0012-9402/04/030429-11
DOI 10.1007/s00015-004-1138-1
Birkhäuser Verlag, Basel, 2004

Eclogae geol. Helv. 97 (2004) 429–439

From extension to transpression during the final exhumation of the Pelvoux and Argentera massifs, Western Alps

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Key words: fission track ages, exhumation, extensional tectonic denudation, external crystalline massifs, fault-striation analysis, horse-tail termination, inversion tectonics, transcurrent fault, transpression, Western Alps

ABSTRACT

Like the other "external crystalline massifs" (ECM) of the Western Alps, the Pelvoux and Argentera massifs record a late and important uplift of the Prealpine basement in the immediate foreland of the internal nappes. Recently published structural and fission track data indicate distinctly different final stages of exhumation for the two massifs. The last main exhumation of the SE Pelvoux basement took place in the Late Miocene, when an extensional tectonic regime widely affected the internal arc. This exhumation occurred mainly through extensional denudation below the inverted Briançonnais Frontal Thrust. Final exhumation of the NE Argentera basement, however, took place in the Pliocene, while it was thrust southward in a transpressive regime. This exhumation mainly resulted from erosion of the created relief. Late orogen-parallel faulting within the High Durance Fault Zone records this two-stage late history, which is coeval with the outward propagation of compressional structures in the external arc. The last, dominantly transpressive, stage could be common to all the ECM around the western Alpine arc, explaining the striking similarities regarding their present-day structural setting.

RESUME

Comme pour les autres "massifs cristallins externes" (ECM) des Alpes occidentales, la mise à l'affleurement des roches cristallines du Pelvoux et de l'Argentera résulte d'un soulèvement majeur tardif du socle préalpin juste en avant des nappes internes. La synthèse de données structurales et d'âges par traces de fission récemment publiés, permet de proposer que le processus d'exhumation dominant ait changé d'un massif à l'autre au cours du temps. Au Miocène supérieur, le socle de la partie SE du Pelvoux a achevé son exhumation alors qu'un régime extensif affectait largement l'arc alpin interne. Cette exhumation est essentiellement intervenue par dénudation tectonique en extension sous le chevauchement briançonnais frontal alors inversé. Au Pliocène, le socle de la partie NE de l'Argentera a achevé son exhumation dans un régime transpressif. Cette exhumation est essentiellement intervenue par érosion d'un compartiment de socle chevauchant. Les failles longitudinales à l'arc alpin comme la zone faillée de haute-Durance ont conservé la trace de cette histoire biphasée qui apparaît contemporaine de la propagation de structures compressives au travers de l'arc alpin externe. Le dernier stage, essentiellement transpressif, pourrait être commun à tous les ECM autour de l'arc alpin occidental, expliquant leurs similitudes frappantes actuelles.

Introduction and geological setting

In the French-Italian Western Alps, the internal arc derives from an oceanic accretionary wedge, which was incorporated in a wider orogenic wedge during Paleogene collision (review in Schmid & Kissling 2000). During the Neogene, this arc underwent widespread ductile to brittle extension, the tectonic significance of which (internal Alpine body forces versus boundary forces) remains controversial (Sue & Tricart 2002 and references therein). The external arc was essentially built from the Oligocene onwards under collisional conditions (Coward & Dietrich 1989). Its late evolution, coeval with extension in the internal arc, was globally dominated by an increasing amount of nearly radial shortening by outward propagating fold-thrust structures, associated with orogen-parallel and orogen-oblique/transverse wrench faulting (e.g. Lemoine et al. 2000). More in detail, multistage deformation and locally complex kinematics resulted in imbricate arcuate structures visible in map view. They have been reviewed by Lickorish et al. (2002) who also compare the main available tectonic models. The southern part of the external arc is characterised by early E-W trending folds, overprinted by the arcuate fold-thrust system mentioned above. Often referred to as "Pyrenean-Provençal" or "pre-Nummulitic" they are classically attributed to the movement of Iberia, the southern microplate (e. g. Ford 1996).

A striking morphological and structural feature in the external arc is the high level of the outcropping Prealpine basement in the "external crystalline massifs" (ECM). These massifs constitute one of the major Alpine crest lines along the internal fringe of the external arc (Dauphiné or Helvetic/Dauphinois zone), in the footwall of the major thrust at the

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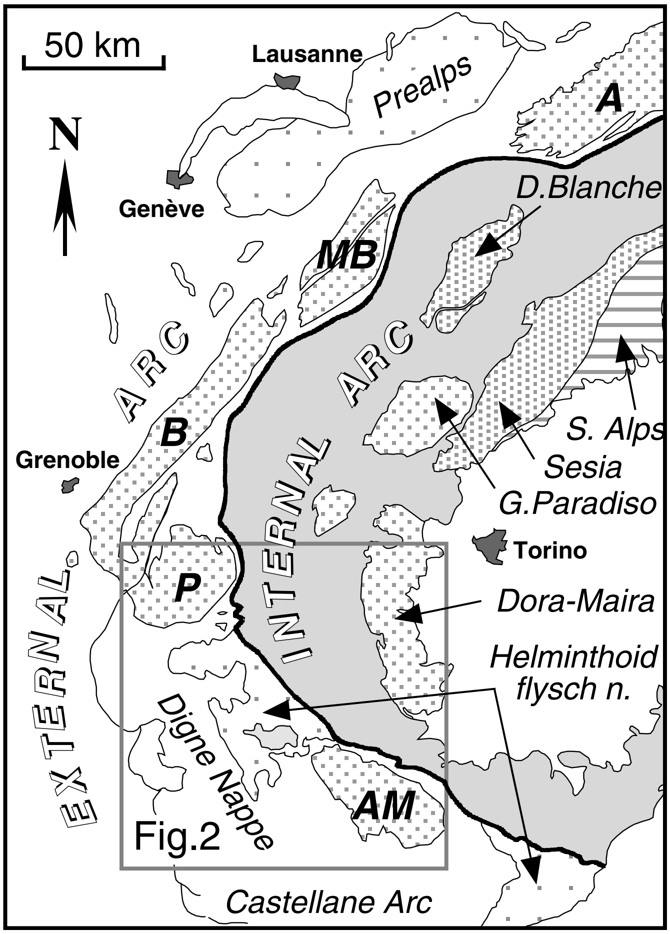

Fig. 1. The main External Crystalline Massifs in the Western Alps. A: Aar; MB: Mont-Blanc and Aiguilles-Rouges; B: Belledonne; P: Pelvoux; AM: Argentera-Mercantour. The rectangle locates the map of Fig. 2.

front of the metamorphic internal arc (Penninic zones; Fig.1). Ménard (1979) demonstrated the thickened character of the crust below most ECM (Pelvoux, Belledonne, Aiguilles-Rouges and Mont-Blanc) and proposed that they underwent compressionally induced uplift along mid-crustal thrust ramps from the Miocene onwards. This general hypothesis in terms of a stack of thrust slices within the upper crust was supported by the interpretation of the deep seismic ECORS-CROP profile across the northern branch of the Western Alps (e.g. Mugnier et al. 1990). Subsequently, fission track (FT) ages allowed Seward & Manktelow (1994) to propose more complex kinematics for the northern ECM. According to these authors, final uplift occurred in a transpressional regime, associated with dextral shear along orogen-parallel late faults and with extensional reactivation along the nearby major thrust bounding the internal arc (Penninic frontal thrust).

A common feature of the ECM is their recent and ongoing uplift, which was constrained to be in the order of 1 mm/yr according to geodetic surveys (precision levelling) between the Pelvoux and Aar massifs (review in Ribolini 2000). This uplift is consistent with the final cooling history revealed by an increasing amount of FT data. In the ECM, apatite and zircon FT ages are typically in the 3 to 10 and ~10 to ~20 Ma range, respectively (review in Fügenschuh & Schmid 2003). Assuming a geothermal gradient (25 or 30°C/km), the correlation with the sampling altitude allows the calculation of final exhumation scenarios favouring erosional denudation in response to basement uplift.

The NE-SW elongated Belledonne and Mont-Blanc massifs have been extensively studied (Fügenschuh & Schmid 2003 and references therein). Cooling histories allow the proposition that a more or less moderate exhumation rate prevailed during most of the Miocene (of the order of 0.5 mm/yr) and was followed by a significantly faster exhumation rate (of the order of 1 mm/yr) during the past 7 Myr. Concerning the southern ECM, studied more recently, a comparable two-stage scenario cannot be deduced from the available data in the Pelvoux massif (Seward et al. 1999). However, such a scenario was proposed for the Argentera massif, where the cooling acceleration possibly occurred slightly more recently (Bogdanoff et al. 2000; Bigot-Cormier et al. 2000, 2004; Bigot-Cormier 2002). In the Aar massif Miocene exhumation was particularly fast, which prevents the detection of a comparable final acceleration (review in Bogdanoff et al. 2000).

We focus onto the NW-SE oriented southern branch of the external arc and its two ECM, namely the Pelvoux and Argentera massifs, which occupy a symmetrical situation on either side of the Embrunais-Ubaye structural depression (Fig. 2). These massifs are often considered as similar, especially regarding their early uplift history, as recorded by sedimentation, erosion and nappe trajectory deflection (Tricart 1982 and references therein). However, the development of low temperature thermochronology allows to determine and compare their final uplift, cooling and exhumation histories more accurately. In this paper we confront this final history constrained from recently published FT data in both massifs with the now available kinematic data on the late Alpine fault system along the internal-external arc boundary between these massifs. This exercise leads to the proposition that the main exhumation process changed through time from one massif to the other.

The Pelvoux massif

The peculiar structure of this almost circular massif, 40 km in diameter, originates from its mosaic of faulted blocks which are mainly inherited from the Mesozoic Tethyan rifting phase and which underwent successive Cenozoic compressional phases with different directions (e.g. Sue et al. 1997). In the central part of the massif, blocks are mainly composed of Variscan granites and high-grade metamorphic rocks (Le Fort 1973), their Mesozoic sedimentary cover being only locally preserved from erosion (Dumont et al. 2004 and references therein). A second difference in respect to the other ECM is the importance of early ("Pyrenean-Provençal") uplift and erosion, resulting from N-S compression that predated the Pri-

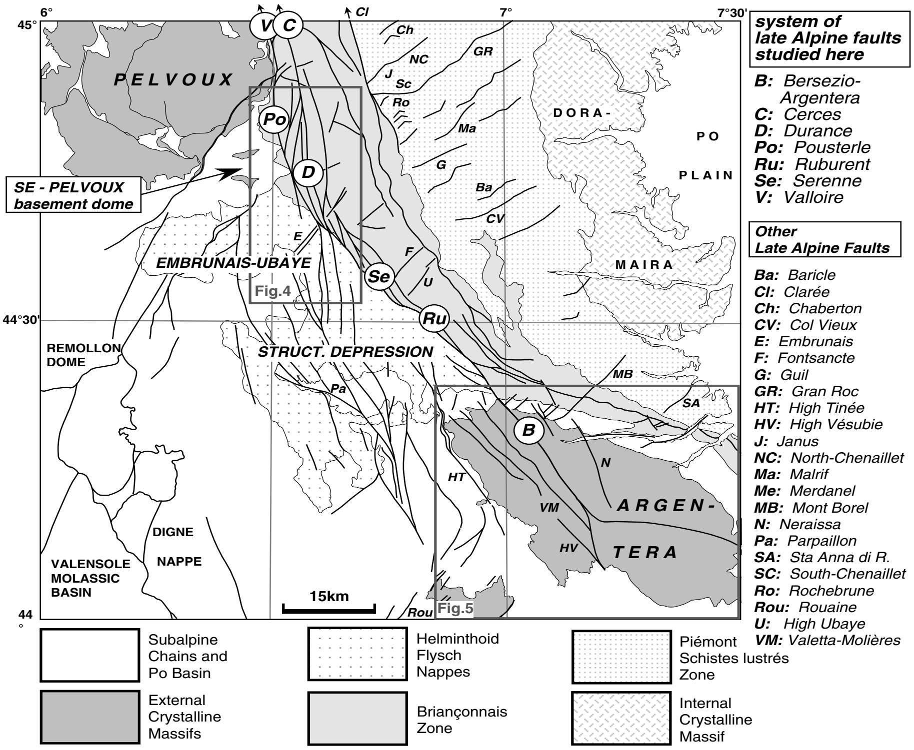

Fig. 2. Structural sketch map of the Pelvoux-Argentera area, emphasizing the late fault system along the external-internal arc boundary. For the location of the area in the western Alpine arc see Fig. 1. The rectangles locate the maps depicted in Figs. 4 and 5. The Permian sedimentary cover around the Argentera massif has been grouped with the crystalline basement.

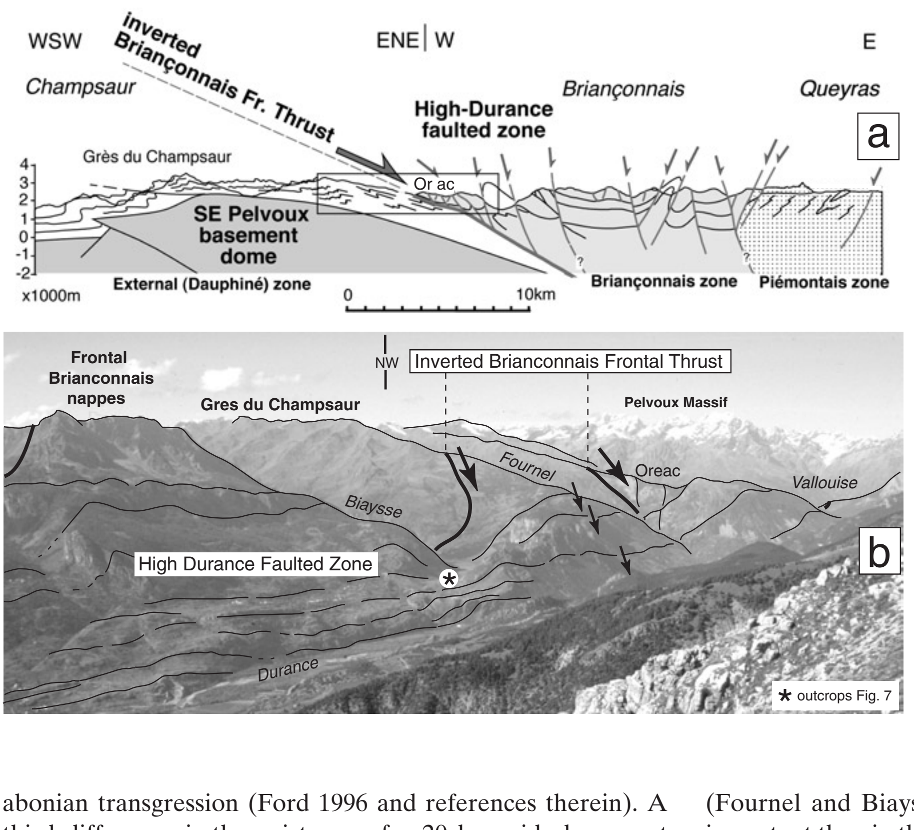

Fig. 3. Inverted Briançonnais Frontal Thrust and High Durance Fault Zone, SE of Pelvoux. (a) Simplified cross-section passing along the Fournel Valley in its western part (location Fig. 4); the rectangle locates the main structures visible in b. (b) Panoramic view from the SE.

abonian transgression (Ford 1996 and references therein). A third difference is the existence of a 20 km wide basement dome in the SE part of the Pelvoux massif (Fig. 2) where the basement top outcrops at an altitude of only 1600–2000m (Fournel and Biaysse valleys). There, the final uplift is less important than in the central part of the Pelvoux massif, where the eroded basement (top not visible) outcrops up to an altitude of 4100 m.

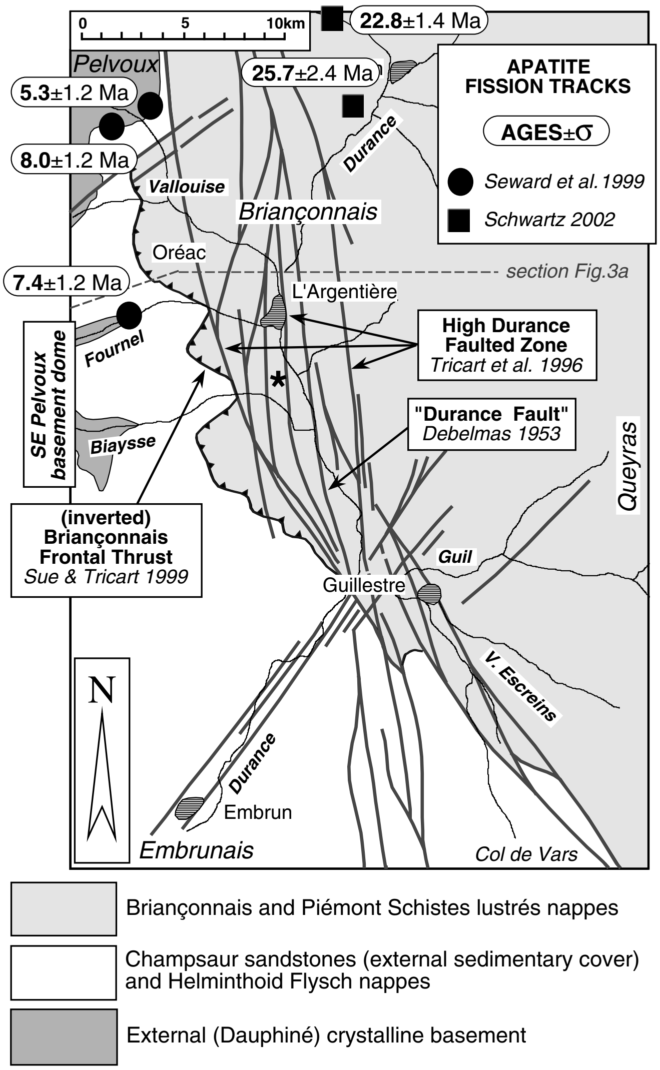

Fig. 4. Sketch map of the High Durance Fault Zone, from Tricart et al. (1996). For discussion of the apatite fission track ages, see text and Tricart et al. (2001). The location of this area is indicated in Fig. 2. The dashed line locates the section in Fig. 3a. The asterisk locates the field structures illustrated in Fig. 7.

The SE Pelvoux basement dome (Fig. 3 and 4) is overlain by its Late Eocene-Oligocene sedimentary cover (Champsaur Sandstones, less than 1 km thick). This (par-) autochthonous cover is sometimes referred to as "Ultradauphinois" (review in Tricart et al. 2004b). It is itself overlain by the Helminthoid flysch thrust sheets, the Autapie and Parpaillon nappes, which are less than 1km thick, and their thin basal tectonic slices (Kerckhove 1969; Merle 1982; Tricart 1984; Fry 1989; Bürgisser & Ford 1998). Along its eastern edge, the entire pile is overthrust by the Briançonnais zone and its small frontal tectonic lenses (Subbriançonnais zone). The inferred age of this deep-seated Briançonnais Frontal Thrust (BFT) is Early Oligocene (Tricart 1984). The basement dome at the SE edge of the Pelvoux massif seems to have been initiated as a west-verging low amplitude anticline during the main regional folding-thrusting phase. This anticline that developed in the footwall to the active BFT, is itself located at the site of a major paleo-high that may be reconstructed in the Champsaur Sandstones sedimentary basin according to onlap structures. Further and significant accentuation of this embryonic dome, including the overlying tectonic pile, is proposed to have occurred after the main folding-thrusting phase, in the context of the inversion of the BFT (Sue & Tricart 1999).

General uplift and cooling

Seward et al. (1999) proposed a thermochronological analysis of the southern Pelvoux massif, including its SE updomed part. Due to insufficient thermal overprint (less than 10 km burial?), the zircon FT chronometer was only locally reset and most reset ages are provided by FT in apatite. This only allows for dating of the final exhumation history (from around 4 km depth). In the Pelvoux massif itself, these apatite FT ages are younger than 5 Ma, like in the other ECM, but without comparable simple age-elevation relations. In the SE Pelvoux basement dome and its sedimentary cover apatite FT ages are slightly older, ranging roughly from 5 to 12 Ma.

Link with inversion along the Briançonnais Frontal Thrust and widespread extension in the internal arc

SE of Pelvoux, along the E-W sections provided by the Vallouise, the Fournel and the Biaysse valleys (western tributaries of the Durance river: Fig. 3 and 4), the detailed field analysis on the BFT by Sue & Tricart (1999) demonstrates a polystage history. After thrusting of the Briançonnais zone onto the SE Pelvoux basement and its Tertiary sedimentary cover (Champsaur Sandstones), the associated west-directed syn-cleavage fold-thrust structures were overprinted by extensional brittle structures, mainly westward tilted blocks between east-dipping faults. The reactivation of the BFT surface as a low angle normal fault may be directly observed; especially where it contains slices of ductile Subbriançonnais black shales (see Fournel section in Fig. 3).

The regional-scale geometry of the superimposed extensional structures implies that the BFT thrust has been inverted at depth as an east-dipping first order extensional detachment below the Briançonnais zone and the nearby Piémont zone. Widespread late normal faulting in these internal zones can be dynamically and kinematically related to this inversion, at least along the SE Pelvoux-Briançonnais-Queyras transect (see discussion in Sue 1998). The NNW-SSE faults along the Durance valley between Briançon and Guillestre (e.g. the Durance Fault Zone discussed below) are also related to this extension and are inferred to branch at depth into the inverted BFT ("short-cut" structure, see Tricart et al. 1996).

Below the inverted BFT, the SE Pelvoux basement and its sedimentary cover escaped late normal faulting. The accentuated dome-like structure of this basement and its high elevation with respect to the Briançonnais zone, that was initially

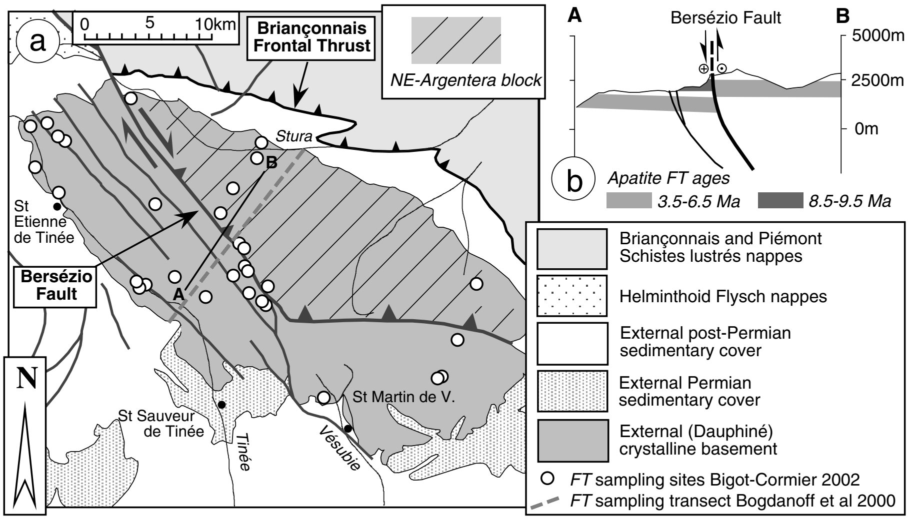

Fig. 5. The Argentera massif. (a) Structural sketch map, modified from Bigot-Cormier (2002) with location of the main available FT data. For location of the map, see Fig. 2. Broken line: location of the transect sampled by Mansour (1991), see Bogdanoff et al. (2000) in the central part of the massif. Open circles: location of the sampling sites of Bigot-Cormier (2002) scattered over the whole massif. Contrary to Bogdanoff et al. (2000), Bigot-Cormier (2002) argues for a post 3.5 Ma relative uplift of the NE-Argentera block along the dextral-reverse Bersézio Fault. (b) Vertical offset of the apatite FT partial annealing zone, attributed to the post 3.5 Ma movement along the Bersézio Fault zone according to Bigot-Cormier (2002).

thrust onto it, may be attributed to its late tectonic denudation when the BFT was reactivated as an extensional detachment (Tricart et al. 1996). This scenario was consolidated and time-calibrated by considering the contrasting final cooling histories on both sides of the BFT (Tricart et al. 2001; Fig. 4). In the hangingwall of the BFT two apatite FT ages close to 23 and 26 Ma (Briançon Zone Houillère, see Schwartz 2002) suggest that the final exhumation of the Briançonnais zone was consecutive to its thrusting onto the external domain along the BFT, which occurred during the Oligocene. Erosion of the resulting relief could have represented the dominant denudation process. An apatite FT age of around 7 Ma in the SE Pelvoux basement dome from just below the BFT (Fournel valley, see Seward et al. 1999) implies much younger exhumation, consistent with tectonic denudation in the footwall to the BFT, while this thrust was reactivated by extension. This final exhumation of the SE Pelvoux basement dome below the inverted BFT from less than 4–5 km depth during the Late Miocene occurred while normal faulting affected the nearby Briançonnais zone, and during the development of the Durance Fault Zone.

This scenario certainly applies to the SE corner of the Pelvoux massif. North of Pelvoux, however, where the tectonic pile situated between the Pelvoux basement and the Briançonnais nappes thickens, Fügenschuh and Schmid (2003) proposed an alternative interpretation of the cooling history of the main thrust sheets. These authors favour late stage ("out of sequence") outward thrusting and erosional unroofing in order to explain the younger ages in the Pelvoux basement. Subsequent (post-5 Ma) moderate extensional reactivation occurs only locally and along different thrust surfaces located within the internal arc itself (Fügenschuh et al. 1999), and is not concentrated along the main frontal thrust, as is described in case of the BFT further to the south. Additional structural and thermochronological data are needed in order to better interpret these differences concerning the final evolution of the northern and southern branches of the arc of the Western Alps.

The Argentera massif

This massif, also called Mercantour, represents the southernmost ECM. It forms a 22 km wide and 55 km long outcrop of crystalline basement that trends NW-SE. Two major units of Variscan basement constitute the massif, separated by the Valetta-Molière and Bersézio Fault zones, oriented N120-140°E (Malaroda et al. 1970; Fig. 2). This basement was unconformably overlain by an up to 7 km thick series of Permian to Cenozoic sediments. SW-directed thrusting of the internal nappes started in Late Eocene to Early Oligocene times (Kerckhove 1969; Merle 1982; Fry 1989). Maximum burial of the basement between 8 (Bigot-Cormier 2002) and 10 km (Bogdanoff et al. 2000) was reached during the Early Oligocene, allowing for nearly complete resetting of the zircon FT system and complete resetting of the apatite FT system. SW of the Argentera massif (Fig. 1) the sedimentary cover, detached within the Triassic evaporites, is involved in fold-thrust structures building the Castellane arc and the southern part of the Digne nappe (e.g. Labaume et al. 1989).

General uplift and cooling

Mansour (1991; see also Bogdanoff et al. 2000) provides 16 apatite FT ages along a NE-SW trending profile crosscutting the central part of the massif. Ages range between around 8 and around 2.4 Ma. A linear relationship between age and altitude observed for most samples allows for the recognition of two stages during the final history of the massif, taken as a whole. From around 8 Ma to around 3–4 Ma, cooling proceeded at a moderate rate (close to 6°C/Myr), suggesting a mean exhumation rate approaching 0.25 mm/yr. During the last 3–4 Myr, however, cooling and exhumation rates accelerated and were on the order of 25–35°C/Myr and 1 mm/yr, respectively. Bigot-Cormier (2002; see also Bigot-Cormier et al. 2000, 2004) also recognised this Plio-Quaternary acceleration.

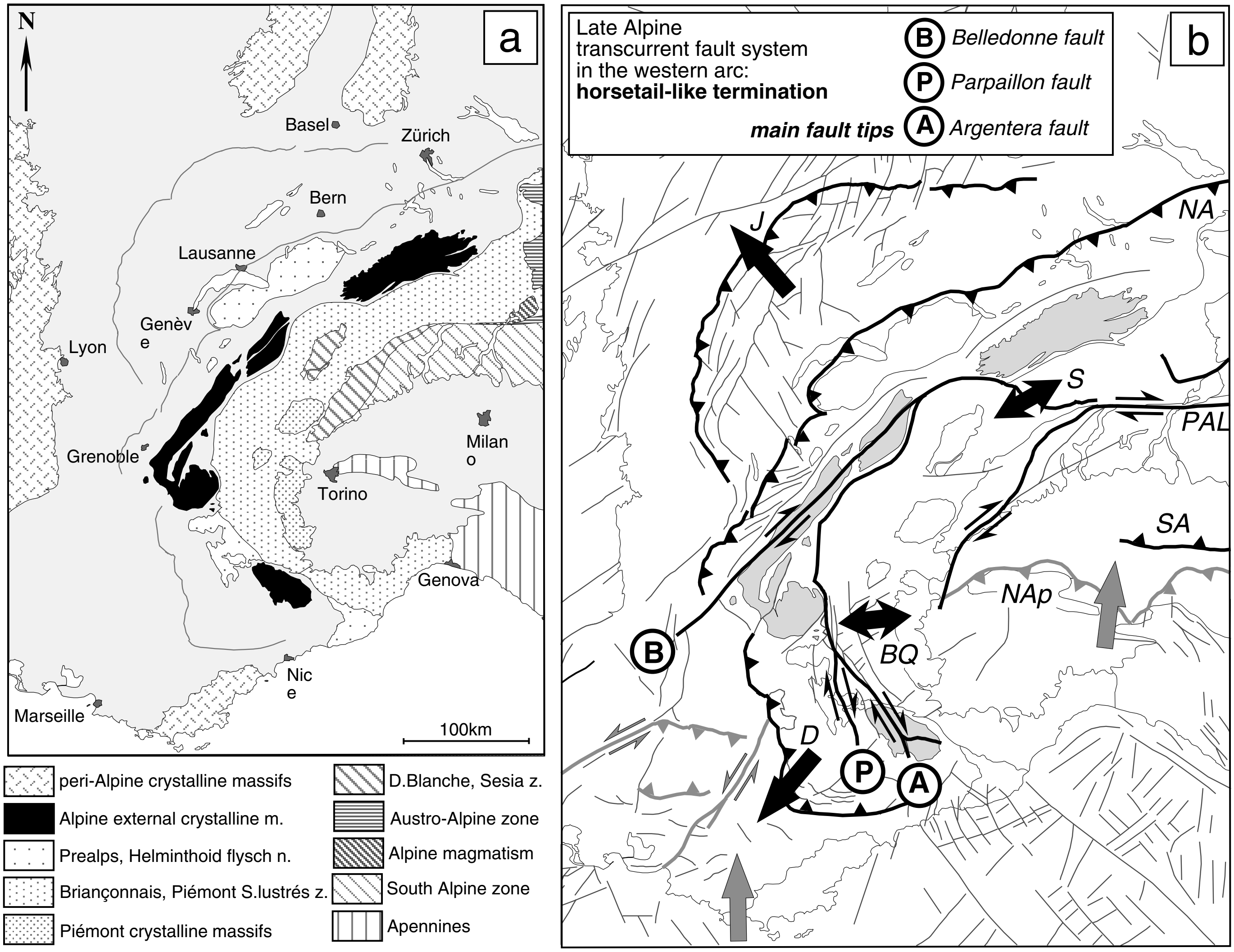

Fig. 6. The Late-Alpine orogen-parallel transcurrent fault system of the Western Alps and its kinematic setting. (a) Simplified tectonic map. (b) Main faults and selected kinematic indications for the past 10 Ma. Grey arrows depict kinematics of movement that are peripheral to the Alps (see Lemoine et al. 2000 for discussion): (1) N-S shortening in Provence, i.e. in the Alpine foreland, could be a direct effect of Africa-Europe convergence; (2) northward progression of the northern Apennine front (NAp) in the Alpine hinterland could be driven by subduction rollback below the chain. Black arrows depict the kinematics within the Alps s. str.. Simple black arrows refer to fold-thrust structures propagating outward from the Alpine arc in the Jura (J) and Digne (D) areas. Double black arrows refer to orogen-parallel extension-transtension in the Simplon area (S) and to more radial extension in the Briançonnais and Queyras areas (BQ). Note the dextral strike-slip fault system following the arc, its oblique splays that die out southwards. Circled letters locate these fault tips that evoke a “horse-tail” termination of the transcurrent fault system: B: Belledonne Fault; P: Parpaillon Fault; A: Argentera-Bersézio Fault. The other abbreviations are: NA: northern Alpine front; SA: southern Alpine front (buried); PAL: Periadriatic fault.

In addition, thanks to an adapted dense sampling in the whole massif (Fig. 5a) for both zircon and apatite *FT* dating, she could distinguish different cooling histories and proposed that several tectonic blocks were subject to distinct vertical paths.

According to Bigot-Cormier (2002), the whole Argentera massif yielded zircon FT ages ranging between 29 and 20 Ma, i.e. according to sampling site elevation, except for its NW extremity (Saint Etienne de Tinée) that underwent a specific early history. The age vs. altitude relations allow the identification of a strong pulse in the cooling rate at around 22 Ma, the corresponding exhumation rate approaching 1.3 mm/yr. This pulse is interpreted in terms of erosional denudation of the relief that was created by thrust tectonics during the Miocene. General basement thrusting was coeval with major folding and thrusting in the outer sedimentary cover (Subalpine Chains: Castellane arc), especially during the Late Miocene (Laurent et al. 2000). Apatite FT ages between 12.5 and 3.5 Ma allow for the calculation of an apparent mean exhumation rate of 0.2 mm/yr for the Late Miocene. The cooling rate strongly increased at around 3.5 Ma, indicating accelerated exhumation by up to 1.1 or 1.4 mm/yr, depending on the chosen geothermal gradient (30 or 25°C/km). This is attributed to renewed surface uplift in response to transpressional tectonics, as will be discussed below.

Accelerated exhumation of the NE Argentera basement during the Pliocene

According to the thermochronological study by Bigot-Cormier (2002), the apatite FT ages are significantly older to the SW of the Bersézio Fault zone as compared to the NE, after correcting for sampling site elevation. Hence, a 500m vertical offset of the apatite FT partial annealing zone along the fault zone is proposed (Fig. 5b). This offset is attributed to Pliocene uplift and erosion of the NE part of Argentera Massif while it was thrust onto the southern part. This major basement thrusting, starting around 3.5 Ma ago, was coeval with out-of-sequence thrusting in the outer sedimentary cover, in particular the building of the Nice arc to the south (Laurent et al. 2000; Bigot-Cormier 2002).

Link with transcurrent faulting along the internal-external arc boundary

The Pliocene thrusting of the NE Argentera onto the rest of the massif is kinematically linked to dextral strike-slip along the Bersézio Fault zone that acts as a steep lateral ramp (transpressive transcurrent fault). Before being dated by Bigot-Cormier (2002), dominant dextral movement along the Bersézio Fault was recognised by several geologists (e.g. Sturani 1962), and the horizontal relative movement was estimated to be up to 3 km (Vernet 1965). A previous attempt to date this dextral movement was undertaken by Labaume et al. (1989) who envisaged a Quaternary age, based on a comparison with the faulting sequence recognised along the same direction in the inner part of the Digne nappe, further to the SW (Fig. 1).

We could recognise clear indications for final dextral movement along the NW extension of the Bersézio Fault, corresponding successively to the Ruburen Fault, the Serenne Fault and the Durance Fault Zone (Fig. 1). For example, brittle structures associated with major dextral transcurrent movement are widely exposed in Val d'Escreins, between the Serenne pass and Guillestre, at the transition between the Serenne and Durance Fault zones. Along the Durance Fault Zone, this dextral movement corresponds to the already known major reactivation, post-dating the extensional movement, as discussed below.

Late Alpine faulting between Pelvoux and Argentera

Detailed mapping in the Briançonnais zone (Gidon et al. 1994; Barfety et al. 1997) and the nearby Piémont Schistes lustrés zone ("Piedmont Calcschists", Tricart et al. 2004a) allows for the recognition of the density and the regional-scale continuity of the "late Alpine" fault network. These faults overprint all the ductile Alpine structures, including the latest east-verging fold-thrust structures associated with the classical back-movements (Tricart et al. 2004b) and will be described below.

Faults parallel and oblique to the Alpine structure

The main fault nomenclature is given in Fig. 2. An orogen-parallel family of faults ("longitudinal faults") follows the curvature of the arc, especially along the Briançonnais zone. Some complementary oblique faults crosscut the external-internal arc boundary, branching onto the longitudinal faults at their northern tip, and dying out within the external arc at their southern tip. At the scale of the whole Western Alps (Fig. 6), their arrangement may evoke a "horsetail fault termination", consistent with the dextral movement identified along the entire fault system (see below). Another major family crosscuts the main Alpine structures at high angle, with a dominant NE-SW to E-W direction between Pelvoux and Argentera ("transverse faults" like G, F or U in Fig. 2).

In the Briançonnais and Piémont Schistes lustrés zones, these orogen-parallel and orogen-transverse faults developed together as normal faults in response to a multitrend, almost radial extension (Sue 1998; Sue & Tricart 2003). Subsequently, as the tectonic regime acquired a more transcurrent character, the longitudinal and transverse faults were reactivated as dextral and sinistral strike-slip faults respectively (Sue 1998; Sue & Tricart 2003). This reactivation is responsible for an often anastomosing pattern of the fault system at a regional scale, especially along the longitudinal family, and it could also explain the "horsetail termination" pattern mentioned above.

The High Durance Fault Zone: a key structure

The longitudinal faults are widely exposed in the high Durance valley between Briançon and Guillestre, where they regroup within the 6–7 km wide High Durance Fault Zone (HDFZ), oriented N160E (Tricart et al. 1996; Fig. 4). Among them, the Durance Fault was the first major late fault identified in this part of the Alps (Debelmas 1953). These steep faults display spectacular slickensides with giant (up to 20–30m high) subhorizontal grooves, indicating important dextral movement. However, the corresponding total offset along the HDFZ remains unknown.

A detailed analysis (Tricart et al. 1996) allows demonstrating that most faults initially represented normal faults that were reactivated as strike-slip faults subsequently (Fig. 7). During initial extensional faulting horst and graben type structures, with steep conjugate faults and domino-like tilted blocks, did dominate. Some of them escaped reactivation according to a scenario that has now been recognised in the whole Briançonnais region (Sue 1998; Sue & Tricart 2003). To the east of the Durance Fault, around Guillestre, the down-

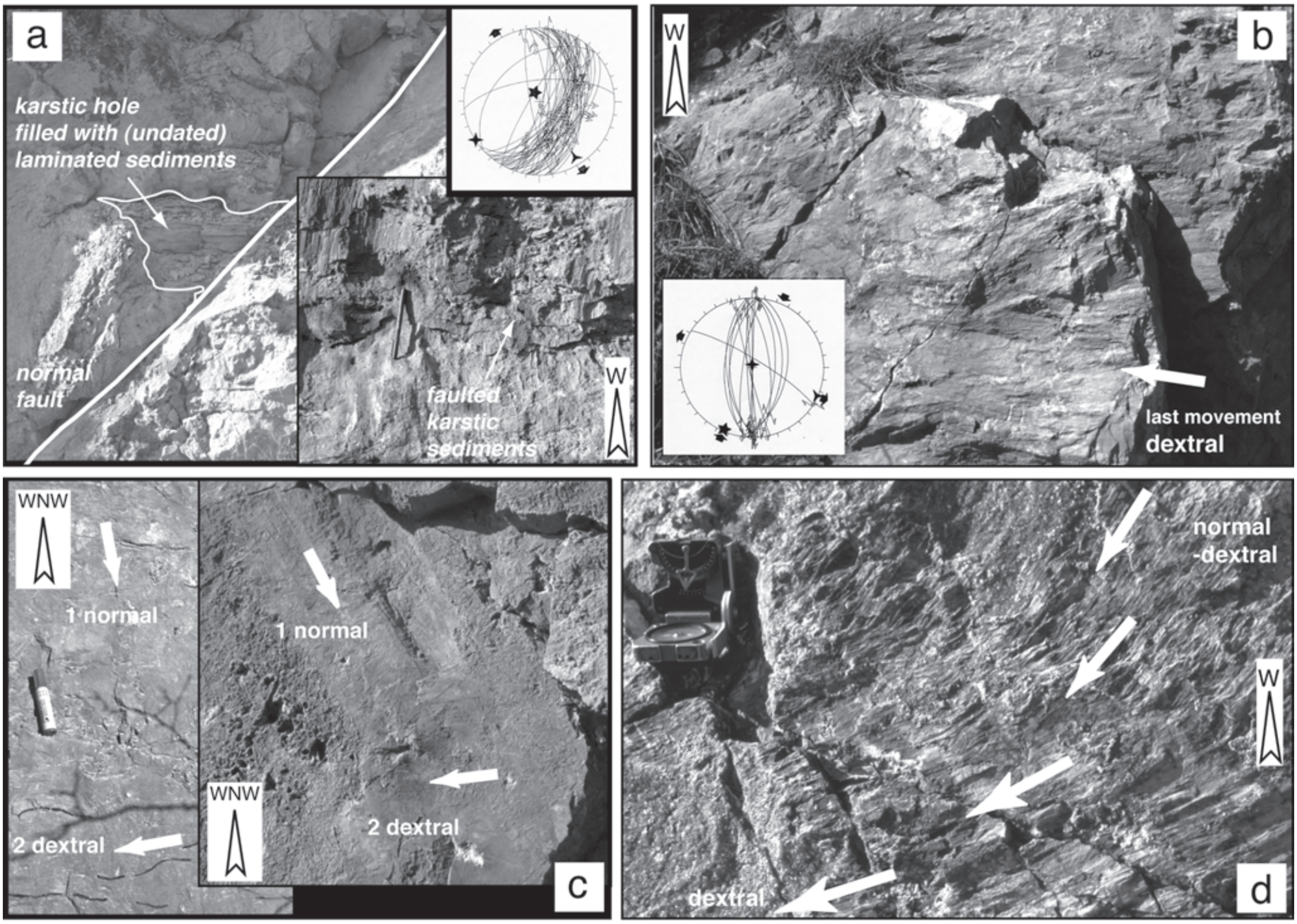

Fig. 7. Structures characteristic of the High Durance Fault Zone (outcrops located in Fig. 4). (a) Pure extensional fault with karstic pockets, subsequently filled with red continental sediments that are in turn affected by the continuation of extensional faulting (inset lower right). Such normal faults constitute the original fault zone. (b) Horizontal striae and grooves associated to the transcurrent final movements in the fault zone (in this case dextral along N160°E fault). (c) Superimposed slickenlines on east-facing fault surfaces indicating dip-slip extension followed by dextral strike-slip. (d) Curved slickenfibres on an east-facing fault surface suggesting a continuous evolution from an extensional to a transcurrent regime. Insets in (a) and (b) depicting pole figures: striated fault analysis with computed main stress axes, from unpublished work by Dick (pers. comm.); equal area projection, lower hemisphere.

throw of the Briançonnais nappe pile is up to 1 km according to Debelmas (1953). This offset is inherited from the initial extensional faulting. On some fault planes, curved slickenfibres suggest that the change from extensional dip-slip to dextral strike-slip could have been progressive, at least locally (Fig. 7d). This change remains undated, but as will be proposed later, it occurred at the beginning of the Pliocene (see below).

Local geodetic surveys near Briançon (Sue et al. 2000), as well as a general seismotectonic analysis (Sue 1998; Sue et al. 1999), both confirm that the HDFZ remains a major active structure. At present, the movement along the NNW-SSE faults nearly corresponds to an E-W extension. It implies that the regional-scale tectonic regime changed again recently. This last change remains to be dated and interpreted.

To the west of the Durance river, between L'Argentière and Guillestre, Sue & Tricart (1999) demonstrated that initial normal faulting within the HDFZ occurred simultaneously with dense normal faulting that affected the western Briançonnais zone, and at a time when the frontal thrust (BFT) was reactivated as a low-angle normal fault. This implies that the uplift of the SE Pelvoux basement dome and its exhumation through extensional denudation below the inverted BFT was closely related to the development of the HDFZ as a major zone of normal faults along which the axial and eastern Briançonnais zone was lowered with respect to the western Briançonnais zone. As already discussed in this contribution (see also Tricart et al. 2001), apatite FT ages suggest that this extension was active during the Miocene, including the Late Miocene.

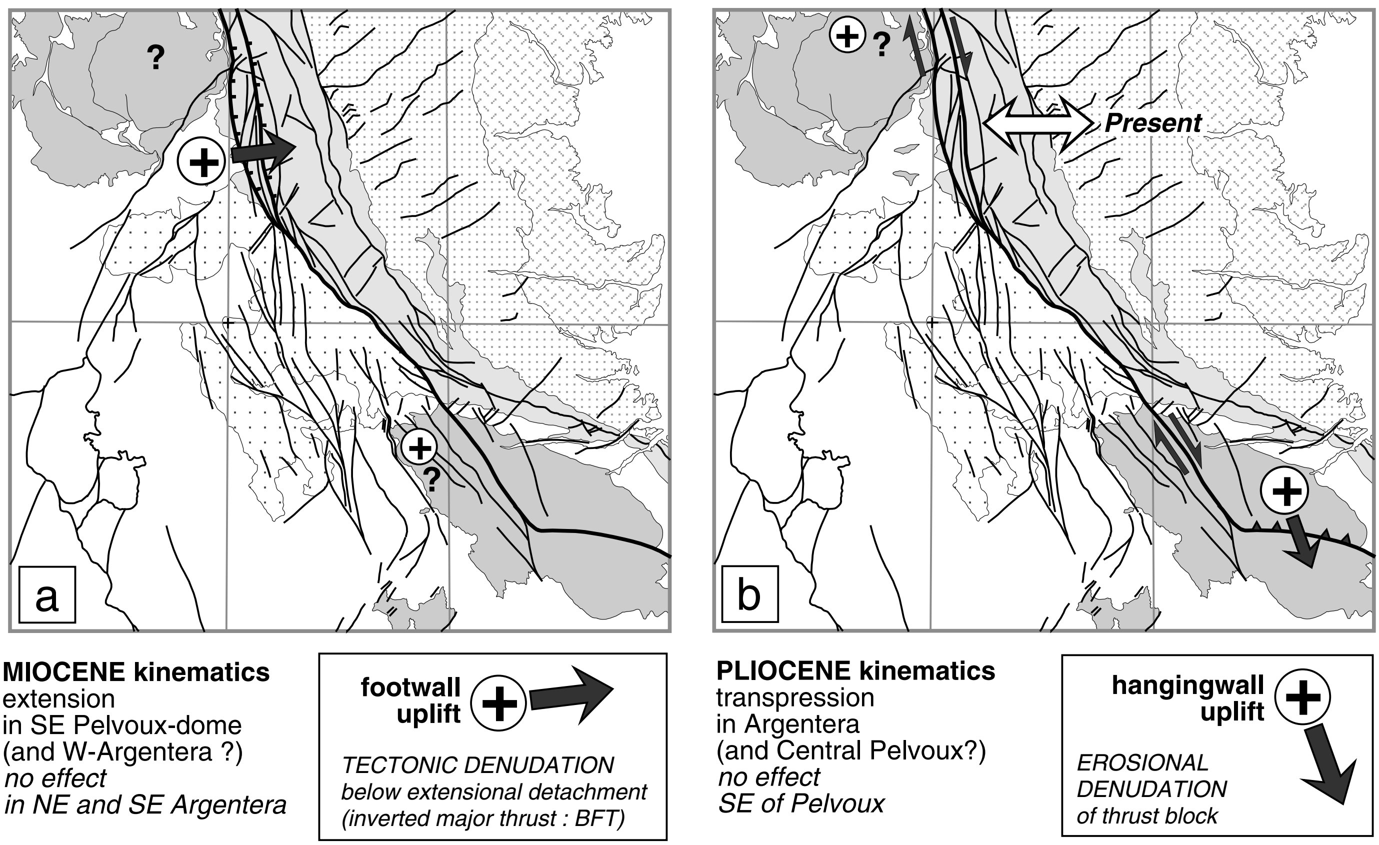

Fig. 8. Proposition of a two-step kinematic scenario (for a structural map, see Fig. 2). (a) Miocene kinematics is dominated by orogen-transverse extension. The highlighted movements are (1) tectonic denudation of the SE Pelvoux basement below the east-dipping frontal thrust of the Briançonnais zone (BFT), inverted as an extensional detachment and (2) important orogen-parallel normal faulting along the high Durance valley immediately to the east. (b) Pliocene kinematics that became dominantly transpressional, particularly in the south. The highlighted movements are (1) southward thrusting of the NE Argentera basement onto the rest of the massif and (2) dextral strike-slip along orogen-parallel faults, including the high Durance Fault zone, acting as lateral ramps. The double arrow SE of the Pelvoux massif recalls that transverse extension prevails again currently, as is proposed by the seismotectonic analysis of Sue (1998).

A two-step scenario for the final exhumation of the southernmost ECM

The geochronological and structural data discussed so far suggest a link between the final cooling history of the southernmost ECM (especially the SE Pelvoux and NE Argentera massifs) and the movement history along the late fault network that follows the internal-external arc boundary between both massifs. The general Alpine tectonic context is outward thrusting of the ECM that drives their erosional denudation during the Miocene. This Miocene exhumation is identifiable in all the ECM, including the Argentera, but not in the Pelvoux massif where zircon FT ages were only partially reset during the last thermal event. In the following we focus onto the final exhumation processes and their timing.

During the Miocene (Fig. 8a), the SE Pelvoux basement dome experienced its final exhumation (passing at 4–5 km depth at around 7 Ma) by extensional denudation below the BFT that was now reactivated as a crustal low angle normal fault. Coevally, the overlying Briançonnais and western Piémont zones underwent intense brittle extension (e.g. Durance Fault Zone). Exhumation of these higher units was comparatively slow, either due to extensional collapse or due to erosion. At that time, the behaviour of the bulk of the Pelvoux massif itself just to the north, including its eastern fringe, remains insufficiently documented. As a working hypothesis it is proposed, that the NW Argentera massif, which has comparable apatite FT ages, could have experienced the same exhumation path as the SE Pelvoux basement dome.

During the Pliocene (Fig. 8b), longitudinal normal faults such as the Durance Fault, became major transcurrent faults. In the Argentera massif, dextral slip along this fault set acted as a lateral ramp and was accompanied by the southward thrusting of the NE Argentera onto the rest of the massif. The erosion of this uplifted allochtonous block resulted in its final cooling and exhumation, passing at 4–5 km depth at < 3.5 Ma ago.

It is possible that this dextral transpressive regime along the southern branch of the arc also affected the Pelvoux massif, triggering its recent final uplift in a similar manner to that demonstrated in the Argentera massif, but this remains speculative. In any case, the SE Pelvoux dome escaped this recent and important uplift, as is suggested by its specific cooling history and its present moderate elevation (Fig. 8b). Such a contrasting behaviour could find its origin in the 3D geometry of the active fault system, that still needs to be better constrained at depth.

Conclusions

By coupling cooling history and late stages of the faulting history we propose that the exhumation of the ECM changed through time from one massif to the other along the southern branch of the western Alpine arc. The scenarios of exhumation of the Pelvoux and Argentera massifs, representing the symmetric high-level basement massifs to both sides of the Embrunais-Ubaye structural depression, differ in terms of processes and timing. In the SE Pelvoux, the main final exhumation resulted from the doming and tectonic uncovering of the footwall to an inverted old major thrust during the Late Miocene. In the NE Argentera, however, final exhumation resulted from the erosion of the uplifted hangingwall to an active out-of-sequence thrust during the Pliocene.

East and SE of the Pelvoux massif, the present-day tectonic regime in the upper crust of the Briançonnais seismic arc is again extensional (Delacou et al. 2004 and references therein) as was the case during the Miocene, but not during the Pliocene. This significant and very recent new change illustrates the short-time variability (a few Myr?) of the regional stress and strain fields, at least along the southern branch of the arc. This variability, already envisaged by Sue (1998), must be taken into account when discussing the internal versus external origin of the driving forces during the "late-Alpine" tectonic evolution.

The 3-4 Ma old cooling pulse in the Argentera massif results from the onset of a transpressive tectonic regime with dextral wrench faulting along the southern branch of the arc, close to the internal-external arc boundary. This seems consistent with the model proposed by Seward and Manktelow (1994) in the northern branch of the western Alpine arc where orogen-parallel dextral wrench faulting close to the limit between external and internal arcs plays an increasing role during the final exhumation of Mont Blanc and Belledonne massifs. It is quite feasible that the accelerated final cooling recognised in most ECM during the Late or Latest Miocene reflects a change in the tectonic regime that drives the uplift of the ECM all around the western Alpine arc. This (fully or partly) transpressive regime is associated with the development of the horsetail-like system of dextral faults at the scale of the arc (Fig. 6b). Such a common process driving final uplift could explain the striking similarities of the ECM all around the arc, as seen presently in map view, despite the fact that all these massifs experienced a varied earlier exhumation history during Miocene times.

Acknowledgements

F. Bigot-Cormier and P. Van Der Beek reviewed an early version of the manuscript. M. Ford, M. Rahn and S. Schmid helped to improve the submitted version.

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Manuscript received December 22, 2003
Revision accepted November 22, 2004