal discontinuity between external zone and internal zones, which corresponds to the *FPT* in the north and to the *FBT* in the south.

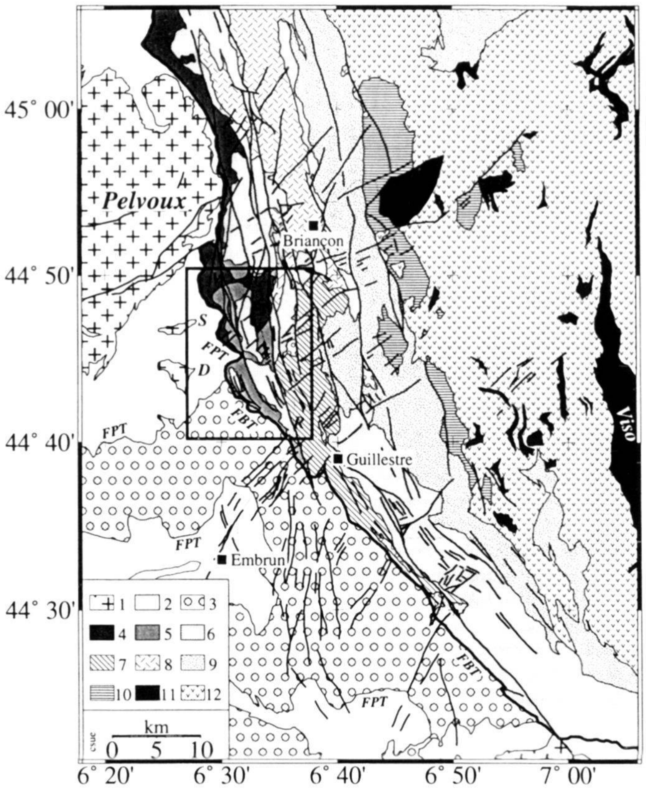

Fig. 2. The late Alpine fault system and the main structural units to the SE of the Pelvoux massif. *FPT* and *FBT*, see figure 1.
Footwall of the *FBT*:
1, external (Dauphiné) crystalline massifs
2, external (Dauphiné) Meso-Cenozoic sedimentary cover
3, Helminthoid flysch nappes and associated tectonic lenses
Hangingwall of the *FBT*:
4, Subbriançonnais lenses
5, Briançonnais Roche Charnière nappe
6, Briançonnais Champcella nappe
7, Briançonnais Peyre Haute nappe
8, Briançonnais zone Houillère nappe
9, Briançonnais internal nappes
Piémont zone:
10, continental margin derived nappes
11, main ophiolitic massifs
12, oceanic metasediments
R, Réotier and Plan de Phasy; S, La Salce (Fournel valley); D, Dormillouse (Biaysse valley); V, Vallouise.

interpreted along the Ecors-Crop seismic profile, 100 km to the north (Bayer et al. 1987; Sénéchal & Thouvenot 1991; Mugnier et al. 1993), both thrust surfaces correspond to the emergence of a single deep seated thrust ramp (Tricart 1986), the Pennine Front thrust zone, the *FBT* being a splay off the *FPT*.

To understand the structural relationships between external and internal zones, and the significance of the *FPT* to the SE of the Pelvoux massif we must consider the following steps in the regional history.

1.) In Mesozoic times, during Tethyan extension, the Subbriançonnais represented a faulted zone (Kerckhove 1969) between independent Dauphiné and Briançonnais paleogeographic domains (Lemoine et al. 1986; Stampfli 1993).
2.) In the Late Eocene, the Briançonnais nappes were thrust toward the NW under HP-LT synmetamorphic conditions (Lawsonite bearing green-schist to blue-schist facies). The orogenic front reached the Subbriançonnais domain (Tricart 1984).
3.) To the west, in the Champsaur foredeep, flysch sedimentation ended in the early Oligocene, with the arrival from the NE of the first internal nappes, *i.e.* the non-metamorphic Helminthoid flysch (Kerckhove 1969). They seem to have been deviated toward the SW by an early Pelvoux massif whose uplift was a consequence of the Pyrenean-Provençal N-S compression (Kerckhove 1969; Tricart 1981; Merle & Brun 1984). They only develop to the south of the area studied in this paper.

4.) By mid-Oligocene, the *FPT* to the north of the Biaysse valley (studied area) developed as the major thrusting of the already metamorphosed and shortened Briançonnais zone onto the Champsaur foreland (Tricart 1984).
5.) The whole structure underwent a late east-directed shear, giving rise to synschistosity back-folds and back-thrusts (Tricart 1975) that developed to the South of the Pelvoux massif (Tricart 1986). This last major Alpine contraction, possibly Miocene in age (Tricart 1984) is responsible for the backfolding of the *FBT* close to Guillestre (vertical slices at Réotier and Plan-de-Phasy: location Fig. 2).
6.) In the whole Briançonnais zone, all ductile shortening structures are overprinted by "late Alpine" joints and faults at various scales, showing a complex extensional and transcurrent brittle deformation that remains undated (*e.g.* Virlouvet et al. 1996; Sue 1998).

In the vicinity of the Pelvoux massif, the narrow Subbriançonnais domain, then the very pinched Subbriançonnais zone between the *FPT* and the *FBT* corresponds to a first order discontinuity in the European crust, which acted during the whole Tethyan-Alpine history. As described below, it has probably been reactivated during the late Alpine faulting phase.

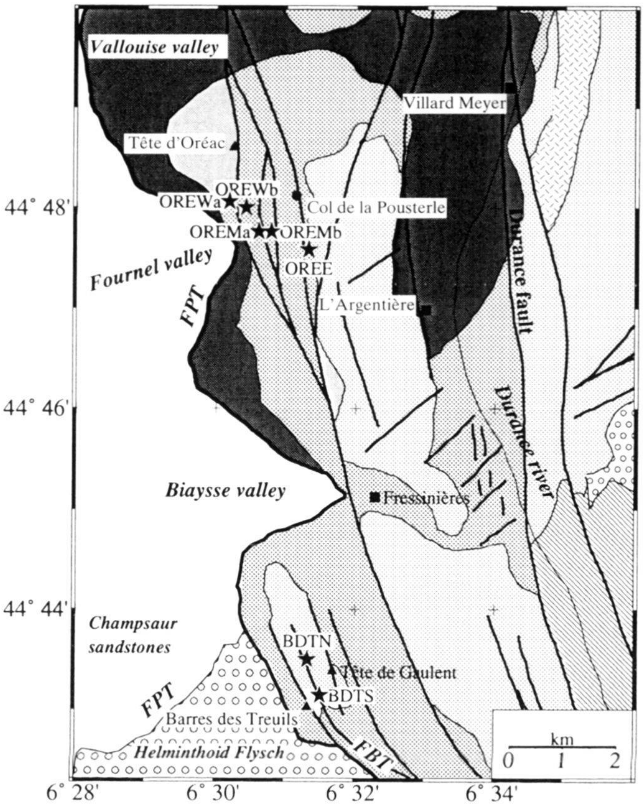

Fig. 3. Location of the measurement sites (same symbols as Fig. 2).

3. The geologic section along the Fournel valley

The Fournel and the Biaysse torrents (Fig. 3) are glacial valleys up to 1,5 km deep and more than 20 km long crosscutting the *FPT*. Good exposures allow the analysis of the structural relationships between external and internal Alpine zones and their evolution through time, including the late Alpine stage, never dealt with previously. We will focus on the northern flank of the Fournel valley, which provides a classical section already described by Lory (1864), Termier (1903), Gignoux & Moret (1938) and Goguel (1942) according to Debelmas (1955: 128), and Bürgisser & Ford (1998).

3.1 The main tectonic units

From bottom to top and from west to east the structural pile cut by the Fournel valley comprises the following units:

(1) Paleozoic migmatitic gneisses at La Salce (southern extension of the Pelvoux crystalline basement, Debelmas 1980).
(2) The Late Eocene-Early Oligocene foredeep is represented by the classical trilogy of Moret (in Gignoux 1936; see also Waibel 1990): 10 m of transgressive conglomerates and Nummulitic limestones, a few tens of metres of Globigerina marls indicating a rapid deepening of the basin, and alternating shales, marls and sandstones corresponding to the main infill of the flexural basin (Champsaur Sandstones, at least 600 m original thickness). The upper olistostrome develops to the south of the Fournel torrent.
(3) The strongly sheared Subbriançonnais zone is represented in the section by 50 m thick of Eocene black schists overridden by lenses of Triassic evaporites. They are often hidden by moraines and meadows and correspond to a recess in the topography (e.g. pass W of the Tête d'Oréac). To the north (Vallouise: Barféty & Pêcher 1984; Barféty et al. 1996) and the south (Biaysse), Mesozoic units, in particular Vallouise limestones (Dogger), allow the identification of a sliced Subbriançonnais series. Similarly, to the east, in the L'Argentière nappe window, a classical Subbriançonnais series (Dogger to Late Cretaceous) crops out (Debelmas & Lemoine 1966).
(4) The Briançonnais frontal unit (Roche Charnière nappe, Debelmas, 1955) detached within the Carboniferous shales. It consists of a thick competent series of lower Triassic quartzites ("Scythian", 80–100 m) and dolomitic limestones (Anisian-Ladinian: 120 m). The series are deeply eroded below the post-rift unconformity and are overridden by a few metres of Dogger-Malm limestones, a few hundred metres of Late Cretaceous-Paleocene metamorphosed pelagic marls (Planktonic calcschists) then some remnants of Eocene black schists.
(5) A higher Briançonnais nappe (Champcella nappe of Debelmas 1955, symbol 11 Fig. 2), appears to have been detached within the evaporites at the top of the lower Triassic quartzites.

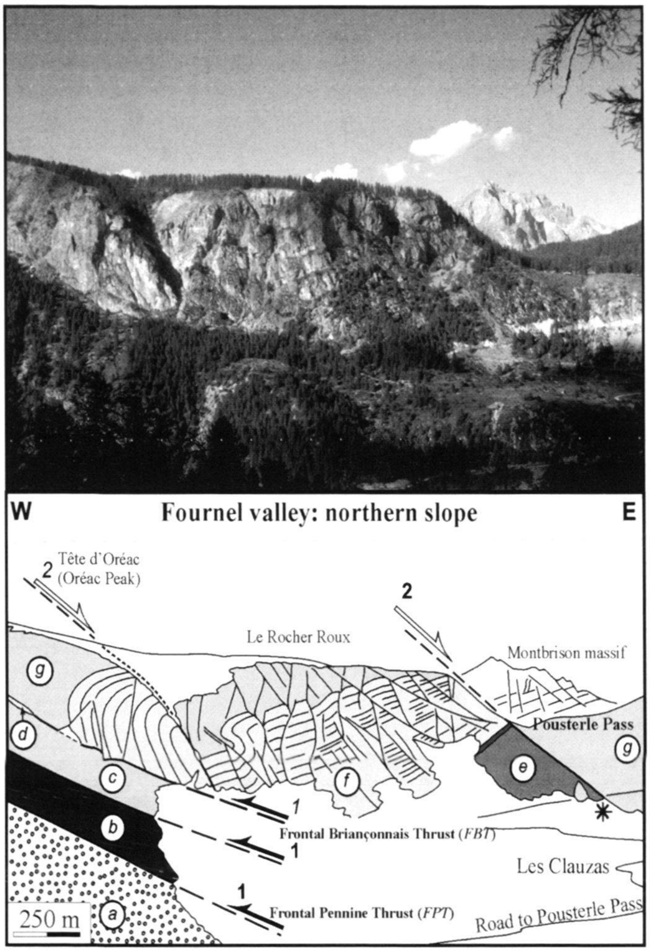

Fig. 4. The Briançonnais and Subbriançonnais front as crosscut by the Fournel valley (panorama width is 2 km).
a, Champsaur Sandstones (external, Dauphiné zone)
b, Eocene black schists (Subbriançonnais tectonic lense)
c, Senonian-Paleocene calcschists (Subbriançonnais tectonic lense)
d, tectonic slice of Middle Triassic dolomite and Jurassic limestones (detail: see figure 6)
e to g, Briançonnais front (Roche Charnière nappe):
e, Lower Triassic quartzites ("Scythian") topped by thin schists and evaporites;
f, Middle Triassic dolomites and Jurassic limestones
g, Senonian-Paleocene calcschists
The star locates the outcrop represented on figure 7
Late Alpine extension results in collapse to the east along east dipping normal faults (arrows 2) bounding westward tilted blocks. It clearly overprints the west directed folds asociated to the Oligocene main phase of thrusting (arrows 1) onto the external zone (FPT and FBT).

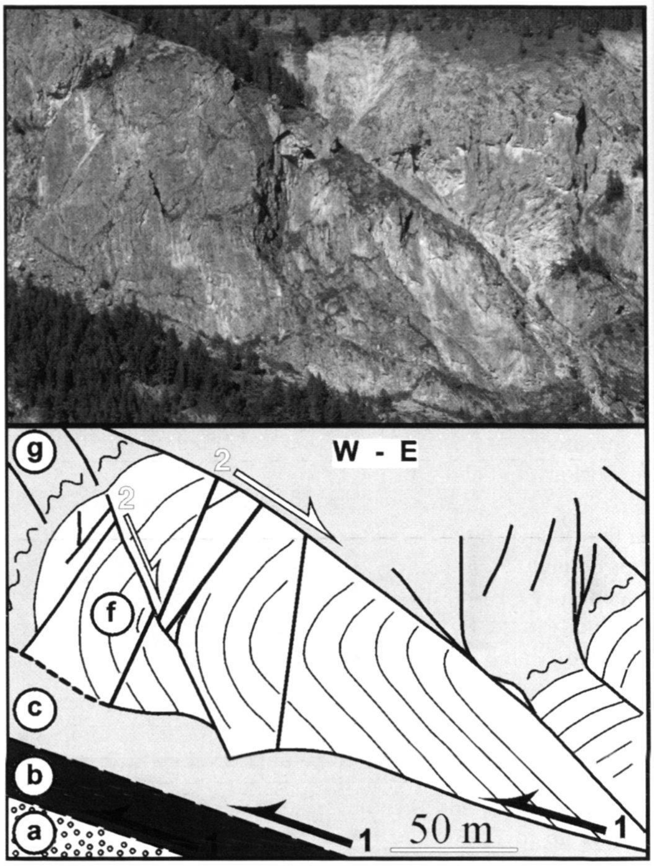

Fig. 5. Superposition of extensional and compressional structures on the southern slope of Oréac Peak (detail of Fig. 4; same symbols). The west directed anticline with truncated reverse limb (first movement: Oligocene thrust onto the external zone) is overprinted by east dipping normal faults (second movement: late Alpine collapse of the Briançonnais zone). 10–30m high trees give scale.

3.2 The structures linked to the Oligocene major phase of thrusting

Below the Subbriançonnais lenses, the "Champsaur Sandstones" flysch forms west-vergent kilometric chevron-type folds, interpreted as drag folds in a top-to-the-west horizontal shear between the overlying *FPT* and the underlying Pelvoux basement. The Nummulite-bearing limestones remain in a normal stratigraphic contact with the crystalline basement which dips eastward below the pile of internal nappes. The folding in the flysch and the detachment at its base are associated with the development of a slaty cleavage in anchizonal to upper epizonal metamorphic conditions. Flysch fold axes trend N160 and the transport in the basal shear zone is toward N280 (Tricart 1986). This is the first regional-scale synmetamorphic tectonic event in this part of the Dauphiné zone (Tricart 1984).

In the hangingwall of the *FPT*, the corresponding westward shear causes the slicing of Subbriançonnais units and, above, the folding and slicing of the Briançonnais nappes, giving rise to kilometric structures well visible in the Triassic and Jurassic competent carbonate layers (Fig. 4). A good example is the frontal fold (Roche Charnière nappe) along the Fournel section. It shows a N160 trending hinge and a high angle truncation of it overturned limb (Fig. 4). All these structures are associated to a crenulation cleavage in argillaceous and marly formations, in particular in Cretaceous and Eocene formations, and characterise the second tectonic event in the Briançonnais zone (Tricart 1984).

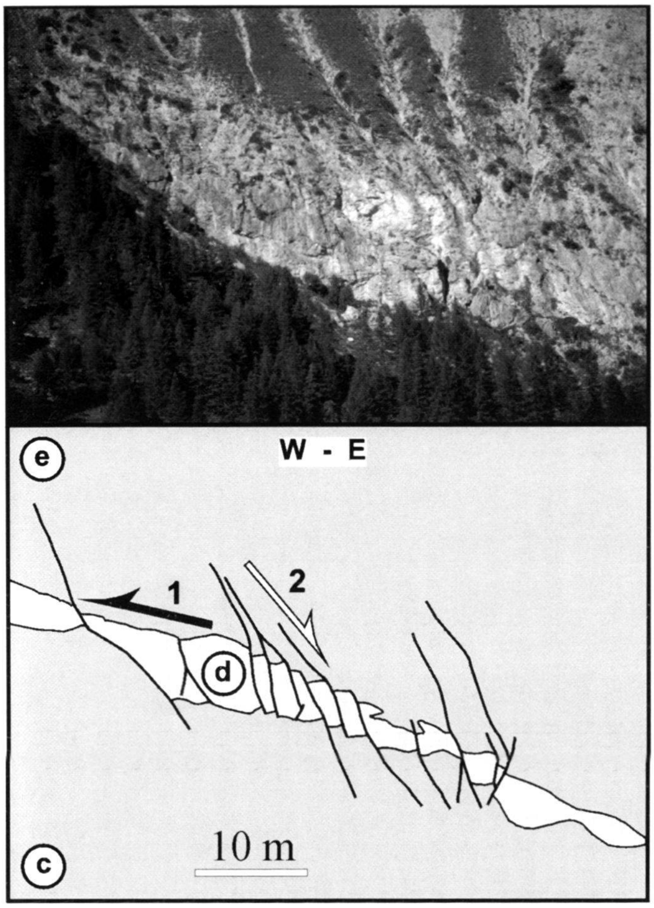

Fig. 6. Detail of a thrust slice in the FBT (location d on Fig. 4; same symbols). The pinch and swell boudinaged horse (first movement: westward thrusting) is cut into a set of westward tilted blocks bounded by east-dipping normal faults (second movement).

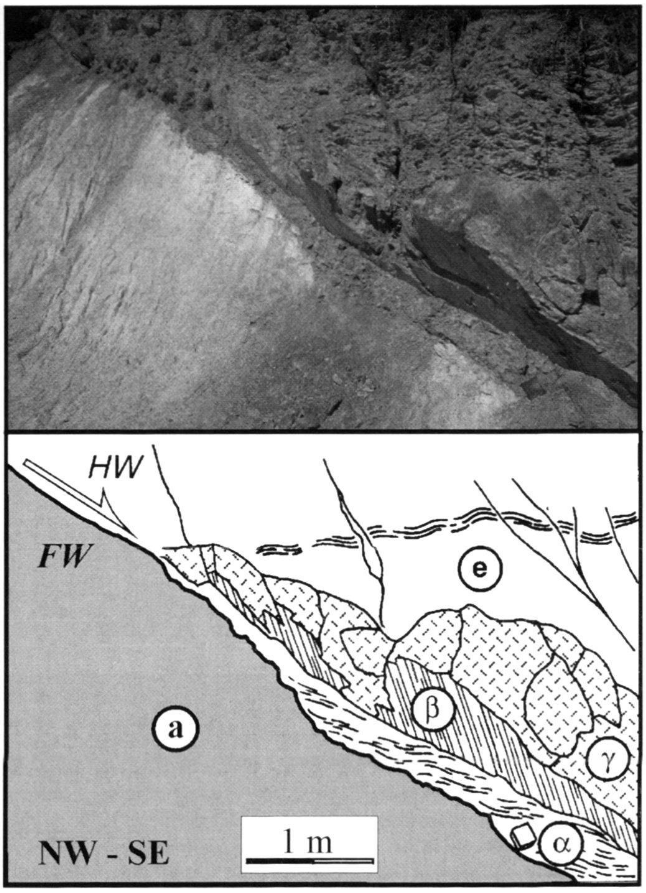

Fig. 7. N15,52E oriented fault and associated gouge and breccias were exceptionally well exposed along the Pousterle Pass road during summer 1996 (location: star on Fig. 4). Lower Triassic quarztites in the footwall (FW) and Senonian-Paleocene calcschists in the hangingwall (HW) indicate a more than 300 m downthrow to the east. 10 cm wide compass gives scale.
a, cataclastic "sand" derived from quartzites (thickness 2–3 m)
α, gray and red clay (thickness 10–20 cm) with down-to-east shearing (oblique schistosity)
β, perfectly planar slickenside
γ, horse of cataclastite derived from Middle Triassic dolomites (thickness 0.5–1 m)
e, foliated calcschists with small normal faults branching into the main fault

3.3 First report of superimposed extensional structures

In the Oréac-Pousterle area, the imbricated and folding pile of Briançonnais nappes is crosscut by a dense network of normal faults oriented N160 to N170 and N50 to N80 (Fig. 5). Figures 4 and 6 give examples of compressional structures overprinted by late NNW-SSE faults, that represent the dominant direction. Faults, microfaults and joints developed as conjugate shear planes, associated with vertical tension gashes. Originally (before block tilting), shear planes were steep (70°) and planar in the Triassic and Jurassic competent carbonate layers and more gently dipping (40°–50°) and curved in the Cretaceous and Eocene calcschists and schists. Westward tilting (generally 20°–30°, up to 35°) along east-dipping normal faults dominates; to the west of La Pousterle Pass, some of these faults, about 100 m apart from each other, display a pronounced curved (listric) geometry and branch downward into the 10–20 m thick evaporites and schists at the top of the lower Triassic quartzites. In the Briançonnais zone this ductile level often played the role of a detachment level during initial nappe thrusting. Other larger listric faults (Oréac peak: Fig. 4) display a geometry that implies they merge at depth into the Subbriançonnais slices.

Throw typically ranges from a few metres to tens of metres along the medium scale faults (100 m spacing), but can exceed 100 m along the major faults (spaced more than 500 m). The general style appears as distributed deformation on a great number of faults with small individual offset. For the whole Oréac-Pousterle area, the extension factor (β), corresponding to major and intermediate scale fault heave, ranges between 1,5 and 2.

A major E-dipping normal fault running through the Pousterle Pass has a throw of 300 m, juxtaposing lower Triassic quartzites with Senonian-Paleocene calcschists. A spectacular outcrop along the Pousterle pass southern road (Fig. 7) shows cataclastically deformed quartzites forming a 3 m thick fault breccia below the main fault surface. The fault plane itself consists of a continuous 10–20 cm thick layer of gray argillites (fault gouge) overlain by up to 1 m of brecciated Middle Triassic dark-grey dolomite forming a pinch-and-swell structure. Associated with these dolomite cataclasites, there exist sheared centimetric to decimetric lenses of red argillites and siltstones derived from a recent (but still undated) karst filling. Similar sediments occur along the late Alpine normal faults in the Durance valley (Tricart et al. 1996). In the Oréac-Pousterle area, several other faults are marked by 10 to 50 cm thick tectonic breccias. These breccias often display large and exceptionally fresh polished fault planes. The well-polished fault planes indicate low coefficients of friction, which could be partly related to the low angle character of major faults (Turcotte & Schubert 1982: 354).

This late normal faulting in the Oréac-Pousterle area can be followed eastward to the Durance valley and its N–S trending fault zone (High Durance fault zone: Tricart et al. 1996; location see Fig. 3) linked to the same regional-scale fracturing event.

In the Fournel section as well as along the adjacent valleys, late normal faulting nowhere affects the Champsaur Sandstones and their substratum: the footwall of the *FPT* escaped the late brittle extension. This key observation implies that the *FPT* and the associated Subbriançonnais sheared zone were reactivated as an extensional detachment to accommodate the extension in the hangingwall. Due to the poor quality of the outcrops in the Subbriançonnais tectonic lenses it is not possible to estimate the amount of contribution of the *FPT* itself and that of the *FBT*, and we consider the thrust zone as a whole during this extensional tectonic inversion.

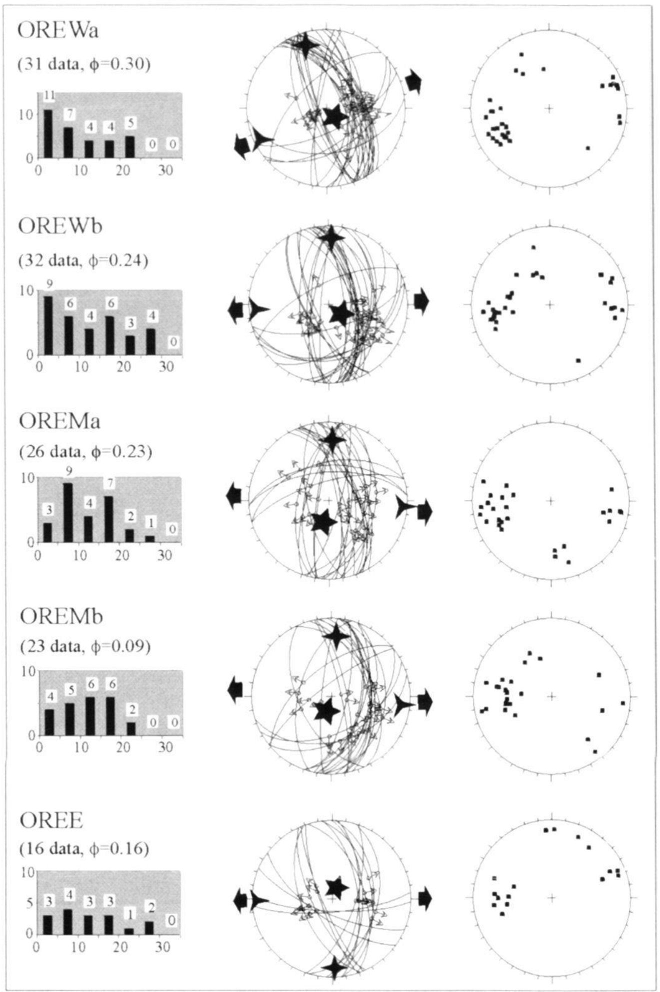

Fig. 8. Paleostress tensors associated to the main brittle extension in the Oréac-Poursterle area. Same symbols as table 1. For each measurement site, we provide two stereonets: (1) on the left-hand the fault planes and striae, and the computed paleostress tensor; the 5, 4 and 3 branch stars indicate respectively the orientation of the computed σ1, σ2 and σ3 axes. (2) on the right-hand the poles to measured fault planes, allowing to evaluate more easily the spatial distribution of the data. The histogram of the differential angles between the measured striae and the theoretical one on the left side gives a quality estimate. Stereonets are equal area projection, lower hemisphere.

4. Brittle deformation analysis

4.1 Microtectonic observations

Along the major faults (hectometric to kilometric), grooves and striae are locally preserved. In addition, numerous small scale (some centimetres to some metres) conjugate normal fault surfaces display striae and fibres. The dihedral angles between conjugate normal faults range from 30° to 70°, depending on lithology (large angles in Cretaceous calcschist and small ones in competent Middle Triassic dolomite). Movements on these small-scale structures started before and continued during activity on the major east-dipping faults and often underwent a 10° to 30° westward tilting in the intervening blocks. Even without clear offset of marker horizon, shear sense can be determined from small scale structures such as drag folds, fibres and en échelon tension gashes on the slickensides themselves. Their systematic observation confirms that: (i) on all scales extensional faulting dominates along the two directions of faults recognised on the regional scale, (ii) dip-slip dominates, (iii) NNW-SSE and ENE-WSW trending normal faults acted together, (iv) locally extensional movement was followed by strike-slip movement with dextral displacement along NNW-SSE trending faults and sinistral displacement along ENE-WSW trending faults. Superimposed calcite fibers growing behind small steps in the fault planes clearly record the relative chronology of movement. These examples are rare and, however, restricted to the NNW-SSE faults.

4.2 Paleostress tensors calculation

To constrain this brittle deformation, a systematic microtectonic analysis of faults and striae has been carried out in the entire Oréac-Pousterle area (Fig. 3). The *Stress* software

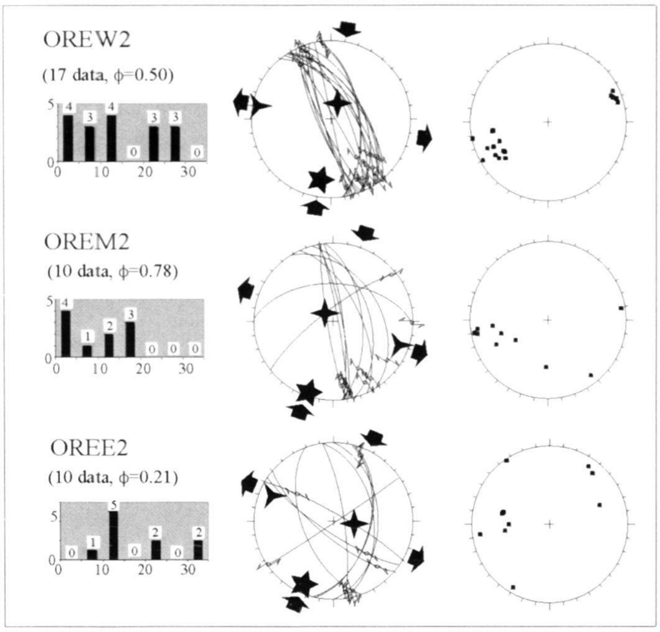

Fig. 9. Paleostress tensors associated to the strike-slip reactivation of normal faults in the Oréac-Poursterle area (same symbols as Fig. 8).

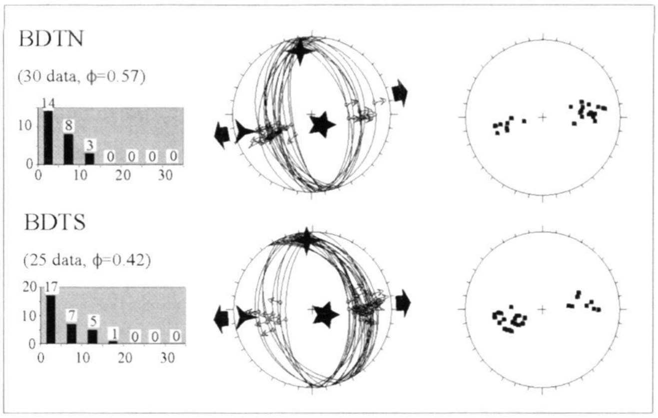

Fig. 10. Paleostress tensors associated to the main brittle extension in the Barre des Treuils area (same symbols as Fig. 8).

(Villemin & Charlesworth 1992), which applies the *direct inversion method* developed by Angelier (1990) allows the determination of several reduced paleostress tensors. These tensors are defined by the orientation of the three principal stress axes, σ1, σ2 and σ3 (with σ1>σ2>σ3) and the ratio $\phi=(\sigma 2-\sigma 3)/(\sigma 1-\sigma 3)$ of principal stress differences (shape ratio of the stress tensor ellipsoid). This analytical method is based on the assumption that the lineation on a fault plane follows the direction and sense of the maximum shear stress in the plane (Carey & Brunier 1974).

We computed separately the paleostress tensors associated with the early extensional faulting and those associated to the subsequent strike-slip reactivation; the two subsets of data

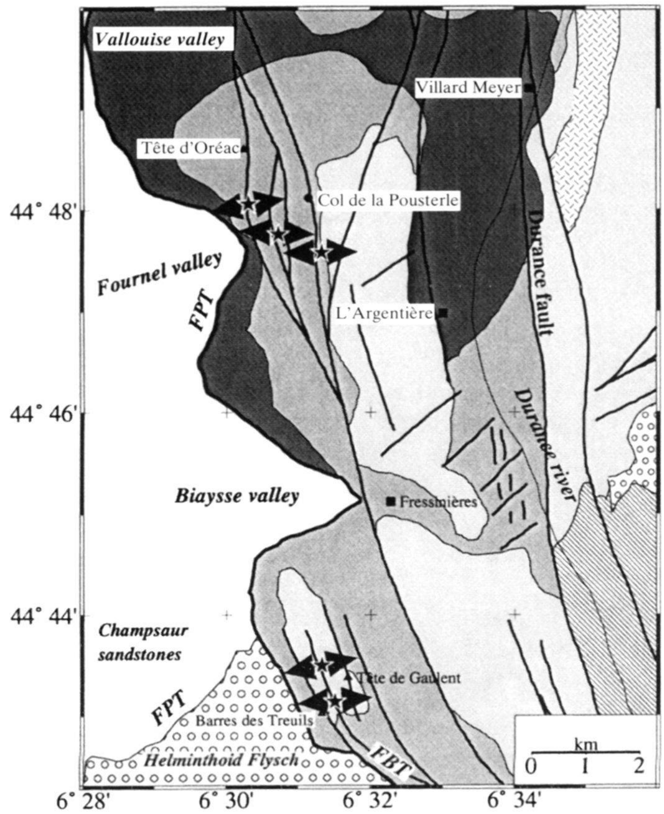

Fig. 11. Kinematics of the brittle extension in the region context. Arrows give the horizontal projection on the map of the calculated σ3 axis (same symbols as Fig. 2).

were distinguished during outcrop analysis (we did not use an automatic choice process). In the Oréac-Pousterle area, paleostress tensors associated with the main extension have been determined at five localities (Fig. 8). The subsequent strike-slip movements have been constrained at three localities (Fig. 9). For comparison, Figure 10 displays two paleostress tensors computed with the normal faults cutting the Briançonnais frontal nappes in the Biaysse valley (Barre des Treuils area, southern equivalent of Oréac-Pousterle structure) which have escaped strike-slip reactivation. The parameters associated with the computed paleostress tensors are listed in table 1.

For the Oréac-Pousterle area, the computed paleostress tensors associated with the extensional regime show a large range of fault trend and dip, good associated quality parameters *Ang* (differential angle average) and good differential angle histograms; they indicate that the paleostress tensors are well constrained. The subsequent strike-slip faulting provides less well constrained paleostress tensors, due to the restrictive fan of trends for the reactivated faults. The Barre des Treuils area provides high quality parameters and differential histograms, but the distribution of the fault planes remains unimodal, implying an important variability for the stress axes.

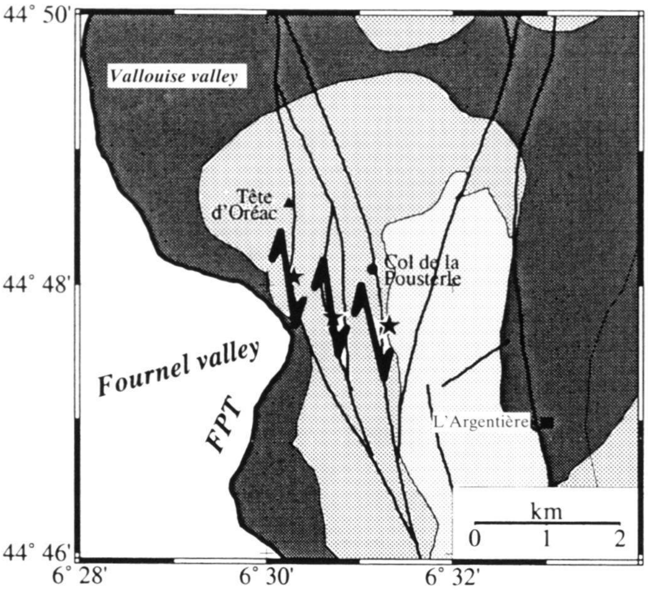

Fig. 12. Kinematics of the dextral reactivation along the NNW-SSE fault system in the Oréac-Pousterle area (same symbols as Fig. 2).

4.3 A multitrend extension followed by a strike-slip tectonic regime

Late E-W extension, close to the FPT (Fig. 8, 9 and 11). The microtectonic sites of the Oréac-Pousterle area, as well as those in the Barre des Treuils, are characterised by an E-W trending subhorizontal $\sigma3$ axis. A detailed analysis of the direct inversion results shows that the ϕ ratio decreases eastward between the OREWa and the OREMb sites, and remains very low in the whole Oréac area. This can be linked to a similar magnitude of $\sigma2$ and $\sigma3$ principal stresses. These observations point out a multitrend extensional regime, even if the paleostress tensors are mainly constrained by movements along the NNW-SSE fault direction. The ENE-WSW faults develop increasingly toward the east and control the low values of the ϕ ratio. The analysis of the Barre des Treuils microtectonic sites characterises a different state of stress, with a higher ϕ ratio, linked to the unimodal distribution of the fault planes. The brittle deformation of this area is clearly controlled by the NNW-SSE fault system, sub-parallel and very close to the *FPT* in this place.

Strike-slip faulting (Fig. 10 and 12). The two fault directions (NNW-SSE and ESE-WNW) developed during multitrend extension were partly reactivated as conjugate strike-slip faults, in a tectonic regime characterised by a NNE-SSW $\sigma1$ axis and a ESE-WNW $\sigma3$ axis. Immediately to the east of the *FPT*, this strike-slip reactivation only occurs locally and remains poorly developed. Nevertheless, Sue et al. (1997) and Sue (1998) point to a more important strike-slip reactivation to the east in the Briançonnais zone. Our field data cannot distinguish between (1) a continuous evolution of a unique stress state during the same tectonic event and (2) a succession of two separate tectonic events.

5. Discussion and conclusion

5.1 The inversion of the FPT to the SE of the Pelvoux massif

After thrusting onto the Dauphiné zone, the western Briançonnais nappes underwent intensive normal faulting, longitudinal and transverse to the belt's trend, the dominant movement at a regional scale being a downthrow to the east. This post-thrust brittle extension is restricted to the hangingwall of the *FPT*. It is particularly well developed in a NNW-SSE elongated narrow zone bounded to the west by the *PFT* and to the east by the major Durance fault zone (Debelmas 1953; Barféty et al. 1968), where the longitudinal faults seems to branch into the *PFT* at depth. This area largely escaped reactivation by strike-slip dextral movement as observed on the Durance fault and some normal faults further to the east (Barféty et al. 1968; Barféty & Gidon 1975; Tricart et al. 1996). To the north of Guillestre, the Durance fault itself is linked to a 1 km downthrow of the eastern block (Debelmas 1955). It has also been proposed that this main fault branches at depth into the *PFT* (Tricart et al. 1996; Sue et al. 1997; Sue 1998). These characteristics strongly suggest a reactivation of this thrust zone as an extensional detachment. This conclusion is supported by the orientation of the calculated $\sigma3$ axis, as it trends almost perpendicular to the strike of the *PFT*. We thus propose that the inverted *FPT* controlled the late Alpine collapse of the western Briançonnais zone with respect to the eastern Dauphiné zone at the SE corner of the Pelvoux massif. The high amount of extension (β up to 2) we calculated in the Briançonnais frontal units is consistent with such a geometry.

The late faulting in the frontal Briançonnais nappes shares common characteristics, concerning the geometry of the fault network, its timing, and its tectonics, with the late Alpine faulting identified in the rest of the Briançonnais zone and in the Piémont zone along a Pelvoux-Viso transect (Lazarre *et al.* 1994; Virlouvet et al. 1996). Thus, the spectacular normal faulting we described in the frontal Briançonnais nappes to the SE of the Pelvoux massif would have a regional-scale tectonic significance and would correspond to the amplified expression of a regional late Alpine brittle extension, which affected the pile of HP-LT metamorphic internal nappes. We propose that inversion of the *FPT* controlled the regional-scale collapse of this pile of nappes with respect to the external zone.

5.2 A still ongoing activity?

The onset of this late Alpine brittle extension, which affect a great part of the internal zones (*e.g.* Sue 1998) cannot be dated. Along the High Durance fault zone, between Briançon and Guillestre, the related faults and joints guided the development of a network of karstic cavities (up to 10 m wide). They were subsequently filled with sediments but continuation of fault activity often resulted in their striation or brecciation (Tricart et al. 1996). No fossils were found in this sedimentary infill that derives from the erosion of hematite-rich soils. Nevertheless, paleoclimatic considerations led Mercier (1977) to suggest a Pliocene-Quaternary age (see also Barféty *et al.* 1995). Moreover, faulted Quaternary sediments are very scarce: Würm fluvioglacial sands near Villard-Meyer (Barféty et al. 1995; Tricart et al. 1996; Fig. 3), or moraines and scree surfaces in altitude, for example around Guillestre.

Nervertheless, the seismic activity of the Briançon-Guillestre region is one of the most important in the Alps (Rothé 1941; Fréchet & Pavoni 1979; Thouvenot 1996; Sue 1998; Sue et al. 1999). In spite of the low magnitude of earthquakes, well-constrained focal mechanisms can be calculated, in particular using the Sismalp seismic network (Thouvenot et al. 1990). A majority of them are compatible with 5 to 15 km deep extensional movements along longitudinal and transverse faults, comparable to the faults described in this paper (Fréchet & Pavoni 1979; Ménard 1988; Guyoton et al. 1990; Thouvenot et al. 1991; Sue et al. 1997; Sue 1998; Sue et al. 1999). Thus, seismotectonic investigations provide the best indication that the tectonic regime, which caused the outlined late Alpine faulting to the SE of the Pelvoux massif, could be currently still active.

5.3 Late Alpine Geodynamic context

In this paper, we propose to link: (i) multitrend brittle extension in the Briançonnais zone to the SE of the Pelvoux massif (ii) collapse of this zone with respect to the external zone and (iii) inversion of the *FPT* as an extensional detachment. Through different approaches, extensional reactivation of the *FPT* has also been proposed to the SE of the Belledonne massif (Aillières et al. 1995; Cannic et al. 1995) and the Mont Blanc massif (Seward & Mancktelow 1994). In this later striking similar example, thermochronological and structural data demonstrate that longitudinal dextral strike-slip coexists with extension along the southeastward dipping *FPT* from the Neogene onwards (Seward & Mancktelow 1994). A first difference is that transcurrent movement mainly locates in front of the *FPT* (NE-SW trending Chamonix zone) and not in its hanging-wall like to the SE of the Pelvoux massif (NNW-SSE trending Durance fault). The second difference is a change in the structural trend related to the Alpine curvature so that in both sites a dextral slip tangential to the arc coexists with a radial extension. It suggests that the late faulting in the Briançonnais nappes to the SE of the Pelvoux massif does not represent a local phenomenon but must be relevant to the late Alpine dynamics at the scale of the whole western Alpine arc.

Globally the western Alpine arc is considered to undergo a dextral transpressive regime, longitudinal to the belt trend, for the Neo-Alpine to present day period, linked to the convergence and counterclockwise rotation of the Apulia indenter with regard to the stable Europe (*e.g.* Anderson & Jackson 1987, Ménard 1988). Seward & Mancktelow (1994) consider the extension in the Pennine nappe pile at the back of the Mont Blanc massif as a consequence of the fast uplift of this massif, itself controlled by the general Alpine transpression. Such an interpretation could be proposed for the area analysed here but we have no data on vertical movements allowing to estimate the contribution of the Pelvoux massif uplift to the collapse of the Briançonnais zone. Moreover, the area that underwent late Alpine brittle extension widely exceeds in surface the strict rear side of the Pelvoux massif (Sue 1998; Sue et al. 1999).

This extension seems to be the expression of a regional scale stress regime superimposed to the general transpressive regime and interfering with it. As a working hypothesis, the driving force for extension could be buoyancy (Lyon-Caen & Molnar 1989) but the underlying deep root structure still remains poorly constrained. The current geophysical exploration of the Alpine arc's southern branch, through the GéoFrance 3D program should provide such key information.

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Site	Code	Age	Lithology	Str	Num	σ1	σ2	σ3	ϕ	Ang
West Oréac	OREWa	Middle Triassic	dolomite and limestone	N	31	122-80	343-07	252-06	0.30	9.5
West Oréac	OREWb	Cretaceous	calcareous schist	N	32	144-75	000-12	268-08	0.24	11.2
Oréac middle zone	OREMa	Cretaceous	calcareous schist	N	26	195-76	003-14	093-03	0.23	12.0
Oréac middle zone	OREMb	Cretaceous	calcareous schist	N	23	199-75	002-14	093-04	0.09	11.4
Pousterle pass	OREE	Lower Triassic and Cretaceous	quartzites and calcareous schist	N	16	15-77	178-13	269-04	0.16	12.6
North Barre du Treuil	BDTN	Cretaceous	calcareous schist	N	30	142-77	349-18	258-06	0.57	4.7
South Barre du Treuil	BDTS	Cretaceous	calcareous schist	N	25	108-83	356-03	265-06	0.42	4.8
West Oréac	OREW2	Middle Triassic	dolomite and limestone	S	17	192-15	018-75	283-01	0.50	13.5
Oréac middle zone	OREM2	Cretaceous	calcareous schist	S	10	200-02	310-83	111-07	0.78	8.5
Pousterle pass	OREE2	Lower Triassic and Cretaceous	quartzites and calcareous schist	S	10	203-05	096-73	295-16	0.21	17.8

Table 1. Parameters for the paleostress tensors presented figures 8, 9 and 10.
Site and Code refer to the measurement site; Age and Lithology refer to the faulted sedimentary formation; Str indicates the stress regime: normal (N) or strike-slip (S) faulting; Num is the number of inverted data (fault plane+stria); σ1, σ2 and σ3 give the orientation (azimut - plunge) of the main stress axes; ϕ is the shape ratio of the stress tensor ellipsoid [$\phi = (\sigma2-\sigma3)/(\sigma1-\sigma3)$]; Ang is the average angle between the measured and the computed striae (differential angle, calculated for each data).

REFERENCES

AILLERES, L., BERTRAND, J.M., MACAUDIÈRE, J. & CHAMPENOIS, M. 1995: New structural data from the "zone Houillere Brianconnaise" (French Alps), neoalpine tectonics and consequences for the interpretation of the Pennine Front. C. R. Acad. Sci. Paris, Ser. II A, 321: 247–254.

ANDERSON, H. & JACKSON, J. 1987: Active tectonics in the Adriatic region. Geophys. J. r. astron. Soc., 91: 937–983.

ANGELIER, J. 1990: Inversion of field data in fault tectonics to obtain the regional stress – A new rapid direct inversion method by analytical means. Geophys. J. int., 103: 363–376.

BARFÉTY, J.-C. & GIDON, M. 1975: La place des failles longitudinales dans la structure du Briançonnais oriental (Alpes occidentales, France). C. R. Acad. Sci. Paris, Ser. II A, 281: 1677–1680.

BARFÉTY, J.C. & PÊCHER., A. 1984: Carte géologique de la France (1/50 000), feuille Saint-Christophe en Oisans, Bur. Rech. géol. Min. ed., Orléans.

BARFÉTY, J.-C., GIDON, M. & KERCKHOVE, C. 1968: Sur l'importance des failles longitudinales dans le secteur durancien des Alpes internes françaises. C. R. Acad. Sci. Paris, Ser. II A, 267: 394–397.

BARFÉTY, J.-C., LEMOINE, M., GRACIANSKY, P.C. de , TRICART, P. & MERCIER, D. 1995: Notice explicative de la feuille Briançon (1/50 000), Bur. Rech. géol. Min. ed., Orléans: 180p.

BARFÉTY, J.-C., LEMOINE, MERCIER, D., POLINO, R., NIEVERGELT, P., BERTRAND, J., DUMONT, T., AMAUDRIC DU CHAFFAUT, S., PÊCHER, A. & MONTJUVENT, G. 1996: Carte géologique de la France (1/50 000), feuille Briançon, Bur. Rech. géol. Min. ed., Orléans.

BAYER, R., CAZE, M., DAL PIAZ, G.V., DAMOTTE, B., ELTER, G., GOSSO, G., HIRN, H., LANZA, R., LOMBARDO, B., MUGNIER, J.-L., NICOLAS, A., NICOLICH, R., POLINO, R., ROURE, F., SACCHI, R., SCARASCIA, S., TABACCO, I., TAPPONNIER, P., T., M., TAYLOR, M., THOUVENOT, F., TORREILLES, G. & VILLIEN, A. 1987: Premiers résultats de la traversée des Alpes occidentales par sismique réflexion verticale (programme ECORS-CROP). C. R. Acad. Sci., Paris, Ser. II A, 305: 1461–1470.

BÜRGISSER, J. & FORD, M. 1998: Overthrust shear deformation of a foreland basin; structural studies SE of the Pelvoux massif, SE France. J. Struct. Geol., 20 (11): 1455–1475.

CANNIC, S., MUGNIER, J.-L. & LARDEAUX, J.-M. 1995: Mise en évidence d'une faille normale ductile dans l'unité du Roignais-Versoyen (Alpes occidentales, France). C. R. Acad. Sci. Paris, Ser. II A, 321: 513–519.

CAREY, E. & BRUNIER, B. 1974: Analyse théorique et numérique d'un modèle mécanique élémentaire appliqué à l'étude d'une population de failles. C. R. Acad. Sci. Paris, Ser. II A, 279: 891–894.

DEBELMAS, J. 1953: Schéma structural du bassin de la Durance entre Queyrières et Guillestre (Hautes-Alpes). Bull. Soc. géol. France, (6), III: 123–131.

– 1955: Les zones subbriançonnaise et briançonnaise occidentale entre Vallouise et Guillestre (Hautes-Alpes). Mém. expl. carte géol. détail. France, Paris, : 159.

– 1974: Les chaînes plissées du cycle alpin et leur avant pays. Géologie de la France, Doin, Paris, 554pp.

– 1980: Carte géologique de la France (1/50 000), feuille Orcières, Bur. Rech. géol. Min. ed., Orléans.

DEBELMAS, J. & LEMOINE, M. 1966: Carte géol. France (1/50 000), feuille Guillestre, Bur. Rech. géol. Min. ed., Orléans.

FRÈCHET, J. & PAVONI, N. 1979: Etude de la sismicité de la zone briançonnaise entre Pelvoux et Argentera (Alpes occidentales) à l'aide d'un réseau de stations portables. Eclogae geol. Helv., 72(3): 763–779.

GIGNOUX, M. 1936: Tectonique et stratigraphie du Nummulitique à l'Est du Pelvoux. Bull. Soc. géol. France (V), 6: 425–438.

GIGNOUX, M. & MORET, L. 1938: Description du bassin supérieur de la Durance. Trav. Lab. Géol. Univ. Grenoble, 21: 295p.

GOGUEL, J. 1942: La chaîne de Montbrison: essai de coordination tectonique. Bull. Serv. Carte Géol. France, 43 (212): 389–398.

GRACIANSKY, P.-C. DE, DARDEAU, G., LEMOINE, M. & TRICART, P. 1989: The inverted margin in the French Alps and foreland basin inversion. J. geol. Soc. London, Spec. Publ. Ser., 44: 87–104.

GUYOTON, F., FRÈCHET, J. & THOUVENOT, F. 1990: La crise sismique de janvier 1989 en Haute-Ubaye (Alpes de Haute Provence, France): étude fine de la sismicité par le nouveau réseau SISMALP. C. R. Acad. Sci. Paris, Ser. II A, 311: 985–991.

KERCKHOVE, C. 1969: La "zone du Flysch" dans les nappes d'Embrunais-Ubaye. Géol. Alp., 45: 5–204.

LAZARRE, J., TRICART, P. & VILLEMIN, T. 1994: L'extension cassante tardi-orogénique dans les Schistes lustrés piémontais du Queyras (Alpes occidentales, France). C. R. Acad. Sci. Paris, Ser. II A, 319: 1415–1421.

LEMOINE, M., BAS, T., ARNAUD-VANNEAU, A., ARNAUD, A., DUMONT, T., GIDON, M., BOURBON, M., GRACIANSKY, P.-C.DE, RUDKIEWICZ, J.-L., MÉGARD-GALLI, J. & TRICART, P. 1986: The continental margin of the Mesozoïc Tethys in the Western Alps. Marine and Petroleum Geology, 3: 179–199.

LORY, C. 1864: Description géologique du Dauphiné. Savy ed., Paris: 747p.

LYON-CAEN H. & MOLNAR P. 1989: Constraints on the deep structure and dynamic processes beneath the Alps and adjacent regions from an analysis of gravity anomalies. Geophys. J. int. 99: 19–32.

MÉNARD, G. 1988: Structure et cinématique d'une chaîne de collision : les Alpes occidentales et centrales. Thèse d'Etat, Univ. Grenoble I: 268p.

MERCIER, D. 1977: Les modalités de la transgression jurassique dans la zone briançonnaise (région de Briançon, Haute Alpes) : étude stratigraphique et sédimentologique. Thèse 3ème cycle, Univ. Paris 6, 351p.

MERLE, O. & BRUN, J.-P. 1984: The curved translation path of the Parpaillon nappe (French Alps). J. Struct. Geol., 6 (6): 711–719.

MUGNIER, J.L., LOUBAT, H. & CANNIC, S. 1993: Correlation of seismic images and geology at the boundary between internal and external domains of the western Alps. Bull. Soc. géol. France, 164(5): 697–708.

ROTHÉ, J.-P. 1941: Les séismes des Alpes françaises en 1938 et la séismicité des Alpes occidentales. Ann. Inst. Phys. Globe Strasbourg, 3(3): 1–105.

SÉNÉCHAL, G. & THOUVENOT, F. 1991: Geometrical migration of line-drawing: a simplified method applied to ECORS data. Geodyn. Ser., 22: 401–407.

SEWARD, D. & MANCKTELOW, N. 1994: Neogene kinematics of the central and western Alps: Evidence from fission-track dating. Geology, 22: 803–806.

STAMPFLI, G.M. 1993: Le Briançonnais, terrain exotique dans les Alpes ? Eclogae geol. Helv., 86: 1–45.

SUE, C. 1998: Dynamique actuelle et récente des Alpes occidentales internes – Approche structurale et sismologique. Thèse, Univ. Grenoble I: 324p.

SUE, C., FRÈCHET, J., THOUVENOT, F. & TRICART, P. 1997: Late orogenic extension in the Briançonnais zone, French Alps: tectonic and seismotectonic approaches. Terra Nova (Abst. sup. 1), 9: 307.

SUE, C., FRÈCHET, J., THOUVENOT, F. & TRICART, P. 1999: Widespread extension in the core of the western Alps revealed by earthquake analysis. J. Geophys. Res., in press.

TERMIER, P. 1903: Les montagnes entre Briançon et Vallouise. Mém. Serv. Carte Géol. France. 182p.

THOUVENOT, F. 1996: Aspects géophysiques et structuraux des Alpes occidentales et de trois autres orogènes (Atlas, Pyrénées, Oural). Thèse d'état, Univ. Grenoble I: 378p.

THOUVENOT, F., FRÈCHET, J., GUYOTON, F., GUIGUET, R. & JENATTON, L. 1990: SISMALP: an automatic phone-interrogated seismic network for the western Alps. Cah. Cent. europ. Géodyn. Séism., 1: 1–10.

THOUVENOT, F., FRÈCHET, J., VIALON, P., GUYOTON, F. & CATTANEO, M. 1991: Les séismes de Cervières (Hautes Alpes) des 11 et 13 février 1991 : un coulissage dextre entre zones piémontaises et briançonnaises. C. R. Acad. Sci. Paris, Ser. II A, 312: 1617–1623.

TRICART, P. 1975: Les rétrocharriages dans les Alpes franco-italiennes : évolution des structures sur la transversale Embrunais-Queyras (Hautes-Alpes). Sci. Géol. Bull., Strasbourg, 28(3): 239–259.

– 1981: Les marqueurs des mouvements verticaux du socle aux abords du massif du Pelvoux (Alpes occidentales). Rev. Géogr. Phys. Géol. Dyn., 23 (4): 289–300.

– 1984: From passive margin to continental collision a tectonic scenario for the Western Alps. amer. J. Sci., 284: 97–120.

– 1986: Le chevauchement de la zone briançonnaise au Sud-Est du Pelvoux: clé des rapports zone externe-zones internes dans les Alpes occidentales. Bull. Soc. géol. France, 2 (8): 233–244.

TRICART, P. & LEMOINE, M. 1986: From faulted blocks to megamullions and megaboudins: Tethyan heritage in the structure of the Western Alps. Tectonics, 5(1): 95–118.

TRICART, P., BOUILLIN, J.-P., DICK, P., MOUTIER, L. & XING, C. 1996: Le faisceau de failles de haute-Durance et le rejeu distensif du front briançonnais au SE du Pelvoux (Alpes occidentales). C. R. Acad. Sci. Paris, Ser II A, 323: 251–257.

TURCOTTE, D. & SCHUBERT, G. 1982: Geodynamics. John Wiley and sons ed., 450p.

VILLEMIN, T. & CHARLESWORTH, H. 1992: An interactive computer program to determine paleostress axes using data from striated faults. Cordillera transect and cordilleran tectonic workshop, Alberta.

VIRLOUVET, B., TRICART, P. & VILLEMIN, T. 1996: Blocs basculés tardi-alpins dans les nappes briançonnaises de Haute-Durance (Alpes occidentales, France) et évolution neotectonique des zones alpines internes. C. R. Acad. Sci. Paris, Ser II A, 322: 475–481.

WAIBEL, A.F. 1990: Sedimentology, petrographic variability, and very-low-grade metamorphism of the Champsaur sandstone (Paleogene, Hautes Alpes, France). PhD, Univ. Genève: 140p.

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