

Late stages of deformation and exhumation of an orogen constrained by fission-track data: A case study in the Western Alps

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ABSTRACT

New zircon and apatite fission-track data, combined with a structural analysis, provide constraints regarding the large-scale tectonic evolution of part of the French/Italian Alps. The observed migration of cooling toward more external units is interpreted to be due to thrust propagation. In the absence of significant amounts of crustal thinning, the exhumation has been dominantly by erosion.

The most internal unit investigated (the Penninic Houillère zone) started to cool at ca. 35 Ma, after an earlier tectonometamorphic event that only affected Penninic units. Fission-track data from the Cheval Noir unit (replacing the Valaisan unit in the south) constrain the age of metamorphism in these frontal Penninic units to be older than 32 Ma. There, cooling started with the onset of a second stage of the tectonic evolution, i.e., with top-to-the-west-northwest movement along the Roselend thrust at ca. 32 Ma. This Oligocene to early Miocene thrusting led to burial and metamorphism in the external massifs and their cover (Dauphinois unit). During a third tectonic stage, thrust-related culminations formed in the external massifs. Between 20 and 15 Ma, this stage led to the onset of exhumation in the Dauphinois and in the northern frontal Penninic units (Valaisan units), caused by erosion that followed tilting in the backlimb of these culminations. Northward-increasing amounts of Miocene–Pliocene shortening in front of and below the external massifs led to significantly higher amounts of exhumation in the north. Finally, and in very recent times (post-5 Ma), the frontal thrust of the Houillère

zone was reactivated as a normal fault with moderate offset (<3 km).

Keywords: fission-track dating, Western Alps, low-grade metamorphism, cooling history, exhumation history.

INTRODUCTION

Deciphering the cooling and exhumation history of rocks by means of geochronological data has become a common tool applied to a wide range of geologic settings. Therefore, fission-track (FT) analysis still forms one of the most promising methods with respect to the near-surface and/or low-temperature part (i.e., from ~320 °C to ~60 °C) of the cooling history.

FT analysis does not date cooling through a “closure temperature” (Dodson, 1973). Instead, FT studies make extensive use of the “partial annealing zone” (PAZ) concept (Wagner, 1972; Wagner and Van den Haute, 1992). Together with modeling methods (e.g., Gallagher, 1995; Willett, 1997), such FT analysis provides details concerning the cooling rates over the entire temperature range that defines the PAZ. In this work the PAZ temperature ranges are taken to be 60–120 °C for apatite (Green et al., 1989) and 200–320 °C for zircon (Tagami et al., 1998). Further, when determining a singular temperature (T) vs. time (t) point during cooling (e.g., when providing a “central age”), mean values of 90 °C (apatite) and 260 °C (zircon) are used.

The French-Italian Western Alps represent a spectacular young and still-evolving, high-relief orogen that comprises numerous tectonic units, many with distinct structural and thermal histories (e.g., Debelmas and Kerckhove, 1980; Choukroune et al., 1986; Ricou and Sidans, 1986; Platt et al. 1989). In such a setting, conclusions drawn from a local data set may not be valid for neighboring areas. A

dense data set over a reasonably wide area is required for FT analysis, and the FT data must be supported with tectonic and stratigraphic control. Both requirements are met in this study.

GEOLOGIC SETTING

The investigated area extends from the Aosta valley (Italy) in the northeast to the Arc valley (France) situated ~100 km farther to the southwest. From internal to external (i.e., tectonically shallower to deeper), the following tectonic units are involved: Houillère zone (part of the Briançonnais units), Subbriançonnais, Valaisan, Cheval Noir flysch, and Dauphinois (Figs. 1 and 2).

The area is governed by two major tectonic boundaries, namely the “Roselend thrust,” also referred to as “Pennine front” (e.g., Mugnier et al., 1993) or “Penninic frontal thrust” (e.g., Schmid and Kissling, 2000), and the “Houiller front” (Figs. 1B and 2), both imaged in the ECORS-CROP (Etude de la Croûte continentale et Océanique par Reflexion Sismique-progetto della Crosta Profonda) seismic line (Roure et al., 1996). This paper uses the term “Roselend thrust,” proposed by Ceriani et al. (2001), to refer to a west-northwest-directed late (post-Priabonian) thrust, whereas “Penninic basal contact” is used to denote the boundary between Penninic and Helvetic/Dauphinois units in general (Fig. 1A). The term “Houiller front” (Fig. 2) simply denotes the western margin of the Houillère zone (e.g., Fügenschuh et al., 1999).

The most internal tectonic unit studied is the Middle Penninic Houillère zone (e.g., Escher et al., 1997). It is predominantly made up of Carboniferous–Permian sedimentary rocks with a minor Alpine metamorphic overprint that ranges from epizonal to lower greenschist facies in the more internal parts (Debelmas, 1989; Frey et al., 1999; Ceriani,

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2001). Published FT data for the Houillère zone can be found in Soom (1990), Seward and Mancktelow (1994), and Fügenschuh et al. (1999). Rb/Sr phengite data from the Petit St. Bernard pass area yielded ages older than Middle Jurassic, in agreement with the inferred low grade of Alpine metamorphism (Freeman et al., 1998).

The Subbriançonnais cover nappes (Fig. 2) comprise a throughgoing stratigraphic record from Upper Triassic to Upper Jurassic (Barbier, 1948). Ceriani (2001) determined a high-anchizonal metamorphic grade in the Subbriançonnais units by means of illite crystallinity measurements, which corresponds to temperatures of ≤ 300 °C (Frey and Ferreiro-Mählmann, 1999). No geochronological data have been published from this unit so far.

The Valaisan units (Fig. 2) are derived from the more external North Penninic (or Valais) oceanic basin (Trümpy, 1955; Frisch, 1979). Two different domains have been distinguished (Fügenschuh et al., 1999; Loprieno, 2001). The external Valaisan represents an eroded carbonate platform unconformably overlain by postrift sedimentary rocks of Barremian to Tertiary age (Trümpy, 1955; Antoine, 1971). It has been affected by greenschist-facies metamorphism (Goffé and Bousquet, 1997). In the internal Valaisan ("Versoyen"), however, identical postrift sedimentary rocks, deposited onto an oceanic basement (Fügenschuh et al., 1999; Loprieno, 2001), are characterized by high-pressure-low-temperature metamorphism (Schürch, 1987; Goffé and Bousquet, 1997). Available geochronological data include Ar/Ar and Rb/Sr phengite ages ranging between 33 and 27 Ma (Cannic, 1996; Freeman et al., 1998) and FT data (Seward and Mancktelow, 1994; Fügenschuh et al., 1999).

The Cheval Noir unit forms the frontal-most Penninic thrust sheet in the area south of Môtiers (Ceriani et al., 2001). This unit mainly comprises Priabonian detrital flysch-type sedimentary rocks, which unconformably overlie a Briançonnais-type substratum (Martinez-Reyes, 1980). The Cheval Noir unit was formerly attributed to the so-called "Ultradauphinois" (Gignoux and Moret, 1937; Serre et al., 1985), together with the Aiguilles d'Arves flysch of almost identical lithologic composition, but was subsequently attributed to the Penninic paleogeographical domain by Ceriani et al. (2001). The Cheval Noir unit is separated from the Aiguilles d'Arves unit by the Penninic basal contact (Ceriani et al., 2001). Illite crystallinity data for the Cheval Noir yielded values indicative of epizonal to lower-

anchizonal conditions (Ceriani, 2001). Apatite FT ages range between 4.7 and 3.2 Ma (Le-large, 1993).

The external crystalline massifs, and their Mesozoic to Tertiary cover (Dauphinois paleogeographical domain), display a metamorphic gradient of Alpine age. Grade increases from the top (youngest cover series found behind the massifs) toward the bottom (pre-Alpine basement). Superimposed is an along-strike gradient with grade increasing from south (Pelvoux) to north (Mont Blanc massif) (Desmons et al., 1999). Previously published radiometric work in the Dauphinois unit includes K/Ar dating of white mica, biotite, and amphiboles, as well as FT analysis (see Hunziker et al. [1992] and Desmons et al. [1999] for compilations).

The Alpine tectono-metamorphic evolution of the investigated area is characterized by the following stages: (1) subduction of the North Penninic (or Valais) trough, followed by final collision between Briançonnais-Subbriançonnais units and Dauphinois unit in a sinistrally transpressive setting (e.g., Choukroune et al., 1986; Ricou and Siddans, 1986; Fügenschuh et al., 1999); (2) post-Priabonian west-northwest-directed thrusting of the previously stacked internal (mostly Penninic) units onto the European foreland (Dauphinois) along the Roselend thrust (Schmid and Kissling, 2000; Ceriani et al., 2001); and (3) Pliocene to present-day extensional reactivation of former thrusts indicating east-west-directed extension across the Western Alps (e.g., Fügenschuh et al., 1999; Sue et al., 1999).

ANALYTICAL PROCEDURE

Eighty-two samples were analyzed. A list of samples is available.¹

INTERPRETATION OF SINGLE-GRAIN FISSION-TRACK DATA

FT data can be interpreted through a combination of an apparent age and track-length measurements (Gleadow et al., 1986). On the basis of numerous annealing studies of FTs in standards and test samples (e.g., Green et al., 1986; Laslett et al., 1987; Crowley et al., 1991), thermal histories can be modeled from track lengths (e.g., Gallagher, 1995; Willett, 1997). Single-grain age distributions (the technique used in this study) are affected by the

distinct annealing behavior of individual grains. The dependence of FT annealing on chemical composition is well known for apatite, especially in respect to its F/Cl ratio (e.g., Gleadow and Duddy, 1981; Green et al., 1985, 1986). Differences in zircon annealing characteristics are less understood, but compositional variation likely plays a minor role because of zircon's restricted compositional range (e.g., Brandon and Vance, 1992). Zircon etching properties are not significantly affected by variations in Hf, the main substitute for Zr (Krishnaswami et al., 1974). A systematic study has not been made, although Kasuya and Naeser (1988) showed that thermal stability of FTs in zircon decreases with increasing α -radiation damage and that the density of α -recoil tracks appears to be the controlling factor for zircon.

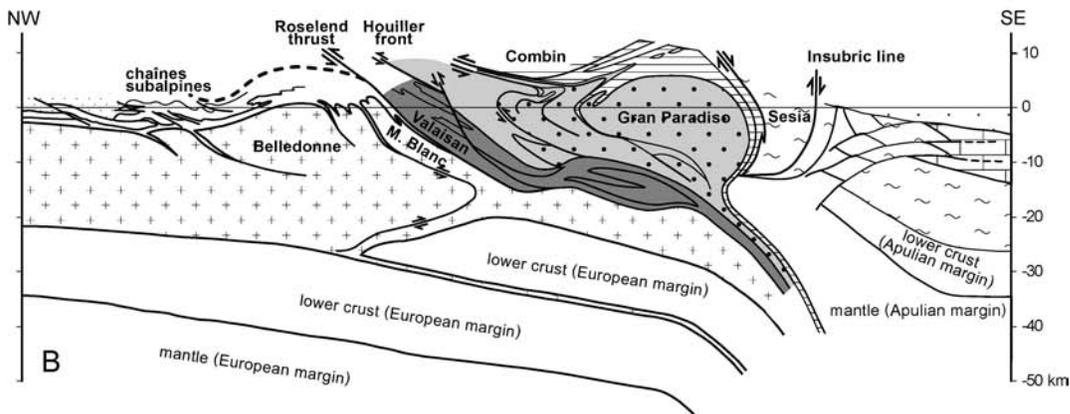
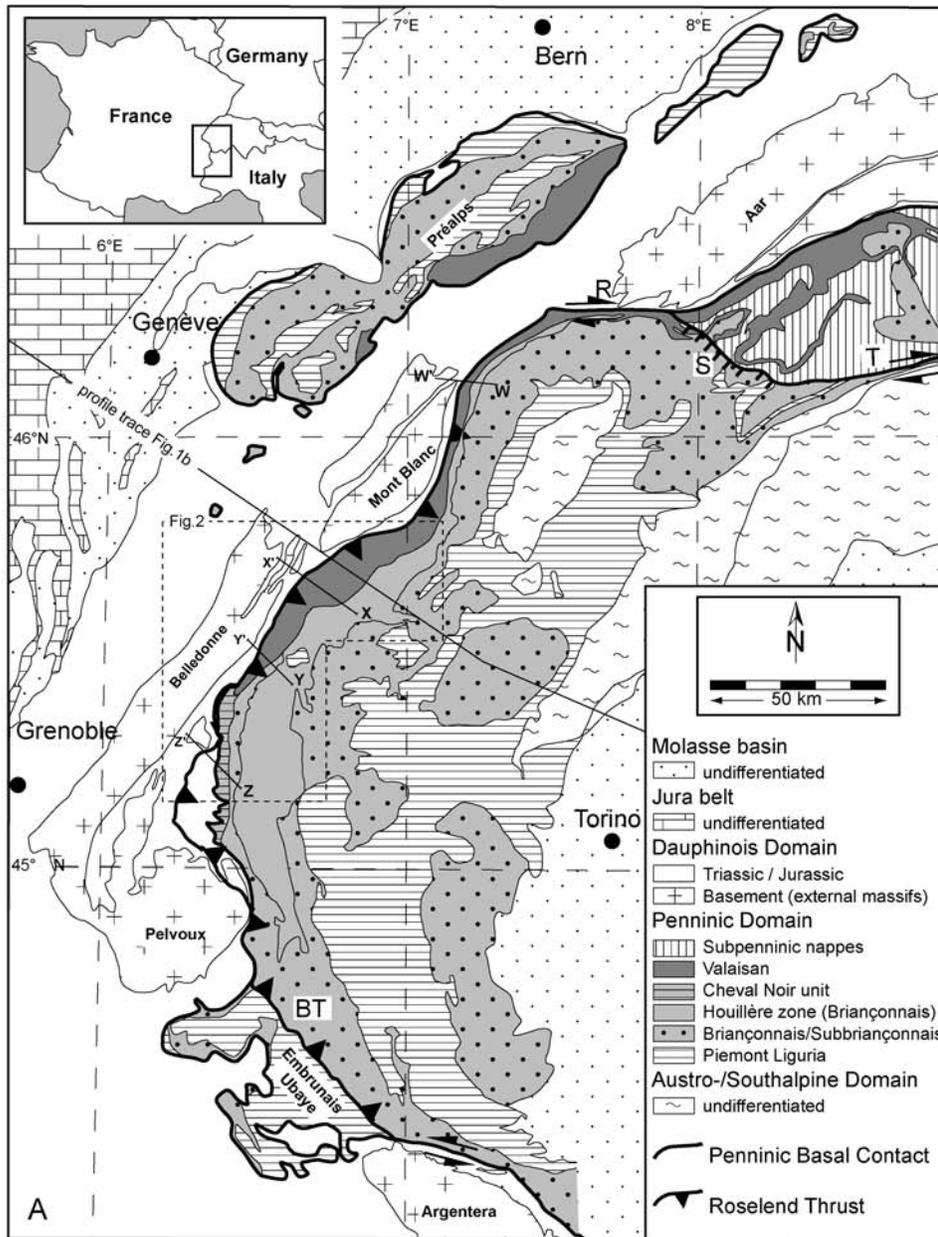
Thermal information, particularly the youngest cluster of ages, is interpretable in samples displaying a large spread in single-grain ages (e.g., Seward and Rhoades, 1986; Green, 1989; Brandon and Vance, 1992; Sobel and Dumitru, 1997; Brandon et al., 1998).

Single-grain age distributions are not only due to the different track retentivity of the individual grains within one sample, as will be assumed in the forthcoming discussion, but also to statistical and geometrical factors. The Poisson error results from the relatively low number or strongly skewed statistical ratios of counted tracks, whereas the geometrical error is related to the inhomogeneous distribution of U within the original intact analyzed grain. Together with possible gradients in neutron flux during irradiation, the scatter is the superposed result of all these effects.

In nonmetamorphosed sedimentary rocks (Fig. 3A) a large spread is commonly found for single-grain ages. By applying binomial peak-fitting methods (Galbraith and Green, 1990; Brandon, 1992), subpopulations (P1 and P2 in Fig. 3A), likely to represent different source areas, may possibly be distinguished (e.g., Spiegel et al., 2000; Berner et al., 2001). The youngest age cluster may be as young as the stratigraphic age.

A second scenario (Fig. 3B) involves slow cooling of previously fully annealed samples; for zircon FT analysis, temperatures must have exceeded 320 °C for full annealing (e.g., Tagami et al., 1998). During slow cooling (a few degrees per million years), individual grains with distinct amounts of α -radiation damage are thought to cause differences in track retention (Kasuya and Naeser, 1988). If it can be assumed that the sample includes individual zircon grains with maximum (~ 320 °C, corresponding to the upper limit of the zir-

¹GSA Data Repository item 2003xxx, apatite and zircon fission-track samples and analytical details and data, is available on the Web at <http://www.geosociety.org/pubs/ft2003.htm>. Requests may also be sent to editing@geosociety.org.



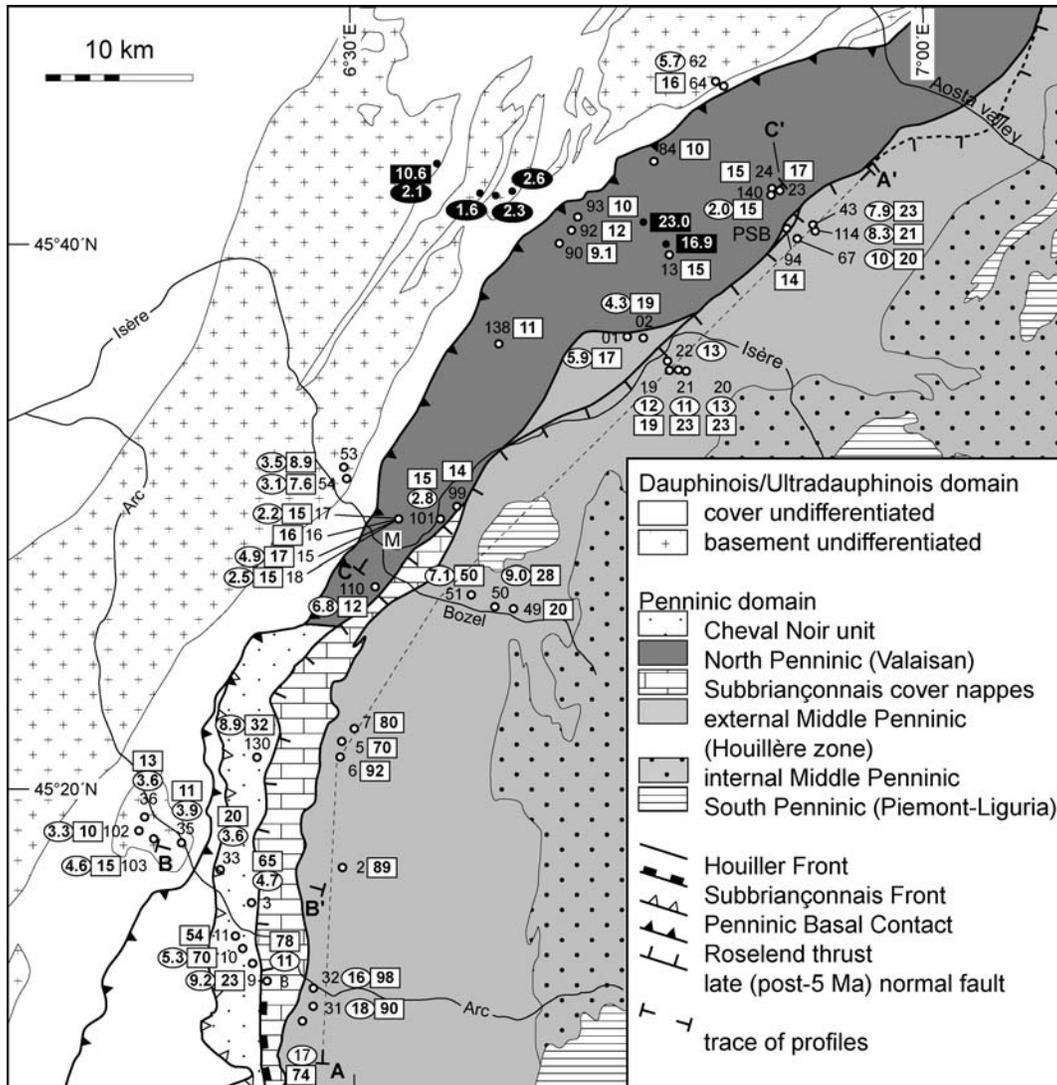


Figure 2. Tectonic sketch map displaying the location of analyzed samples (see Table DR1), together with their zircon (rectangles) and apatite (ellipses) fission-track central ages. Profile traces A, B, and C refer to Figures 4, 7, and 8, respectively. M—Moûtiers, PSB—Petit St. Bernard pass. Data with black symbols are from Seward and Mancktelow (1994).

con PAZ) and minimum (200 °C, corresponding to the lower limit of the zircon PAZ) track-retention temperatures, and if the closure-temperature concept of Dodson (1973) is valid, the oldest and youngest single grains date the passage of the sample through both ends of the PAZ (times t_1 and t_2 in Fig. 3B). However, the retention temperatures of the zircon grains analyzed in a particular sample are unlikely to cover the entire temperature interval associated with the PAZ. Hence, the oldest

and youngest grains may only yield minimum and maximum ages for t_1 and t_2 , respectively.

A further scenario (Fig. 3C) involves sedimentation and lithification, followed by metamorphism and cooling, peak-metamorphic temperatures (at t_m) being situated midway within the PAZ. By sampling contact-metamorphosed sedimentary rocks around a pluton, Tagami and Shimada (1996) provided a well-documented example illustrating this case. The youngest single-grain ages found in

partially annealed samples turned out to be identical with the zircon FT central age of the fully annealed samples. Hence, the youngest single-grain ages from partially annealed samples may represent cooling ages. In the case of Figure 3C, this cooling age t_2 applies to the lower temperature limit of the PAZ and post-dates the peak of metamorphism at t_m .

Figure 3D depicts a two-stage cooling history. From the single-grain age distributions alone, this scenario is indistinguishable from

Figure 1. (A) Simplified tectonic map of the Western Alps (redrawn after Bigi et al. [1983] and Ceriani et al. [2001]; location of main map shown in inset) and (B) geologic profile along the ECORS-CROP transect (after Schmid and Kissling, 2000). BT—Briançonnais thrust; R—Rhône line; S—Simplon line; T—Tonale line. Profile traces W–W', X–X', Y–Y', and Z–Z' refer to Figure 10.

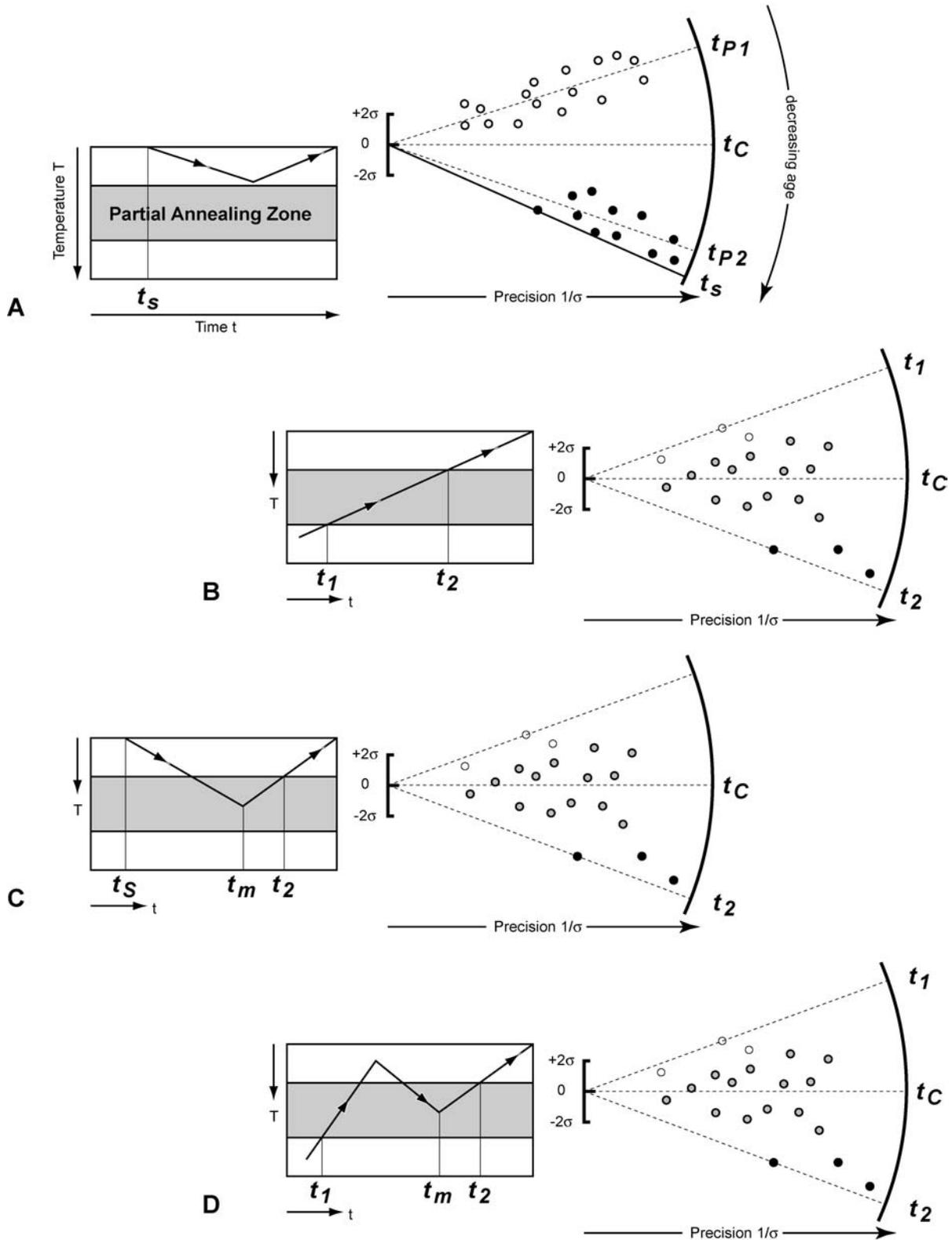


Figure 3. Simple thermal histories together with possible single-grain age distributions shown as radial plots (Galbraith, 1990); t_C —central age (Galbraith and Laslett, 1993). Note that temperature (T) increases in a downward direction. (A) Deposition followed by lithification and then minor heating; t_s —stratigraphic age, t_{P1} and t_{P2} refer to the inherited ages of detrital populations 1 and 2, respectively. (B) Slow cooling through the entire PAZ. (C) Same as A, but thermal peak situated within the PAZ at t_m . (D) Two-stage cooling history. For further explanations, see text.

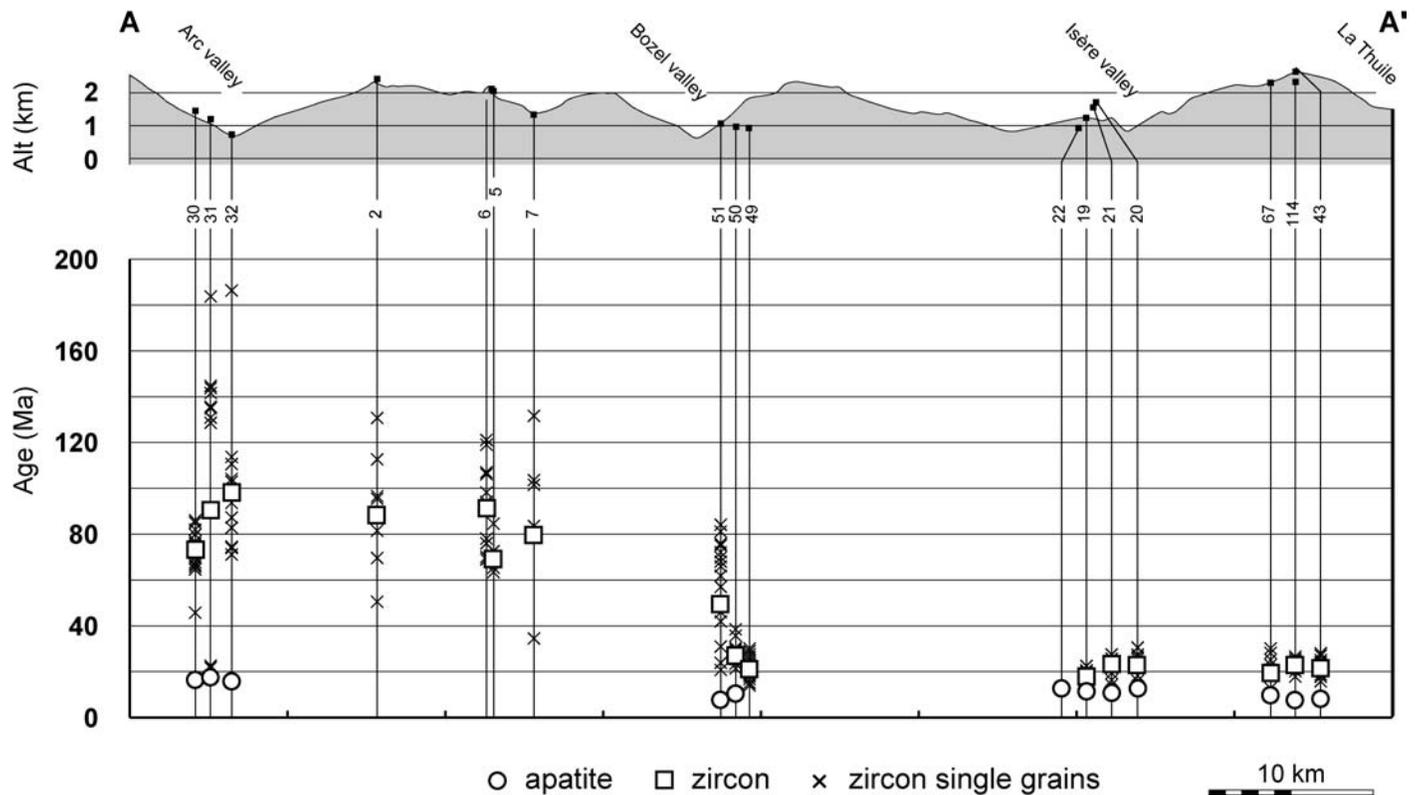


Figure 4. North- to northwest-trending along-strike profile (vertical exaggeration 2 \times) through the Houillère zone (for location, see profile trace A-A' of Fig. 2). Top—sample location and altitude (Alt). Bottom—apatite (circles) and zircon (squares) central ages and zircon single-grain ages (crosses). Only those samples located in the hanging wall of the late normal fault depicted in Figure 2 are shown.

that of Figure 3B. The interpretation of the youngest and oldest single-grain ages, however, is identical.

PRESENTATION AND DISCUSSION OF FISSION-TRACK DATA

Houillère Zone

The FT data from the 33 Houillère zone samples (locations in Fig. 2) cover some 80 km along strike and are mostly located within 1 km of the Houiller front (Fig. 2). Three samples (01, 02, and 94) are located in the immediate footwall of a late normal fault overprinting the Houiller front (Fig. 2). All other samples are located in its hanging wall. FT ages on apatite range between 18 and 4.3 Ma; those on zircon fall between 98 and 19 Ma. Generally, older ages are observed in the south (Fig. 2).

The along-strike profile of Figure 4 displays FT ages and zircon single-grain age distributions from Houillère zone samples. Apatite FT ages range between 13 and 7.1 Ma in the north and slightly increase to values between 16 and 18 Ma in the farthest-south samples. Zircon

ages, however, increase significantly from ca. 20 Ma in the north to almost 100 Ma in the south. Samples yielding old central ages are characterized by a large spread in single-grain ages and by their failure of the chi-square test (Table DR1). Hence, it is concluded that this marked increase in zircon central ages mainly reflects a change from fully annealed samples in the north to only partially annealed samples in the south.

Illite crystallinity (IC) data from the southern part of the Houillère zone (Ceriani, 2001) indicate epizonal conditions, whereas the zircon FTs are only partially annealed in the same area (Fig. 4). Hence, metamorphic temperatures were above 270 °C, as indicated by the IC data (lowermost possible limit of the epizone, Ferreiro-Mählmann, 1996), but below 320 °C (upper temperature limit of the zircon PAZ, Tagami et al., 1998), according to the large spread in zircon single-grain ages in the southern Houillère zone. For the reconstruction of the temperature vs. time ($T-t$) path discussed later (Fig. 5), a mean temperature of 295 °C was chosen. In the northern part of the Houillère zone, no exact temperature estimates are available. The fully annealed zircon

samples indicate temperatures in excess of 320 °C. Freeman et al. (1998) provided an upper temperature limit of 450 °C for this area, based on mineral assemblages. The $T-t$ paths discussed subsequently assume a T_{\max} of 400 \pm 50 °C for the northern part of the Houillère zone.

Possible $T-t$ histories for the Houillère zone are illustrated in Figure 5A. For the northern Houillère zone, a $T-t$ path may be derived by using the zircon (260 °C) and apatite (90 °C) FT central ages only (solid line). Alternatively, the $T-t$ path can be constructed by additionally using the information provided by the single-grain ages (cf. Fig. 5B). This $T-t$ path (dashed line) assumes that the oldest and youngest zircon single-grain ages date cooling through 320 °C and 200 °C, respectively (see Fig. 3B). By linearly extrapolating a constant cooling rate above 320 °C, the estimated peak-metamorphic temperatures of 400 \pm 50 °C are inferred to have started to decrease no later than 35 Ma. Note that the $T-t$ path, which is solely derived by using the zircon and apatite FT central ages (solid line), only partly coincides with the alternative path. It allows us to propose a constant cooling rate over the entire

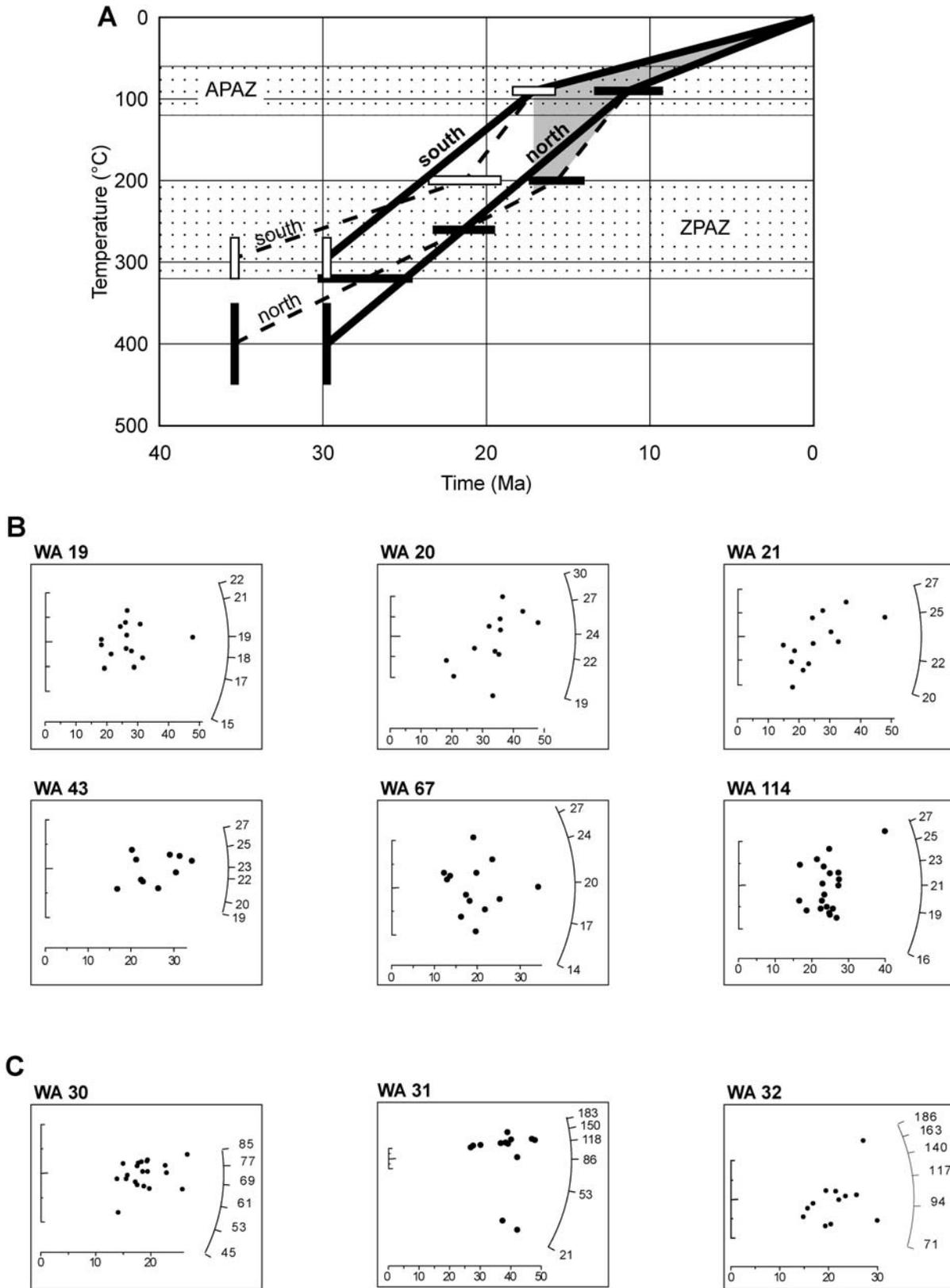


Figure 5. (A) $T-t$ paths for the northern and southern parts of the Houillère zone, respectively (cf. Fig. 4). Solid lines— $T-t$ paths deduced from central ages; dashed lines— $T-t$ paths incorporating single-grain age data. For the northern Houillère zone, the means of the zircon and apatite central ages (solid line) and zircon single-grain ages (dashed line) of samples shown in (Caption continued on p. 000.)

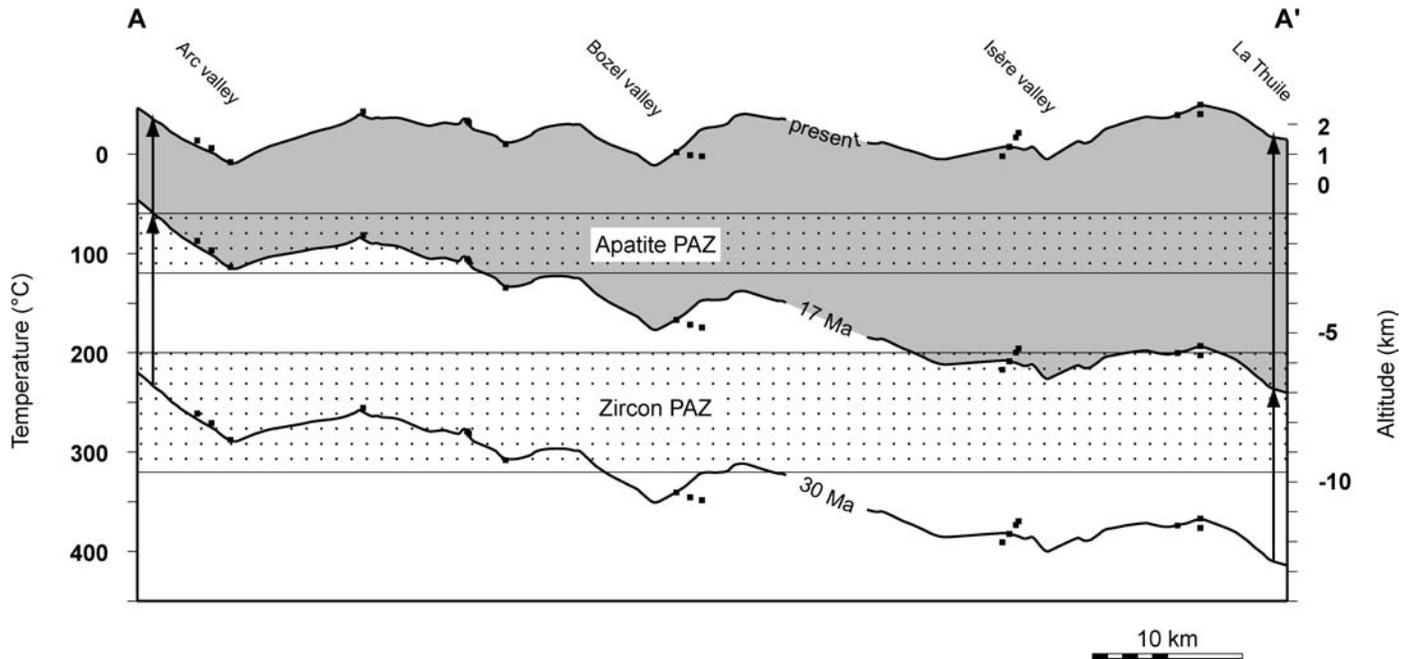


Figure 6. Proposed exhumation history of the Houillère zone depicted on the along-strike profile of Figure 4 and based on the $T-t$ paths shown in Figure 5, assuming a geothermal gradient of $30\text{ }^{\circ}\text{C}/\text{km}$. Gray field refers to time of differential exhumation (cf. Fig. 5). Some 5.5 km of additional exhumation in the north resulted in a 4° tilting. Note that the $0\text{ }^{\circ}\text{C}$ isotherm is arbitrarily located at the valley bottoms and refers to the present-day altitude of 1 km.

temperature interval above $90\text{ }^{\circ}\text{C}$. Also, it would either indicate unrealistically high peak temperatures at 35 Ma or, alternatively, an age for peak temperature conditions of some 30 Ma, which is too young (see later discussion of data on the Cheval Noir unit).

The $T-t$ path of the southern specimens is less well constrained. It may either follow only the apatite central ages (solid line) or include the youngest zircon single-grain ages of ca. 21 Ma (cf. Fig. 5C, sample WA 31), dating cooling through $200\text{ }^{\circ}\text{C}$ (dashed line). The early parts of the $T-t$ paths are again assumed to intersect peak temperatures (previously estimated at $\sim 295\text{ }^{\circ}\text{C}$) at 35 Ma, i.e., contemporaneously with the northern Houillère zone.

The $T-t$ paths using the zircon single-grain ages (Fig. 5A, dashed lines) provide the basis for reconstructing the exhumation history along the same northeast-southwest to north-

south profile (Fig. 6). This reconstruction uses a geothermal gradient of $30\text{ }^{\circ}\text{C}/\text{km}$. Field geologic evidence indicates that the investigated part of the Houillère zone represents a homogeneously cooled and exhumed rigid block. These two assumptions (the geothermal gradient and the homogeneous nature of the study area) indicate a tilt of $\sim 4^{\circ}$ around a northwest-southeast-oriented axis, i.e., normal to the general strike of the units, during exhumation. Tilting started at ca. 17 Ma, i.e., the time when the cooling rate for the southern area started to significantly slow down. During tilting (gray area in Fig. 5A), the southern samples remained close to, or below, the lower limit of the apatite PAZ, whereas the northern samples cooled down to and through the apatite PAZ (Figs. 5 and 6). Figure 6 shows that at ca. 17 Ma, the average exhumation rates of $\sim 0.45\text{ km}/\text{m.y.}$ decreased to below

$0.2\text{ km}/\text{m.y.}$ at the southern end of the profile, whereas they decreased later and less markedly at the northern end.

The zircon data, together with estimates on grade of metamorphism, allow us to conclude that significantly deeper levels of the Houillère zone are currently exposed in the Petit St. Bernard pass region, compared to the Arc valley farther south. On the basis of a reconstruction of the cooling and exhumation history, this difference in original depth of $\sim 5.5\text{ km}$ is interpreted to be due to late-stage tilting around an axis normal to the strike of the Houillère zone.

Subbriançonnais Unit

Unfortunately, only one sample from the Subbriançonnais (WA 8, see Table DR1) could be dated. This Middle Jurassic lime-

Figure 5. (Continued.) (Caption continued from p. 000) Figure 5B are used. Linear extrapolations of the inferred cooling rates to the peak-metamorphic temperature of $400^{\circ}\text{C} \pm 50^{\circ}\text{C}$ yields an age of ca. 35 or 30 Ma for the onset of cooling. For the southern Houillère zone, the mean of the apatite central ages (samples WA 30, 31, and 32) is used. The dashed line additionally shows ages of the youngest zircon single grains in sample WA 31 (Fig. 5C). Error bars for ages are 1σ . Gray field indicates time of differential cooling and exhumation of southern and northern samples. (B) Radial plots of zircon samples used to construct the $T-t$ path of the northern samples (for plot legend, see Fig. 3A; ages on right are in Ma, $\pm 2\sigma$ error on central age is shown by left-hand error bars, and x-axis shows precision $[1/\sigma]$). (C) Radial plots of zircon sample WA 31 used to construct the $T-t$ path of the southern samples. Samples WA 30 and 32 from the south are shown for comparison.

stone yielded an apatite FT age of 11 Ma and a zircon age of 78 Ma. The apatite age most likely represents a cooling age. The zircon age, however, represents a “mixed” age, the single-zircon grain ages in this sample ranging between 163 and 42 Ma, the oldest ages corresponding to the stratigraphic age of the sample. The inferred temperature range (200–320 °C) is compatible with illite crystallinity data indicating high-anchizonal conditions (Ceriani, 2001), i.e., between 250 and 280 °C.

Cheval Noir Unit

The Cheval Noir unit yielded five apatite and six zircon ages, ranging from 9.2 to 3.6 Ma and from 70 to 20 Ma, respectively. The sample localities are projected onto a schematic cross section through the Cheval Noir unit (Fig. 7), essentially characterized by a syncline formed during local D2 deformation and postdating an earlier schistosity (D1). In a broader context this local D2 is related to the “Roselend phase” associated with west-northwest-directed thrusting (D3 according to Ceriani, 2001). Four samples are from the stratigraphically youngest formation exposed in the core of this syncline (WA 3, 10, and 11) and toward the limb (WA 9). Two come from the basal breccia and wildflysch formations (WA 33 and 130) in the fold limbs.

Apatite central ages for all samples display a clear age vs. altitude correlation, indicating a common exhumation rate of 0.18 km/m.y. (Fig. 7). Zircon central ages for samples from the limb of the syncline (WA 9, 33, 130) are younger than stratigraphic age, whereas those from the core of the Cheval Noir syncline yielded central ages (54–70 Ma) that are older than the stratigraphic age. Hence, the zircon data clearly indicate that grade of metamorphism in the youngest sedimentary rocks in the core of the syncline is significantly lower, which is confirmed by studies on illite crystallinity from the same area (Ceriani, 2001). Therefore, D2 folding must have postdated the peak of metamorphism associated with D1. This metamorphism predates the onset of cooling at ca. 32 Ma (zircon age of sample WA 130). Because the reset zircon ages from the limbs depend on altitude (exhumation rate of 0.12 km/m.y., Fig. 7), subsequent exhumation either postdated folding, or alternatively, folding was accompanied by erosion and thus coeval with exhumation. Because fully annealed and moderately to nonannealed samples are found at the same present-day elevations, the second model is favored. We conclude that post-32 Ma exhumation is associated with the local D2 deformation

(“Roselend phase”). This interpretation is compatible with studies on the deformation history on a larger scale, including stratigraphic arguments, indicating that the west-northwest-directed Roselend thrust is of middle Oligocene to early Miocene age (Ceriani, 2001).

Valaisan Units

A total of 16 zircon and 6 apatite ages were derived from the Valaisan units. The small number of apatite ages, which range from 6.8 to 2.0 Ma, does not provide enough information concerning the details of the late cooling history. However, it is clear that cooling is significantly younger compared to the adjacent Houillère zone.

The larger number of zircon FT data allows for more detailed information. Zircon central ages, ranging between 16.9 and 9.1 Ma, are also younger than those found in the Houillère zone. Radial plots are displayed in Figure 8A. Central ages are plotted against altitude in Figure 8B. Figures 8A and 8B also include three samples (samples WA 01, 02, and 94; for locations, see Fig. 3) from that part of the Houillère zone that is, together with the Valaisan units, located in the footwall of a late normal fault (Fügenschuh et al., 1999) and that therefore exhibit a similar exhumation history.

Zircon single-grain ages range between 23 and 7 Ma. They exhibit a similarly small spread in ages all along strike within the Valaisan, in contrast to the findings in the Houillère zone (compare Fig. 4). All samples pass the chi-square test. Hence, all samples are thought to be fully annealed and to represent cooling ages. Peak-metamorphic temperatures must have been >320 °C everywhere within the Valaisan units.

In spite of full annealing, no age vs. altitude correlation emerges from Figure 8B, indicating that the isotherms (and related isochrons) did not remain horizontal everywhere because of postannealing deformation, assuming initially horizontal isotherms. Surprisingly, no clear along-strike trend is visible either, as was observed in the Houillère zone (Fig. 4). However, some interpretation is possible after subdividing the samples into three geographical groups (I, II, and III; see Fig. 8).

Group I includes the northern samples, located closest (within 2 km) to the Roselend thrust. These samples clearly display distinctly younger ages compared to sample group II, including northern samples found in a more internal position and at only slightly higher elevation. This age pattern suggests a tilt of

former isotherms along an axis parallel to strike; the tilting differentially exhumed the external group I during or after cooling through the FT annealing zone, i.e., certainly later than 20 Ma.

Although group III, including all southern samples, is situated at considerably lower altitude compared to group II, these two groups exhibit almost identical zircon FT cooling ages. This result corresponds to a tilt of the paleoisotherm on the order of a few degrees around an axis perpendicular to strike. This inference is supported by geologic evidence that indicates that the internal Valaisan (i.e., the Versoyen) units axially plunge toward the southwest underneath the tectonically higher external Valaisan units and the Houillère zone (see Fügenschuh et al. [1999] and Loprieno [2001]).

Dauphinois Unit

The 14 new FT data from the external massifs and their cover range between 15.5 and 7.6 Ma (zircon) and between 5.7 and 3.1 Ma (apatite), with mean track lengths of 13 to 14 μm . These data are discussed in a broader regional context and together with literature data from outside the study area (Fig. 3).

On the Aar and Mont Blanc massifs, a large number of zircon and apatite FT data and radiometric ages are available (Schaer et al., 1975; Wagner et al., 1977; Soom, 1990; Michalski and Soom, 1990). On the basis of the age vs. altitude relationships, Michalski and Soom (1990) concluded that the Aar massif (Fig. 1) was exhumed at rates of 0.5–0.6 km/m.y. between early and late Miocene (7 Ma); exhumation rates possibly increased after that time. Concerning the Mont Blanc massif, Soom (1990) proposed that cooling and exhumation started no later than 15–12 Ma and that exhumation rates were as high as 0.9–1.0 km/m.y. since 7 Ma. In the Belledonne and Chatelard massifs, still farther south, apatite FT data by Lelarge (1993) indicate cooling and exhumation since the late Miocene at rates between 0.4 and 0.7 km/m.y., again with a possible increase during the past few million years.

The fission-track data provided by this study clearly support the interpretations given by the aforementioned authors. The age vs. altitude plot (Fig. 9) shows that all external massifs display a remarkably similar pattern. Cooling and exhumation started in the Miocene. The steeper slope defined by the apatite data indicates that cooling and exhumation rates indeed accelerated at or after 10 Ma.

South of the study area depicted in Figure

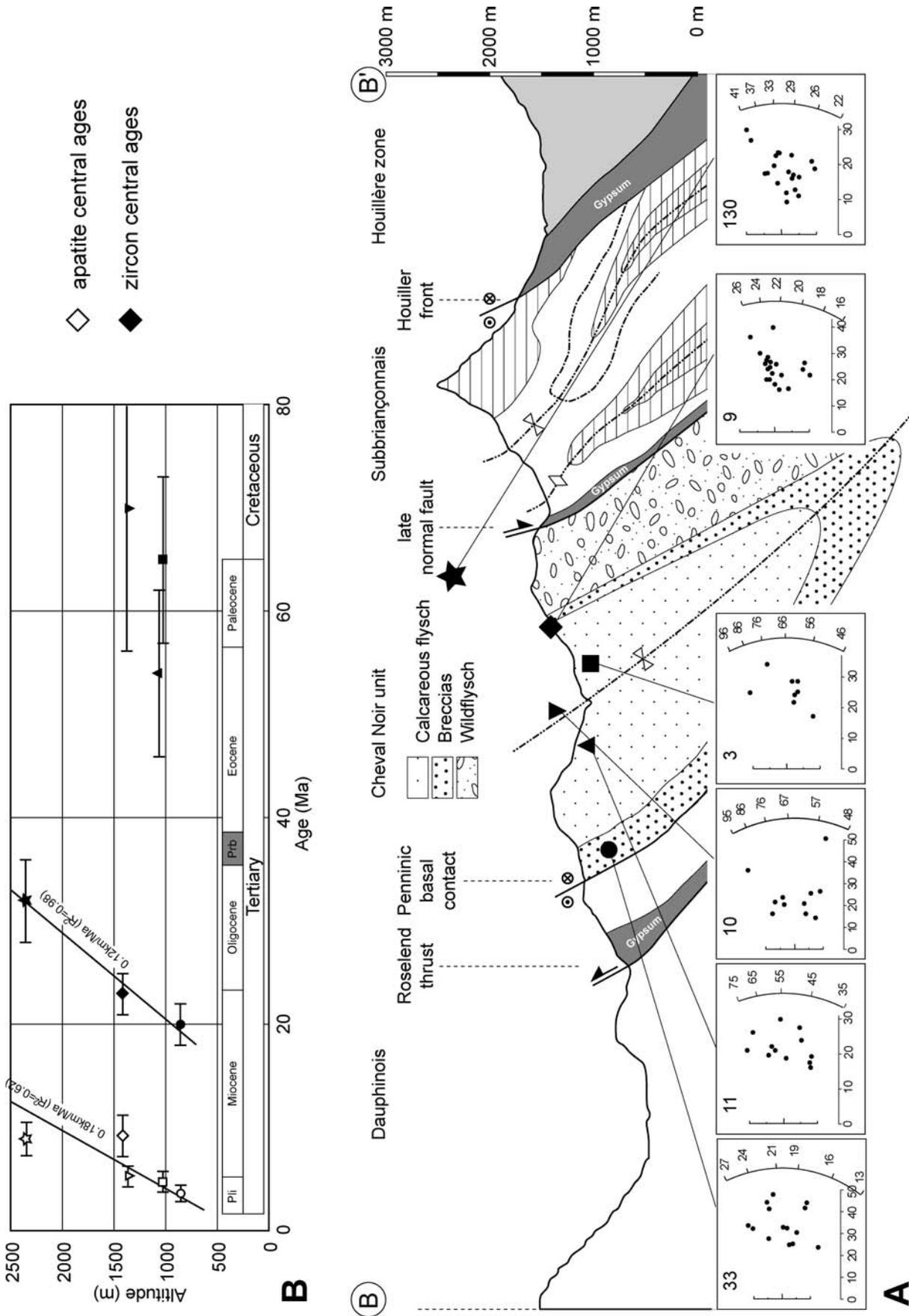


Figure 7. (A) Schematic northwest-trending profile (see Fig. 2 for trace of profile B-B') through the external Penninic units. Sample localities are projected onto the profile, and corresponding radial plots are also depicted. (B) Age vs. altitude plot for the samples from the Cheval Noir unit: apatite (open symbols) and zircon (large solid symbols) central ages. Squares, circles, etc., in B correspond to samples identified in A. Abbreviations: Pli—Pliocene; Prb—Priobonian; SBF = Subbriançonnais front.

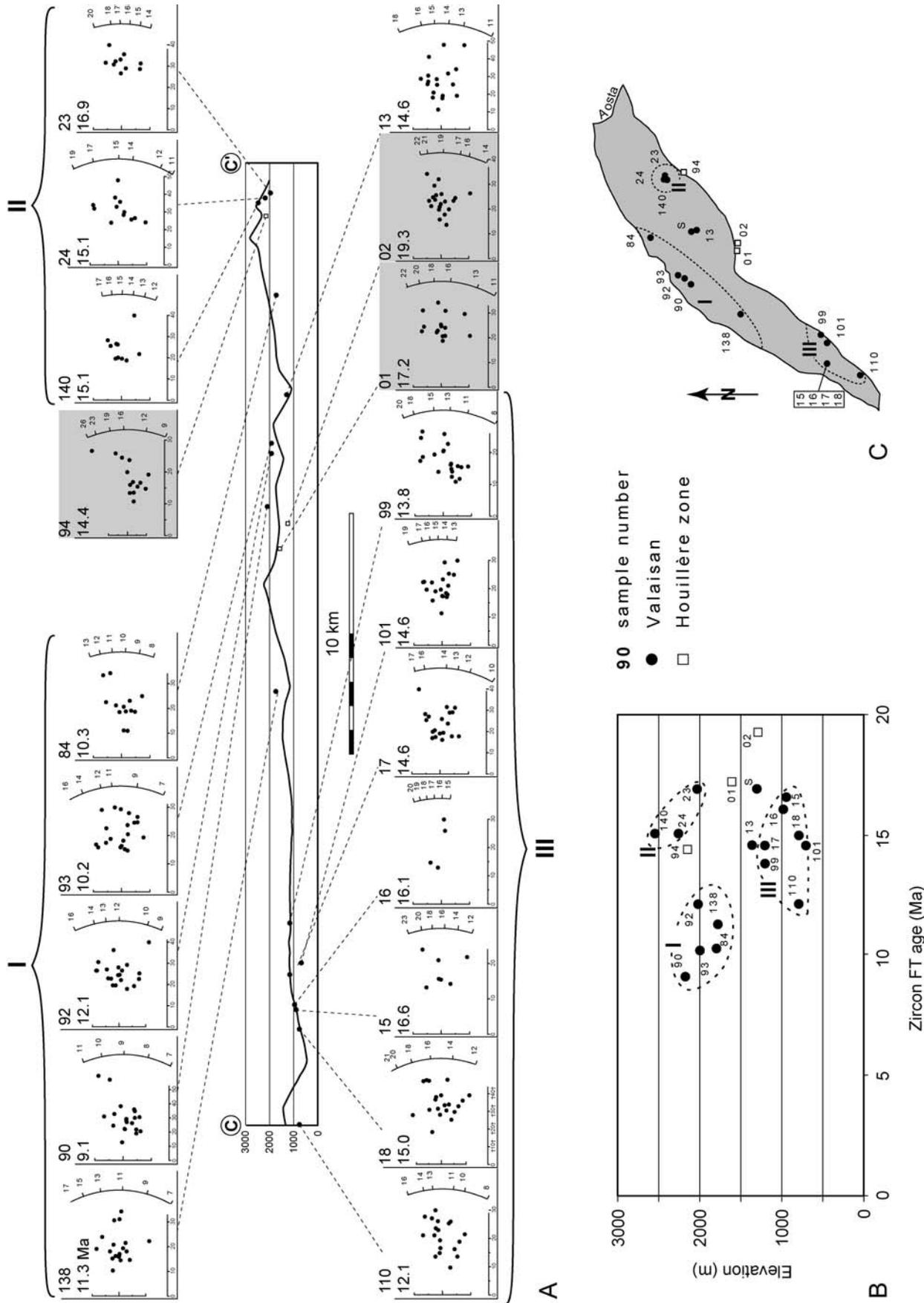


Figure 8. (A) Radial plots of samples projected onto a southwest-trending profile through the Valais units (profile trace C-C' indicated in Fig. 2). Three samples (radial plots with gray background) from the Houillère zone, located in the footwall of the late normal fault depicted in Figure 2, are also included. The subdivision into groups I, II, and III is arbitrary and refers to the geographical distribution of the samples as defined in Figure 8C. (B) Age vs. altitude plot; sample "s" from Seward and Mancktelow (1994). (C) Map of the Valaisian with locations of sample groups I, II, and III.

2, the zircon data are significantly different. Zircons from the southern Pelvoux area (Seward et al., 1999) are apparently only partially annealed and display a large spread in single-grain ages; central ages range between 170 and 38 Ma. The change from fully annealed zircons in the north and northeast to only partially annealed zircons farther south and in the Pelvoux area indicates an along-strike change in degree of metamorphism, as was also found for the Houillère zone. This result agrees with other estimates on grade of metamorphism (Desmons et al., 1999). Apatite ages, however, become only slightly older in the Pelvoux area, indicating Miocene cooling and exhumation also for this area; the rates were ≤ 0.5 km/m.y. (Seward et al., 1999).

Inferences Regarding the Tectonic Contacts Between the Different Units of the Western Alps

Fission-track analysis, in combination with structural evidence, provides information on the nature and age of major tectonic contacts. Hence, we now discuss a series of northwest-trending profiles, perpendicular to the tectonic contacts between the different units (for locations of profile traces, see Fig. 1).

In a study of the Penninic basal contact, separating the Valais units from the Dauphinois unit, Seward and Mancktelow (1994) published FT data for a section through the Rhone valley near Martigny, i.e., northeast of our study area (Fig. 10A). These authors wrote: "the results suggest that there may be a limited discrete jump in the zircon fission-track ages at the Frontal Pennine thrust as part of a broader gradient." This statement was often overinterpreted as providing evidence for significant normal faulting across the Penninic basal contact (e.g., Sue et al., 1999). Our new data (Figs. 10B and 10C) do not support a discrete jump in the Frontal Pennine thrust (i.e., the Penninic basal contact of this paper). Figures 10A–10D clearly depict an overall gradient of steadily not abruptly increasing zircon ages across the Penninic basal contact and toward more internal units. Moreover, normal faulting is in contradiction to structural observations, which indicate that the Penninic basal contact is characterized by top-to-the-west-northwest movement along the Roselend thrust (Fügenschuh et al., 1999; Ceriani et al., 2001; Loprieno, 2001). Note that this late thrust coincided with, and reactivated, the Penninic basal contact, as shown in Figures 10A–10C. The steadily increasing zircon and apatite ages in Figure 10 postdate top-to-the-west-northwest thrusting (see discussion in

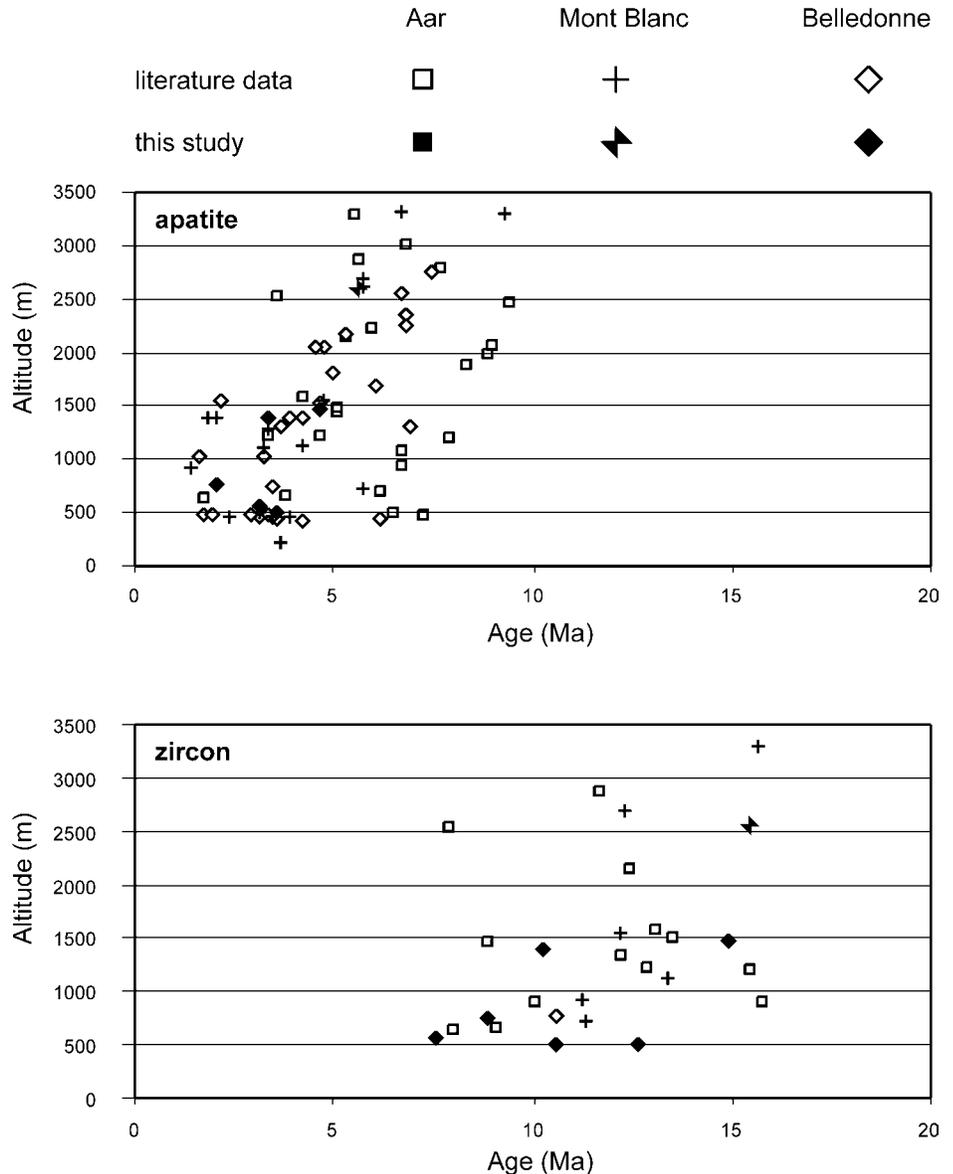


Figure 9. Age vs. altitude correlation of zircon and apatite fission-track data from the Aar, Mont Blanc, and Belledonne external massifs. This plot includes all the data from this study and literature data from Soom (1990), Michalski and Soom (1990, and references therein), Lelarge (1993), and Seward and Mancktelow (1994). Note different age vs. altitude correlation for the apatite and zircon data, respectively, indicating accelerating exhumation rates at ca. 10 Ma.

Ceriani et al., 2001) and indicate tilting of the isograds around a strike-parallel axis. We interpret this tilting to be related to late Miocene (post-13 Ma) to early Pliocene thrusting of the external massifs, i.e., synchronous with Jura folding (Burkhard and Somaruga, 1998). Tilting occurs in the backlimb of the thrust-faulted external massifs (see profile of Fig. 1B); exhumation results from erosional unroofing.

The three southernmost profiles across the

Roselend thrust and the Penninic basal contact (Figs. 10B–10D) display the same trend of steadily increasing zircon FT ages. Yet, because unsuitable lithologies allowed for discontinuous sampling only, there are considerable gaps in the data. Hence, it is not easy to decide on the basis of the FT data alone whether the ages change continuously or discontinuously across the Penninic basal contact. However, the structural evidence for top-to-the-west-northwest thrusting across the

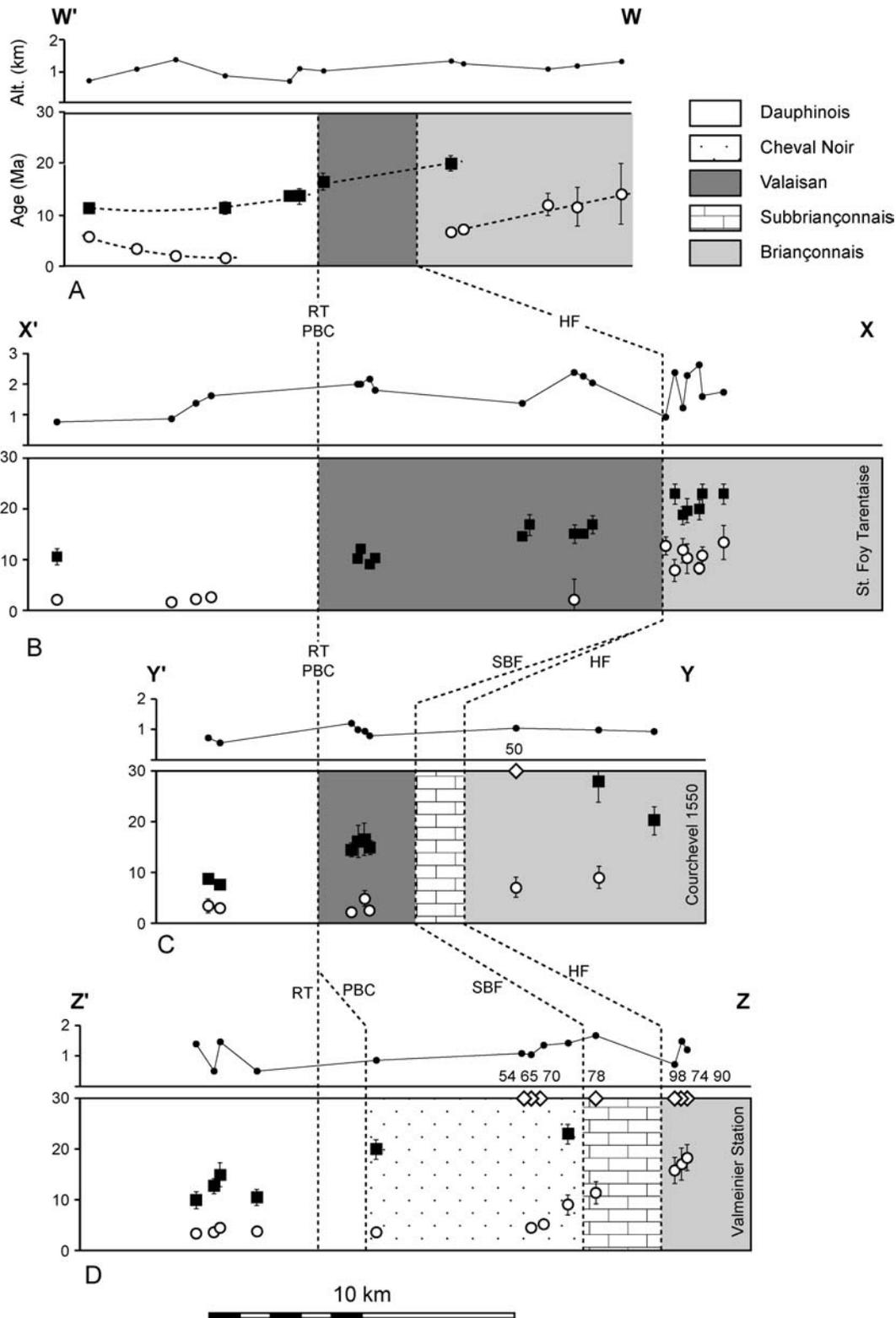


Figure 10. Apatite (circles) and zircon (squares) FT ages, projected onto four schematic northwest-southeast-oriented sections across major tectonic contacts: RT—Roselend thrust; PBC—Penninic basal contact; SBF—Subbriançonnais front; HF—Houiller front. (A) Val des Bagnes section taken from Seward and Mancktelow (1994). (B) Cormet des Roselend section from Fügenschuh et al. (1999), complemented by new data. (C) Bozel section running through Moûtiers. (D) Vallée de l'Arc section. For profile traces, cf. Figure 1. Diamonds located at the 30 Ma line indicate partially annealed zircon samples. Numbers above diamonds give ages in Ma.

boundary between the Penninic and Dauphinois units is unambiguous (Ceriani et al., 2001; Ceriani, 2001; Loprieno, 2001).

The more internal part of the profile depicted in Figure 10B, however, is documented by very closely spaced FT data over the Valaisan/Briançonnais boundary. The new data confirm the discrete jump offsetting both zircon and apatite ages across the Houillère front in the area near the Petit St. Bernard pass, as proposed by Fügenschuh et al. (1999). Published structural observations indicate normal faulting at the Houillère front, along a steeply southeast-dipping plane, downfaulting the Houillère zone parallel to a former thrust (Fügenschuh et al., 1999; Loprieno, 2001). On the basis of the available fission-track data, the vertical offset across this fault is on the order of 2–3 km. Normal faulting also offsets the apatite ages and is therefore very young (younger than 5 Ma).

The third profile (Fig. 10C) runs through Moûtiers and additionally crosses the Subbriançonnais unit. Toward the southeast, apatite ages markedly increase, whereas zircon ages pass from fully annealed to partially annealed. The poor resolution of the data does not permit an interpretation of the tectonic contacts based on fission-track data alone. However, structural evidence indicates that an equivalent late-stage normal fault (cf. Fig. 10B) overprints the Subbriançonnais front in the area of the profile of Figure 10C (see Fig. 2). Hence, the changes of zircon and apatite ages are probably discontinuous across this normal fault.

The fourth profile (Fig. 10D) runs parallel to the Maurienne valley and is located near the cross section depicted in Figure 7. Here, the Roselend thrust no longer coincides with the Penninic basal contact, but forms a second, more externally located tectonic thrust within the Dauphinois domain (Fig. 2; Ceriani et al., 2001). According to structural evidence, normal faulting reactivated former thrusts such as the Subbriançonnais front, whereas the Houillère front was not reactivated by normal faults here (Ceriani, 2001). Hence, apart from a possible discontinuity across a normal fault reactivating the Subbriançonnais front, both the increase in apatite fission-track ages and the change from fully annealed to nonannealed zircon samples seen in Figure 10D are again systematic and continuous within the resolution of the available age data.

In summary, the increase of FT ages toward more internal zones is interpreted to be primarily due to tilting, followed by erosional unroofing. This tilting is related to Miocene thrusting of the external massifs. Locally, this

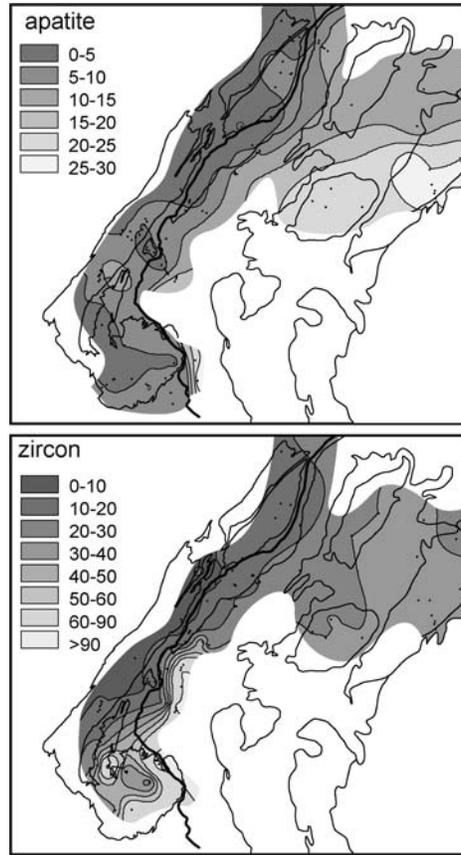


Figure 11. Contoured isochron map of the Western Alps including data from Fügenschuh et al. (1999), Hurford and Hunziker (1989), Hurford et al. (1991), Lelarge (1993), Sabil (1995), Seward and Mancktelow (1994), Seward et al. (1999), Soom (1990), Tricart et al. (2001), and this work. Fission-track ages are not corrected for sample elevation, and data points are indicated by black dots, interpolation was by kriging.

increase was documented to be discontinuous (Fig. 10B) and related to post-5 Ma faulting that reactivated former thrusts but had a normal sense of movement.

CONCLUSIONS

The late cooling pattern of the Western Alps is characterized by decreasing cooling ages from internal toward external units (Fig. 11, cf. Hunziker et al., 1992). With the exception of one documented offset by post-5 Ma normal faulting, this increase in ages is a steady one. The steady nature suggests a systematic migration of the time of cooling, and hence exhumation, toward more external units. Cooling in the Houillère zone started at ca. 35

Ma. Migration of the time of enhanced cooling toward more external units can be inferred from comparing Figures 5 and 9. Although rapid cooling in the Houillère zone predated 10 Ma everywhere, it accelerated after 10 Ma in the external massifs.

We interpret migration of cooling (and exhumation) toward external units to be related to thrust propagation. In the absence of significant normal faulting, exhumation was primarily by erosion. Exhumation followed tilting of more internal units in the backlimb of thrust-related culminations, such as that of the external massifs during the last stage of the tectonic evolution (see profile of Fig. 1B and kinematic reconstruction in Fig. 8 of Schmid and Kissling, 2000). Earlier (i.e., pre-20 to 15 Ma) cooling, as observed in the Penninic units, is most likely related to thrusting along the Roselend thrust. This late-stage thrusting was initiated in middle Oligocene times, i.e., at ca. 32 Ma. It caused burial and metamorphism in the external Dauphinois unit (see discussion in Ceriani et al., 2001), which was exhumed very much later.

Additionally, we documented an along-strike gradient. This gradient is very pronounced in the Houillère zone of the Briançonnais. As shown in Figure 11, particularly the zircons indicate a marked increase in apparent ages toward the south. The interpretation of single-grain ages in the Houillère zone indicates that this increase in age primarily reflects decreasing grade of metamorphism. Hence, the southernmost areas were less deeply buried. In the case of the Houillère zone, this interpretation results in a tilt around a strike-perpendicular axis (Fig. 6), which started at ca. 17 Ma. The age of the onset of this tilting coincides with the estimated onset of cooling in the external massifs between 20 and 15 Ma. The latter show a similar, although less pronounced, age trend along strike, zircons in the Pelvoux massif being only partly reset. By interpreting cooling in the external massifs to also result from a combination of thrusting and erosional unroofing, we suggest that the lower amount of exhumation in the Pelvoux massif is related to decreasing amounts of Miocene–Pliocene shortening toward the south. Hence, northward-increasing shortening in the Dauphinois, independently documented by Gratier et al. (1989), would be the cause of tilting around an axis perpendicular to strike.

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LATE STAGES OF DEFORMATION AND EXHUMATION IN THE WESTERN ALPS

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