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The late extension in the inner western Alps: a synthesis along the south-Pelvoux transect

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Keywords. – Western Alps, Exhumation, Denudation, Extension, Boudinage, Normal faulting, Seismicity, Geodesy, Thermochronology

Abstract. – During the Oligocene, in the central western Alps, tectonic accretion of the external domain to the internal orogenic wedge along the Briançonnais frontal thrust (BFT) was followed by backfolding, resulting in the Alpine fanning structure. The Briançonnais fan axis was rapidly exhumed by erosion. This growing wedge at the scale of the entire Alpine structure was a short-lived situation that ended with the onset of extension in its internal part, before the end Oligocene. To the east, in the Queyras Piedmont Schistes lustrés, extension in ductile then brittle conditions accommodated the tectonic denudation of the Dora-Maira crystalline massif below the Monviso ophiolites, themselves exhumed below the Queyras Schistes lustrés. Consistently, the final cooling of these Schistes lustrés becomes younger eastwards during the Miocene. To the west, inversion of the BFT was directly associated with dense normal faulting in the Briançonnais-Piedmont nappe stack. Local reactivation of thrust surfaces resulted in spectacular trains of tilted blocks oriented parallel and normal to the orogen. When considered at the scale of the entire internal zones, the brittle extension developed during the Neogene globally displays a multitrend character. It is a close to radial spreading that strongly suggests the gravitational collapse of an overthickened crust. Extensional movement along the BFT and multitrend normal faulting in its hangingwall continue at present, resulting in shallow depth seismic activity. From the Neogene onwards, the Alpine structure underwent contrasting tectonic regimes. Extension limited the growth of the internal wedge or accompanied its thinning at least in its upper part. Concurrently the external wedge continued growing through successive folding-thrusting phases.

L'extension tardive dans les Alpes occidentales internes : synthèse suivant la transversale du sud-Pelvoux

Mots clés. – Alpes occidentales, Exhumation, Dénudation, Extension, Boudinage, Failles normales, Sismicité, Géodésie, Thermochronologie

Résumé. – A l'Oligocène, au centre des Alpes occidentales (transversale du sud-Pelvoux), l'accrétion de l'arc externe au prisme orogénique interne suivant le chevauchement briançonnais frontal (BFT) engendre un prisme impliquant toutes les zones alpines. Des rétrodéversements suivent et engendrent une structure en éventail centrée sur la zone briançonnaise qui est rapidement exhumée par l'érosion. La croissance d'un prisme à l'échelle de toute la chaîne est une situation nouvelle mais éphémère qui s'achève avant la fin de l'Oligocène, avec l'avènement d'un régime distensif dans la partie interne du prisme. Au Néogène, le rejeu en extension du BFT s'accompagne de failles normales affectant largement les zones internes. Dans les nappes briançonnaises et les nappes piémontaises occidentales, aux lithologies contrastées, de spectaculaires basculements de blocs accompagnent le rejeu en extension des surfaces de charriages. Il en résulte de fortes extensions parallèles ou perpendiculaires à la chaîne, le bilan à l'échelle régionale étant une extension multidirectionnelle. Dans les Schistes lustrés piémontais du Queyras, la dernière déformation ductile, en conditions de schistes verts, accompagne une extension perpendiculaire à la chaîne. Progressivement concentrée dans des zones de failles normales ductiles pentées à l'ouest, cette extension accompagne l'exhumation par dénudation tectonique du massif cristallin Dora-Maira et des ophiolites du Monviso.

Le passage à une extension cassante a localement été enregistré en Queyras oriental, probablement vers la limite Oligocène – Miocène. L'extension devient alors multidirectionnelle, sous la forme de blocs faillés entrecroisés de toutes tailles. Cette fracturation accompagne un basculement vers l'ouest des Schistes lustrés du Queyras, répercutant à distance l'accentuation du bombement dans Dora-Maira. En cohérence avec ce basculement, le refroidissement final des Schistes lustrés du Queyras et des ophiolites du Monviso, enregistré par les traces de fission dans l'apatite est plus récent vers l'est au cours du Miocène. L'analyse des failles normales qui se développent durant tout le Miocène en zones briançonnaise et piémontaise permet de caractériser une extension multidirectionnelle. Cet étalement radial suggère l'effondrement gravitaire d'une croûte surépaissie. En zone briançonnaise, des processus karstiques enregistrent la poursuite d'activité des failles normales au Plio-Quaternaire. Le rejeu en extension du BFT et la fracturation normale à l'est de cet accident se poursuivent actuellement, expliquant la sismicité de l'arc interne. Au total, depuis la fin de l'Oligo-

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cène, de l'extension accompagne l'exhumation finale des unités métamorphiques HP-BT et limite la croissance de la partie interne du prisme alpin, voire accommode son désépaississement. Durant la même période, la partie externe du prisme alpin poursuit sa croissance, avec une accélération à la faveur du chevauchement-soulèvement récent du massif du Pelvoux. Tout au long du Néogène et encore actuellement la chaîne a donc connu des régimes tectoniques contrastés, extensif dans l'arc interne et compressif dans l'arc externe.

INTRODUCTION

We focus on the central part of the western Alpine arc (fig. 1 and 2), where the west-vergent structure involves series originating from the Liguria-Piedmont Tethyan ocean and its European stretched margin. The "Penninic Frontal Thrust" is a major thrust zone, best defined in the north-western part of the arc. It corresponds to the "Briançonnais Frontal Thrust (BFT)" in the transect described here. To the east, the internal arc displays a stack of distal margin and ocean derived nappes in which HP-LT metamorphism and strong polyphased shortening increase eastwards. This arc contrasts with the younger, less shortened and nearly non-metamorphic external arc (Helvetic-Dauphinois fold-thrust belt) originating from the proximal European margin. The "crystalline massifs" (fig. 1) display pre-Alpine granitic-gneissic basements. The rather competent external massifs (e.g. Pelvoux) contrast with the internal massifs (e.g. Dora-Maira) that display a ductile Alpine nappe stack [Lemoine *et al.*, 2000].

Along a transect running south of the Pelvoux massif (fig. 2), the earliest Alpine structure was the Queyras Schistes lustrés accretionary wedge, built in blueschist metamorphic conditions during the Paleocene-Eocene subduction of the oceanic lithosphere. After rapid burial and exhumation, the eclogitized ophiolites of the Monviso were accreted to this wedge. They were followed by the Dora-Maira coesite-bearing units that derive from the distal margin. All these units were subsequently refolded and constitute the present-day Piedmont zone [Tricart *et al.*, 2003]. While occurred the transition from subduction to collision, the Briançonnais nappe stack, originating from the central part of the margin, was accreted to the Piedmont wedge in Late Eocene times, building a wider wedge at the origin of the present-day internal arc. The subsequent main Alpine contraction, in Oligocene times, built a wedge at the scale of the entire Alps [Tricart, 1984]. Subsequently this wedge underwent in its internal parts a widespread and long-lived extensional regime, the importance of which was only recognized recently [e.g. Sue and Tricart, 2002]. Here, we review the main new data that constrain in space and time this extension and lead us to revise the scenario for the "late Alpine" structure building along this classical transect.

STARTING SITUATION: THE WESTERN ALPS AFTER THE OLIGOCENE MAIN SHORTENING

During Late Eocene times, in front of the Briançonnais – Piedmont orogenic wedge (present-day internal arc), a deep flexural basin formed (Champsaur sandstones; fig. 3a). It lied along the easternmost margin of the Dauphinois domain, also called the Ultradauphinois domain. During the Early Oligocene an important shortening phase occurred (fig. 3b) that remains poorly dated [Tricart *et al.*, 2001]. The Ultradauphinois domain was underthrust along the BFT, below the Briançonnais – Piedmont nappe stack that underwent itself a new shortening. Folds and thrusts were set up in the external zone, locally associated with cleavage development and low-grade metamorphism. It resulted in a single orogenic wedge, the first to be common to the external and internal Alpine zones [Tricart, 1984]. The synorogenic sedimentation moved outwards, took a molasse character and recorded the shortening of the external arc, through repeated shortening phases during the Oligocene.

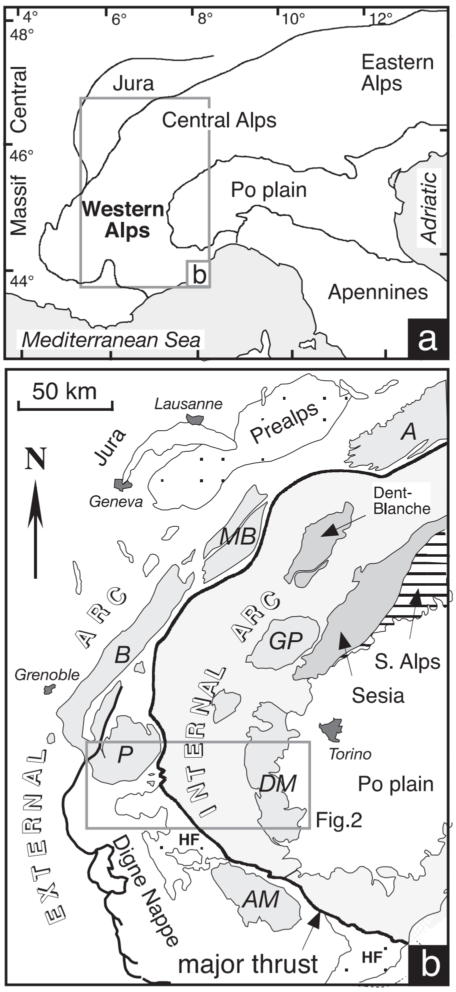


FIG. 1. – Location maps. External crystalline massifs: A, Aar; MB, Mont-Blanc and Aiguilles-Rouges; B, Belledonne; P, Pelvoux; AM, Argentera-Mercantour. Internal crystalline massifs: GP, Gran-Paradiso; DM, Dora-Maira. HF: pellicular nappes of exotic flysch (Helminthoid flysch).

FIG. 1. – *Cartes de localisation. Massifs cristallins externes : A, Aar ; MB, Mont-Blanc et Aiguilles-Rouges ; B, Belledonne ; P, Pelvoux ; AM, Argentera-Mercantour. Massifs cristallins internes : GP, Gran-Paradiso ; DM, Dora-Maira. HF : nappes pelliculaires de flyschs exotiques (flyschs à Helminthoïdes).*

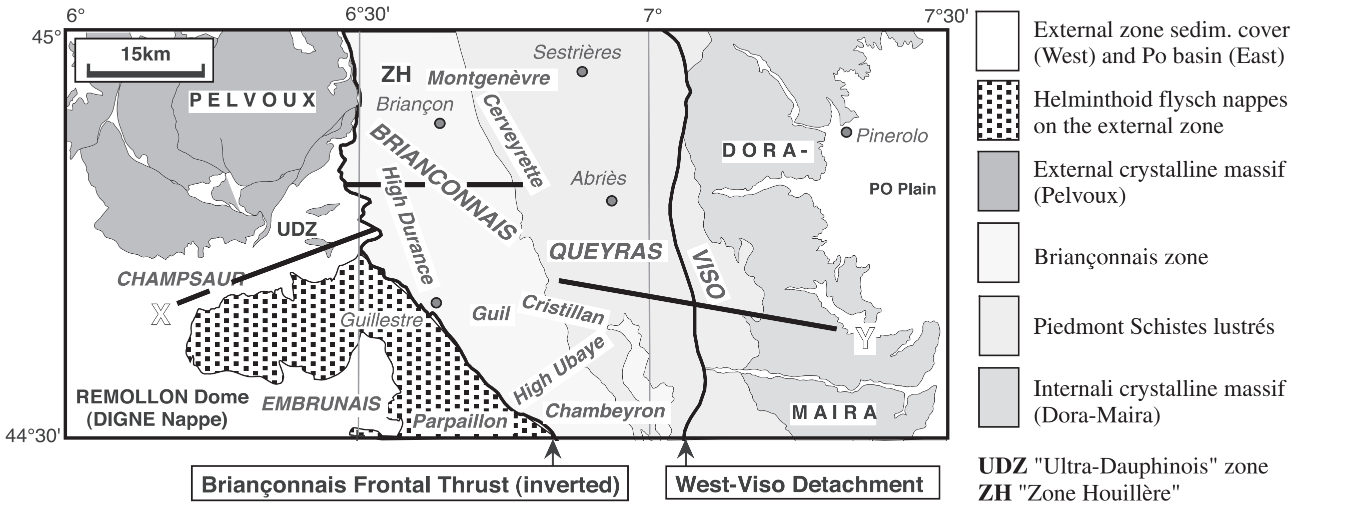


FIG. 2. – South-Pelvoux transect: main structures, tectonic zones and localities mentioned in the text. Between the internal and external arcs, the Briançonnais frontal thrust (BFT) represents the southern extension of the Penninic frontal thrust as defined in the northwestern Alps [see Tricart *et al.*, 2001 for discussion]. Strait lines locate the composite section X-Y in figure 8.

FIG. 2. – *Transversale du sud-Pelvoux : principales structures, zones tectoniques et localités mentionnées dans le texte. Entre les arcs interne et externe, le chevauchement briançonnais frontal (BFT) constitue le prolongement méridional du chevauchement pennic frontal tel que défini dans les Alpes nord-occidentales [voir Tricart* et al.*, 2001 pour discussion]. Les segments de droite localisent la coupe composite X-Y de la figure 8.*

This shortening continued during the Neogene and remains locally active [review in Lemoine *et al.,* 2000].

LAST FOLDING "PHASE" REVISITED

Still during the Oligocene, a last generation of folds affected the pile of tectonic zones, SE of the Pelvoux massif (fig. 3c). The Briançonnais nappes were deformed in east-vergent regional-scale folds, well visible along the Guil and Ubaye valleys. To the west, the Ultradauphinois zone was locally bent in an east-vergent flexure (Embrunais) also affecting the surface of the BFT. To the east, the Briançonnais zone was overturned onto the Piedmont zone ("backfolded" in Ubaye, Cristillan and Montgenèvre) or backthrust onto it (Cerveyrette) in a top-to-the-east regional shear [review in Tricart and Sue, 2006]. Shear intensity increased eastwards across the Briançonnais zone, associated with an E-W to ENE-WSW oriented stretching lineation and a west-dipping crenulation cleavage. Equivalent major-minor east-vergent folds also affected the westernmost part of the Piedmont zone (Montgenèvre, Cerveyrette, Guil, Cristillan and upper Ubaye areas). Everywhere they represent the last generation of compressional structures. By interfering with the previous west-vergent structures, they resulted into the Briançonnais structural fan [Tricart, 1984; see fig. 8].

Further east within the Piedmont zone (Queyras, upper Ubaye, Monviso and Piedmont valleys) this last east-vergent folding may be followed as far as in the Dora-Maira massif [Mahwin *et al.*, 1983]. The major folds disappear but not the minor folds, which are associated with a west-dipping crenulation cleavage, an ENE-WSW stretching lineation and greenschist facies metamorphism [Schwartz, 2002]. These folds are most developed in the calcschist-rich formations of the Schistes lustrés complex (fig. 4). They display a sub-isoclinal geometry and a "reverse limb" asymmetry, each upper limb being longer than the corresponding lower limb. In the absence of any major associated fold, these minor folds cannot longer be attributed to a general eastwards overturning of the entire structure as classically considered [e.g. Tricart, 1984]. They rather represent drag folds resulting from top-to-the-west shearing along the general foliation. As proposed further north [Agard *et al.*, 2001], this shearing could result from late doming in the Dora-Maira stack of gneissic nappes, accommodating E-W extension at the scale of the inner tectonic pile.

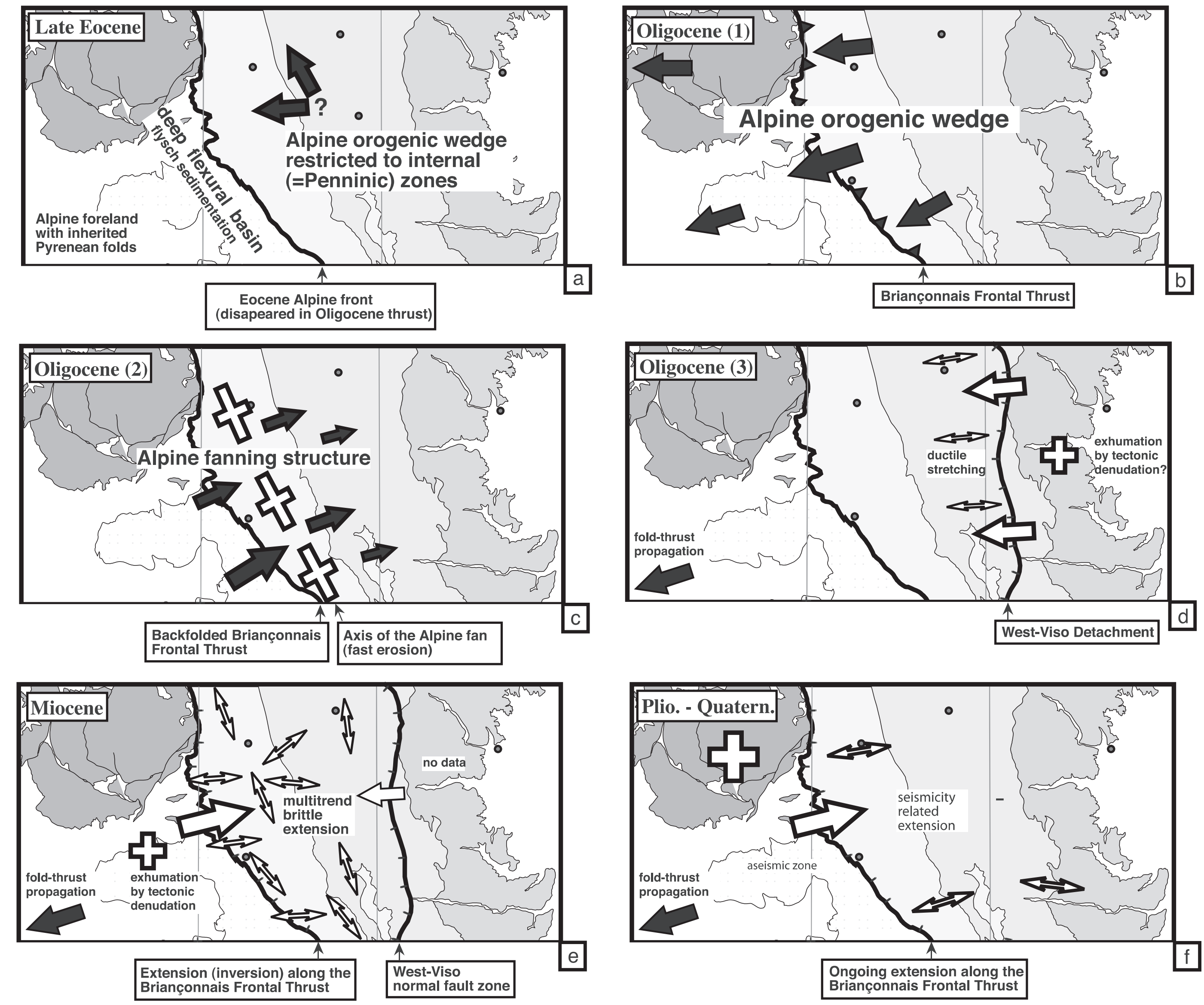
Consequently the last folding phase in the internal zones, classically regarded as restricted to backmovements, was composite. In the Briançonnais zone and along its borders, it corresponded to an accentuation of thickening and E-W shortening through east-vergent folds and thrusts. More to the east, in the Piedmont zone, folds essentially represented drag folds associated with ductile extensional doming in the Dora-Maira massif. The regional-scale continuity of the cleavage and stretching lineation argues for a single but composite tectonic "phase". As discussed further, it still would be Oligocene in age.

FROM DUCTILE TO BRITTLE EXTENSION IN THE PIEDMONT SCHISTES LUSTRES

The Piedmont calcschists remain most ductile in upper greenschist metamorphism conditions. As mentioned above their last folding phase was essentially expressed at a mesoscopic scale (fig. 4). It accommodated a general tilting of the structure and the associated bed-to-bed (intrafolial) slip, resulting in the present-day west-dipping isoclinal structure. During shearing, the nearly E-W trending stretching lineation underlined by greenschist minerals, was definitively emplaced (fig. 3d). On both flanks of the Monviso ophiolitic slab, extension was localized within late west-dipping ductile shear zones, which dip steeper than the regional foliation. These ductile normal faults (fig. 3d) accommodated the final exhumation of the Dora-Maira dome below the Monviso ophiolites, themselves being exhumed below the Queyras Schistes lustrés [Ballèvre *et al.*, 1990; Blake and Jayko, 1990]. The late folds and ductile faults were both associated with the same E-W extension and accompanied the final stage of tectonic exhumation of the inner and deepest units relatively to outer ones. As shown in the next sections, this Piedmont ductile extension was followed as a continuum by brittle extension affecting both the Piedmont and Briançonnais zones. The ductile-brittle transition could be locally observed in the Piedmont Schistes lustrés.

Several outcrops of Schistes lustrés (eastern Queyras, western flank of the Monviso massif) present lithologies favourable to a boudinage process: decimetric-metric beds of prasinites (Bric Bouchet, NE of Abriès) or meta-arkoses (Taillante-Pain de Sucre, SE of Abriès; fig. 5) interbedded with Malm-Neocomian marbles and/or Early Cretaceous schists, calcschists and limestones. These outcrops show that an extensional regime already prevailed when the Queyras Schistes lustrés structure crossed the ductile-brittle transition, during exhumation [Schwartz, 2002]. Comparable observations were made in the Schistes lustrés to the north of the Queyras [Agard *et al.*, 2003].

During final cooling, while E-W ductile stretching continued in the schists, calcschists and limestones, the prasinite and arkose beds were disrupted into mesoscopic boudins. In the veins between the boudins, quartz syntectonic fibres grew, associated with greenschist facies minerals (classical "late Alpine" veins). The orientation of the veins and fibres suggests the continuation of the general E-W stretching. While cooling accentuated, the schists, calcschists and limestones enclosing the boudins, became themselves brittle and underwent micro-normal faulting. The veins in the previously boudinaged beds favoured the nucleation of the faults and were subsequently sheared. The attitude of these conjugate small-scale normal faults and the orientation of their striae suggest that the E-W stretching



regime continued from ductile to brittle conditions. As recently described below a crustal detachment in the Cyclades, boudinage localized normal fault development when crossing the ductile-brittle transition [Mehl *et al.*, 2005].

Some outcrops allow additional, 3D and chronological observations. As the boudinage process was active, E-W veins appeared, crosscuting the N-S primitive ones. Subsequently, new N-S and E-W veins formed, resulting in a chocolate tablet structure. When small-scale normal faulting occurred, it was also along sub-orthogonal directions. Slickenline analysis allows us to compute a multidirectional, close to radial, extension. The same tectonic regime continued while normal faulting developed at a regional-scale (see next section). In the eastern Queyras and Monviso areas, the geometric relationships between the successive generations of veins and striated surfaces demonstrate that boudinage and normal faulting were coeval with an accentuation of westwards tilting in the entire structure i.e. with the last stage of updoming in the Dora-Maira massif [Tricart *et al.*, 2004]. Beyond this tilting, transition from ductile to brittle extension in the Queyras Schistes lustrés was accompanied by an evolution from unidirectional stretching associated with top-to-the-west shearing to a close to radial spreading implying a subvertical shortening.

GENERALIZED NORMAL FAULTING IN THE INTERNAL ZONES

Numerous metric to kilometric normal faults, associated with dense jointing, overprint all the ductile structures to the east of the BFT, in the Briançonnais (fig. 6) and Piedmont zones (fig. 7). Their local preliminary description [Lazarre *et al.*, 1994; Virlouvet *et al.*, 1996] was followed by systematic analysis in the entire Briançonnais and Piedmont Schistes lustrés zones, between the latitude of Briançon in the north and the upper Ubaye valley in the south [Sue, 1998; Sue and Tricart, 2002 and 2003]. Most of the faults display a steeply dipping plan. Their extensional character was clearly evidenced by observing the bed offsets and the associated tectoglyphes, drag folds and veins. Sets of conjugate normal faults develop along two dominant directions: NNW-SSE, parallel to the Alpine structure (“longitudinal faults”), and NE-SW to E-W, at high angle with this structure (“transverse faults”). Both families crosscut each other clearly indicating that they are related to the same regional-scale multidirectional extensional tectonics (fig. 3e). Further north, near Sestriere, Agard *et al.*, [2003] proposed that uniaxial brittle extension in the Schistes lustrés was coeval with a general horizontal rotation of the structure like the rotation of the Briançonnais nappe stack at the front of the internal arc [Thomas *et al.*, 1999]. Our data from the Queyras Schistes lustrés do not

FIG. 3. – Tectonic evolution along the south-Pelvoux transect from the Oligocene. Simplified sketch-maps: see figure 2. Single arrows indicate the shear sense (the top by respect to the base): black arrows refer to general thickening (e.g. thrusting) and white arrows refer to thinning (e.g. extensional tectonic denudation). Double arrows indicate extension.

FIG. 3. – Evolution tectonique suivant la transversale du sud-Pelvoux depuis l' Oligocène. Croquis structuraux simplifiés : voir figure 2. Les flêches simples figurent le sens du cisaillement (mouvement des parties hautes relativement aux parties basses) ; les flêches sont noires pour une tectonique d'épaississement (exemple : chevauchement) et blanches pour une tectonique d'amincissement (exemple : dénudation tectonique en extension). Les doubles flêches schématisent de l'extension.

a. Late Eocene: completion of the internal (Penninic) orogenic wedge building (present-day internal arc); its western front has disappeared in the BFT (see Oligocene 1 map) together with the eastern part of the foreland flysch basin (Champsaur sandstones: present-day Ultradauphinois zone). The main direction of thrusting remains discussed.

a. Eocène supérieur : le prisme orogénique interne (Pennique) achève sa construction (actuel arc interne) ; son front occidental n'est plus visible, disparu dans le BFT (voir la carte Oligocène 1) de même que la frange orientale du bassin à flyschs d'avant-pays (Grès du Champsaur : actuelle zone ultradauphinoise). La direction principale des charriages reste discutée.

b. Oligocene (1): accretion by the Helvetic-Dauphinois units and building of the Alpine orogenic wedge. Possible early backfolding and backthrusting in the Piedmont zone (not represented).

b. Oligocène (1) : construction d'un prisme orogénique à l'échelle des Alpes par accrétion des unités delphino-helvétiques. Des rétrodéversements et rétrochevauchements précoces sont possibles en zone piémontaise (non représentés).

c. Oligocene (2): last shortening in the internal zones and building of the Alpine bivergent structure with fast erosion along the fan axis (Briançonnais zone). The location of the eastern limit of backmovements in the Piedmont zone remains poorly constrained. More to the east, ductile extension may have already appeared (not represented).

c. Oligocène (2) : dernier raccourcissement en zones internes aboutissant à la structure en éventail de la chaîne ; érosion rapide suivant l'axe de l'éventail de structures (zone briançonnaise). La limite orientale des rétromouvements en zone piémontaise reste mal connue. Plus à l'est, de l'extension ductile peut apparaître déjà (non représentée).

d. Oligocene (3): westwards propagation of folds and thrusts across the Helvetic-Dauphinois zone, building the external arc; ductile extension in the Piedmont zone (Schistes lustrés); tectonic denudation and doming of Dora-Maira massif. This extension could have partly coexisted with the last backmovements in the westernmost Schistes lustrés (Oligocene 2 map).

d. Oligocene (3) : propagation vers l'ouest des plis et chevauchements au sein de la zone delphino-helvétique et structuration de l'arc externe ; extension ductile en zone piémontaise (complexe des Schistes lustrés) ; dénudation tectonique et bombement du massif Dora-Maira. Cette extension pourrait avoir partiellement coexisté avec les derniers rétromouvements dans les Schistes lustrés les plus occidentaux (carte Oligocène 2).

e. Miocene: continuation of folding and thrusting within the external arc; development of a foreland basin with molasse sedimentation at the front of this zone; widespread brittle extension in the Briançonnais and Piedmont zones (Queyras, Monviso); probable uplift of Dora-Maira dome (internal crystalline massif).

e. Miocène : poursuite des plissements et chevauchements au sein de l'arc externe ; développement d'un bassin d'avant-pays à sédimentation molasssique au front de cette zone ; extension cassante largement répandue en zones briançonnaise et piémontaise (Queyras, Monviso) ; soulèvement probable du dôme de Dora-Maira (massif cristallin interne).

f. Plio-Quaternary: continuation of folding and thrusting in the external arc (e.g. Digne nappe); continuation of brittle extension in the internal arc. Rapid terminal uplift of the Pelvoux massif (external crystalline massif). Strike-slip faulting in the Briançonnais zone is not represented.

f. Plio-Quaternaire : poursuite des plissements et chevauchements dans l'arc externe (exemple : nappe de Digne) ; poursuite de l'extension cassante dans l'arc interne. Surrection finale rapide du massif du Pelvoux (massif cristallin externe). La fracturation en coulissage de la zone briançonnaise n'est pas représentée.

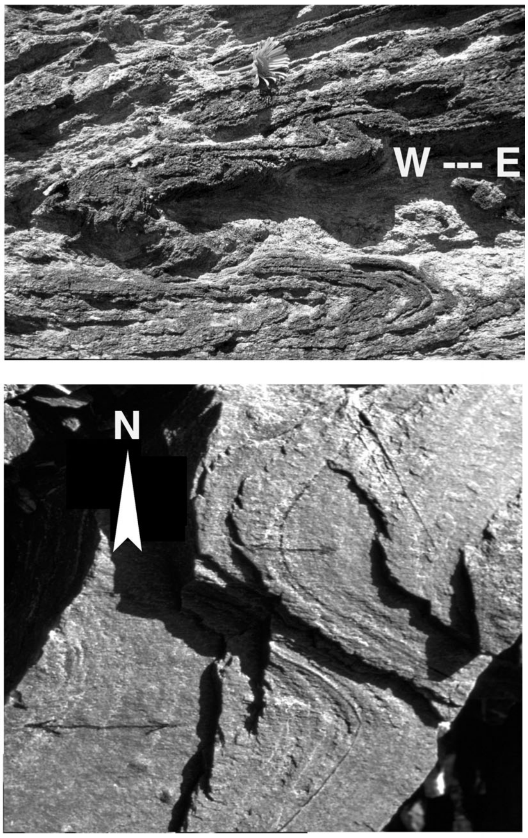


FIG. 4. – Last ductile deformation in the Piedmont zone (Queyras Schistes lustrés). Top: submeridian mesoscopic folds in calcschists with west-dipping axial planes, interpreted as east vergent folds with a reverse limb asymmetry (see discussion in text); flower (2 cm) for scale. Bottom: the same generation of folds, with NW-SE to NE-SW curved axes and E-W stretching lineation (looking down flat-lying beds).

FIG. 4. – *Dernière déformation ductile en zone piémontaise (Schistes lustrés du Queyras). Haut : plis mésoscopiques subméridiens dans des calcschistes, avec plans axiaux pentés à l'ouest et interprétés comme des plis à vergence orientale avec une dissymétrie de type flanc inverse (voir discussion dans le texte) ; la fleur (2 cm) donne l'échelle. Bas : plis de la même génération, avec des axes courbes passant de NW-SE à NE-SW ; la linéation d'étirement est orientée E-W (couches subhorizontales vue par dessus).*

confirm this interpretation. On the contrary, careful observation of the varied local fault chronologies lead us to consider that normal faulting was coeval with a regional scale westwards tilting of the structure [Tricart *et al*, 2004].

In the Queyras Schistes lustrés, normal faults are dominantly closely spaced with limited throw, corresponding to a distributed deformation. In the Briançonnais zone as in the western part of the Piedmont zone (distal margin units), strong contrasting lithologies make the fault geometry more variable. The reactivation of the evaporite-bearing decollement surfaces explains that spectacular trains of kilometric tilted blocks locate within narrow zones such as the book shelf structure, SE of Briançon city [Virlouvet *et al.,* 1996]. These trains of blocks trend close to N-S (orogen-parallel extension) or close to E-W (orogen-perpendicular extension) depending on the geometry of the reactivated trust and backthrust structures [Tricart and Sue, 2006].

Dynamic analysis of striated fault planes provided many stress paleotensors confirming the multidirectional character of extension and also illustrating how this character varied from one measurement site to another [Sue, 1998; Sue and Tricart, 2002 and 2003; Tricart *et al.,* 2004]. In addition, many longitudinal normal faults were reactivated as dextral strike-slip faults and some transverse normal faults as sinistral strike-slip faults. Sue [1998] proposed that these secondary movements do not systematically correspond to a new tectonic phase, since they can also reflect an instability of the stress state through time with permutation between the mean stresses. Along the upper Durance fault and its southern extension (Serenne-Ruburent-Bersezio fault) into the Argentera massif, a major dextral reactivation could be indirectly dated Pliocene [Tricart, 2004 and references therein].

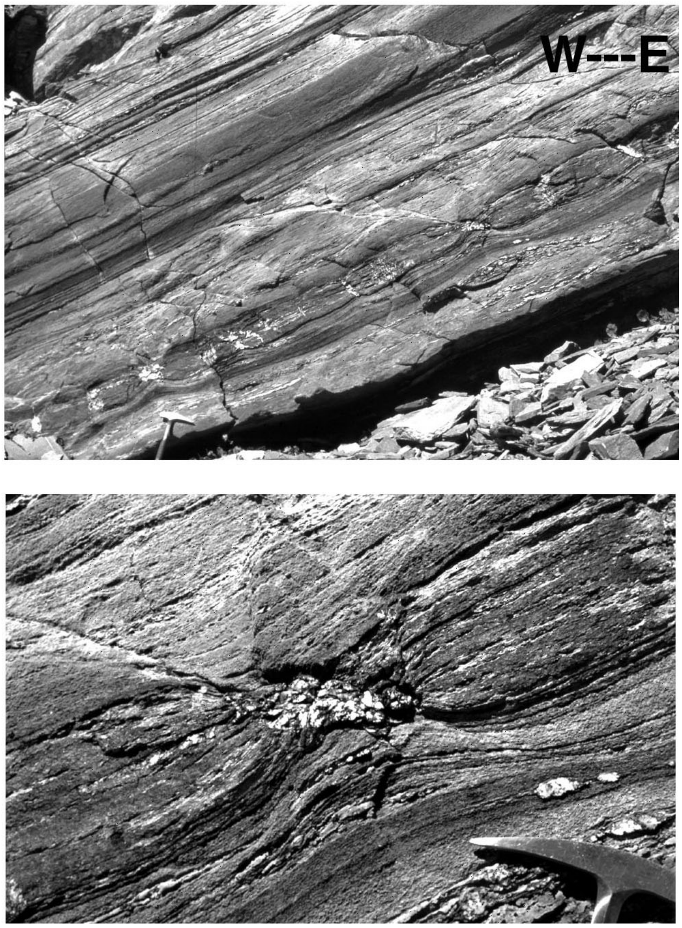


FIG. 5. – Transition from ductile to brittle behaviour during late E-W stretching in the Piedmont Schistes lustrés (eastern Queyras: Taillante – Pain de Sucre area). Top: boudinage restricted to a meta-arkose decimetric bed, within calcschists (in white: tension gashes filled with quartz) followed by normal faulting across the metasedimentary pile. Bottom: detail of an inter-boudins vein, with a superimposed micro-normal fault. Hammer for scale. All views are looking northwards.

FIG. 5. – *Etirement E-W tardif dans les Schistes lustrés piémontais (Queyras oriental : secteur Taillante – Pain de Sucre), développé dans les conditions de la transition ductile – cassant. Haut : boudinage d'un lit décimétrique de méta-arkoses au sein des calcschistes (blanc : fentes de tension à remplissage quartzeux) auquel succède le développement de failles normales dans l'ensemble de la série. Bas : détail d'une fente de tension inter-boudin, avec superposition d'une micro-faille normale. Le marteau donne l'échelle. Toutes les vues sont prises en regardant vers le nord.*

INVERSION ALONG THE BRIANÇONNAIS FRONTAL THRUST (BFT)

In the SE foot of the Pelvoux massif, the Oligocene main thrust at the front of the internal arc, the BFT, is well exposed in the Fournel valley. In its hangingwall, the Briançonnais frontal nappe stack is affected by dense late normal faulting. East-dipping faults dominate, bounding westwards tilted blocks. The westernmost faults join at depth the surface of the BFT, itself reactivated in extension. On the contrary the Ultradauphinois basement and sedimentary cover in the footwall of the BFT never experienced late brittle extension, like the entire Dauphinois zone to the west. When normal faulting developed in the Briançonnais zone, the BFT was inverted as an extensional detachment (fig. 3e); this inversion controlled the tectonic denudation of the Ultradauphinois zone and prevented it from late normal faulting [Sue and Tricart, 1999].

To the east, this structure is limited by the upper Durance fault zone better known for its dextral late reactivation [Tricart, 2004]. Between Briançon and Guillestre, this fault zone was initiated as a set of east-dipping normal faults, east of which the Briançonnais nappe pile was tilted westwards with a kilometric downthrow. The Durance valley follows the corresponding half-graben. This major fault zone probably roots into the BFT at depth [Tricart *et al.*, 1996]. Southwards, in Embrunais and Ubaye valley, the surface of the BFT is deformed by the late east-vergent folds and was not inverted. Further south, the normal faults spread into the eastern Dauphinois sedimentary cover and the overlying Helminthoid flysch nappes [Labaume *et al.*, 1989]. At the opposite, to the north of the Pelvoux massif, behind the Belledonne massif, inversion of former thrusts close to the limit between internal and external zones (front of the Valais zone, Subbriançonnais zone or Zone Houillère) is frequent but not systematic [Aillères *et al.*, 1995; Cannic *et al.*, 1999; Fügenschuh *et al.*, 1999]. Further north, no important inversion of the same thrust zone was directly observed at the back of the Mont-Blanc massif [e.g. Leloup *et al.,* 2005].

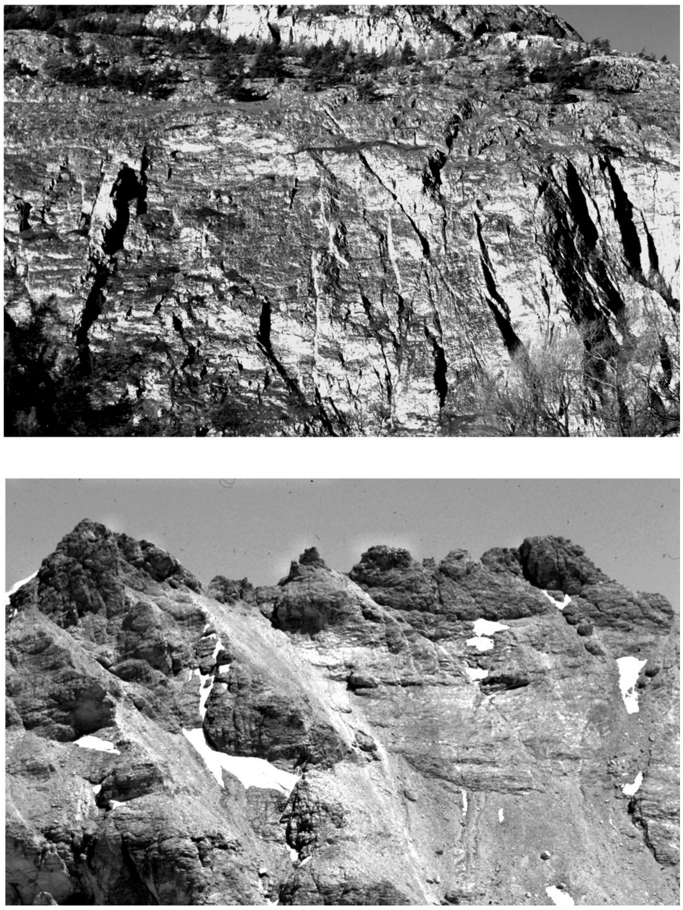


FIG. 6. – Late normal faulting in the Briançonnais zone, south of Briançon. Top: steep conjugate faults in Scythian quartzites (Rocher Baron, Champcella nappe); height of the cliffs in the foreground: 250 m. Bottom: less steep faults in Cretaceous-Eocene calcschists (Haut-Mouriare, Peyre-Haute nappe); height of slopes: 400 m. All views are looking eastwards.
FIG. 6. – *Developpement de failles normales tardives en zone briançonnaise, au sud de Briançon. Haut : failles conjuguées raides dans les quartzites du Scythien (Rocher Baron, nappe de Champcella) ; hauteur des falaises au premier plan : 250 m. Bas : failles moins raides dans les calcschistes crétacés-éocènes (Haut-Mouriare, nappe de Peyre-Haute) ; hauteur des pentes : 400 m. Toutes les vues sont prises en regardant vers l'est.*

FINAL P-T-T PATH OF INTERNAL UNITS

Fission track (FT) measurements were performed. The cooling below a temperature close to 240 °C and 110 °C was dated in the zircon and apatite respectively, which corresponds to an exhumation at shallower depth than 9-10 km and 4-5 km, for a geothermal gradient close to 25 °C/km. The main data summarized here, originate from Schwartz [2002].

The cooling at 110 °C of the Briançonnais Zone Houillère around Briançon occurred near the Oligocene-Miocene boundary, after the last phase of ductile shortening associated with back-movements that itself followed the main shortening associated with the BFT during the Early Oligocene. Cooling and exhumation were faster in the Briançonnais and westernmost Piedmont zones than in the rest of the Piedmont zone. The Briançonnais zone exhumed just after it acquired its fan-shaped structure. We propose that a line of more important relief along the fan axis was more actively eroded. This can explain that the Briançonnais zone was already in brittle conditions before the end Oligocene. It can also explain that the ductile-brittle transition was not recorded by the Briançonnais extensional structures, contrary to the eastern Queyras Schistes lustrés. Late Oligocene fast cooling of the Briançon-Guillestre area is also consistent with the fossilisation of the same reverse magnetic field at the end of the folding history, before the onset of synextension block tilting [Thomas *et al.*, 1999].

Final cooling in the Ultradauphinois zone was dated Late Miocene for the passing through 110 °C [Seward *et al.*, 1999]. This age is about 14 m.y. younger than in the Briançonnais zone below which it was underthrust. This more recent final cooling may result from the extensional denudation of the Ultradauphinois zone below the inverted BFT, which implies that inversion was active as early as the beginning of the Miocene or even the end Oligocene [Tricart *et al.*, 2001]. It is likely the same for the normal faulting in the Briançonnais zone, closely associated with this inversion [Sue and Tricart, 1999].

In the Piedmont Schistes lustrés and ophiolites, FT ages from the Queyras [Schwartz, 2002] are younger than those from more northerly transects [see review in Malusà *et al.*,

FIG. 7. – Steep conjugate normal faults in the Piedmont zone. Top: pillowed basalts in the Montgenèvre ophiolite (Collet Vert, Chenaillet massif); height of the cliff: 50 m. Middle: Tithonian marbles in the eastern Queyras Schistes lustrés (Taillante). Bottom: prasinites in the Monviso ophiolite (Monviso, Viso di Vallanta, Punta Caprera); total height of cliffs: 1500 m. All views are looking eastwards or northeastwards.

FIG. 7. – Failles conjuguées raides en zone piémontaise. Haut : basaltes à débit en coussins des ophiolites du Montgenèvre (Collet Vert, massif du Chenaillet) ; hauteur de la falaise : 50 m. Milieu : marbres tithoniens en Queyras oriental (Taillante). Bas : prasinites dans les ophiolites du Monviso (Monviso, Viso di Vallanta, Punta Caprera) ; hauteur totale des falaises : 1500 m. Toutes les vues sont prises en regardant vers l'est ou le NE.

2005]. FT analysis shows a slow final cooling (of the order 10 °C/m.y.) during the Miocene, probably corresponding to a slow exhumation rate about 0.5 mm per year in eastern Queyras and Monviso units. This exhumation was coeval with regional extension. As mentionned above a boudinage structure developed in eastern Queyras at the transition from ductile to brittle extension. Thermo-barometric calculation based on the chemical compositions of chlorite associated with quartz fibres in veins between boudins coupled with fluid inclusion analysis in these fibres provide P-T conditions of 360 ± 20 °C and 2,5 – 5,1 kbar corresponding to a depth of 8 to 17 km [Schwartz, 2002]. In such a carbonate-rich lithology, the age of the syn-extension ductile-brittle transition is supposed to approach that indicated by FT in zircon, i.e. close to the Oligocene-Miocene boundary [Schwartz, 2002]. In the Schistes lustrés just to the north of the Queyras, $^{40}Ar/^{39}Ar$ ages provided by Agard *et al.* [2002] are not fully consistent with our chronology since they imply that the last ductile stretching occurred as early as during the Late Eocene.

As a whole, our data suggest that brittle extension in the internal zones appeared as early as the beginning of the Miocene or even a little before (around 25 Ma?). In the Briançonnais zone it postdated the last compressive structures rapidly eroded during the Oligocene. In the Queyras Schistes lustrés, brittle extension took place in the dynamic and kinematic continuity of the ductile Late Oligocene stretching. In both the Briançonnais and Piedmont zones, this Neogene brittle extension corresponds to a slow final exhumation, from a depth of the order of 10-20 km. This suggests a weak erosion activity and can explain the partial conservation of the crest line between western (Rhône) and eastern (Po) drainage basins, possibly inherited from the Eocene orogenesis. It also allows to understand why the upper Durance river system, which emplaced at the back of the inverted BFT during the Miocene, remained so far. The contrast is striking with the younger relief, deeply incised in the Pelvoux massif and its neighbourhoods along the eastern margin of the Dauphinois zone. These high relief massifs constitute the new crest-line of the western Alps, consequence of the permanent compressive regime in the external zone, from the Early Oligocene onwards.

RECENT AND ONGOING EXTENSION

Neotectonic observations remain rare in this part of the Alps [Sue, 1998]. In the upper Durance valley, late normal faults guided the development of a karst, which was subsequently sealed by red continental sediments possibly derived from "Terra rossa". These sediments were widely affected by the extensional reactivation of the faults [Tricart *et al.*, 1996]. Considered as "likely of latest Tertiary or Early Quaternary age" by Barféty *et al.* [1996], they could not be better dated. Nevertheless, this illustrates the continuation of normal faulting while the now exposed faulted blocks were exhumed at shallow depth, at most a few hundreds of metres.

Seismotectonic data constrains better the ongoing Alpine dynamics along the studied transect (fig. 3f). The seismicity of the western Alps is moderate and inhomogeneous [e.g. Thouvenot, 1996; Eva *et al.*, 1997; Bistacchi *et al.*, 2000]. It concentrates in the "Briançonnais and Piedmont seismic

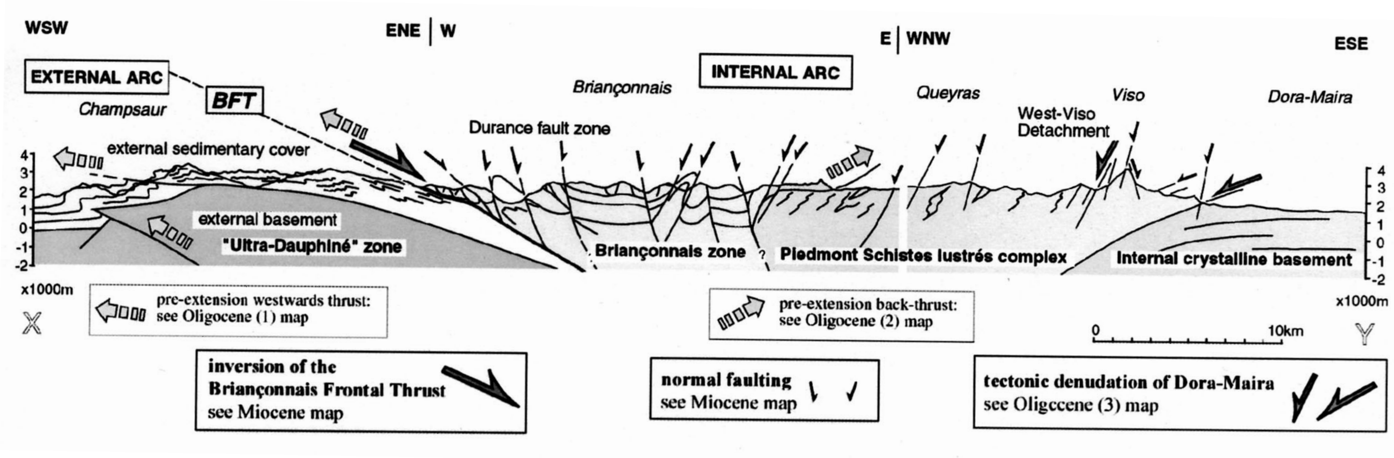


FIG. 8. – Composite cross section partly inspired from Kerckhove [1969] and Bürgisser and Ford [1998] for the Champsaur area, from Claudel [1999] for the Briançonnais area and from Schwartz [2002] for the Queyras, Monviso and Dora-Maira areas; the general stucture has been simplified to better show the overprint of extensional structures on thrust and backthrust structures within the internal arc. Location in figure 2.

FIG. 8. – Coupe transverse composite partiellement inspirée de Kerckhove [1969] et Bürgisser and Ford [1998] pour le Champsaur, de Claudel [1999] pour le Briançonnais et de Schwartz [2002] pour le Queyras, le Monviso and Dora-Maira ; la structure générale a été simplifiée pour mieux montrer comment les structures en extension se surimposent aux structures de chevauchement et de rétrochevauchement au sein de l'arc interne. Localisation figure 2.

arcs" of Rothé [1941], with local Richter magnitudes ranging from 1 to 4. Sue [1998; see also Sue *et al.*, 1999; Delacou *et al.,* 2004] has detailed them and provided the following three evidences. (1) To the SE of the Pelvoux massif, earthquakes are located in the hangingwall of the BFT, in a depth range 0-15 km. This observation can be widened to the entire "Briançonnais seismic arc" in its relationships with the Penninic Frontal Thrust between the Mont-Blanc and Argentera transects, that is over a distance of 250 km. This first order fault ramp [Schmid and Kissling, 2000 with references therein], remains a major active structure. (2) The geometry of the "Piedmont seismic arc" is better constrained as a 100 km-long and poorly bent arc joining the Dora-Maira and Argentera massifs. Earthquakes are a little deeper (down to 20 km) than in the Briançonnais arc. The link with an Adriatic mantle indenter (the so-called Ivrea geophysical body) is argued by Paul *et al.* [2001]. (3) Focal solutions characterize an extensional regime in both seismic arcs, with horizontal T axes oriented close to radial in the Briançonnais arc and oblique in the Piedmont arc. The similarity between the seismotectonic data and the structural data collected on exposed late faults suggests a permanence of the stress field through time in the main part of the internal Alpine arc.

As a whole, the first seismotectonic studies emphasised the existence of focal solutions in compression, and lead to draw horizontal P axes compatible with the expected effects of the Adria indentation, especially in the external arc [Fréchet and Pavoni, 1979; Pavoni, 1980; Pavoni and Roth, 1990]. On the contrary, all more recent data since Eva *et al.* [1998] and Sue [1998] show that the internal arc is currently undergoing extension. Furthermore extensional reactivation along the major thrust at the front of the internal arc currently controls uncoupling between external and internal arcs (fig. 3f), extending the Miocene situation [Sue and Tricart, 2003 and references therein]. At the scale of the Alpine belt, extension in the internal arc is contemporaneous with shortening in both external arc and Po plain, resulting in a strong crustal-scale strain partitioning.

Geodetic measurements focus on horizontal movements. A network of 18 geodetic points surveyed in 1972 by the Institut Geographique National in a seismically active part of the Briançonnais zone near Briançon was measured again by GPS in 1996 [Sue *et al.*, 2000]. An E-W oriented extension was evidenced, which strengthens the conclusions of the seismotectonic analysis. A N-S shortening component would indicate a partly transcurrent tectonic regime. A surprisingly high extension rate (> 2 mm/year) regarding the low magnitude of earthquakes suggests an essentially aseismic deformation. In an enlarged Alpine frame, the continuous measurement of horizontal movements between the major Alpine structures at permanent GPS sites (REGAL network implemented since 1996) is most suitable to quantify the deformation that the seismotectonic regime implies. According to the preliminary results [Calais *et al.*, 2002] extension currently prevails in the central part of the western Alpine arc and in its northern branch whereas a N-S to NW-SE shortening prevails in the southern part of the arc and Provence. This complex strain field with low displacement velocities with respect to the stable Europe (around mm/year) may be explained by a counterclockwise rotation of the Adria block around a pole located in the northern Po plain, as proposed by Calais *et al.* [2002].

DISCUSSION

The tectonic evolution of the western Alpine arc ends with the development of an extensional regime in its inner part, giving rise to multiscale structures, including at the entire arc scale. We attempt to constrain this regime in space and time.

Geographic distribution of late extensional regimes

Multitrend subradial extension has now been systematically documented from the Montgenèvre (Chaberton) in the north, to the upper Ubaye (Chambeyron) in the south: – in the Briançonnais zone, including the Zone Houillère; – in the Piedmont Schistes lustrés complex exposed in the Queyras region and nearby valleys. The same extensional regime was recognized eastwards as far as in the Monviso massif but not yet systematically prospected in the Dora-Maira massif. Current analyses try to follow this extension southwards, in the Briançonnais and Piedmont zones, to the south of the Ubaye valley, where it likely predated the severe dextral strike-slip that dominates in the brittle structure exposed at present. Northwards, extension clearly affects the same internal zones in most of the NE-SW trending northern branch of the Alpine arc [Bistacchi *et al.*, 2001; Bistacchi and Massironi, 2001; Sue and Tricart, 2002]. Nevertheless, Champagnac *et al.* [2004] recently demonstrated that rather than a multitrend extension, this branch underwent the succession of two distinct late tectonic regimes: (1) NE-SW orogen-parallel extension, interpreted as a syn-orogenic lateral extrusion resulting from Adria indentation; (2) NW-SE orogen-perpendicular extension, attributed to a post-orogenic gravitational collapse. As already mentioned the external zone nearly escaped extension. As a summary, late extension has now been identified in most of the internal arc but true multitrend extension appears restricted to its central part, between the Pelvoux and Dora-Maira massifs.

Structure and relief

Along the transect studied here (fig. 8), a major structure is the inverted BFT. Above, in the frontal Briançonnais nappes, normal faulting is particularly dense. To the east, the upper Durance fault zone would root at depth into the inverted BFT. Farther east along the same transect, the ductile normal faults bounding the Monviso massif would represent other major structures. Contrary to the Briançonnais zone, they allow us to document how ductile extension predated brittle extension. They dip westwards and could form with the inverted BFT a system of faults with conjugate movements. At the eastern end of the transect, the Dora-Maira massif is a gneissic dome partly exhumed in response to the same extensive regime, in essentially ductile conditions. When considering the entire transect, there is a striking difference between the Pelvoux and Dora-Maira crystalline massifs. The former is an elevated massif, recently raised above crustal thrust ramps like the other external crystalline massifs [review in Lacombe and Mouthereau, 2002]. The lower second massif has an older relief partly controlled by a process of extensional exhumation – denudation. This difference can also be underlined along more northerly transects passing through the Belledonne or Mont-Blanc external massifs and the Gran-Paradiso internal massif [Rolland *et al.*, 2000]. In the western Alps, the contrast between external and internal crystalline massifs illustrates the final dynamic decoupling between the external and internal arcs, documented here at upper crust level. It also explains the westwards jump of the Alpine crest line during the Neogene, the high Dauphinois massifs taking over from the more internal Eocene crest line.

Paleomagnetic data from the Briançonnais nappes between the Pelvoux and Argentera transects suggest that the Briançonnais zone bending occurred in Late Oligocene times at the end of the back-folding phase [Thomas *et al.*, 1999; Collombet *et al.* 2002]. Negative "fold test" on tilted blocks clearly indicate that generalized normal faulting postdated the horizontal rotations. It is really the innermost part of the already formed Alpine arc that underwent late extension.

Chronological marks

The onset of the above mentioned extensional processes is documented: (1) to the west, by thrust inversion at the front of the internal zones (BFT) and (2) to the east, in the eastern Queyras Schistes lustrés, by the last syn-greenschist deformation corresponding to a ductile extension. In both cases, considering reliable cooling rates, these events must have occurred during the latest Oligocene (around 25 Ma in Briançonnais, possibly a little before in eastern Queyras). In the Briançonnais zone around Briançon, the first extensional structures developed in fully brittle conditions. This is consistent with a rapid exhumation and cooling, driven by rapid erosion along the axis of the Alpine fan created during the last shortening phase. To the east, in the eastern Queyras Schistes lustrés and Monviso ophiolites, final extension appeared in ductile conditions before going on in brittle conditions. In both areas, extension developed during the whole Miocene. The neotectonic, seismotectonic and geodetic data converge and allow us to propose that this extension continued in Plio-Quaternary times and is still active.

A new scenario for the last stage of Alpine collision

In the classical reconstruction of the western Alps building, the continuation of the plate convergence after the beginning of the collision, induces the progression of the compressive front towards the outer parts of the arc and the accretion to the chain of more and more external domains of the European paleo-margin [e.g. Tricart, 1984]. Since all these domains have been inverted, the crustal shortening-thickening is supposed to increase in all the Alpine zones in response to ongoing plate convergence. This increase was especially documented in the external zone, where the molasse sedimentation recorded the continuation of folding and thrusting from the Oligocene onwards. A major event was the uplift of the external crystalline massifs along out-of-sequence thrusts from the latest Miocene onwards. This continuity of the compression-related orogenesis in the Alpine external zone remains acquired. In the internal zones, the classical scenarios included an increasing crustal shortening-thickening through successive phases of backfolding and backthrusting, moreover poorly dated. These characteristic phases of a mature stage for the collision process, would have contributed to accentuate the fanning structure of the chain. Even if it was early questioned [Dal Piaz *et al.*, 1972], erosion was implicitly considered as the main process limiting crustal and lithospheric thickening. Actually, in the scenario proposed here, a fanning structure ended to built through successive compressive phases during the Oligocene, but the resulting wide orogenic wedge, involving the entire Alpine realm, represented only a very transient structure. Indeed, as early as in Oligocene times, an extensive regime developed in its internal part in ductile then brittle conditions. It contributed to thin the internal part of the wedge at least in its upper levels. We document this thinning in the upper 15-20 km of the crust, in particular through inversion of thrust surfaces. All along the Neogene, this thinning coexisted with a generalized growth of the external wedge, driven by compression. These contrasting tectonic regimes and the resulting uncoupling between the external and the internal Alpine arcs continue at present.

Remaining questions

The inner arc of the western Alps underwent a dominantly extensional tectonic regime since its late Oligocene bending. Widespread and long-lived "Late Alpine" normal faulting was first evidenced in the central part of the arc, between the Pelvoux and Dora-Maira massifs. It now appears that the multitrend character of this brittle extension represents an exception in the arc.

Neogene extension continues at present but the kinematic boundary conditions for the Alps have changed since the Miocene. The timing and modes of this change remain poorly constrained. In addition, we do not know for the present and for the Neogene period, to what extent extension evidenced at shallow depth affects the deeper crust and mantle units. As a consequence, and for both periods, the nature of the dynamic and kinematic link between the external and internal Alpine arcs remains problematic.

Syncollision extension in the inner part of an orogenic wedge at an advanced stage of its growth was first predicted by Platt [1986] and the application of his critical wedge theory to the Alps has been widely discussed and modeled [e.g. Jiménez-Munt *et al.,* 2005]. In the NW branch of the arc, this theory explains that orogen-perpendicular extension relayed through time orogen-parallel extension associated with syn-indentation lateral escape [Champagnac *et al.,* 2004]. In the central part of the arc, the current multitrend close to radial spreading is consistent with gravitational collapse in the most thickened part of the wedge after cessation of convergence [Delacou *et al.,* 2004]. Transposition to the Miocene multitrend extension remains problematic since Alpine convergence was still active, even if had slowed down at this time [see discussion in Jiménez-Munt *et al.,* 2005]. To address this question we need to better know the tectonic evolution of the southern branch of the internal arc during that period. Ongoing field studies focus there.

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