Journal of the Geological Society, *London*, Vol. **164**, 2007, pp. 163–174. Printed in Great Britain.

Diachronous late-stage exhumation across the western Alpine arc: constraints from apatite fission-track thermochronology between the Pelvoux and Dora-Maira Massifs

PIERRE TRICART[1], PETER VAN DER BEEK[1], STEPHANE SCHWARTZ[2] & ERIKA LABRIN[1]

[1]*Laboratoire de Géodynamique des Chaînes Alpines, Université Joseph Fourier, BP 53, 38041 Grenoble Cedex, France (e-mail: ptricart@ujf-grenoble.fr)*

[2]*Laboratoire Interdisciplinaire de Recherche Impliquant la Géologie et la Mécanique, Université Joseph Fourier, BP 53, 38041 Grenoble Cedex, France*

Abstract: We present new apatite fission-track (AFT) data from the central western Alps that confirm the synchronicity and high cooling rates during Latest Miocene–Pliocene final exhumation of the External Crystalline Massifs but also provide evidence for diachronous Neogene evolution along and across the internal arc. To the SE of the Pelvoux Massif, across the front of the internal arc (Penninic Frontal Thrust), the jump in AFT ages (*c*. 22 Ma) and in final cooling rates is significantly larger than further north. This difference results from reversal of movement along a major Oligocene thrust. In its hanging wall, the western Briançonnais Zone provides a mean AFT age of *c*. 27 Ma, which is older than further north. Early cooling in the southern Briançonnais Zone would result from rapid erosion of the compressional fan structure built during the Oligocene. Across the entire Briançonnais and Piémont nappe stack, with the exception of the Dora-Maira Massif, AFT ages young eastward and span the entire Miocene, a period during which this structure underwent extension. Further north a reverse gradient with ages younging northwestward has been described, prompting the question of the asymmetry of the internal western Alpine arc during its late-stage tectonic and morphological evolution.

The evolution of the European Alps (Fig. 1) is linked to Eurasian–African plate boundary processes. Rifting and oceanic spreading during Mesozoic times, followed by convergence, subduction and collision from the Cretaceous onward, resulted in the complex present-day structure (e.g. Schmid *et al*. 2004). Although the Alpine collision has been studied in detail for a century, the late orogenic evolution and its links to the present-day dynamics of the belt have only recently been addressed (e.g. Calais *et al*. 2002, and references therein). An important recent finding concerns the role of extensional processes in the late-stage evolution of the belt, particularly in the western Alps (an extensive review has been given by Selverstone 2005).

Within the western Alpine arc (Fig. 1), a relatively large and growing number of apatite fission-track (AFT) data (Seward & Mancktelow 1994; Bistacchi & Massironi 2000; Bistacchi *et al*. 2000; Fügenschuh & Schmid 2003; Malusà *et al*. 2005) permit the kinematics and timing of exhumation to be constrained within the northern branch of the arc (i.e. along the Mont Blanc–Gran Paradiso and Belledonne–Susa valley transects). Such constraints have been more difficult to obtain for the central part of the arc (i.e. between the Pelvoux and Dora-Maira Massifs), where currently available data (Seward *et al*. 1999; Schwartz 2002) remain unevenly distributed, partly because of the relative paucity of outcropping lithologies that contain sufficient apatite. Further south, existing AFT ages are concentrated in the external zone (Argentera Massif; see Bigot-Cormier *et al*. 2000, for a review). However, the rare data available from the internal zones suggest that this southernmost branch has its own late orogenic dynamics, possibly linked to the development of the Ligurian Basin immediately to the south.

Here, we present new AFT ages and track length distributions from *in situ* samples collected in the central western Alpine arc (Fig. 2). Samples were collected from both crystalline basement and overlying cover in the eastern and southeastern Pelvoux Massif, from apatite-bearing inliers within the Briançonnais nappe stack around Briançon and from the crystalline basement nappes of the northern Dora-Maira Massif. A comparison with the existing dataset, mostly collected further north, provides evidence for significant diachronicity in the late-stage evolution of the internal western Alpine arc, both along and across strike of the major structures.

The western Alpine arc

The western Alps form an arcuate belt around the Adriatic promontory, which has been moving westward since *c*. 30 Ma (e.g. Ceriani *et al*. 2001). The building of the arc is most easily explained by considering the Adriatic promontory as a rigid indenter (Schmid & Kissling 2000, and references therein). This indenter has been recognized at depth as a mantle wedge located in the core of the arc (e.g. Vernant *et al*. 2002).

In the outer part of the arc, where Alpine tectonics is limited to upper crustal deformation, the Dauphiné (or Helvetic) Zone originates from the proximal part of the European margin of the Tethys Ocean (a review has been given by Lemoine *et al*. 2000). Its prealpine (Hercynian or older) basement forms the External Crystalline Massifs (Aar, Mont Blanc, Belledonne, Pelvoux, Argentera), where distinct crystalline basement blocks were exhumed during a major Miocene shortening phase (e.g. Corsini *et al*. 2004). They currently form the morphologically highest part of the western Alps and include nearly all >4000 m peaks, although they do not form the drainage divide of the range. The detached and folded Mesozoic–Cenozoic sedimentary cover forms the Sub-Alpine chains further west (e.g. Gratier *et al*.

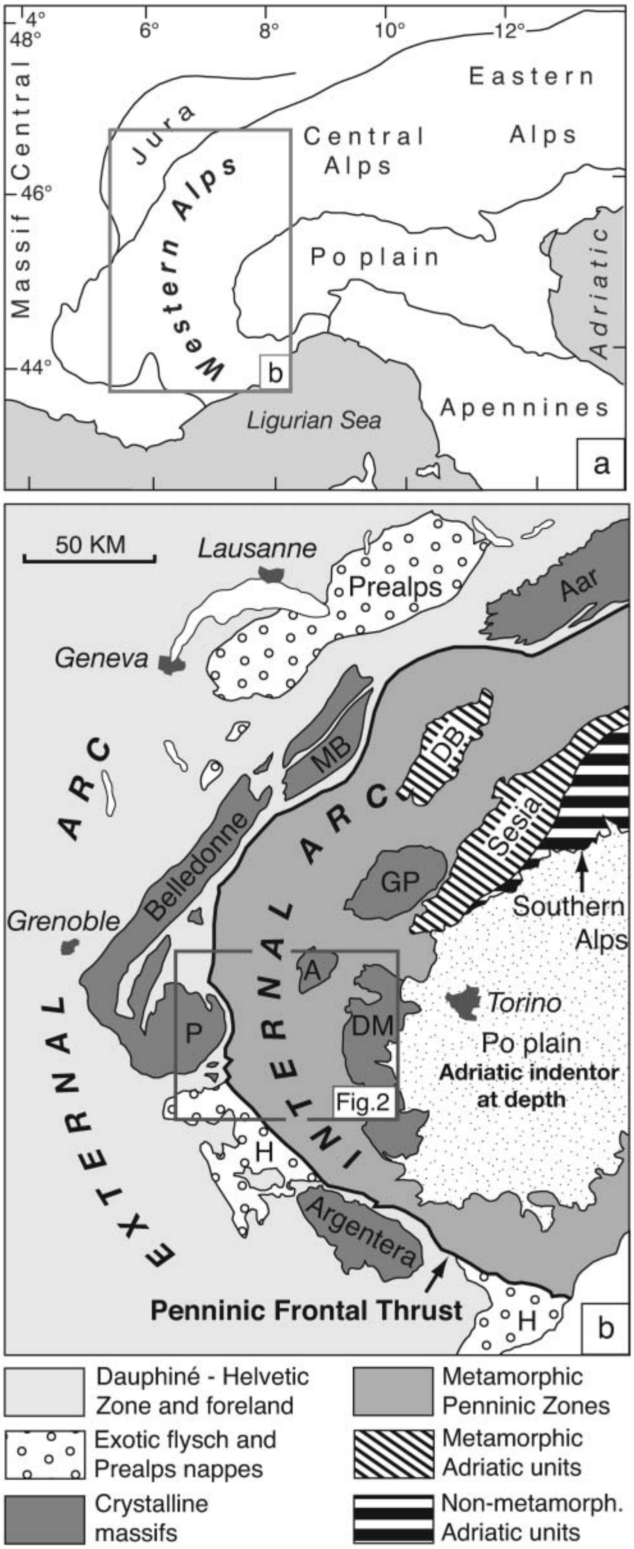

Fig. 1. (**a**) Geographical setting of the western Alpine arc showing location of (**b**); (**b**) tectonic sketch map of the western Alpine arc. Inset shows location of Figure 2. A, Ambin Dome; DB, Dent-Blanc massif; DM, Dora–Maira Dome; GP, Gran Paradiso Massif; H, Helminthoid Flysch nappes; P, Pelvoux Massif.

1989). In the southern half of the external arc, Late Cretaceous–Eocene east–west-trending folds interfere with the Oligocene–Neogene folds that developed concentrically to the arc (Lemoine 1972).

The internal arc consists of a complex imbricate stack of basement and cover nappes of both continental and oceanic origin, known as the Penninic domain. Widespread blueschist and eclogite metamorphic assemblages provide evidence for a pre-collisional subduction stage. The HP–LT metamorphic grade increases towards the interior of the arc, reaching UHP conditions in some coesite-bearing units of the Dora-Maira massif (see Goffé *et al*. 2004, for a review). Differences in palaeogeographical origin and tectonic evolution of the different nappes permit the distinction of the classic Alpine zones (e.g. Schmid *et al*. 2004). In the central part of the arc, the most important of these are the Briançonnais Zone, a rift shoulder that developed into a passive margin, and the Piémont Zone, representing the distal passive margin and the Tethyan Ocean.

The boundary between the external and internal arc forms a zone of lithospheric-scale thrusts that developed during Oligocene times, as the Adriatic indenter caused deformation to propagate from the internal to the external arc (e.g. Schmid & Kissling 2000). Its most clearly defined surface expression is the Penninic Frontal Thrust, which locally corresponds to either the 'Valaisan Front' or the 'Subbriançonnais Front' and is closely associated with the 'Briançonnais' or 'Houiller' thrust-front (for details, see Tricart *et al*. 2001).

Neogene ductile to brittle extensional tectonics is widespread in the internal arc (Sue & Tricart 2003). Extensional faulting is associated with reversal of movement along the Penninic Frontal Thrust, best visible to the SE of the Pelvoux Massif (see review by Tricart *et al*. 2006). Further north, the importance of this reversal may decrease (Fügenschuh & Schmid 2003; Malusà *et al*. 2005). Further south, the fault zone is mostly reactivated in a strike-slip sense (Tricart 2004, and references therein). Seismicity (Sue *et al*. 1999) and global positioning system (GPS) data (Calais *et al*. 2002) indicate that extension in the internal arc continues at present.

The Pelvoux to Dora-Maira transect

We analyse both new and existing AFT data along two roughly east–west-trending transects from the Pelvoux Massif in the west to the Dora-Maira Massif in the east (Fig. 2–4). The Pelvoux External Crystalline Massif is made up of basement blocks thrust up along steeply dipping faults with varied trends. Many of these represent Jurassic normal faults that were reactivated during Alpine convergence (Ford 1996).

A NE–SW-trending fault zone with a complex kinematic history runs along the southeastern border of the Pelvoux Massif (Tricart 1981, and references therein). To the north of this fault zone, the highest >4000 m peaks in the central part of the massif consist of basement rocks, whereas to the south, the top of basement is found below 2000 m elevation in the asymmetrical Dormillouse Dome. There, the Mesozoic sedimentary cover has been deeply eroded and a Palaeogene flysch succession, which includes the Champsaur sandstone, unconformably overlies the basement. These stratigraphic relationships provide clear evidence for early uplift and erosion of the southern Pelvoux basement, probably related to Late Cretaceous–Eocene shortening (e.g. Gupta & Allen 2000). Further south, the Embrun structural depression is filled with exotic, mainly Helminthoid Flysch, nappes (Fig. 2).

The Palaeogene flysch succession was deposited in a flexural

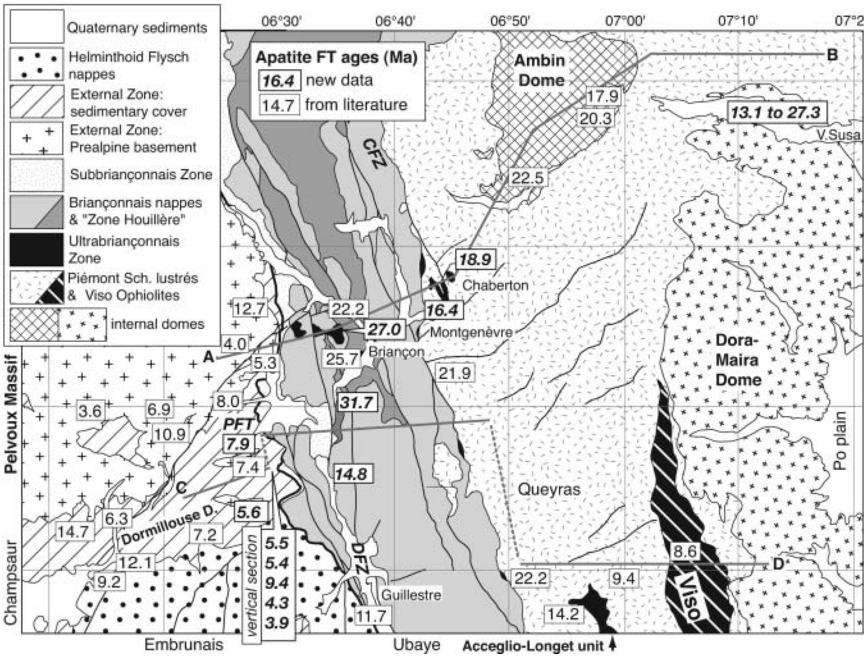

Fig. 2. Geological map of central western Alpine arc showing the locations of new and previously published AFT ages. Transects A–B and C–D are shown in Figures 3 and 4, respectively. PFT, Penninic Frontal Thrust; CFZ, Clarée Fault Zone; DFZ, Durance Fault zone.

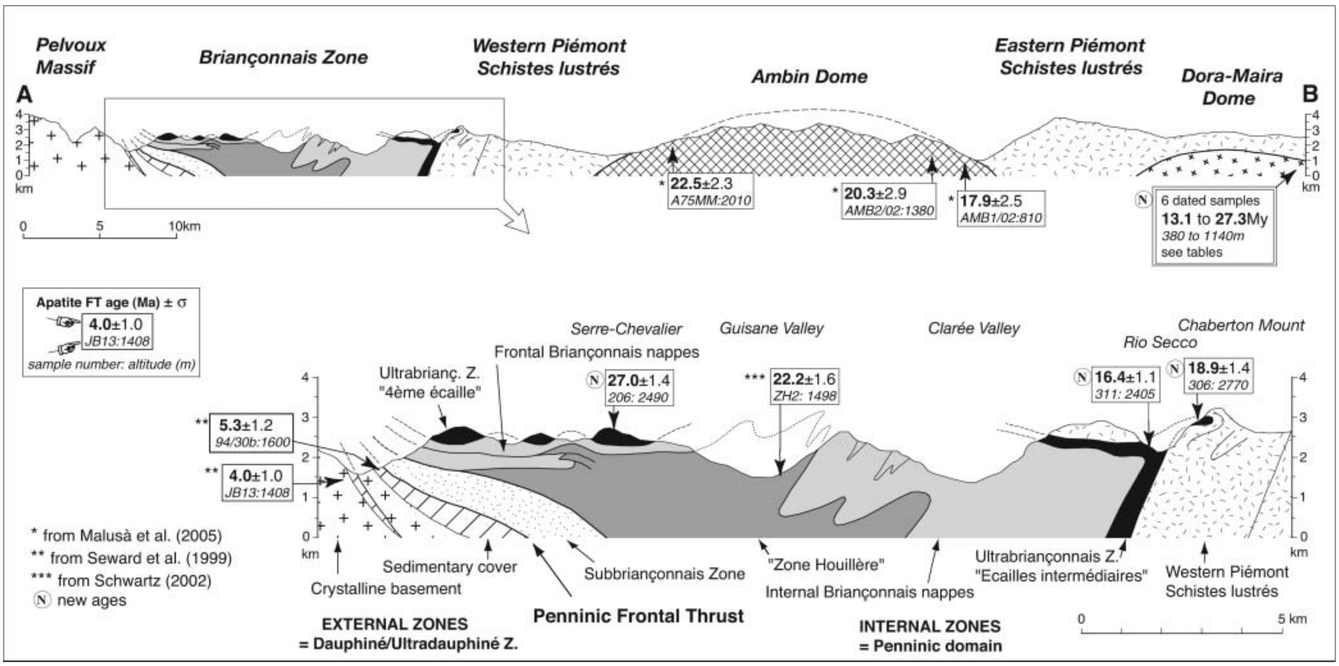

Fig. 3. Schematic cross-section from the Pelvoux Massif to the Dora–Maira Dome, showing locations of new and previously published AFT ages. Shading of the tectonic units is as in Figure 2.

basin that developed in front of what is now the internal arc (e.g. Sinclair 1996). In the footwall of the Penninic Frontal Thrust, often called the Ultradauphiné Zone (Debelmas 1980), the Champsaur sandstone formation contains a train of spectacular kink folds, indicating west- to SW-directed shear (Tricart 1984; Bürgisser & Ford 1998). To the south, thin-skinned nappes of Helminthoid Flysch are thrust over the Champsaur sandstone. Remnants of these flysch nappes on top of some Briançonnais nappes indicate that they were thrust from a more internal domain early in the Alpine deformation history (Debelmas & Lemoine 1966). On the eastern border of the Pelvoux Massif, the Penninic Frontal Thrust directly overlies the Champsaur sandstone and is associated with kilometre-scale or smaller tectonic slices that contain a Mesozoic–Cenozoic sedimentary succession characteristic of the Subbriançonnais Zone (Debelmas 1980).

The hanging wall of the Penninic Frontal Thrust is largely made up of the Briançonnais Zone, which is subdivided into the 'Zone Houillère', a folded thick Carboniferous sedimentary succession, and the Briançonnais Nappes, which contain Triassic to Eocene reduced carbonate-rich series detached along Triassic evaporite levels (Debelmas & Lemoine 1966).

To the east, the boundary between the Briançonnais and

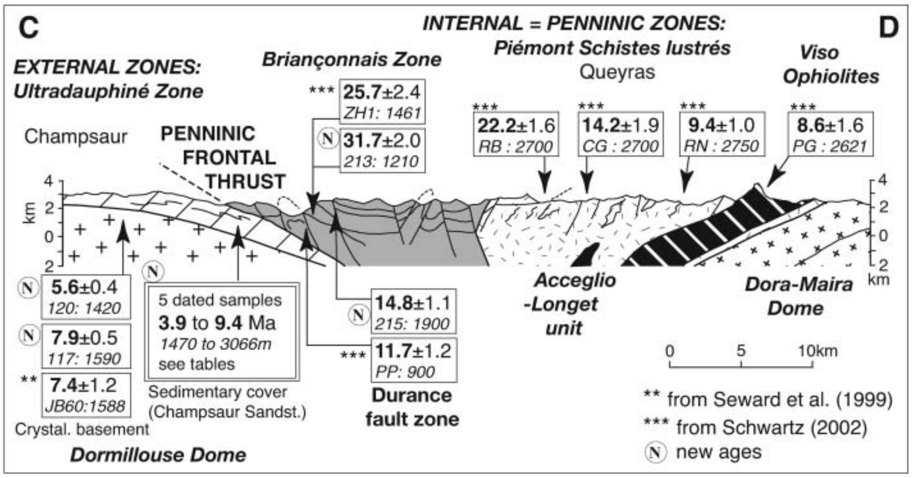

Fig. 4. Schematic cross-section from the southeastern Pelvoux Massif to the Viso Massif, showing locations of new and previously published AFT ages. Shading of the tectonic units is as in Figure 2.

Piémont Zones corresponds to an old west-directed thrust (the Piémont Front) that was subsequently deformed or reactivated. Within this major contact, tectonic slices contain both continental basement and a very reduced Mesozoic sedimentary cover, suggesting a provenance from the most internal part of the Briançonnais domain that was uplifted and deeply eroded during rifting. These slices represent the Ultrabriançonnais (or Acceglio) Zone and are considered as part of the Briançonnais Zone *sensu lato* (e.g. Lemoine *et al*. 2000). The Ultrabriançonnais Zone is mainly exposed north of Montgenèvre and west of Mt. Chaberton in the Rio Secco gorge and is also preserved as small klippen on top of the westernmost Briançonnais Zone (Barféty *et al*. 1996). The peculiar geometry of the Ultrabriançonnais Zone (Figs 2 and 3) is explained by late-stage east-vergent backfolding of the entire eastern Briançonnais and western Piémont nappe stack (Lemoine 1969).

The Briançonnais Zone units further east, consisting of prealpine crystalline basement and its Palaeozoic sedimentary cover, build up the Ambin Massif, a dome-shaped nappe stack exposed as a tectonic window beneath the Piémont Schistes lustrés (Debelmas 1980). In the upper Ubaye Valley further south, the Ultrabriançonnais Zone is exposed similarly in a east-vergent antiformal stack at the base of the Schistes lustrés ('Acceglio-Longet' unit, Gidon *et al*. 1994).

In the Piémont zone, the Schistes lustrés Complex consists of a pile of thrust sheets with varied metasedimentary series. Breccia-rich series that locally preserve remnants of a Triassic dolomitic platform at their base originate from the distal European rifted margin whereas ophiolite-bearing series originate from the ocean and from the continent–ocean transition. All series were initially very marly and have been metamorphosed into calcschists ('Schistes lustrés', Lemoine & Tricart 1986). Thrust sheets were initially stacked within an oceanic accretionary wedge in blueschist metamorphic conditions and were subsequently strongly folded during Alpine collision (Schwartz 2002; Tricart *et al*. 2003).

Along the eastern limit of the Schistes lustrés Complex, a thick pile of eclogite-bearing thrust sheets of gabbros and basalts, associated with large volumes of serpentinite and thin remnants of sedimentary cover, crops out in the Viso ophiolitic Massif (Lombardo *et al*. 1978; review by Tricart *et al*. 2003). Further east, the Dora-Maira 'Internal Crystalline Massif' forms an elongate north–south-trending dome of nappes with varied HP to UHP metamorphic imprint. It lies structurally below the Schistes lustrés Complex (Figs 2 and 3) and mainly exposes prealpine crystalline basement as well as its Palaeozoic sedimentary cover. Its domal structure resembles that of the Ambin Massif (Sandrone *et al*. 1993). The Dora-Maira Massif bounds the Po Plain and its thick fill of Neogene–Quaternary sediments, which overlies the Adriatic basement and its Tethyan sedimentary cover.

Apatite fission-track data

Sampled units

Samples were collected in four selected areas (Fig. 2; Table 1). Within the external arc, we completed the study of Seward *et al*. (1999) by collecting samples in the Dormillouse Dome, both from the basement in the Fournel and Biaysse valleys (samples 117 and 120) and in the overlying Champsaur sandstone (Ultradauphiné Zone). Within the latter unit, an age–elevation profile (samples 123, 127, 130, 132 and 133) was collected at the eastern limit of the massif, in the footwall of the Penninic Frontal Thrust along the crest separating the Fournel and Biaysse valleys.

Within the internal arc, a first target was the westernmost Briançonnais Zone in the hanging wall of the Penninic Frontal Thrust. As the Briançonnais nappes contain very few apatite-bearing levels, we sampled specific lithologies that crop out only very locally. These included a sample (213) from a microdioritic intrusion in the Zone Houillère near Briançon that complements two ages obtained by Schwartz (2002) in the same area, a sample (215) from a slice of meta-arkose (remnant of an Helminthoid Flysch nappe) that is pinched between Briançonnais nappes, and a sample (206) from the Ultrabriançonnais basement klippen on top of the Briançonnais nappe stack at Serre-Chevalier summit (the 'quatrième écaille' of Barféty *et al*. 1996).

Two samples (306, 311) were collected from the Ultrabriançonnais Zone at the eastern margin of the Briançonnais Zone to the north of Montgenèvre, on each side of the Rio Secco gorge ('Écailles Intermédiaires' *sensu* Lemoine 1969). Again, this specific sampling strategy permitted us to obtain data from close to the front of the Piémont Zone where margin-derived nappes display lithologies that are poor in apatite.

Further east within the Piémont Zone, more favourable lithologies crop out to the south of this transect. We use data from Schwartz (2002), who sampled meta-albitites (trondhjemitic protoliths) and meta-arkoses within the ophiolite-bearing Schistes lustrés Complex in the Queyras and Ubaye areas. These data follow an east–west transect across the Schistes lustrés and into the Viso ophiolites.

Finally, we report ages from six samples (901, 903–907) collected across the Susa Valley in the Dora-Maira basement. We also reproduce the recent results of Malusà *et al*. (2005) from the Susa Valley and the nearby Ambin Dome for comparison.

Table 1. *Location of sampled sites*

Sample	Field number	Location, *x*–*y* coordinates	Altitude (m)	Lithology	Tectonic zone or unit
117	APT99-17	Fournel Valley: La Salce $x = 298850$, $y = 4962587$	1590	Aplite and gneiss	Ultradauphiné Zone Prealpine basement
120	APT99-20	Biaysse valley: Dormillouse park $x = 298075$, $y = 4956550$	1420	Gneiss	Ultradauphiné Zone Prealpine basement
123	APT99-23	Biaysse valley: Tête Raisins $x = 301375$, $y = 4960287$	2630	Champsaur sand	Ultradauphiné Zone Sedimentary cover
127	APT99-27	Biaysse valley: Tronches Torrent $x = 302550$, $y = 4959350$	2017	Champsaur sand	Ultradauphiné Zone Sedimentary cover
130	APT99-30	Biaysse valley: Malafoisse $x = 303725$, $y = 4958737$	1470	Champsaur sand	Ultradauphiné Zone Sedimentary cover
132	APT99-32	Biaysse valley: Dormillouse crest $x = 299400$, $y = 4960212$	3066	Champsaur sand	Ultradauphiné Zone Sedimentary cover
133	APT99-33	Biaysse valley: Dormillouse crest $x = 300062$, $y = 4960400$	2908	Champsaur sand	Ultradauphiné Zone Sedimentary cover
206	APT99-06	Guisane valley: Serre-Chevalier $x = 306596$, $y = 4975961$	2490	Gneiss	Ultrabriançonnais Zone '4ème écaille'
213	APT99-13	Durance valley: Le Villaret $x = 310052$, $y = 4969885$	1210	Microdiorite (sill)	Briançonnais Zone Zone Houillère
215	APT99-15	Durance valley: Rocher Rouge $x = 310100$, $y = 4960000$	1900	Meta-arkose	Briançonnais Zone Flysch tectonic sliver
306	CRS-06	Montgenèvre: Chaberton crest $x = 322180$, $y = 4982191$	2770	Gneiss	Ultrabriançonnais Zone 'Écailles intermédiaires'
311	CRS-11	Montgenèvre: L'Alpet $x = 320042$, $y = 4980735$	2405	Gneiss	Ultrabriançonnais Zone 'Écailles intermédiaires'
901	VS-1	V. Susa: Chiusa di S. Michele $x = 367316$, $y = 4995560$	380	Leucogranite	Dora–Maira Dome Prealpine basement
903	VS-3	V. Susa: San Antonio di Susa $x = 363479$, $y = 4994224$	780	Leucogranite	Dora–Maira Dome Prealpine basement
904	VS-4	V. Susa: San Antonio di Susa $x = 363708$, $y = 4993774$	1070	Meta-arkose	Dora–Maira Dome Prealpine basement
905	VS-5	V. Susa: San Antonio di Susa $x = 363525$, $y = 4994124$	970	Meta-arkose	Dora–Maira Dome Prealpine basement
906	VS-6	V. Susa: San Antonio di Susa $x = 363500$, $y = 4997042$	380	Leucogranite	Dora–Maira Dome Prealpine basement
907	VS7	V. Susa: San Antonio di Susa $x = 363505$, y = 4998722	1140	Leucogranite	Dora–Maira Dome Prealpine basement

x and *y* coordinates are in metres, and use the UTM 32N projection of the WGS84 datum.

The combination of these new AFT data with previously reported data provides a view of the late-stage exhumation of the central western Alpine arc along two transects: a northern transect from the easternmost Pelvoux Massif to the northern part of the Dora-Maira Massif and crossing the southeastern part of the Ambin Dome (Fig. 3) and a more composite southern transect from the Dormillouse Dome in the west to the Viso ophiolites in the east (Fig. 4).

AFT dating: methods

Apatites were recovered from whole-rock samples using standard magnetic and heavy liquid separation techniques, mounted in epoxy, polished and etched in a 5M HNO_3 solution at 20 °C for 20 s. All samples were dated by the external detector method, using U-poor mica as the external detector and a zeta calibration factor for Fish Canyon and Durango age standards (Hurford 1990). Samples were irradiated at the well-thermalized ORPHEE facility of the Centre d'Etudes Nucléaires in Saclay, France, with a nominal fluence of *c.* 5×10^{15} neutrons cm^{-2}. Neutron fluences were monitored using NBS962 dosimeter glasses. Mica detectors were etched in 48% HF at 20 °C for 20 min. All samples were analysed by E. Labrin. In samples with sufficiently high track density, confined track length measurements were performed by digitizing the track ends using a drawing tube. Additionally, in samples that were selected for thermal history modelling, the etch-pit width parallel to the *c*-axis (D_{par}) of 100 tracks crossing the etched internal surface was measured using the same digitizing technique.

All results (ages, lengths, D_{par}) are presented in Table 2. AFT ages are quoted as central ages (Galbraith & Laslett 1993) with $\pm 1\sigma$ uncertainties throughout. Radial plots (Galbraith 1990) and confined track-length distributions for representative samples from each area are shown in Figure 5.

AFT dating: results

The two samples from the Dormillouse Dome basement have ages of 5.6 ± 0.4 and 7.9 ± 0.5 Ma, respectively, which are consistent with ages of 5.3–8.1 Ma reported by Seward *et al.* (1999) for the same area. These new data appear to confirm the general geographical distribution of younger AFT ages (3–4 Ma) in the core of the massif and older ages toward its rims, as suggested by Seward *et al.* (1999).

Four out of five samples collected along the vertical profile in the Champsaur sandstone are near-perfectly aligned along a steep (1.0 km Ma^{-1}) age–elevation trend (Fig. 6a) between 3.9 ± 0.3 Ma at 1470 m and 5.5 ± 0.4 Ma at 3066 m. Sample 123 lies outside this trend, however, with an age of 9.4 ± 0.7 Ma at 2630 m, and appears to be aligned with the two basement samples along a slightly older but parallel trend. A similar pattern was reported by Van der Beek (2004) for an age–elevation profile collected entirely within basement rocks at La Meije, to the NW of the present location. However, there is no clear difference in track-length distributions, nor in annealing

Table 2. *New apatite fission-track data from the central western Alps*

Sample	Sample field no.	Elevation (m)	N	ρ_s (10^6 cm^{-2})	(N_s)	ρ_i (10^6 cm^{-2})	(N_i)	ρ_d (10^6 cm^{-2})	(N_d)	$P(\chi^2)$ (%)	D (%)	Age (Ma) $\pm$ 1σ	MTL $\pm$ 1σ (μm)	st.dev. (μm)	No.	Dpar $\pm$ 1σ (μm)
Eastern Pelvoux																
117	APT99-17	1590	31	0.158	(292)	1.808	(3344)	0.520	(13449)	60.8	7	7.9 $\pm$ 0.5				
120	APT99-20	1420	20	0.100	(195)	1.598	(3113)	0.520	(13449)	>99.9	≪1	5.6 $\pm$ 0.4	12.2 $\pm$ 0.2	1.7	100	1.72 $\pm$ 0.04
123	APT99-23	2630	26	0.166	(221)	1.590	(2121)	0.520	(13449)	99.3	≪1	9.4 $\pm$ 0.7	12.5 $\pm$ 0.2	1.7	80	1.25 $\pm$ 0.03
127	APT99-27	2017	49	0.091	(326)	1.315	(4713)	0.365	(15631)	63.5	19	4.3 $\pm$ 0.3	12.1 $\pm$ 0.2	1.5	59	2.00 $\pm$ 0.04
130	APT99-30	1470	29	0.082	(153)	1.347	(2511)	0.365	(15631)	99.4	1	3.9 $\pm$ 0.3				
132	APT99-32	3066	45	0.101	(270)	1.168	(3118)	0.365	(15631)	98.0	8	5.5 $\pm$ 0.4	12.0 $\pm$ 0.2	1.5	77	
133	APT99-33	2908	15	0.120	(121)	1.406	(1423)	0.365	(15631)	96.4	≪1	5.4 $\pm$ 0.5				
Briançonnais Zone: Western Piémont Schistes Lustrés																
206	APT99-06	2490	38	0.198	(634)	0.464	(1484)	0.366	(15841)	99.2	≪1	27.0 $\pm$ 1.4	13.5 $\pm$ 0.2	1.7	100	2.10 $\pm$ 0.04
213	APT99-13	1210	55	0.132	(417)	0.268	(845)	0.371	(15841)	>99.9	≪1	31.7 $\pm$ 2.0	12.8 $\pm$ 0.3	1.4	29	
215	APT99-15	1900	38	0.188	(482)	0.835	(2137)	0.373	(15841)	9.0	30	14.8 $\pm$ 1.1	12.2 $\pm$ 0.3	2.0	59	1.38 $\pm$ 0.03
306	CRS-06	2770	23	0.191	(359)	0.630	(1184)	0.356	(15841)	80.7	11	18.9 $\pm$ 1.4	11.0 $\pm$ 0.2	1.4	35	
311	CRS-11	2405	29	0.207	(527)	0.784	(2000)	0.364	(15841)	4.1	19	16.4 $\pm$ 1.1	12.0 $\pm$ 0.2	1.5	100	
Dora-Maira Dome																
901	VS-1	380	20	2.572	(1124)	15.947	(6969)	0.541	(14306)	1.5	13	15.2 $\pm$ 0.7	11.5 $\pm$ 0.2	1.6	103	1.82 $\pm$ 0.03
903	VS-3	780	20	0.029	(60)	0.232	(473)	0.597	(14691)	>99.9	≪1	13.1 $\pm$ 1.8	13.4 $\pm$ 0.3	1.2	15	
904	VS-4	1070	20	0.189	(386)	0.839	(1712)	0.599	(14691)	>99.9	≪1	23.4 $\pm$ 1.4	12.5 $\pm$ 0.3	1.9	55	
905	VS-5	970	17	0.202	(77)	0.692	(264)	0.540	(14306)	>99.9	≪1	27.3 $\pm$ 3.6	13.1 $\pm$ 0.3	1.6	25	
906	VS-6	380	20	0.080	(136)	0.465	(789)	0.595	(14691)	96.5	≪1	17.8 $\pm$ 1.7	13.3 $\pm$ 0.3	1.4	25	
907	VS-7	1140	20	0.276	(459)	1.349	(2241)	0.598	(14691)	76.4	1	21.2 $\pm$ 1.2	12.8 $\pm$ 0.2	1.9	108	1.14 $\pm$ 0.02

All age determinations were performed by E. Labrin with $\zeta\zeta = 346.6 \pm 6.3$ for glass dosimeter NBS962; all ages are reported as central ages (Galbraith & Laslett 1993). N, number of grains counted; ρ_s, spontaneous track density; ρ_i, induced track density; ρ_d, dosimeter track density; N_s, N_i, N_d, number of tracks counted to determine the reported track densities; $P(\chi^2)$, chi-square probability that the single grain ages represent one population; D, age dispersion; MTL, mean confined horizontal track length; No., number

kinetics (characterized by D_{par}) between 'older' basement and 'younger' Champsaur sandstone samples. All samples are characterized by low age dispersions (D <10%, except for sample 123) and mean confined track lengths (MTL) of 12.0–12.5 μm, with standard deviations (σ) of 1.5–1.7 μm. Below, we will use inverse modelling of the track-length distributions to assess whether the differences in age between these samples are significant.

The two new AFT ages from the western Briançonnais Zone in the Briançon area (samples 206 and 213) are 27.0 $\pm$ 1.4 and 31.7 $\pm$ 2.0 Ma, respectively. These ages are independent of either structural position or topographic elevation (Fig. 6b) and are slightly older than two ages of 22.2 $\pm$ 1.6 and 25.7 $\pm$ 2.4 Ma obtained by Schwartz (2002) in the Zone Houillère around Briançon. They clearly confirm the large jump in AFT ages (at similar elevations) across the Penninic Frontal Thrust proposed by Tricart *et al*. (2001), based on preliminary data. Both samples show low age dispersions (D ≪1%) and slightly longer track–length distributions (MTL = 12.8–13.5 μm; σ = 1.4–1.7 μm) than the Pelvoux samples. They also indicate the continuity of AFT ages between the Zone Houillère and the klippe of Ultrabriançonnais Zone, i.e. between the lowest and the highest thrust sheets within the westernmost part of the Briançonnais Zone.

The third sample from the western Briançonnais Zone (215) has a significantly younger age of 14.8 $\pm$ 1.1 Ma and a shorter MTL of 12.2 μm (σ = 2.0 μm). The single-grain ages in this sample are widely dispersed; however (D = 30%); using a binomial peak-fitting method (Brandon 1996), we identify three component ages of 10.1 $\pm$ 1.3, 16.9 $\pm$ 2.0 and 30.3 $\pm$ 7.6 Ma, respectively (Fig. 5). This sample was collected from a locality along one of the main branches of an active extensional-strike slip fault zone that is followed by the north–south upper Durance valley beween Briançon and Guillestre (Durance Fault Zone *sensu* Tricart *et al*. 1996) and is characterized by significant local cataclasis. Schwartz (2002) obtained an AFT age of 11.7 $\pm$ 1.2 Ma from the cataclastic Plan-de-Phasy granite, located along another branch of this fault zone, near Guillestre. This latter age is close to the minimum age component of sample 215; in both cases, the anomalously young ages can be interpreted as (partial or total) annealing of samples by hydrothermal fluid systems, analogous to those that feed currently active hot springs along the fault zone at Plan-de-Phasy, Réotier and Monétier-les-Bains (see Tricart *et al*. 1996). Such an interpretation implies that the fault zone has been active since middle Miocene times, as previously suggested by Tricart *et al*. (2001).

The two samples from the Ultrabriançonnais Zone to the east of the Briançonnais Zone have AFT ages of 16.4 $\pm$ 1.1 and 18.9 $\pm$ 1.4 Ma. They are significantly younger than those in the klippen of the same unit farther west. MTL are also significantly shorter (11.0 and 12.0 μm, respectively) for both samples, suggesting different thermal histories for the eastern and western borders of the Briançonnais Zone. In contrast, these ages differ little from those obtained by Schwartz (2002) from the frontal Piémont Schistes lustrés (21.9 $\pm$ 0.8 Ma and 22.2 $\pm$ 1.6 Ma, respectively), suggesting a continuity of AFT ages and thermal histories across the Piémont Front. Schwartz (2002) suggested a tendency for AFT ages to young toward the east within the Schistes lustrés Complex of the Queyras area as well as the Viso ophiolites; from 22.2 $\pm$ 1.6 Ma in Ubaye Valley to 8.6 $\pm$ 1.6 Ma in the Viso. The new ages obtained north of the transect studied by Schwartz (2002) are consistent with this regional gradient.

Finally, samples from the Dora-Maira basement in the Susa Valley show a relatively wide spread in ages, between 13.1 $\pm$ 1.8 and 27.3 $\pm$ 3.6 Ma, and are only weakly correlated with elevation (age–elevation gradient corresponding to 100 m Ma^{-1}; $r^2 = 0.39$; Fig. 6c). All samples except 901 have small age dispersions (D <1%). Track-length distributions also vary significantly between samples, with MTL between 11.5 μm (σ = 1.6 μm) and 13.4 μm (σ = 1.2 μm). Cadoppi *et al*. (2002) and Malusà *et al*. (2005) found similarly scattered ages between 18 and 26 Ma in the lower Susa Valley, and between 18 and 23 Ma in the Upper Susa valley, respectively. The age dispersion between samples within this unit is comparable with the regional variation in AFT ages that we consider significant. Regardless of this dispersion, however, the above-mentioned tendency for AFT ages to young toward the east across the Piémont Zone appears not to continue as far east as the Dora-Maira crystalline massif; all ages from the massif are significantly older than those reported by Schwartz (2002) from the Viso ophiolites.

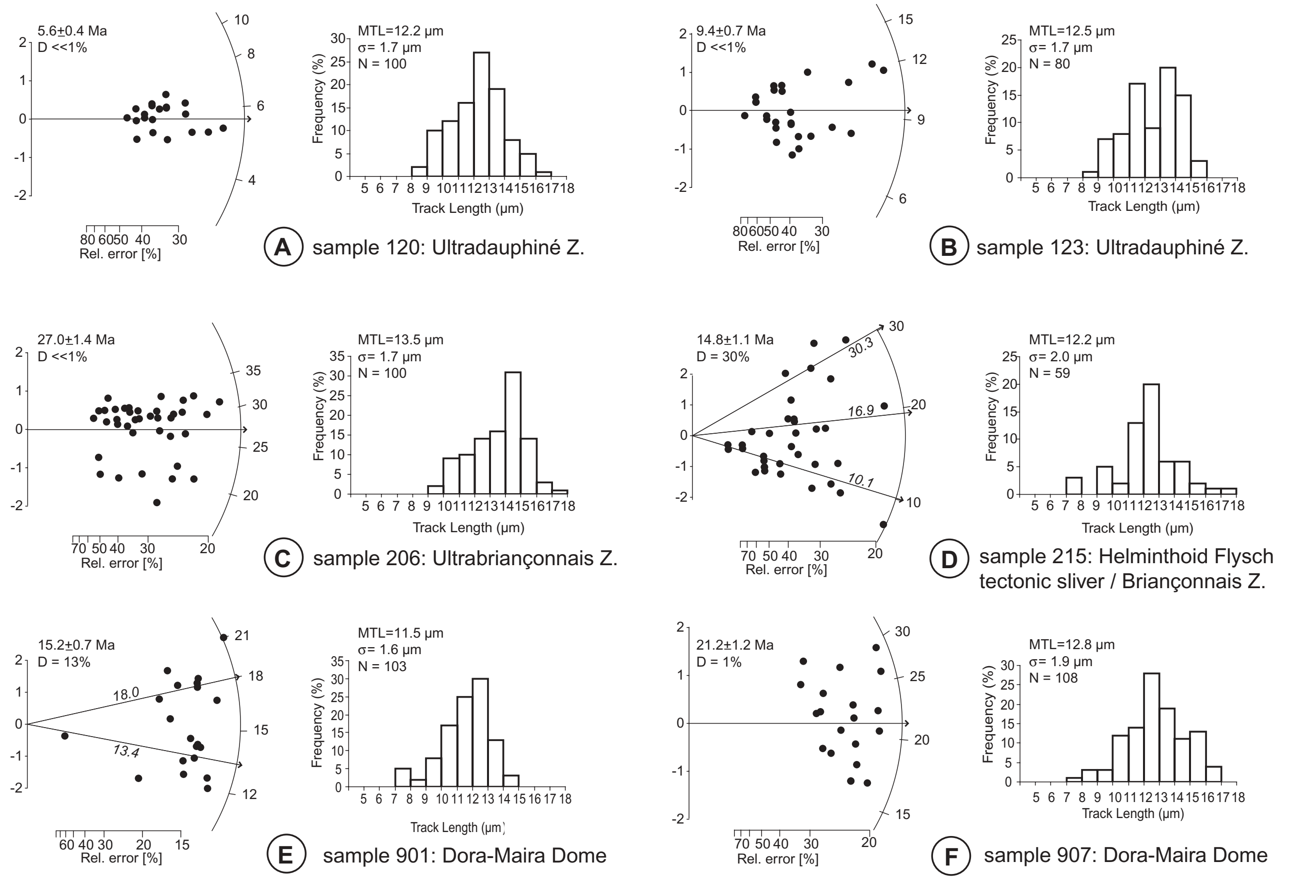

Fig. 5. Radial plots and confined AFT length distributions for selected representative samples in this study. (**a**) Sample 120 from the prealpine basement of the Ultradauphiné Zone; (**b**) sample 123 from the Champsaur sandstone of the Ultradauphiné Zone; (**c**) sample 206 from the prealpine basement of the Ultrabriançonnais Zone (klippe on the western Briançonnais Zone); (**d**) sample 215 from a tectonic slice of Helminthoid Flysch nappe in the Briançonnais zone; (**e**) sample 901 from the prealpine basement of the Dora–Maira Dome; (**f**) sample 907 from the prealpine basement of the Dora–Maira Dome.

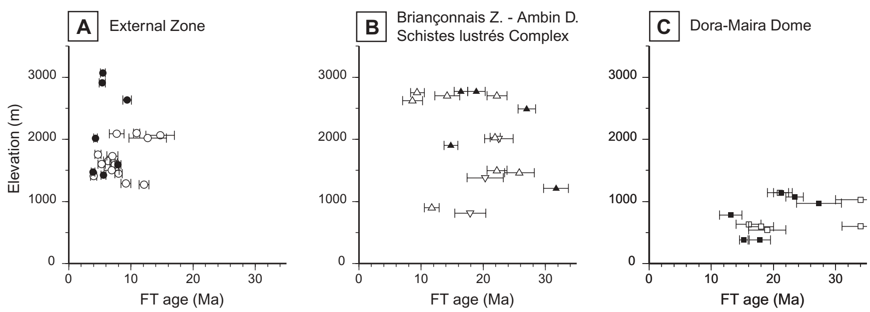

Fig. 6. AFT age–elevation plots: (**a**) external zone; (**b**) Briançonnais Zone *sensu lato*, Piémont Schistes lustrés Complex and Ambin Dome; (**c**) Dora–Maira Dome. Filled symbols are data from this study; ○, from Seward *et al*. (1999); △, from Schwartz (2002); ▽, from Malusà *et al*. (2005); □, from Cadoppi *et al*. (2002).

Thermal history modelling: methods

To quantify the inferred differences in cooling history between the various tectonic zones sampled, we invert the track-length distributions of selected samples to obtain thermal histories. Samples were selected on the basis of three criteria: (1) a sufficiently large number (preferably ⩾100) of track lengths; (2) a representative geographical distribution between the units sampled; (3) samples representative of the variation within any specific unit. We use the inversion code AFTSolve (Ketcham *et al*. 2000), based on the annealing algorithm of Ketcham *et al*. (1999), for the inversion. This approach has the advantage over previous annealing algorithms that it is able to incorporate differences in annealing kinetics between samples. We monitor annealing kinetics by measuring etch-pit widths (D_{par}) and incorporate these in the inversion. Although the AFTSolve code is capable of handling multiple kinetic populations within a single sample, we did not use this approach because we were unable to obtain AFT ages, track lengths and D_{par} on the same single grains, becaue of the low track densities of most of our samples. The standard deviation of our D_{par} measurements is generally <0.3 μm, except in samples 901 (0.33 μm) and 206 (0.42 μm). Of these, sample 901 also shows widely dispersed single-grain ages that could imply significantly variable annealing behaviour between grains. We use a simple Monte Carlo approach to search the time–temperature space, placing constraints on the search domain by trial and error. Resulting thermal histories are shown in Figure 7 and are based on at least 10 000 trial histories in the final model run. The model fit to both the single-grain age and track-length data is described by the relevant Kolmogorov–Smirnov (KS) statistic (Ketcham *et al*. 2000).

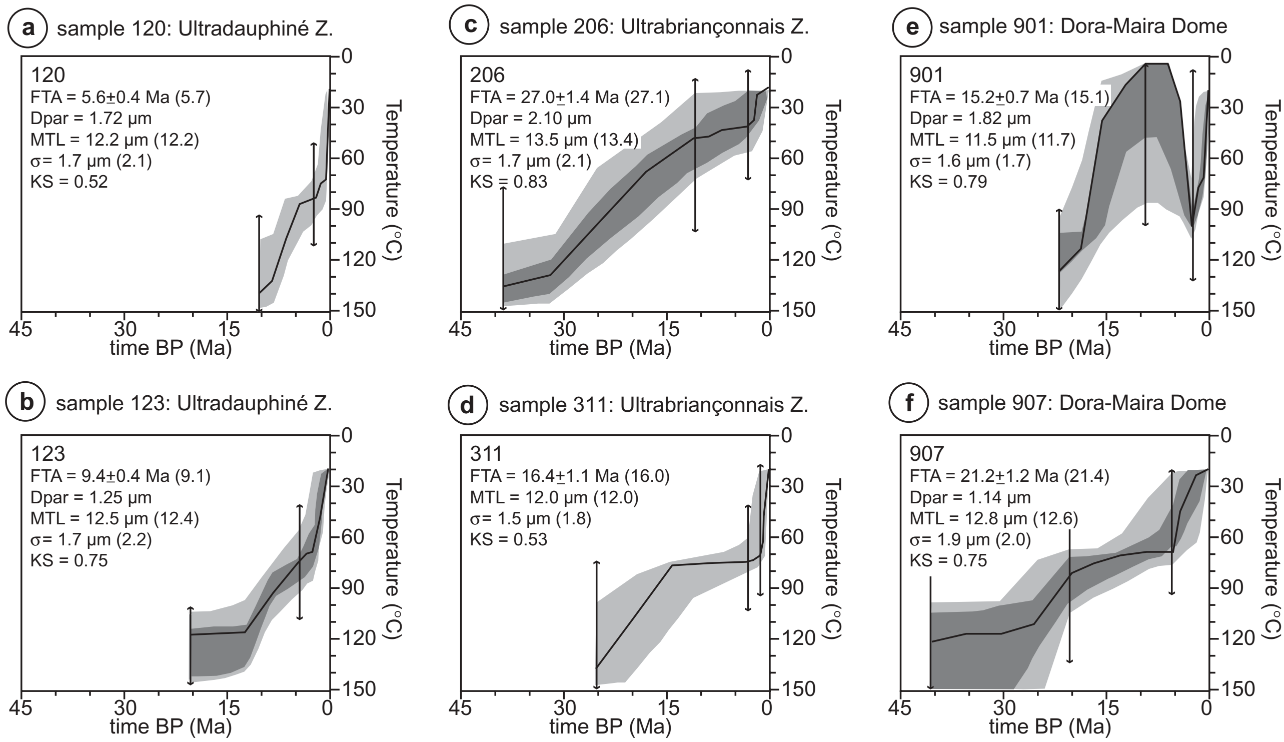

Fig. 7. Modelled cooling histories for selected representative samples from inversion of AFT length distributions, using AFTSolve software (Ketcham *et al.* 2000). (**a**) Sample 120 from the Ultradauphiné Zone; (**b**) sample 123 from the Ultradauphiné Zone; (**c**) sample 206 from the Ultrabriançonnais Zone; (**d**) sample 311 from the Ultrabriançonnais Zone; (**e**) sample 901 from the Dora–Maira Dome; (**f**) sample 907 from the Dora–Maira Dome. Bold black line is absolute best-fitting history (merit function KS statistic given in legend); grey shaded region encompasses well-fitting histories (merit function >0.5); light shaded region are acceptable histories (merit function >0.05). (See Table 1 for location of samples.)

Thermal history modelling: results

To place constraints on the thermal history of the southeastern Pelvoux Massif, we used sample 120 from the basement in the Byaise Valley (Dormillouse Dome) and the ‘outlying’ sample 123 of the age–elevation transect in the Champsaur sandstone. Although AFT ages are significantly different for these samples, they both suggest similar thermal histories consisting of close to linear cooling (at 11–15 °C Ma^{-1} and 8–12 °C Ma^{-1}, respectively) since *c*. 10 to *c*. 12 Ma, with a possible slight acceleration in cooling rates during the last 2–3 Ma. These relatively rapid cooling rates correspond to denudation rates of 0.25–0.75 km Ma^{-1} for reasonable values of the geothermal gradient (20–35 °C km^{-1}), significantly less than the denudation rate of 1.0 km Ma^{-1} inferred from the age–elevation gradient. This discrepancy suggests that the strong relief of the Pelvoux Massif may have perturbed upper crustal isotherms, leading to an increase in observed age–elevation gradients (e.g. Stüwe *et al*. 1994; Braun 2002).

Sample 206, from the western border of the Briançonnais Zone, shows much slower continuous cooling of 3–4 °C Ma^{-1} since *c*. 30–40 Ma, as indicated by its much older AFT age. According to Tricart *et al*. (2006), the Briançonnais fan structure results from a major late Alpine (Oligocene) shortening phase, and must have formed a high and narrow range (‘Briançonnais cordillera’) that was rapidly eroded during Late Oligocene times. If rapid enough, the resulting cooling could explain why the same reverse polarity magnetization is systematically observed in the entire arcuate southern Briançonnais zone between the north of the Pelvoux Massif in the north and the east of the Argentera Massif in the south (Collombet et al. 2002). To be consistent with the thermal history modelled here, this exhumation must have decelerated before the entrance of the western Briançonnais Zone in the partial annealing zone during final exhumation. This deceleration may be related to the onset of extension in Miocene times through less active relief building.

The eastern border of the Briançonnais Zone, represented by sample 311, shows a two-stage thermal history with initial slow cooling at 2–3 °C Ma^{-1} since 25 Ma, possible thermal stability from *c*. 15 Ma onward, followed by very rapid (30–40 °C Ma^{-1}) cooling in the last 2–3 Ma. The cooling history of the latter sample is qualitatively similar to that of a sample from the SW Ambin Dome (indicated by its age of 22.5 Ma in Fig. 2) modelled by Malusà *et al*. (2005), even though their modelling approach is slightly different in detail. The very fast final cooling recorded by these samples could be related to relief rejuvenation in this part of the Internal Alps as a result of very deep valley incision on the Italian side, which would also explain the location of the Alpine drainage divide within the eastern Schistes lustrés Complex and the relief (e.g. Viso Massif) that is comparable with that observed in the External Crystalline Massifs. As in the Briançonnais nappe stack, the preceding slow cooling stage is consistent with a regionally distributed brittle extension, limiting relief growth.

Within the Dora-Maira Massif, sample 907 shows a prolonged history of slow continuous cooling at 2.5–4 °C Ma^{-1} since *c*. 25 Ma with a possible acceleration to 5–10 °C Ma^{-1} since *c*. 5 Ma. The modelled thermal histories for sample 901 are more problematic: the best-fit thermal histories for sample 901 suggest reheating between *c*. 5 and 2 Ma, but the complete lack of independent geological evidence for such an event leads us to disregard it as a model artefact, possibly related to the fact that we treated this model as monokinetic whereas it contains in fact multiple kinetic populations. We prefer to interpret this history as indicating very slow (1–2 °C Ma^{-1}) cooling since *c*. 22 Ma followed by a late phase of very rapid (40–50 °C Ma^{-1}) cooling since *c*. 2 Ma. It should be noted that this slow cooling immediately followed extremely rapid exhumation of the massif from UHP conditions to shallow crustal levels between 35 and 30 Ma (e.g. Rubatto & Hermann 2001).

Many of the modelled thermal histories are characterized by a late stage of rapid cooling. This stage is most clearly expressed by samples 311 and 901, and least clearly by samples 206 and 907. Such late-stage cooling phases have often been inferred from inversions of AFT track-length distributions and are generally considered as model artefacts. We have therefore tested the robustness of these features and their sensitivity to annealing model parameters. We find that, in most cases, the amount and rate of cooling are sensitive to the choice of annealing model and the value of the kinetic parameter D_{par}, but their timing or existence is not. We also note that the strongest recent cooling is recorded by samples collected in valley bottoms whereas samples from interfluve ridges (e.g. 206, 907) show the least late-stage acceleration in cooling rates. We therefore suggest that these stages are real and are related to rapid valley excavation since 2–5 Ma, possibly as a result of erosion by large valley glaciers during Quaternary glaciations.

Discussion

Our new AFT data across the central western Alps complement existing data both to the north and south and highlight previously little recognized patterns of thermochronological ages within the arc. In the following, we discuss the implications of these new data for the interpretation of various structures in the western Alps.

The Dormillouse Dome, an aborted External Crystalline Massif?

In the southeastern Pelvoux, AFT ages lie between *c*. 4 and 9 Ma, with MTL around 12–12.5 μm, and indicate cooling at rates of 8–15 °C Ma^{-1} over the last 10–12 Ma. In the Belledonne, Mont Blanc and Aar External Crystalline Massifs, very young AFT ages (≤3.5 Ma) have been observed that are strongly correlated to elevation. These data suggest rapid recent exhumation of these massifs at rates of up to 1 mm year^{-1} (reviews by Bogdanoff *et al*. 2000; Fügenschuh & Schmid 2003), similar to present-day rock uplift rates from levelling data in the northern branch of the western Alps (see, e.g. Jouanne *et al*. 1995). These high rates of recent denudation, as well as the high present-day elevation of the External Crystalline Massifs, have been attributed to late out-of-sequence thrusting towards the NE (e.g. Jouanne *et al*. 1995; Kahle *et al*. 1997), although a climatic origin, related to Plio-Pleistocene intensified precipitation and/or glaciation, cannot be ruled out (e.g. Kuhlemann *et al*. 2002; Cederbom *et al*. 2004).

In the southeastern Pelvoux AFT ages are slightly older and the correlation with elevation is less clearly expressed. Zircon fission-track (ZFT) ages have not been completely reset during Alpine deformation and this model may be less applicable. It seems that the Dormillouse Dome did not record the recent acceleration in denudation rates as strongly as the other External Crystalline Massifs, as also suggested by its relatively modest elevation. Instead, the thermal history modelled here for the southeastern Pelvoux basement and its sedimentary cover (Ultradauphiné Zone) may be explained by Late Miocene tectonic denudation below the Penninic Frontal Thrust, reactivated as an extensional detachment, as initially suggested by Tricart *et al*. (2001).

The northwestern part of the Argentera Massif shows a similar late Miocene exhumation, which would have taken place, however, within a transpressive context (Bigot-Cormier *et al*. 2000). It is possible that the evolution of this part of the Argentera Massif, also characterized by relatively modest elevations, *c*. 6 Ma AFT ages and non-reset ZFT ages, is linked to that of the Dormillouse Dome. Such a link is also suggested by the comparable geological histories of these two areas and their remarkably symmetrical structure on either side of the Embrunais–Ubaye structural depression (Tricart 1981).

Diachronous along-strike exhumation in the Briançonnais Zone Houillère

The three AFT ages that are now available at the southern termination of the Zone Houillère in the Briançon region have a mean of 26.5 Ma. This result confirms that internal arc rocks in the hanging wall of the Penninic Frontal Thrust entered the AFT partial annealing zone some 20 Ma before external arc rocks in the footwall (see also Fügenschuh & Schmid 2003; Malusà *et al*. 2005). It also shows that late-stage exhumation of the Zone Houillère is diachronous at the scale of the western Alps, clearly becoming older toward the south. Such diachronous final exhumation contrasts strongly with the relative synchronicity of late-stage exhumation of the External Crystalline Massifs across the entire external arc, from the Aar Massif to the Argentera Massif.

In the northern branch of the western Alps, Malusà *et al*. (2005) have shown that an 'internal domain' (Grand Saint Bernard Nappe, Piémont Schistes lustrés, Grand Paradiso Massif), which cooled through the AFT partial annealing zone during Oligocene to Early Miocene times, overthrusts an 'external domain' that records much more recent final cooling (Late Miocene to Pliocene AFT ages). Malusà and coworkers positioned the Zone Houillère in the external domain, together with the Valaisan Zone and the Belledonne Massif, in contrast to the situation observed here. We suggest that this difference is a direct consequence of the laterally diachronous final exhumation of the Zone Houillère.

Fügenschuh & Schmid (2003) argued that, in the northern branch of the western Alps, the Zone Houillère has undergone tilting toward the south since 17 Ma. Such tilting would explain both the southward disappearance of the Zone Houillère south of Briançon as well as the laterally diachronous final exhumation. In contrast, Malusà *et al*. (2005) explained the observed diachronicity by an evolving late-stage tectonic regime that would become transpressive in the north and transtensive in the south. However, such a compressive regime in the northern branch of the western Alps has not been confirmed by recent palaeostress analyses (Champagnac *et al*. 2004).

Whereas the final exhumation of the Briançonnais Zone is thus clearly diachronous in the northern branch of the western Alps, it appears much more synchronous and also occurs remarkably early in the southern branch, which therefore requires another explanation.

Early final exhumation of the Briançonnais Zone in the southern branch of the western Alps

Only very few AFT ages are known from the internal zones in the southern branch of the western Alpine arc. Carrapa (2002) reported two AFT ages from the Ligurian Alps in the extreme south of the arc, obtained from prealpine basement rocks in the Briançonnais Zone. Both are close to 24 Ma, and they are confirmed by an AFT age of 25.9 Ma for a boulder within Oligocene molasse deposits that rework the basement *in situ*. Although more work is required to confirm these ages, we note the remarkably similar and relatively old AFT ages on both the northern and southern extremities of the southern Briançonnais Arc.

These continuous old ages suggest that the southern branch of the Briançonnais arc has its own exhumation history. Tricart *et al*. (2006) proposed that Oligocene exhumation of the Briançonnais Zone to the SE of the Pelvoux Massif is mainly due to erosion of a major topographic high formed by the rapid succession of the last two Alpine shortening phases: a phase of west-vergent prothrusting onto the external zone and an ensuing east-vergent backthrusting phase onto the Piémont Zone. Their combined effects explain the fan structure of the Briançonnais Zone (Tricart 1984). Whereas the prothrusting phase is well developed throughout the southern branch of the western Alpine arc, the backthrusting phase increases in intensity from north to south. As a result, the structure of the Briançonnais Zone evolves from fan-shaped SE of the Pelvoux Massif to dominantly backthrust in the Ubaye region and, eventually, exclusively backthrust east of the Argentera Massif (Gidon 1972). As a working hypothesis, we suggest that the intensity of both phases, as well as the associated exhumation, rapidly diminishes north of the Pelvoux Massif, explaining the observed diachronicity of final cooling in the Zone Houillère.

The hypothesis of rapid erosional denudation of a topographic high in the Briançonnais Zone of the southern arc during the Oligocene is consistent with the observation that Molasse sediments erode backthrust structures from the Oligocene onward in the Piémontais–Ligurian basin (Carrapa 2002). Thus, the present-day morphology appears to have been inherited from the Oligocene in the southernmost internal part of the western Alps, suggesting little Neogene erosion.

Contrast in cooling ages and rates across the Penninic Frontal Thrust

The new AFT age of 27.0 ± 1.4 Ma from a sample collected in the klippe of the Ultrabriançonnais Zone at Serre-Chevalier is similar to the Oligocene (*c*. 26.5 Ma) ages reported from the western Briançonnais Zone that overthrusts the external zone along the Penninic Frontal Thrust (Tricart *et al*. 2001). Thus, the new data clearly confirm the significant jump in ages across this structure, with a mean age of 4.8 Ma in the footwall of the thrust and a mean age of 26.7 Ma in the hanging wall. The age jump of *c*. 22 Ma is even larger than the initial estimate of 14 Ma by Tricart *et al*. (2001). The jump in ages is accompanied by an associated jump in final cooling rates: from 8–15 °C Ma^{-1} in the easternmost external zone (Ultradauphiné Zone) to only 3–4 °C Ma^{-1} in the Briançonnais Zone.

Tricart *et al*. (2001) have linked this age jump to the reactivation, as an extensional detachment, of the Penninic Frontal Thrust. Field observations also indicate a major late extensional motion on this fault zone (Sue & Tricart 1999). This scenario implies a two-stage exhumation process, beginning with erosional exhumation in the hanging wall during compression, followed by extensional tectonic exhumation in the footwall. Final cooling of the Dormillouse Dome would thus have taken place in Late Miocene times through tectonic denudation from under the extensionally reactivated Penninic Frontal Thrust. Whereas the internal arc was subjected to widespread extension since the Miocene, the external arc was uplifted in a contractional regime (see the review by Tricart *et al*. 2006).

The major and strongly localized jump in ages observed in the central part of the arc is exceptional; further north, the age jumps that can be attributed to late-stage extension within the internal arc are less important and spread out across several fault zones. These are either (generally inward-facing) normal faults superimposed on previously active thrusts, or extensionally reactivated thrust zones straddling the internal–external zone boundary (Aillères *et al*. 1995; Cannic *et al*. 1999; Fügenschuh *et al*. 1999). The northward-younging ages within the Zone Houillère also contribute to the fact that the observed age jump becomes smaller to the north.

Diachronous late-stage cooling across the internal arc

Along our transect, AFT ages within the internal zones become younger eastward, from a mean age of 26.7 Ma in the western Briançonnais Zone to *c*. 18 Ma close to the Piémont Front, and to 8.6 Ma within the Viso ophiolites. This 18 Ma variation in ages does not appear to be recorded in the internal zones further north. In contrast, recent reviews of AFT ages in the northern branch of the western Alpine arc (Fügenschuh & Schmid 2003; Malusà *et al*. 2005) show an inverse gradient, with older ages toward the core of the arc, particularly along the Gran Paradiso transect. This contrasting behaviour poses the problem of whether the late-stage history of the southern branch of the arc was different from that further north.

Our new AFT data from the eastern Briançonnais Zone (i.e. samples 306, 311) indicate a protracted slow cooling history, possibly punctuated by a period of thermal stability followed by rapid final exhumation (Fig. 7). Such slow cooling or thermal stability could be related to the installation of a widespread extensional regime within the internal zones (as discussed above), whereas the rapid final cooling may be related to rapid incision following expansion of the Durance drainage network up to this area that forms the divide between the Po and Rhône catchments.

Limited final doming in Dora-Maira Massif?

Although the ages we obtained from the Dora-Maira Massif are dispersed, they are generally older than those found within the Schistes lustrés Complex and the Viso ophiolites that flank the massif to the west. This age pattern is inconsistent with significant late-stage extensional movement along ductile shear zones forming the western flank of the Dora-Maira Massif. In contrast, the pattern implies that the final doming in the Dora-Maira Massif and the associated tectonic denudation along its western flank (see Tricart *et al*. 2006, for review) occurred at very shallow levels, above the AFT partial annealing zone. By analysing the provenance of the detritus filling the Piemont (Ligurian) molasse basin, Carrapa (2002) has shown that incision into the basement nappe pile forming the Dora-Maira Massif is relatively recent (<10 Ma). The AFT data for the massif reported both here and by Cadoppi *et al*. (2002) indicate that this incision could only result from minor late-stage doming in units that were already close to the surface.

Comparison with other mountain belts

The emerging pattern of late-stage exhumation in the western Alpine arc is characterized by significant lateral and transverse variation in timing and rates.

Conclusions

Our dataset, combined with previously published results, indicates that AFT ages spanning the entire Miocene epoch are encountered in the western Alpine arc and significant diachronicity occurs across and along the belt (Fig. 8).

Across the belt, the major age jump between the internal and external zones is confirmed; final exhumation from the AFT closure temperature depth of 3–4 km took place during Late Miocene–Pliocene times in the external arc, but during the Late Oligocene in the westernmost internal arc. Such an age pattern is consistent with extensional reactivation of the major thrust zone juxtaposing the internal and external arcs. The 22 Ma age jump we demonstrate to the SE of the Pelvoux Massif is significantly larger than that observed further north, where it is also less concentrated on a single fault zone.

East of the Pelvoux Massif, within the internal arc, ages young toward the centre of the arc with an age spread of *c*. 18 Ma over a 40 km distance. Final exhumation took place during Late Oligocene times along the western front of the Briançonnais Zone and during Late Miocene times in the Viso ophiolites. This eastward younging does not continue into the Dora-Maira Massif, based on the relatively dispersed preliminary data presented here. The older ages within this massif are inconsistent with the hypothesis of major tectonic denudation of the massif from under the Viso ophiolites and Schistes lustrés during late-stage extensional doming.

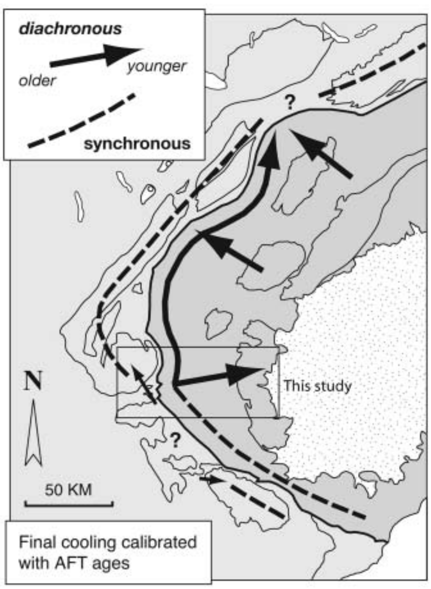

Fig. 8. Summary sketch indicating AFT age-trends observed along and across the western Alpine arc. Same structural map as in Figure 1a.

Diachronicity along the strike of the belt is illustrated in the internal zones by the final exhumation of the Zone Houillère, which becomes younger northward within the northern branch of the western Alpine arc. Between the Mont Blanc and Pelvoux transects, the difference in AFT ages is *c*. 20 Ma over a lateral distance of *c*. 150 km and spans practically the entire Miocene. Further south, final exhumation of the Briançonnais Zone could be synchronous and remarkably early, possibly related to rapid erosional denudation of a major topographic high developed during late-stage Oligocene contractional deformation. Within this southern branch of the arc, major late-stage extension remains to be documented.

Interpreting the significance of these diachronous age patterns in more detail will require a finer sampling grid as well as the use of multiple thermochronometers to obtain cooling ages for different temperatures. Our future work will be guided by two working hypotheses: (1) a varying age and intensity of the late-Alpine contractional phases along strike of the Briançonnais Zone; (2) a variable imprint of late-stage extension in the western Alpine internal arc.

We thank D. Seward and M. Krabbendam for constructive reviews.

References

Aillères, L., Bertrand, J.M., Macaudière, J. & Champenois, M. 1995. New structural data from the 'Zone Houillère Brianconnaise' (French Alps), neoalpine tectonics and consequences for the interpretation of the Pennine Front. *Comptes Rendus de l'Académie des Sciences, Série IIA*, **321**, 247–254.

Barféty, J.-C., Lemoine, M., de Graciansky, P.C., Tricart, P. & Mercier, D. 1996. *Briançon, Geological Map of France, 1:50 000*. Bureau de Recherche Géologique et Minière, Orléans.

Bigot-Cormier, F., Sosson, M. & Poupeau, G. 2000. Differential denudation of the Argentera Alpine external crystalline massif (SE France) revealed by fission tracks thermochronology (zircons, apatites). *Comptes Rendus de l'Académie des Sciences, Série II*, **330**, 363–370.

Bistacchi, A. & Massironi, M. 2000. Post-nappe brittle tectonics and kinematic evolution of the north-western Alps: an integrated approach. *Tectonophysics*, **327**, 267–292.

Bistacchi, A., Eva, E., Massironi, M. & Solarino, S. 2000. Miocene to Present kinematics of the NW-Alps: evidences from remote sensing, structural analysis, seismotectonics and thermochronology. *Journal of Geodynamics*, **30**, 205–228.

Bogdanoff, S., Michard, A., Mansour, M. & Poupeau, G. 2000. Apatite fission track analysis in the Argentera massif: evidence of contrasting denudation rates in the External Crystalline Massifs of the Western Alps. *Terra Nova*, **12**, 117–125.

Brandon, M.T. 1996. Probability density plot for fission-track grain-age samples. *Nuclear Tracks and Radiation Measurements*, **26**, 663–676.

Braun, J. 2002. Quantifying the effects of recent relief changes on age-elevation relationships. *Earth and Planetary Science Letters*, **200**, 331–343.

Bürgisser, J. & Ford, M. 1998. Overthrust shear deformation of a foreland basin; structural studies south-east of the Pelvoux massif, SE France. *Journal of Structural Geology*, **20**, 1455–1475.

Cadoppi, P., Balestrieri, M.L., Bigazzi, G., Riccio, I. & Tallone, S. 2002. Oligocene–Miocene differential exhumation of the Western Alps in the Lower–Middle Susa Valley: evidence from apatite fission track analysis (abstract). *In: Riunione estiva della Società Geologica Italiana. Cinematiche collisionali: tra esumazione e sedimentazione, Torino*. Lit. GEDA, Torino, 73–74.

Calais, E., Nocquet, J.M., Jouanne, F. & Tardy, M. 2002. Current strain regime in the Western Alps from continuous Global Positioning System measurements, 1996–2001. *Geology*, **30**, 651–654.

Cannic, S., Mugnier, J.-L. & Lardeaux, J.-M. 1999. Neogene extension in the Western Alps. *Memorie di Scienze Geologiche, Padova*, **51**, 33–45.

Carrapa, B. 2002. *Tectonic evolution of an active orogen as reflected by its sedimentary record. An integrated study of the Tertiary Piedmont Basin (Internal Western Alps, NW Italy)*. PhD thesis, Vrije Universiteit Amsterdam.

Cederbom, C., Sinclair, H., Schlunegger, F. & Rahn, M. 2004. Climate-induced rebound and exhumation of the European Alps. *Geology*, **32**, 709–712.

Ceriani, S., Fugenschuh, B. & Schmid, S.M. 2001. Multi-stage thrusting at the 'Penninic Front' in the Western Alps between Mont Blanc and Pelvoux

massifs. *International Journal of Earth Sciences*, **90**, 685–702.
Champagnac, J.D., Sue, C., Delacou, B. & Burkhard, M. 2004. Brittle deformation in the inner NW Alps: from early orogen-parallel extrusion to late orogen-perpendicular collapse. *Terra Nova*, **16**, 232–242.
Collombet, M., Thomas, J.C., Chauvin, A., Tricart, P., Bouillin, J.P. & Gratier, J.P. 2002. Counterclockwise rotation of the western Alps since the Oligocene: new insights from paleomagnetic data. *Tectonics*, **21**, 352–366.
Corsini, M., Ruffet, G. & Caby, R. 2004. Alpine and Late-Hercynian geochronological constraints in the Argentera massif (Western Alps). *Eclogae Geologicae Helvetiae*, **97**, 3–15.
Debelmas, J. 1980. Alpes, Bassin Rhodanien, Provence et Corse. *In:* Lorentz, C. (ed.) *Géologie des Pays Européens: France, Luxembourg*. Dunod, Paris, 263–352.
Debelmas, J. & Lemoine, M. 1966. *Guillestre, Geological Map of France 1:50 000*. Service de la Carte Géologique de France, Paris.
Ford, M. 1996. Kinematics and geometry of early alpine, basement-involved folds, SW Pelvoux Massif, SE France. *Eclogae Geologicae Helvetiae*, **89**, 269–295.
Fügenschuh, B. & Schmid, S.M. 2003. Late stages of deformation and exhumation of an orogen, constrained by fission-track data: a case study in the Western Alps. *Geological Society of America Bulletin*, **115**, 1425–1440.
Fügenschuh, B., Loprieno, A., Ceriani, S. & Schmid, S.M. 1999. Structural analysis of the Subbriançonnais and Valais zone in the area of Moutier (Savoy, Western Alps): paleogeographical and tectonic consequences. *International Journal of Earth Sciences*, **88**, 201–218.
Galbraith, R.F. 1990. The radial plot: graphical assessment of spread in ages. *Nuclear Tracks and Radiation Measurements*, **17**, 207–214.
Galbraith, R.F. & Laslett, G.M. 1993. Statistical models for mixed fission track ages. *Nuclear Tracks and Radiation Measurements*, **21**, 459–470.
Gidon, M. 1972. Les chaînons briançonnais et subbriançonnais de la rive gauche de la Stura, entre Bersezio et le val de l'Arma (Prov. de Cuneo, Italie). *Géologie Alpine*, **48**, 87–120.
Gidon, M., Kerckhove, C. & Michard, A. et al. 1994. *Aiguille de Chambeyron, Geological Map of France, 1:50 000*. Bureau de Recherche Géologique et Minière, Orléans.
Goffé, B., Schwartz, S., Lardeaux, J.-M. & Bousquet, R. 2004. Exploratory notes to the map: metamorphic structure of the Alps, Western and Ligurian Alps. *Mitteilungen der Osterreichischen Mineralogischen Gesellschaft*, **149**, 125–144.
Gratier, J.P., Ménard, G. & Arpin, R. 1989. Strain–displacement compatibility and restoration of the Chaînes Subalpines of the Western Alps. *In:* Coward, M.P., Dietrich, D. & Park, R.G. (eds) *Alpine Tectonics*. Geological Society, London, Special Publications, **45**, 65–81.
Gupta, S. & Allen, P.A. 2000. Implications of foreland paleotopography for stratigraphic development in the Eocene distal Alpine foreland basin. *Geological Society of America Bulletin*, **112**, 515–530.
Hurford, A.J. 1990. International union of geological sciences subcommission on geochronology recommendation for the standardization of fission track dating calibration and data reporting. *Nuclear Tracks and Radiation Measurements*, **17**, 233–236.
Jouanne, F., Ménard, G. & Darmendrail, X. 1995. Present-day vertical displacements in the north-western Alps and southern Jura Mountains:data from leveling comparisons. *Tectonics*, **14**, 606–616.
Kahle, H.G., Geiger, A. & Bürki, B.B. et al. 1997. Recent crustal movements, geoid and density distribution: contribution from integrated satellite and terrestrial measurements. *In:* Pfiffner, O.A., Lehner, P., Heitzmann, P., Müller, S. & Steck, A.et al. (eds) *Results of the National Research Program 20 (NRP 20)*. Birkhäuser, Basel, 251–259.
Ketcham, R.A., Donelick, R.A. & Carlson, W.D. 1999. Variability of apatite fission-track annealing kinetics: (3) Extrapolation to geological time scales. *American Mineralogist*, **84**, 1236–1255.
Ketcham, R.A., Donelick, R.A. & Donelick, M.B. 2000. A program for multikinetic modeling of apatite fission-track data. *Geological Materials Research*, **2**, 1–32.
Kuhlemann, J., Frisch, W., Székely, B., Dunkl, I. & Kázmér, M. 2002. Post-collisional sediment budget history of the Alps: tectonic versus climatic control. *International Journal of Earth Sciences*, **91**, 818–837.
Lemoine, M. 1969. *Briançon, Geological Map of France, 1:80 000*. Bureau de Recherche Géologique et Minière, Orléans.
Lemoine, M. 1972. Rythme et modalités des plissements superposés dans les chaînes subalpines méridionales des Alpes occidentales françaises. *Geologische Rundschau*, **61**, 975–1010.
Lemoine, M. & Tricart, P. 1986. Les Schistes lustrés piémontais des Alpes occidentales: approche stratigraphique, structurale et sédimentologique. *Eclogae Geologicae Helvetiae*, **79**, 271–294.
Lemoine, M., de Graciansky, P.-C. & Tricart, P. 2000. *De l'océan à la chaîne de montagnes: tectonique des plaques dans les Alpes*. Gordon and Breach, Paris.
Lombardo, B., Nervo, R. & Compagnoni, R. et al. 1978. Osservazioni preliminari sulle ofioliti metamorfiche del Monviso (Alpi occidentali). *Rendiconti della Società Italiana di Mineralogia e Petrologia*, **34**, 253–305.
Malusà, M.G., Polino, R., Zattin, M., Bigazzi, G., Martin, S. & Piana, F. 2005. Miocene to Present differential exhumation in the Western Alps: insights from fission track thermochronology. *Tectonics*, **24**, doi:10.1029/2004TC001782.
Rubatto, D. & Hermann, J. 2001. Exhumation as fast as subduction? *Geology*, **29**, 3–6.
Sandrone, R., Cadoppi, P., Sacchi, R. & Vialon, P. 1993. The Dora-Maira massif. *In:* von Raumer, J.F. & Neubauer, F. (eds) *Pre-Mesozoic Geology in the Alps*. Springer, Berlin, 317–325.
Schmid, S.M. & Kissling, E. 2000. The arc of the western Alps in the light of geophysical data on deep crustal structure. *Tectonics*, **19**, 62–85.
Schmid, S.M., Fügenschuh, B., Kissling, E. & Schuster, R. 2004. Tectonic map and overall architecture of the Alpine orogen. *Eclogae Geologicae Helvetiae*, **97**, 93–117.
Schwartz, S. 2002. La zone piémontaise des Alpes occidentales: un paléo-complexe de subduction, Arguments métamorphiques, géochronologiques et structuraux. *Documents du BRGM*, **302**, 1–313.
Selverstone, J. 2005. Are the Alps collapsing? *Annual Review of Earth and Planetary Sciences*, **33**, 113–132.
Seward, D. & Mancktelow, N.S. 1994. Neogene kinematics of the central and western Alps—evidence from fission-track dating. *Geology*, **22**, 803–806.
Seward, D., Ford, M., Bürgisser, J., Lickorish, H., Williams, E.D. & Meckel, L.D. 1999. Preliminary results of fission-track analyses in the Southern Pelvoux area, SE France. *Memorie di Scienze Geologiche Padova*, **51**, 25–31.
Sinclair, H.D. 1996. Plan-view curvature of foreland basins and its implications for the palaeostrength of the lithosphere underlying the western Alps. *Basin Research*, **8**, 173–182.
Stüwe, K., White, K. & Brown, R.W. 1994. The influence of eroding topography on steady-state isotherms. Application to fission track analysis. *Earth and Planetary Science Letters*, **124**, 63–74.
Sue, C. & Tricart, P. 1999. Late Alpine brittle extension above the Frontal Pennine Thrust near Briançon, Western Alps. *Eclogae Geologicae Helvetiae*, **92**, 171–181.
Sue, C. & Tricart, P. 2003. Neogene to ongoing normal faulting in the inner western Alps. *Tectonics*, **22**, doi:10.1029/2002TC001426.
Sue, C., Thouvenot, F., Fréchet, J. & Tricart, P. 1999. Widespread extension in the core of the western Alps revealed by earthquake analysis. *Journal of Geophysical Research*, **104**, 25611–25622.
Tricart, P. 1981. Les marqueurs des mouvements verticaux du socle aux abords du massif du Pelvoux (Alpes occidentales). *Revue de Géologie Dynamique et de Géographie Physique*, **23**, 289–300.
Tricart, P. 1984. From passive margin to continental collision: a tectonic scenario for the Western Alps. *American Journal of Science*, **284**, 97–120.
Tricart, P. 2004. From extension to transpression during the final exhumation of the Pelvoux and Argentera massifs, Western Alps. *Eclogae Geologicae Helvetiae*, **97**, 429–439.
Tricart, P., Bouillin, J.-P., Dick, P., Moutier, L. & Xing, C. 1996. Le faisceau de failles de haute-Durance et le rejeu distensif du front briançonnais au SE du Pelvoux (Alpes occidentales). *Comptes Rendus de l'Académie des Sciences*, **323**, 251–257.
Tricart, P., Schwartz, S., Sue, C., Poupeau, G. & Lardeaux, J.M. 2001. La dénudation tectonique de la zone ultradauphinoise et l'inversion du front briançonnais au sud-est du Pelvoux (Alpes occidentales): une dynamique miocène à actuelle. *Bulletin de la Société Géologique de France*, **172**, 49–58.
Tricart, P., Amaudric Du Chaffaut, S. & Ayoub, C. et al. 2003. *Aiguilles–Col Saint Martin, Geological Map of France, 1:50 000*. Bureau de Recherche Géologique et Minière, Orléans.
Tricart, P., Lardeaux, J.-M., Schwartz, S. & Sue, C. 2006. Neogene to current extension in the Internal Western Alps: the overall situation along the Pelvoux–Viso transect. *Bulletin de la Société Géologique de France*, **177**, 299–310.
Van der Beek, P.A. 2004. 'Vertical' age–elevation profiles, denudation rates and relief development (abstract). *In:* Hurford, A.J., Wagner, G., Vanderhaute, P. & Andriessen, P.A.M. (eds) *10th International Conference on Fission Track Dating and Thermochronology, Amsterdam*, 112.
Vernant, P., Masson, F., Bayer, R. & Paul, A. 2002. Sequential inversion of local earthquake traveltimes and gravity anomaly—the example of the western Alps. *Geophysical Journal International*, **150**, 79–90.

Received 16 November 2005; revised typescript accepted 9 May 2006.
Scientific editing by Maarten Krabbendam