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ORIGINAL PAPER

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Faulted backfold versus reactivated backthrust: the role of inherited structures during late extension in the frontal Piémont nappes east of Pelvoux (Western Alps)

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Abstract In the central part of the internal Western Alps, widespread multidirectional normal faulting resulted in an orogen-scale radial extension during the Neogene. We revisit the frontal Piémont units, between Doire and Ubaye, where contrasting lithologies allow analysing the interference with the N–S trending Oligocene compressive structures. A major extensional structure is the orogen-perpendicular Chenaillet graben, whose development was guided by an E–W trending transfer fault zone between the Chaberton backfold to the north and the Rochebrune backthrust to the south. The Chaberton hinge zone was passively crosscut by planar normal faults, resulting in a E–W trending step-type structure. Within the Rochebrune nappe, E–W trending listric normal faults bound tilted blocks that slipped northward along the basal backthrust surface reactivated as an extensional detachment. Gravity-driven gliding is suggested by the general northward tilting of the structure in relation with the collapse of the Chenaillet graben. The stress tensors computed from brittle deformation analysis confirm the predominance of orogen-parallel extension in the entire frontal Piémont zone. This can be compared with the nearby Briançonnais nappe stack where the extensional reactivation of thrust surfaces locally resulted in prominent orogen-perpendicular extension. Such a contrasting situation illustrates how the main direction of the late-Alpine extension may be regionally governed by the nature and orientation of the pre-existing structures inherited from the main collision stage.

Keywords Late orogenic extension · Inversion tectonics · Structural heritage · Piémont zone · Western Alps

Introduction

In the Western Alps, along the Eurasia–Africa plate boundary, the main structure of the internal arc results from repeated folding and thrusting during Tertiary collision, affecting a pile of nappes initially thrust in an active margin context (Schmid and Kissling 2000 for review). In the middle part of this arc, located east of the Pelvoux massif (Fig. 1), the imbricated Briançonnais and Piémont nappes originated from contrasting paleogeographic domains that allow the reconstruction of the ancient transition between the Tethys Ocean and its European margin (Lemoine et al. 1986). We focus on the frontal (i.e. westernmost) Piémont nappes, at the contact with the Briançonnais zone, east of Briançon and Guillestre (Fig. 2). There, the last syn-collisional shortening phase of Oligocene age, produced a foreland dipping schistosity associated to east-verging folds and subordinate east-directed thrusts, the so-called backstructures (Tricart 1984 for review). As recently demonstrated further to the north (Bucher et al. 2004), these backstructures do not necessarily result from an orogen-scale top-east shearing. Nevertheless, they interfere with older west-directed thrusts and associated folds, and thereby they achieved the building of the present-day Alpine fan structure. In the study area, the local style of backstructures varies in a spectacular way from north to south between the Doire and Ubaye valleys (Barféty et al. 1996 with references therein). We revisited them, focusing on their late brittle evolution in the light of recent results on the importance and significance of Neogene extensional faulting (Sue and Tricart 2003). As a

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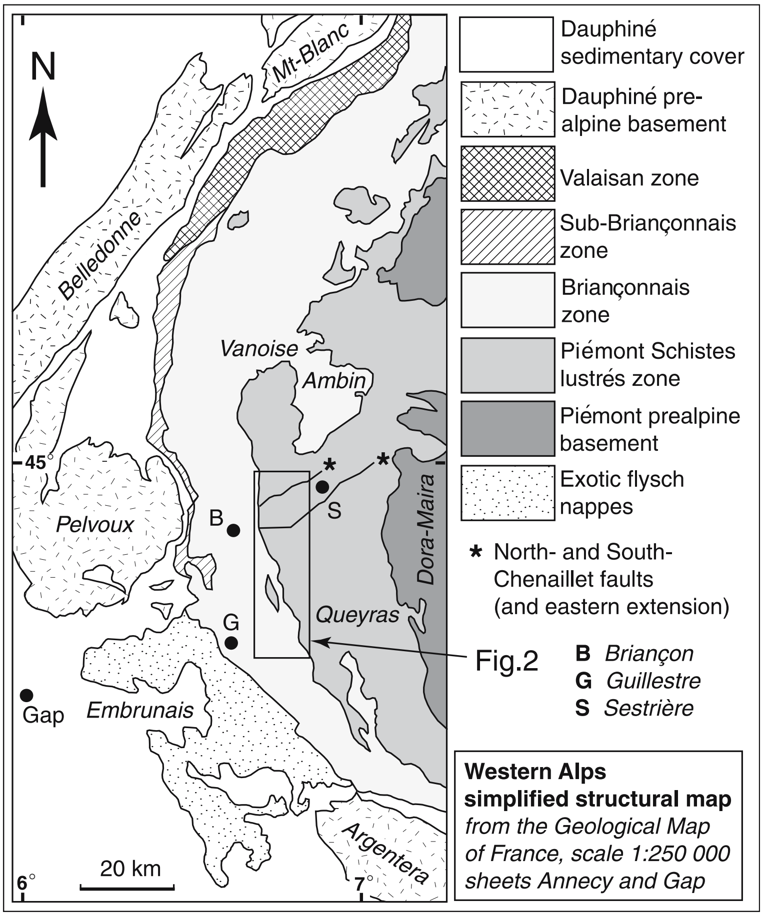
Fig. 1 Location map



consequence of their contrasting lithology, the back-structures in the frontal Piémont nappes guided the style of late faulting.

Alpine tectonic setting

The Briançonnais zone

The nappes of this zone originated essentially from the uplifted shoulder of the Jurassic rift that became the middle part of the European passive margin during the Jurassic-Cretaceous opening of the Tethys Ocean (Lemoine et al. 1986). The overturned eastern fringe of the Briançonnais nappe pile dips westward and represents the internal branch of the classical "Briançonnais fan" (e.g., Goguel 1950; Gidon 1962). This branch was mainly built during the last phase of regional shortening (Tricart 1984 for review), when the stack of the internal Briançonnais nappes was overturned in the eastern lower limb of an east-facing mega antiform, the Briançonnais backfold ("pli en retour" of French geologists since Kilian in Gidon 1962). This NNW–SSE trending fold is best visible around the Ayes pass (east of Briançon: Fig. 2 Sect. C) and farther south, along the Guil (upstream Guil anticline), Cristillan (Cristillan anticline) and Ubaye valleys (Marinet anticline). The Clapière de Ceillac panorama (Cristillan valley) provides a classical view onto its hinge (Fig. 2, Sect. D).

The Briançonnais-Piémont major tectonic contact

Along the initial forethrusting surface of the Piémont zone onto the Briançonnais zone, small tectonic lenses called "intermediate slivers" ("écailles intermédiaires", Acceglio zone: Lemoine 1963) display reduced sedimentary series witnessing of the deep erosion that occurred during the Tethyan rifting in the most uplifted eastern fringe of the Briançonnais domain, the so-called Acceglio domain. In the Chaberton massif, north of the Montgenèvre pass, the old forethrust surface and its intermediate slivers are folded into a multi-kilometre-scale east-facing antiform, well visible in the Rio Secco gully (Fig. 2, Sect. A). To the south, along the Guil, Cristillan and Ubaye valleys, comparable intermediate slivers are inserted within the westerly dipping reversed contact between the Piémont and Briançonnais zones (Lemoine 1963).

The frontal part of the Piémont zone

This zone is derived from early imbricated nappes originating from two different Tethyan domains which

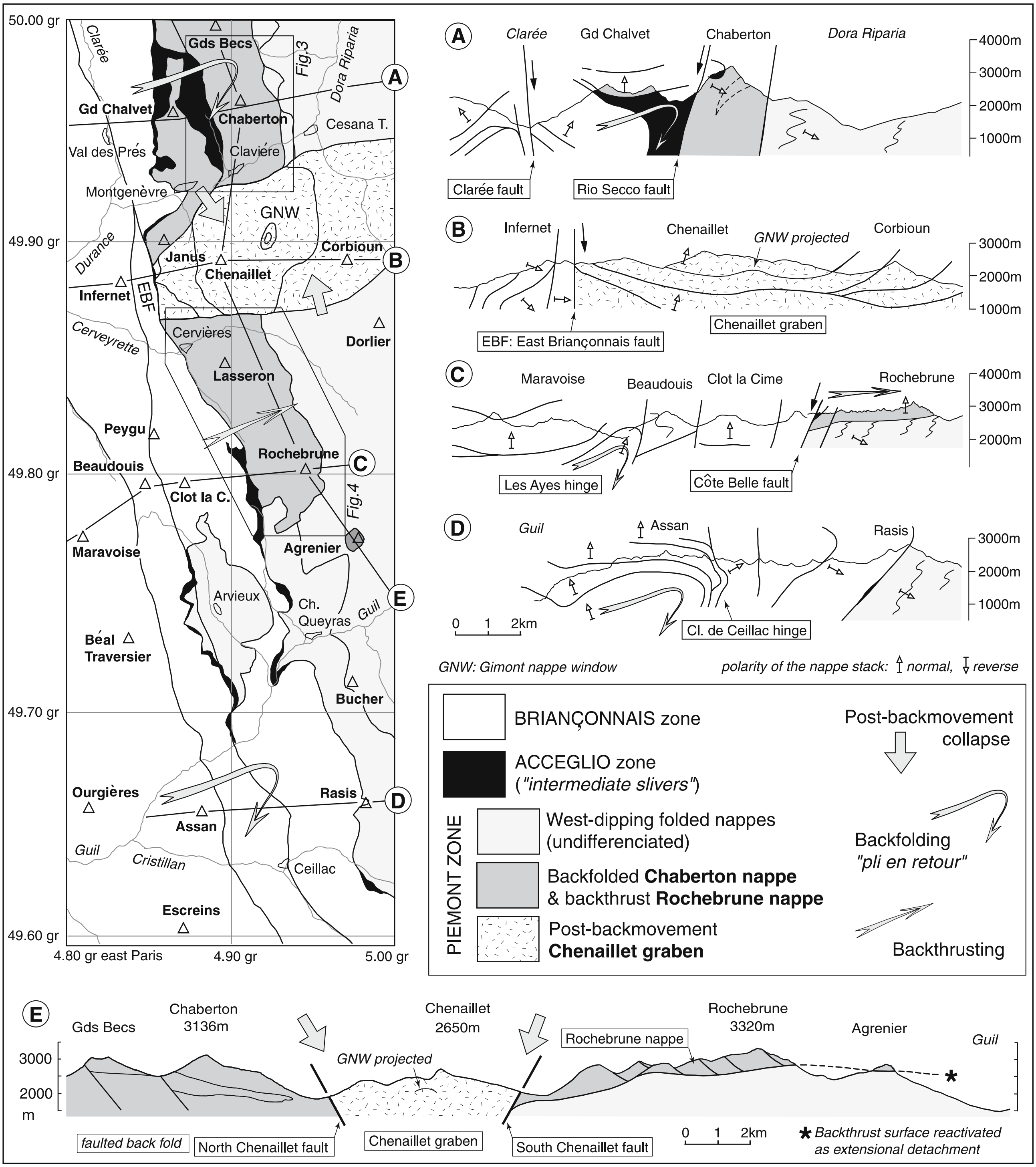


Fig. 2 Structural sketch map with selected tectonic contacts (folded main thrusts, backthrusts and late faults). *Polygons* locate the detailed maps in Fig. 3 (Chaberton massif) and Fig. 4 (Rochebrune massif). *A*, *B*, *C* and *D*, transverse sections; *E*, longitudinal section. The map and the transverse sections are slightly modified from the French geological map, scale 1:50,000, sheets Briançon (Barféty et al. 1996) and Guillestre (Debelmas and Lemoine 1966). See these maps for details on the Briançonnais and Piémont nappe stacks. *Arrows* refer to backmovements and subsequent faulting. To the east of the East Briançonnais fault (*EBF*), the structure at depth in the Chenaillet Graben is poorly constrained. On Sect. B, the base of the Chenaillet upper ophiolitic nappe has been directly projected from the Gimont nappe window (*GNW*)

were initially contiguous (Lemoine et al. 1986): (1) the deepest part of the pre-oceanic rift, at the eastern foot of the rift shoulder, characterized by thick synrift turbidites (Roche des Clots—Grande Hoche series: Lemoine et al. 1978) fed by deep erosion in the nearby Acceglio domain. This domain later became the distal part of the

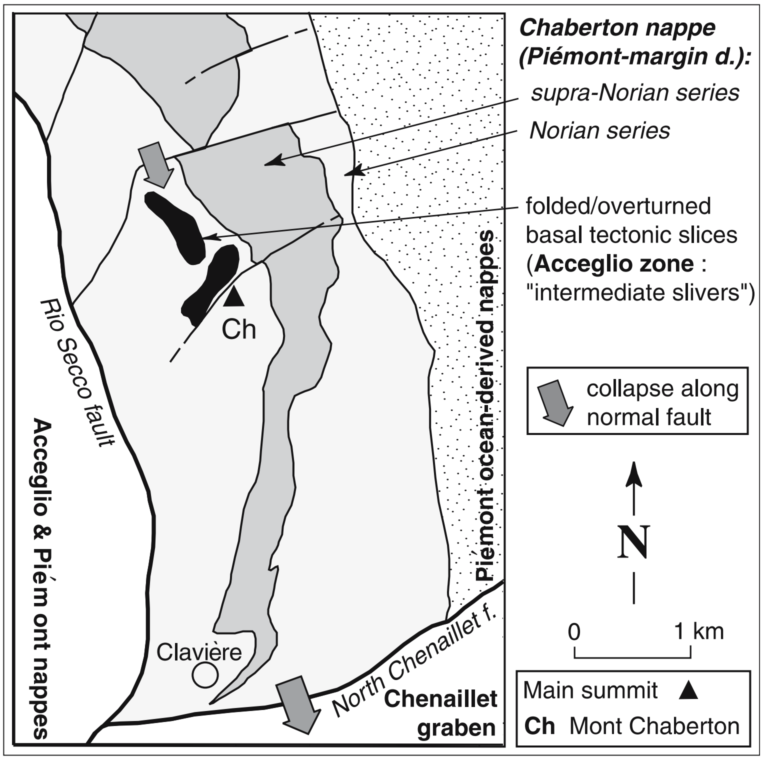


Fig. 3 Structural sketch map of the Chaberton massif from Barféty et al. (1996). Outlines indicated in Fig. 2

European margin. Initially called "Pre-Piémont", it is also often called " Piémont sensu stricto;" (2) the oceanic realm itself, often called "Piémont-Ligurian" or "Ligurian". In this contribution, the nappes originating from these domains will be referred to as "margin-derived Piémont nappes" and "ocean-derived Piémont nappes" respectively, according to the simplified nomenclature proposed by Tricart et al. (2003).

The margin-derived Piémont nappes have been detached within the Carnian evaporites. A Norian dolomitic pile, up to 800-m thick (Lasseron summit, see in Fig. 4 for location) overlies these evaporites and displays a very competent tectonic behaviour. The overlying Rhaetian to Cretaceous metasediments are only a few 100 m thick, but their original upward enrichment in argilaceous and marly muds explains the rapid upward development of several generations of folds and schistosities. This produces a strong deformation gradient normal to the bedding (Tricart et al. 1985).

The ocean-derived Piémont nappes have been locally detached within the mafic-ultramafic basement near its top, mostly at less than a few hundred metres below the sea bottom (Tricart and Lemoine 1988). This produced nappes with a thin and discontinuous ophiolitic sole that suffered later regional-scale boudinage (Tricart and Lemoine 1986). More often, the detachment roughly followed the basement top along a nearly continuous level of sedimentary breccias, rich in serpentinite clasts (ophicalcites: Tricart and Lemoine 1983). The resulting nappes only display a 200–300 m thick pile of deep-sea pelagic sediments attributed to the Jurassic-Cretaceous. Displaying a very ductile behaviour, these argilaceous, marly and calcareous metasediments (Piémont "calcschists" or "Schistes lustrés"; see review in Lemoine and Tricart 1986) are involved in a complex pile of polyphase isoclinal folds.

During the Paleocene-early Eocene, both types of Piémont nappes were imbricated into a blueschist bearing accretionary wedge (Schwartz 2002). Later, the nappe pile underwent several new thrusting-folding phases also involving the Briançonnais zone, while the conditions evolved toward greenschist facies conditions (Tricart et al. 2003 for review). The last synschistosity deformation phase corresponds to the backstructures, inferred to be of late Oligocene age in this area (Tricart et al. 2001).

Array of "Late Alpine" faults

This array is organised along two dominant trends. Faults oriented NNW-SSE (dominantly 160°E) are parallel to the main structures inherited from the backfolding phase and to the mountainous arc itself. Faults oriented NE–SW to E–W (dominantly N50°E–N80°E) are roughly perpendicular to the former. Both families formed coevally as normal faults, characterizing a multidirectional, almost radial extension (Sue and Tricart 2003). Looking closer, the first set dominates in the Briançonnais zone, corresponding to greater extension perpendicular to the belt, while the second family dominates in the frontal Piémont zone resulting in greater extension parallel to the belt. This partitioning will be further discussed later. In this part of the Alpine

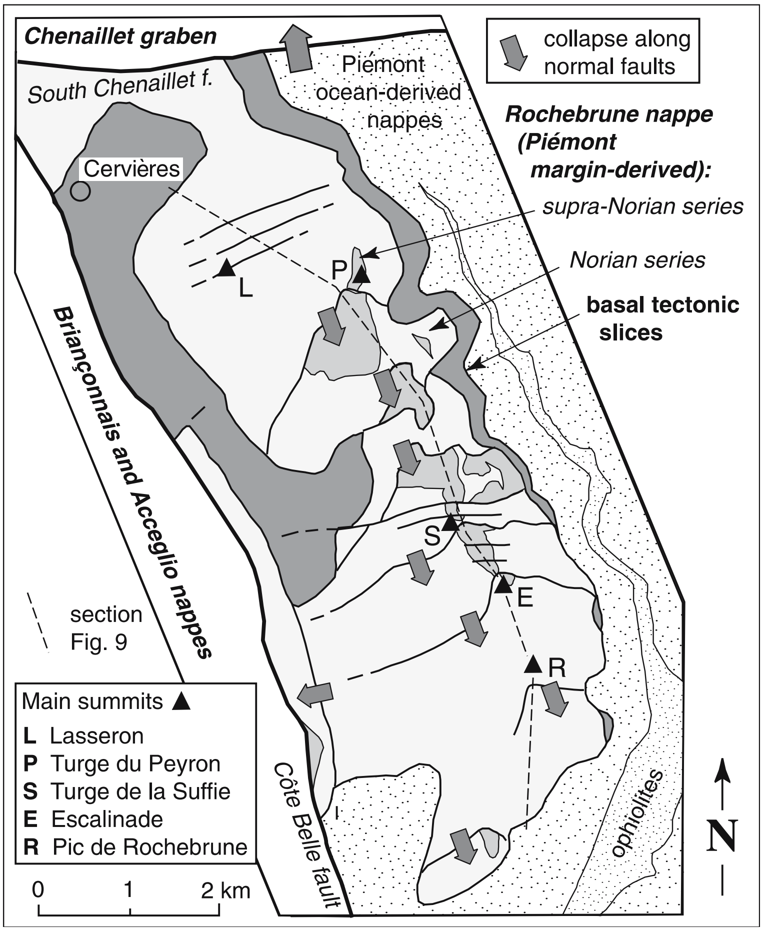


Fig. 4 Structural sketch map of the Rochebrune massif, slightly modified after Dumont (1983). Outlines indicated in Fig. 2

arc, widespread brittle extension is restricted to the internal arc, related to the reversal of movements along the main thrust at the front of this arc (Briançonnais frontal thrust: Sue and Tricart 1999) in terms of normal faulting and block tilting. On the basis of apatite fission track ages, Tricart et al. (2001) proposed that inversion and associated normal faulting were active during the Miocene but this remains a matter of debate (see Fügenschuh and Schmid 2003, for an alternative interpretation).

In response to changing stress conditions, NNW–SSE and NE–SW to E–W normal fault families were variably reactivated as dextral and sinistral strike-slip faults, respectively (Sue and Tricart 2003). Fission track ages suggest that this reactivation occurred during the Pliocene, at least SE of the Pelvoux massif (Tricart 2004). The same fault network remains active today with prominent normal faulting, characterizing presently active radial extension (Sue et al. 1999).

Taking into account this final faulting evolution that is better documented by now, we reinterpret the general structure of the frontal Piémont zone. Thereby we demonstrate the important local role of inherited structures, especially backstructures, during the late brittle extension stage.

Regional structural setting

The general structure in the frontal part of the Piémont zone differs according to the analysed transect (Debelmas and Lemoine 1966; Barféty et al. 1996, with references therein).

Northern transect: backfolded nappes in the Chaberton area

The Piémont nappe pile, including a thick margin-derived Piémont nappe at its top (Chaberton summit), is involved in a plurikilometric east-facing antiform (Fig. 2 Sect. A, Fig. 3). Its hinge is visible along the southern slope of Chaberton Mountain, where it affects a pre-existing isoclinal synform. The core of the antiform preserves folded remnants of the initial surface of forethrusting onto the Briançonnais zone (Rio Secco gully). To the west, the Grand Chalvet sub-tabular structure corresponds to the upper normal limb of the antiform. To the east, a pile of isoclinal folds in ocean-derived Piémont nappes is overturned below the lower reverse limb of the antiform. This major backfold, beautifully exposed in the frontal, i.e. westernmost part of the Piémont zone, is the same structure as the backfold that affects the internal, i.e. esternmost part of the Briançonnais zone.

Southern transect: the overturned nappe pile of the Guil, Cristillan and Ubaye area

In this area, the pile of Piémont nappes regularly dips westward. This pile has been folded and overturned toward the east. It represents the lower reverse limb of an east-facing major antiform, comparable to the Chaberton backfold, but without remnants of the hinge zone or the upper normal limb that were removed by erosion. (Fig. 2 Sect. D). As observed along the Chaberton transect, this major backfold also affected the nearby internal Briançonnais zone, where its entire hinge area is preserved (Clapière de Ceillac).

Central transects: the Rochebrune backthrust and the Chenaillet graben

North of the Guil valley, in the Rochebrune massif, a margin-derived Piémont nappe horizontally lies upon a westward dipping pile of more internal Piémont nappes, which are dominantly of oceanic origin (Fig. 2 Sect. C, Fig. 4). The high angle truncation of this pile at its top is spectacular (“top lap” structure). At the thrust contact, tectonic slices, a few ten of metres thick, contain sedimentary breccias that probably derive from the old continent-ocean boundary (Dumont et al. 1984). This structure has been interpreted as resulting from thrusting towards the east, i.e. backthrusting of the Rochebrune nappe over a distance exceeding 5 km (Tricart et al. 1985). The westerly dipping pile of Piémont nappes in the footwall of this backthrust extends directly northward and southward into the lower reverse limb of the major backfold described in the previous sections (Chaberton, Clapière de Ceillac). In the hangingwall, the Rochebrune allochton derives from the upper normal limb of this backfold, after rupture of its hinge, in a top-east shearing movement. In the regional context dominated by east-verging late folding, the horizontal backthrusting of the Rochebrune unit forms a spectacular exception.

Along the frontal part of the Piémont zone, no transition may be currently observed between the backthrust structure preserved in the Rochebrune massif and the backfold structures well preserved in the Chaberton massif to the north, only partly preserved from erosion in the Guil, Cristillan and Ubaye valleys. Tear faults and/or lateral ramps within E–W trending transfer zones need to be postulated and reconstructed. To the north, such a transfer zone controlled the location of the more recent Chenaillet graben (see further). To the another, transfer zone is probably hidden below the landslides and quaternary deposits of the Guil valley.

Between the Chaberton and Rochebrune massifs, the Chenaillet massif displays well-preserved ophiolites. Having escaped HP–LT subduction-related metamorphism, they are considered as a major witness of an oceanic obduction, preserved at the front on the accretionary wedge in this part of the Western Alps (Barfety et al. 1996 and references therein). These ophiolites lie on other Piémont nappes deriving from both the margin and the ocean, and bearing a blueschist imprint as the other ones to the north and the south. In particular they appear in a very small nappe window restricted to the Gimont gully between the Chenaillet and Corbioun summits (Fig. 2).

The Chenaillet ophiolitic pile is preserved in a late graben located between two major E–W to NE–SW trending faults (Fig. 2 Sects. B and E, Fig. 5), referred to as the north-Chenaillet fault (NCF) and the south-Chenaillet fault (SCF). Before collapsing, the Chenaillet ophiolites toped a flat-laying, dominantly margin-derived nappe pile that could have contained either (1) the southern extension of the Chalvet unit in the upper normal limb of the Chaberton antiform and (2) the northern extension of the Rochebrune nappe, (3) more probably a transitional structure between these two structures (transfer zone: see later discussion). Unfortunately, the deep structure of the Chenaillet graben remains hypothetical.

Revisiting the late brittle structures in the frontal Piémont units

A detailed analysis of the major and minor brittle structures was carried out in this area (Figs. 6, 7), including a dynamic analysis based on the measurements of the striated fault planes. This now classical approach is based on the Wallace (1951) and Bott (1959) principles in which the stria on a fault plane parallels the resolved shear stress on the plane. It allowed to compute the corresponding reduced stress tensors: the orientation of the maximal, intermediate and minimal main stress axes (noted σ_1, σ_2 and σ_3, respectively) and the shape ratio of the stress ellipsoid $\phi = (\sigma_2\text{-}\sigma_3)/(\sigma_1\text{-}\sigma_3)$. We used the direct inversion method developed by Angelier (1990), which analytically solves the inverse problem of the paleostress tensor through the minimization of a function of the angle between the measured striae and the computed one. We restricted our dynamic analysis to tensors with good quality parameters (number and distribution of fault planes, misfit angles). These paleostress tensors are presented in Fig. 7, and the corresponding parameters are listed in Table 1.

Normal faulting across the Chaberton backfold

A major steep fault, oriented nearly N–S, runs along the Rio Secco gully (Rio Secco fault, see profile A in Figs. 2, 3). It explains the lower elevation of the normal limb of

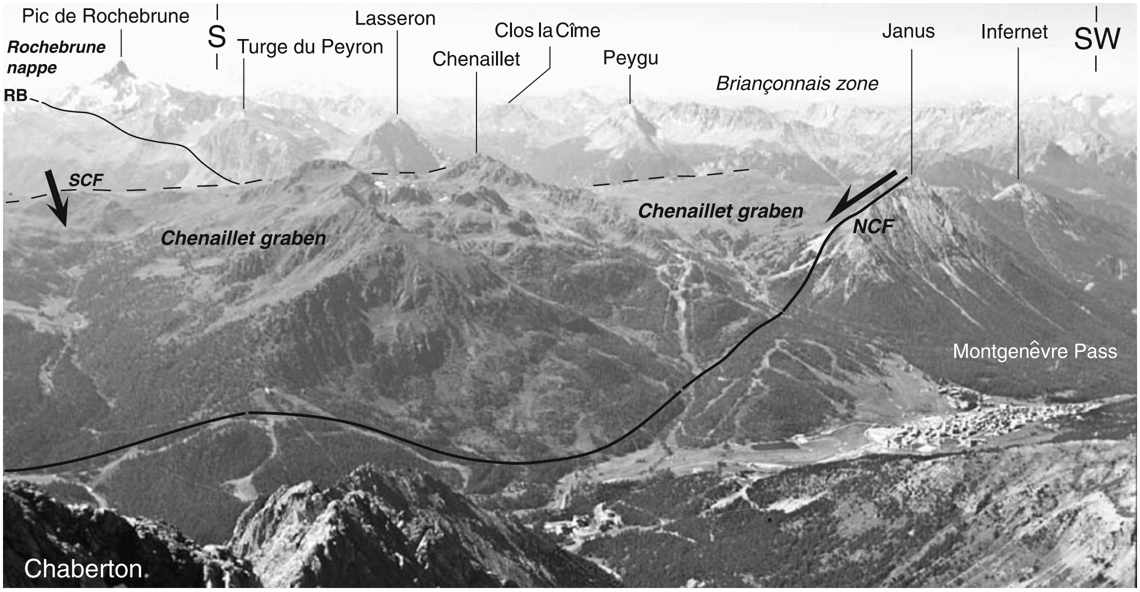


Fig. 5 The Chenaillet graben and Rochebrune nappe viewed towards the SSW from the Chaberton summit. NCF and SCF, north- and south-Chenaillet faults. RB, reactivated backthrust surface at the base of the Rochebrune nappe (see in Fig. 8)

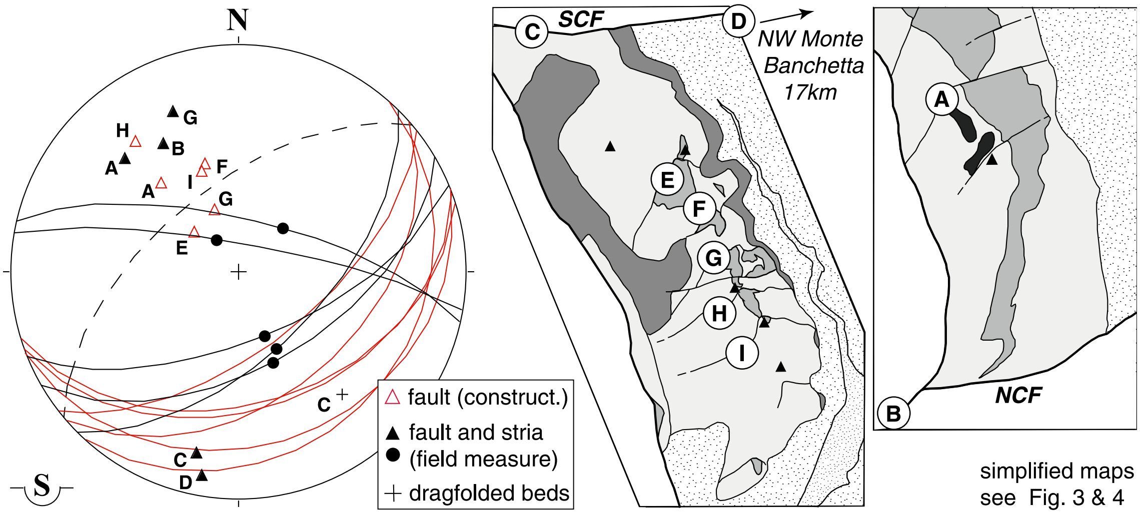


Fig. 6 Attitude of some post-backmovement normal faults: first order faults bounding the Chenaillet graben and second order faults in the Chaberton and Rochebrune massifs. Some faults were constructed using detailed mapping, the other faults could be directly measured. Equal area projection on lower hemisphere (Schmidt net): poles to faults, corresponding cyclographic traces and striae where available. NW dipping beds in site C correspond to a kilometric dragfold in Norian dolomites just to the south of the SCF. Location maps: see Figs. 3 and 4

the Chaberton backfold (Chalvet subhorizontal unit) west of this fault, with respect to the hinge zone of the backfold located east of this fault. Down-throw to the west may reach 1 km near Clavières (Fig. 3). Unfortunately, the fault surface could not be observed directly and the direction of slip remains unknown. In the regional context, it probably corresponds to a normal fault reactivated as a dextral strike-slip fault. Special attention was paid to kilometric SE-dipping faults crosscutting the backfold and clearly overprinting it with a normal offset. The main fault belonging to this system (A in Fig. 6), which runs through the Chaberton pass, is underlined by a 1 m-thick fault breccia originating from the Norian dolomites. Slickenlines on the fault surface indicate pure normal faulting, without strike-slip reactivation. The subhorizontal $\sigma3$ stress axis, computed from the minor associated normal faults, trends close to N147°E (Chaberton site, 1 in Fig. 7). This major kilometric normal fault controls the morphology of the Chaberton massif, and corresponds to a normal throw of several hundreds of metres. The fault plane is regular, and it can be followed all along the track climbing

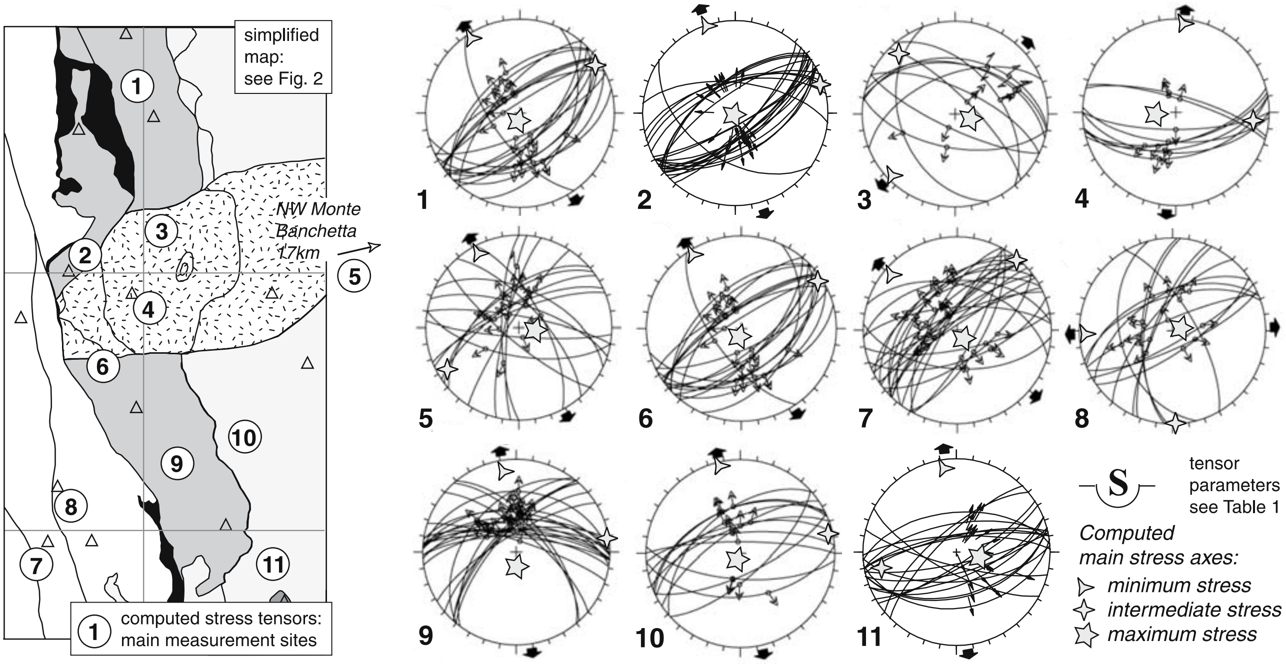


Fig. 7 Computed stress tensors from direct inversion of fault-stria data collected in 11 sites. Equal area projection on lower hemisphere (Schmidt net): poles to faults, corresponding cyclographic traces and striae, main stress axes. See text for discussion and Table 1 for the corresponding parameters

Table 1 Parameters of the computed stress tensors related to late normal faulting

Nb	Site	Latitude	Longitude	N	σ_1	σ_2	σ_3	Φ	m
1	Chaberton	44°58.38′N	6°45.54′E	21	193–83	058–05	327–05	0.4	9.5
2	Janus	44°56.03′N	6°44.31′E	24	208–87	072–02	342–02	0.1	6.1
3	Chenaillet nord	44°55.52′N	6°45.18′E	10	111–76	317–13	226–06	0.4	14.0
4	Chenaillet sud	44°54.74′N	6°45.16′E	10	261–73	097–17	005–04	0.3	11.0
5	Laval	44°56.10′N	6°52.64′E	22	175–75	084–00	354–15	0.4	11.7
6	Cervière	44°53.17′N	6°45.03′E	18	208–76	313–04	044–14	0.3	9.7
7	Pic de Beaudouis	44°49.12′N	6°41.34′E	26	142–80	041–02	310–01	0.3	15.5
8	Col des Peygus	44°49.51′N	6°44.42′E	13	066–78	182–05	273–11	0.2	14.6
9	Turge de la Suffie	44°49.73′N	6°46.84′E	25	181–76	082–02	351–14	0.5	8.8
10	Lac des Cordes	44°50.46′N	6°46.13′E	13	204–84	077–04	347–05	0.4	10.5
11	Coutiers	44°50.30′N	6°46.25′E	20	108–69	258–18	351–10	0.3	12.4

Nb number of the measurement site and corresponding paleostress tensor; *N* number of data (fault/stria); σ_1, σ_2 and σ_3, main stress axes (azimut, plunge); $\phi = (\sigma_2\text{-}\sigma_3)/(\sigma_1\text{-}\sigma_3)$, shape ratio of the stress ellipsoid; m, average value of the angle between measured and computed striae. See in Fig. 7 for the corresponding stereonets

toward the Chaberton summit. Several smaller to minor faults belonging to the same system have been observed in the area nearby. Here, we clearly identified the multiscale late brittle extension that widely affects the internal arc.

The pair of pure extensional faults bounding the Chenaillet graben

The NCF and SCF are the best defined normal faults on both sides of the Chenaillet ophiolites (Lemoine 1964). Along both faults, the throw remains difficult to amount precisely. A minimum of 1 km is required in order to explain that in the small Gimont nappe window, in the western part of the Chenaillet graben (GNW in Fig. 2), the top of a margin-derived Norian sequence crops out close to 2,100 m, while a similar level lies around 2,800 m in the Rochebrune nappe (Turge du Peyron, east of Lasseron) and above 3,131 m at Chaberton Mount. Since several margin-derived nappes were probably stacked, now hidden at depth below the Chenaillet graben or eroded above the Rochebrune and Chaberton units, throw was more important, probably amounting to several kilometres. Eastward, both faults are difficult to follow continuously within the monotonous Schistes lustrés in the ocean-derived Piémont nappes, hidden below vegetation and quaternary deposits and subject to numerous landslides. Nevertheless, toward the east, the SCF may be recognised from place to place, limiting windows of margin-derived Piémont nappes (Caron 1977; Kerckhove 1980; Zaccagna and Mattirolo 1961). Its total length exceeds 25 km, with a trend oscillating between E–W and NE–SW. To the west, contrary to the suggestion of Lemoine (1964), both faults do not extend across the Briançonnais zone but end against a submeridian major fault that is omitted in the French geological map (Barféty et al. 1996). This "East-Briançonnais fault" (EBF in Fig. 2), which is still active (Sue et al. 1999), extends northward into the Clarée fault as defined by Barféty and Gidon (1975) and along which last movement was an important dextral slip.

It was only possible to directly analyse the NCF at the SE foot of the small Janus massif, in poor outcropping conditions (Janus site, B in Fig. 6, 2 in Fig. 7). Actually, the NCF forms the SE face of the Janus summit itself, and was hardly affected by erosion. The main fault plane could not be observed directly, and only minor related faults have been analysed, allowing to compute a σ_3 stress axis oriented close to N162°E.

On the contrary, the SCF is well exposed near Cervières, along a 1 km long secondary crest (Cervières site, C in Fig. 6, 6 in Fig. 7). There, the SCF is marked by several metres thick brecciated rocks and cargneulized dolomites. Indications of the normal movements along this fault have been observed, either directly on preserved faults planes belonging to the SCF, or by drag folds in the adjacent rocks.

The extension of the SCF in Italy could be analysed in detail 20 km to the NE, along the abrupt northern limit of the Banchetta massif (Val Troncea: Laval site, 5 in Fig. 7). In this area, a 1 m-thick breccia underlines the major fault plane that can be observed in a steep gully. Nearby a lot of minor faults (decametre to metre-scale), related to the major fault, have been measured, allowing to compute a σ_3 stress axis oriented close to N174°E.

In summary, the importance of fault breccias was impressive everywhere, but this did not prevent us to observe the major fault plane and numerous associated minor fault planes. All slickensides display a single set of close to dip-slip slickenlines, essentially striae and grooves. This witness of an extensional movement is in accordance with the observed drag folding, for example near Cervières. We conclude that the main faults bounding the Chenaillet graben are normal faults that escaped subsequent strike-slip reactivation, despite their important length in map view and in the regional context.

The analysis of the associated smaller scale normal faults, found also within the graben itself (Chenaillet sites, 3 and 4 in Fig. 7), allowed to identify the multiscale normal faulting that has now been recognised in the entire region and that characterises the late Alpine brittle extension in most of the Western Alpine internal arc (Sue and Tricart 2003). The Chenaillet graben represents a major expression of this extension.

The tilted blocks within the Rochebrune nappe

The base of the Rochebrune nappe structure clearly appears in the landscape thanks to the contrast between the thick allochtonous dolomitic pile and the underlying calcschist-rich metasediments (Fig. 8). The outcropping area of this nappe (10 km N–S/up to 5 km E–W) is limited to the north by the SCF, to the west by the steep Côte-Belle fault (merging to the north with the East Briançonnais fault and the Clarée fault), and to the east and south by erosion (Fig. 4). At the foot of the 200–800 m high dolomitic cliffs, screws and moraines hide the main thrust surface almost everywhere. Nevertheless, the general geometry of this surface could be constrained by using detailed mapping (Dumont 1983). To the south, the surface crops out at an altitude >2,500 m (Agrenier klippe), while to the north, it crops out below 1,800 m (Cervières nappe-window), corresponding to a general dip toward NNW of around 4°. Looking closer (Fig. 9), the nappe consists of two subunits, the northern one being thrust onto the southern one near the Prafauchier pass, along a secondary thrust merging with the main basal thrust to the north (Dumont et al. 1984).

The nappe contains kilometric-scale faulted blocks, limited by SE-dipping normal faults (dominant trend N50°E; E–I in Fig. 6). Six main faults are visible, along which throw increases from 100 m to the south up to 200–300 m further to the north. These faults bound blocks, which were tilted toward NW, with typical dip in the 30–40° range, up to 60° locally. Tilting occurred essentially through rigid-body rotation. Nevertheless, this domino-type structure may be locally associated with drag folding producing asymmetrical very open synclines. Despite the importance of the quaternary deposits and by using continuous marker levels in the underlying calcschists, such as marbles and ophiolites that display no offset, the normal faults appear to be restricted to the nappe and they do not extend below. This important observation led Tricart et al. (1985) to conclude that the faulted blocks predated the backthrusting and were passively transported within the nappe. We can confirm this observation but we propose a different interpretation (see inset of Fig. 9), according to which normal faulting postdates backthrusting. Note that some other more recent and steeper faults crosscut the entire structure, trending N50°E (Lasseron) to N90°E (Turge de la Suffie). They develop in response to a tectonic regime that evolved from an extensional regime towards a more transcurrent regime, also inducing a strike slip reactivation along some normal faults (see Sue and Tricart 2002).

In summary, we propose that the Rochebrune SE-dipping normal faults do not predate nappe transport and hence formed simultaneously with a well developed family of NE–SW trending normal faults, which is in consistent with post-backmovement extension in the nearby massifs (Briançonnais, Montgenèvre, Queyras, Italian Piedmont). The best examples are given by the

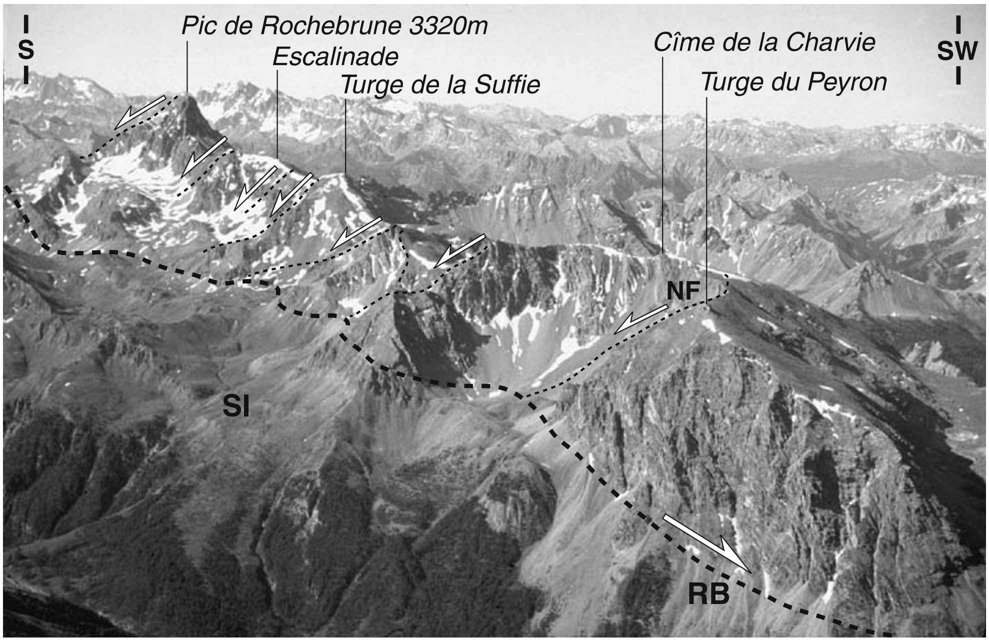


Fig. 8 General view of the Rochebrune massif towards the SSW onto the ENE-facing slopes of this massif (original aerial photo, courtesy Thierry Dumont). RB, reactivated backthrust at the base of the Rochebrune nappe. *NF* normal faults bounding tilted blocks restricted to this nappe, *Sl* ophiolite bearing Schistes lustrés below RB. Following main Alpine forethrusting (i.e. NW- or west-directed thrusting) phases, a two stage history is proposed: (1) Backthrusting (i.e. eastward thrusting) onto the ophiolite-bearing Schistes lustrés (*Sl*) during the last regional shortening and (2) Brittle extension oriented NNW-SSE associated to normal faulting in the nappe (*NF*) and reactivation of the backthrust surface as en extensional detachment (*RB*) during the subsequent "late Alpine" general extension. A general tilting of this surface towards the NNW resulted in gravity-driven gliding of faulted blocks towards this direction (see Fig. 9 and text)

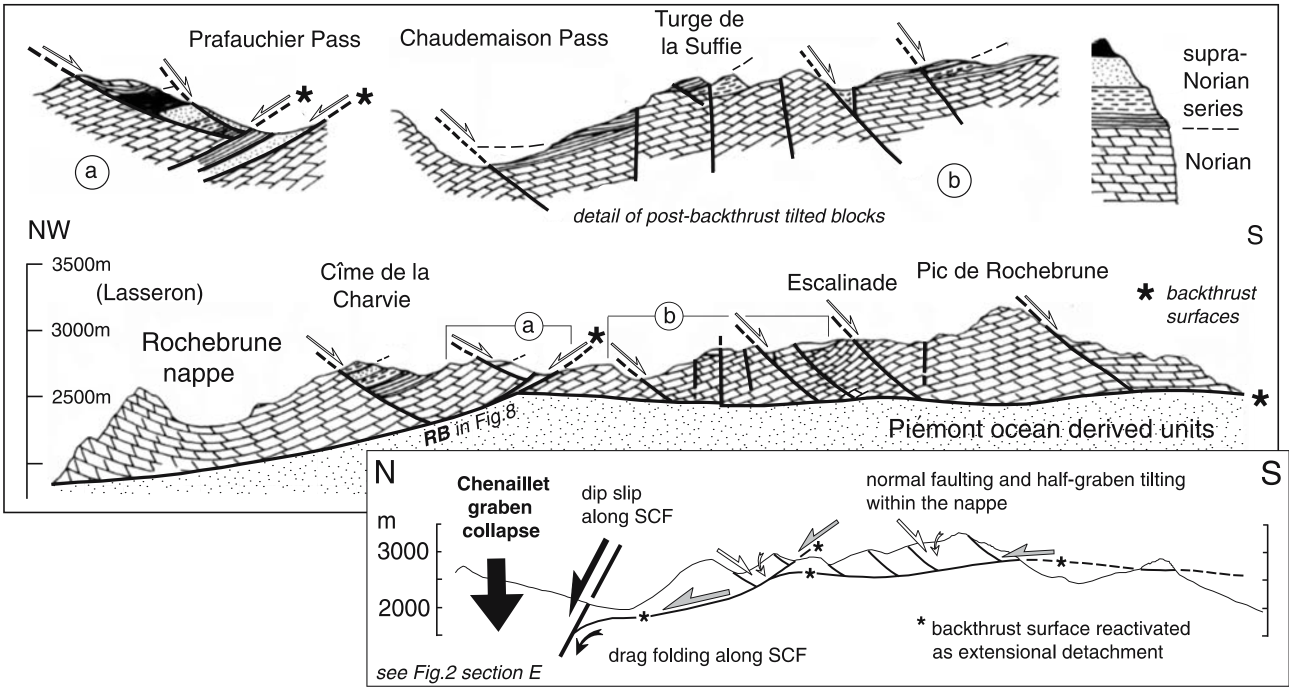


Fig. 9 Longitudinal general section across the Rochebrune nappe modified after Dumont et al. (1984) and Tricart et al. (1985). Location in Fig. 4 **a** and **b** Detailed structure at Prafauchier pass and south of Chaudemaison Pass, respectively. *Inset*, new schematic interpretation of movements during the late brittle extension: the local dragfolding of the Rochebrune basal backthrust surface (RB in Fig. 8) along the south-Chenaillet fault and its general tilting result from the Chenaillet graben collapse. No vertical exaggeration

normal faults that postdate backfolding in the Chaberton massif. Other good examples of these normal faults affect the west-dipping overturned pile of calcschists beneath the Rochebrune nappe (e.g., Lac des Cordes and Coutiers sites, 10 and 11 in Fig. 7). All these faults are associated with the small-scale normal faulting that may be related everywhere to the same regional late brittle extension. The computed stress tensors confirm this attribution (Fig. 7 and Table 1) with maximum main stress axis (σ_1) subvertical and minimum main stress axis (σ_3) oriented close to NNW–SSE. This re-interpretation has an important consequence discussed below.

Extensional reactivation of the basal contact of the Rochebrune nappe

If the normal faults within the nappe post-date its final emplacement during backthrusting while they do not offset the former thrust surface, they must sole out into it. Since this former thrust surface accommodated block tilting, it must have been reactivated as an extensional detachment. Looking closer, the tilting toward the NW or NNW of the blocks within the Rochebrune nappe is in accordance with the NNW–SSE main extension direction that can be deduced from the computed stress tensors. This suggests that the reactivation of the thrust surface occurred along a comparable NNW–SSE direction. This thrust surface presently dips gently toward the NNW, except near Cervières, where it is bent downward into a kilometric drag-fold associated with downthrow to the north of the SCF (see Sect. 2 above). The geometry resulting from tilting and drag folding of the thrust surface is in accordance with collapse of the Chenaillet graben. If all structures refer to the same extensional event, it is likely that the reactivation of the Rochebrune nappe basal surface in terms of an extensional detachment resulted in the sliding down of the hangingwall toward the NNW, in the sense of the gentle slope indirectly created by the Chenaillet graben formation (Fig. 9 inset). We observe that the sense of tilting of the faulted blocks in the nappe is synthetic with respect to the sense of tilting of the whole nappe structure. On the other hand, the sense of shearing along the SE-dipping normal faults bounding these blocks (top-SE) is antithetic with respect to the sense of shearing along the reactivated thrust surface (top-NNW).

Discussion

An old transfer zone reactivated during orogen parallel extension?

During the last Alpine shortening phase in Oligocene times a major transfer fault zone, roughly oriented W–E, was active across the frontal Piémont zone, at the current location of the later formed Chenaillet graben. Along this zone, tear faults and/or lateral ramps accommodated transcurrent movements between the Chaberton area, undergoing backfolding to the north, and the Rochebrune area, undergoing backthrusting to the south. The subsequent development of the Chenaillet graben in terms of importance, orientation and location is consistent with the extensional reactivation of this transfer fault zone at depth.

The contrasting expression of the late Alpine brittle extension

The geometry of the multiscale fault system associated with the Chenaillet graben formation and the corresponding stress tensors allow the attribution of this graben to the late Alpine brittle extension that widely affected the internal arc (Sue and Tricart 2003). This general extension post-dates the so-called backfolding-thrusting phase as defined in the Briançonnais zone and the frontal part of the Piémont zone along this Alpine transect. At the scale of the frontal Piémont zone, the dominant computed extension is nearly oriented N–S. It represents an orogen-parallel extension associated with the collapse of a major graben oriented perpendicular to the belt. Most of the computed stress tensors lead to identify a secondary extension oriented close to E–W. This allows to define an extension that tends to be multidirectional, as already suggested in the nearby areas (Sue and Tricart 2003). To the west, in the Briançonnais nappes, the major extension becomes orogen-perpendicular and is associated with dominant orogen-parallel striking normal faults. Also present, orogen-parallel extension is less important in this area. Considering the entire ensemble, i.e. the whole Briançonnais and frontal Piémont nappes, the extension may be interpreted as globally multidirectional, tending toward radial spreading.

Reactivation versus passive faulting of the backstructures

Due to highly contrasting lithologies in the Piémont nappes, the geometry of the backstructures has greatly influenced the tectonic style during subsequent brittle extension.

In the eastern Briançonnais zone, the nappe pile is either vertical or it steeply dips to the west in the lower limb of the Briançonnais antiformal backfold (“pli en retour briançonnais”). These thrust surfaces between nappes are reactivated as normal faults, limiting neofaulting along the same close to N–S direction. As these reactivations are difficult to detect without a specific analysis, the importance of orogen-parallel normal faulting contributing to orogen-transverse extension, was underestimated in eastern Briançonnais nappes. It is the same situation in the frontal Piémont nappes that have been backfolded, particularly in the Chaberton massif where the Rio Secco normal fault follows a steeply dipping folded thrust surface. On the other hand, the NE–SW trending faults crosscut the backfold at a high-angle, with no influence of the preexisting structures. This produced a step-type structure with poorly tilted blocks. These orogen-perpendicular faults (e.g., at Chaberton pass) represent second order faults with respect to the first order faults bounding the Chenaillet graben (NCF and SCF).

To the south of the Chenaillet transfer fault zone, in the Rochebrune massif, NE–SW second order faults are restricted to the Rochebrune nappe. Associated with the reactivation of the thrust (backthrust) at the base of the nappe, they bound tilted domino-type blocks. Observed in a section oriented N–S, sub-parallel to the major extension direction, the blocks seem to have tilted while they glided down along the north-dipping reactivated backthrust surface. We propose that this gentle dip below most of the nappe is associated with the downward drag folding of its northern fringe along the SCF, i.e. to the Chenaillet graben collapse itself. Gravity driven reactivation of the old backthrust surface as an extensional detachment over a distance reaching 10 km, is suggested here. Farther south and east, other transverse faults oriented between N50 and N90°E are known within the Piémont Schistes lustrés, but without such a clear hierarchical organisation into first and second order faults.

Conclusions

We revisited the structure at the front of the Piémont zone between the Doire and Ubaye valleys, taking into account the importance of the late brittle extension. There, as in most part of the Western Alps internal arc, normal faults trend dominantly parallel and perpendicular to the belt, variably affected by strike-slip reactivation. These faults overprint the backstructures, which are the last direct expression of regional-scale Alpine shortening, confirming the accepted chronology.

In the area studied here, the Chenaillet graben is a first order structure representing a major expression of orogen-perpendicular normal faulting in the regional context and accommodating important orogen-parallel extension. We suggest that the development of the Chenaillet graben was guided by a pre-existing E–W trending transfer zone inherited from backmovements. This transfer zone represented the limit between different dominant tectonic styles (i.e. backfolding and backthrusting) present to the north and to the south, respectively.

Looking closer at the structure in the different frontal Piémont units, a major role was played by the thick competent pile of Norian dolomites, typical for the margin-derived nappes, contrasting with the

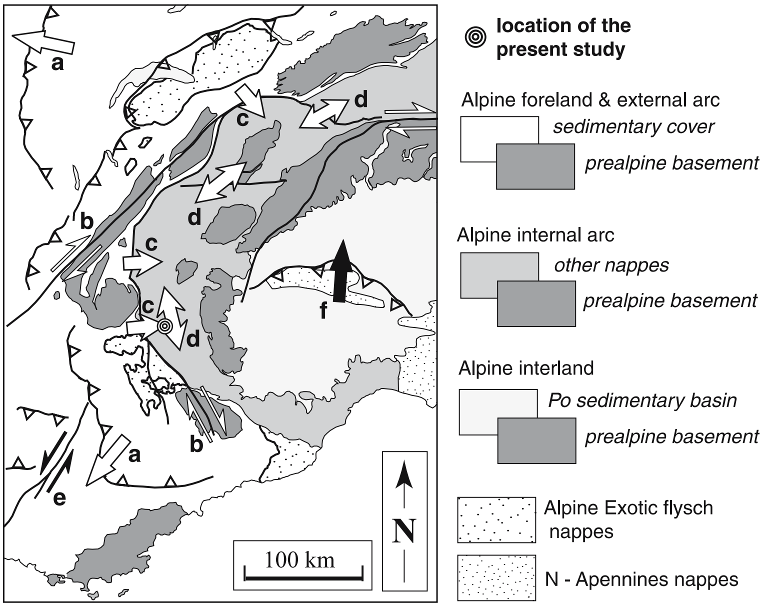


Fig. 10 General Alpine context of the post-backmovement brittle extension analysed here. In the western Alpine arc itself, four main components (*white arrows*) act simultaneously or successively from the Miocene onwards (see Sue and Tricart 2002 for a full discussion): (**a**) outward thrusting in the Jura arc and the Alpine external arc; (**b**) dextral slip along longitudinal faults splaying out the external arc (horse tail termination: Tricart 2004); (**c**) orogen-transverse extension, oriented radial in the outer fringe of the internal arc. SE of Pelvoux, it is associated with reversal of movement along the old major thrust at the front of this arc (inverted Briançonnais frontal thrust: Sue and Tricart 1999) during the Miocene (Tricart et al. 2001) and currently (Sue et al. 1999); (**d**) Orogen-parallel extension in the core of the internal arc (Champagnac et al. 2004 and ref. therein). At the periphery of the Western Alps, other dynamics have been mentioned (*black arrows*), which are not directly associated with the Alpine dynamics sensu stricto (see Sue and Tricart 2002 for details): (**e**) Sinistral NE–SW transcurrent faulting, associated with submeridian compression in Provence and western Mediterranean; (**f**) North-directed thrusting tectonics in the northern Apennines associated with subduction rollback

calcschist-rich nappes originating from the ocean. This explains that the style of brittle extension was widely influenced by the inherited backstructure geometry. Where backfolding dominated, the overturned thrust surfaces with the steepest attitude were reactivated as orogen-parallel normal faults. Consequently, the contribution of this fault family to the regional extension was underestimated. In the Chaberton massif, the east-verging antiformal hinge was cut up passively by orogen-perpendicular normal faults, producing a step-type structure facing southward the Chenaillet graben. In the backthrust structure represented by the Rochebrune nappe, numerous orogen-perpendicular normal faults bound spectacular tilted blocks having slipped northward along the backthrust surface, reactivated as an extensional detachment. The role of gravity is indicated by the general dip of this surface toward the north. We propose that this thrust surface was tilted northward as a consequence of the Chenaillet graben collapse just to the north.

Both directions of normal faulting must be viewed in the general context of multidirectional brittle extension at the scale of the whole central part of the internal arc (Fig. 10). The orogen-perpendicular faults cutting up the frontal Piémont zone accommodate dominant orogen-parallel extension. We propose that it results from the reactivation of a first order inherited transverse structure, represented by a backmovement transfer zone. By contrast, orogen-perpendicular extension dominates to the west, associated with much more developed orogen-parallel faults, in particular when approaching the inverted thrust at the front of the Briançonnais zone (Briançonnais Frontal Thrust). Sue and Tricart (1999) have underlined the role of this major structure inherited from the Alpine phase that predated the backmovement phase in Oligocene times. This suggests that, in response to a general multidirectional extension at the scale of this part of the internal arc as a whole, an orogen-parallel or an orogen-perpendicular component of this extension may locally predominate, depending on the orientation and nature of the pre-existing structures that were reactivated.

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