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Antoine Vernon, Pieter Van Der Beek, Hugh Sinclair, Meinert Rahn

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HAL Id: hal-00286544
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Submitted on 9 Jun 2008

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Increase in late Neogene denudation of the European Alps confirmed by isoage analysis of a fission-track database

A.J. Vernon (1,2)*, P.A. van der Beek (2), H.D. Sinclair (1), M.K. Rahn (3)
(1) School of Geosciences, Grant Institute, University of Edinburgh, Edinburgh EH9-3JW, United-Kingdom
(2) Laboratoire de Géodynamique des Chaînes Alpines, Université Joseph Fourier, 38400 Grenoble, France
(3) Swiss Federal Nuclear Safety Inspectorate, 5232 Villigen-HSK, Switzerland
* Corresponding author: antoine.vernon@ed.ac.uk

Abstract
A sharp increase in deposited sediment volume since Pliocene times has been observed worldwide and in particular around the European Alps. This phenomenon has been linked to a rise in denudation rates controlled by an increase of either climatic or tectonic forcing. Observation of in situ cooling histories for orogens is critical to assess the reality of the inferred increase in denudation rates, and to determine whether this phenomenon is widespread or localized at active tectonic structures. We exploit the unique density of fission track ages in the Western European Alps to reconstruct cooling isoage surfaces and to estimate exhumation rates on the orogen scale between 13.5 and 2.5 Ma. Our novel technique is based on the association of isoage contours with age-elevation relationships. It uses map-view interpolation, enabling a spatio-temporal analysis of exhumation rates over the entire Western Alps. The resulting exhumation histories reconstructed for eight areas of the Western Alps display strong similarities in timing and rates with orogen-wide average denudation rates inferred from sediment volumes. This consistency validates the use of both techniques for the study of an orogen characterized by strong relief and high recent exhumation rates. We conclude that exhumation rates in the Western Alps have increased more than twofold since
late Miocene times. This increase may have been locally modulated by the distinct response
of different tectonic units.

Keywords: Cenozoic exhumation, Fission track, Isoage surfaces, Western Alps

1. Introduction

Widespread indications for an increase of global sedimentation rates in the early Pliocene
have been reported from localities around the world (e.g., Molnar, 2004; Zhang et al., 2001).
However, the cause of this event, its exact timing and synchronicity remain controversial.
Possible causes that have been proposed include global cooling and incipient glaciations
(Ehlers et al., 2006; Hinderer, 2001), an increase in the magnitude and frequency of climate
oscillations (Molnar, 2004; Zhang et al., 2001), and a recent increase in the uplift rates of
major orogens (Raymo and Ruddiman, 1992).

The quantification of sediment volumes in the basins surrounding the European Alps by
Kuhlemann et al. (2002) shows a more than twofold increase in erosion rates in both the
Western and Eastern Alps around 5 Ma (Figure 1). An independent study of the exhumation
of the Molasse basin (Figure 2), based on borehole apatite fission-track data, demonstrated
approximately 1400 m of basin exhumation since 5 Ma, interpreted as a record of isostatic
rebound of the basin driven by accelerated erosional unloading of the Alps (Cederbom et al.,
2004).

The estimation of source-area denudation rates from the sediment record suffers, however,
from poorly quantified uncertainties in both the volumetric calculations and the dating
accuracy (Kuhlemann et al., 2002). Moreover, the impossibility of quantifying the roles of
chemical erosion and sediment recycling may lead to an underestimation or overestimation, respectively, of source-area denudation rates.

An increase in exhumation at ca. 5 Ma, if real, should be recorded more directly by low-temperature thermochronometers in the bedrock of the mountain belt. Classically, the derivation of exhumation rates from thermochronometry is based on temperature-time paths reconstructed from multiple thermochronometer analysis, age-elevation profiles from altitudinal transects or boreholes, or kinetic modeling of apatite fission-track annealing using track-length distributions (e.g., Gallagher et al., 1998; Hurford, 1991). In different regions of the Western Alps, Neogene-age exhumation rates quantified using these approaches range between 0.1 and 1.5 mm/yr (e.g., Leloup et al., 2005; Malusa et al., 2005; Michalski and Soom, 1990; Tricart et al., 2007). However, most of these studies are local or at best regional in scope and a consistent denudation history at the orogen scale has yet to emerge. Apatite fission-track (AFT) thermochronology appears the most suitable technique to study Miocene-Pliocene exhumation rates over a large area such as the Western Alps because of the abundance of ages ready for database compilation, and because the AFT age range (Figure 3-a) comprises the target period of the late Neogene.

The spatial integration of discrete thermochronological data covering large study areas is most easily achieved by interpolating between ages in map view (e.g., Hunziker et al., 1992; Figures 3-a and 3-b). However, this simple technique only presents the integrated result of a possibly complex denudation history and does not allow variations in denudation rate through time to be inferred. Published methods aimed at describing the history of exhumation rates in map view have used either analysis of multiple thermochronometers, or kinetic modeling of fission-track length distributions (e.g., Bistacchi and Massironi, 2000; Gallagher and Brown,
Despite many years of intensive thermochronological studies in the Alps, samples permitting such analyses are still relatively rare, disallowing such a study at the orogen scale. Techniques based on modeling of fission-track length distributions offer the greatest wealth of interpretation in settings characterized by slow long-term denudation, such as rifted continental margins (e.g. Gallagher and Brown, 1999). In rapidly exhuming orogens, in contrast, track-length distributions are not easily measured (because of generally young AFT ages) and are much less discriminative.

We propose a new method in which we exploit the extensive AFT dataset available for the Western Alps (Figures 2 and 3) together with the significant relief of the mountain belt to reconstruct three-dimensional surfaces of equal AFT age (referred to here as isoage surfaces). We subsequently use the difference in elevation between these surfaces to estimate the spatial pattern in rates of exhumation back to middle Miocene times (13.5 Ma), as recorded in the spatial relationship between AFT ages at outcrop today. The aims of this study are to test for the presence of changing exhumation rates during late Neogene times across the Western Alps, and if present, to describe the temporal and spatial variability of this signal. In addition, we present updated maps of interpolated apatite fission-track ages and mean track lengths, as well as zircon fission-track ages. We complete this study by the assessment of evolving trends of exhumation rates using samples with paired zircon and apatite fission-track ages. In the following, we first briefly outline the geological setting and evolution of the Alps and present the thermochronological database we constructed. We then explain the different methods we used to analyze the database. Finally, we present our main results and their implications for the late Neogene denudation history of the Alps as well as its possible tectonic or climatic controls.
2. Geological setting of the Alps

The European Alps (Figure 2) are located at the boundary between the European and Apulian plates. They are the product of the early Cretaceous closure of the Piemont-Ligurian ocean, followed by continental subduction resulting in nappe stacking (cf. reviews in Rosenbaum and Lister, 2005; Schmid et al., 2004).

The main tectonic units in the Alps and their structural relationships have been described extensively within the last century (e.g., Debelmas and Lemoine, 1970; Schmid et al., 2004; Trümpy, 1960). They originate from the European continental margin basement (External Crystalline Massifs) and overlying deposits (Helvetic sediments), the Briançonnais micro-continent and its two bordering oceanic units (Piemont-Ligure and Valais oceanic crust and flysch), and finally basement and sedimentary units of the Apulian margin, grouped as the Austroalpine and the South Alpine units (Figure 2). The North (Molasse) and South (Po) Alpine foreland basins formed by flexure of the lithosphere in response to the weight of the orogenic prism on the European and Apulian plates and are filled with Eocene to Recent flysch, molasse and glacial deposits (e.g., Homewood et al., 1986; Scardia et al., 2006).

One of the most important arc-parallel tectonic boundaries, the Penninic thrust, may have been extensionally reactivated (Seward and Mancktelow, 1994) as part of a series of Neogene extensional features observed throughout the axial region of the Western Alps (e.g., Sue et al., 2007; Tricart et al., 2007 and references therein). Most of these extensional features may be caused by a Neogene dextral transtensive event (Sue et al., 2007) triggered by the anti-clockwise rotation of the Apulian plate. Such rotation can also explain the current strain pattern in the Western Alps (Calais et al., 2002). At present, geodetic and GPS data show
limited (≤2 mm/yr) east-west extension in the Western Alps (Calais et al., 2002; Sue et al., 2007). The lack of present-day convergence in the Western Alps, together with the observation of sediment-sealed thrusts in the western part of the Po basin (Pieri and Groppi, 1981), and the cessation of thin-skinned deformation in the Jura at ca. 4 Ma (Becker, 2000) all suggest very limited current orogenic activity within the chain.

We limit our study area to the Western half of the Alps, as far east as the Silvretta nappe / Engadine window, or approximately the Swiss-Austrian border, which marks the western limit of widespread outcrop of Austroalpine units. The reason for this eastern limit to the study area is that few AFT studies have been published for the Austroalpine units because of the low abundance of apatite in their constitutive lithologies.

3. Data

3.1. Apatite and zircon fission-track databases

During the last thirty-five years, the Western Alps have been extensively sampled for thermochronological analyses, in particular using the apatite and zircon fission-track thermochronometers, characterized by closure temperatures of ca. 120 and 240 °C respectively (e.g., Brandon et al., 1998; Gallagher et al., 1998). We have compiled 740 AFT ages, from data in 37 publications completed by 160 unpublished ages (references are given in the caption of Figure 3-a) from samples located in the European Alps west of 10° 20′ east (an area of ca. 48000 km²). We similarly compiled 380 zircon fission-track (ZFT) ages from 24 publications completed by 22 unpublished ages (see Figure 3-b for references).
3.2. Quality and homogeneity of the data

Early studies (in the 1970’s and early 1980’s, see for instance Wagner and Reimer, 1972) used the population method for AFT dating, whereas the more reliable external detector method (Hurford and Green, 1982) has become the norm since the mid 1980’s. The database contains ages obtained both with the population and the external-detector dating techniques because we feel that, at the regional scale of the study, the benefits of increasing data density outweigh the drawbacks of the error introduced by less reliable data points. We rejected three samples with an obvious mistake in dating, in cases where a ZFT age was younger than or equal to (within error) the AFT age of the same sample.

Additional information collected for each sample included (where reported): (1) geographic coordinates, (2) elevation, (3) mean track length for AFT samples, (4) whether the sample is from a tunnel / borehole or the surface, and (5) whether fission-track ages of samples from Mesozoic and Cenozoic sediments are younger than their stratigraphic age (that is, whether they have been reset during Alpine orogeny). To apply the latter criterion, we assumed that ages from sedimentary samples were non-reset unless we could estimate the depositional age and verify that it was older than the fission-track age. A few publications contained more than one age at a given geographic location (referred to later as points with non-unique ages). We discarded such points from part of the study, in order to prevent problems with map interpolation. Many of the original publications did not report sample elevations and / or coordinates. We obtained this missing information by interviewing the authors whenever possible, or alternatively by reading it off topographic maps or figures from the original publications. As a last resort, we estimated the elevation of samples from the Digital Elevation Model (DEM), which consists of a mosaic of the 38-03, 38-04, 39-03 and 39-04 DEM tiles available from the CGIAR-CSI SRTM 90 m database (http://srtm.csi.cgiar.org).
All numerical data fields in the database (coordinates, altitude, age, etc.) carry a degree of uncertainty that varies between publications. For instance, the relative standard errors affecting the AFT and ZFT ages used in this paper vary between 2.2 and 51.6 % (average: 11.6 %) for the former, and between 0.7 and 23.3 % (average 8.0 %) for the latter.

4. Methods

We have developed three joint approaches to take advantage of the high spatial density of fission-track ages in the Western Alps. First, we interpolated AFT and ZFT ages (Figures 3-a and 3-b); second, we calculated cooling and exhumation rates using samples dated with both methods; and third, we constructed isoage surfaces. The latter were used to infer histories of exhumation rates for different areas of the Western Alps between 13.5 and 2.5 Ma.

4.1. Maps of interpolated ages / track lengths

Using the natural-neighbor interpolation tool provided by the ESRI-ArcMap™ GIS, we created two maps of 635 AFT ages and 296 ZFT ages covering the Western Alps (Figures 3-a and 3-b). For this interpolation, we selected points from the database following three criteria: (1) ages in sedimentary rocks should be reset; (2) samples should be from the surface; and (3) points with non-unique ages are discarded. No potentially arbitrary constraints such as tectonic boundaries or elevation corrections were used in this initial interpolation. The choice of a natural-neighbor interpolator is justified by its conservative properties, resulting in finding at each pixel of the map a weighted average of the neighborhood data points without introducing artefacts (Watson, 1999). However, as we could not introduce a maximum distance of interpolation, localities within the inner Alpine arc are often interpolated between data points located very far apart, at two extremities of the arc. Figure 3-c shows a map of 258 mean AFT lengths, interpolated in the same manner as the ages.
4.2. Exhumation rates calculated from paired ZFT and AFT ages

We extracted from the database a subset of 143 samples with paired AFT and ZFT ages, following the requirements that (1) they are surface samples; (2) both AFT and ZFT ages are younger than 35 Ma (i.e., Alpine cooling ages); (3) AFT and ZFT ages differ by at least 1.6 Myr (an empirical limit set by convergence problems for smaller age differences in the numerical code used); finally (4) points with non-unique ages are discarded. The 143 age pairs offer the opportunity to estimate two successive average exhumation rates: an initial rate during the time between closure of the ZFT and AFT thermochronometers, and a final rate for the time since closure of the AFT system. We used a modified version of the one-dimensional model of Brandon et al. (1998) to calculate iteratively the depth of closure of the ZFT and AFT systems, and then calculate exhumation rate from the value of closure depth and age. This model takes into account the advective perturbation of a steady-state geotherm by exhumation, as well as the dependence of closure temperature on cooling rate (e.g., Dodson 1973). It does not, however, include 2-D or 3-D effects such as non-vertical rock-particle paths, spatial variation in geothermal gradient or topographic effects. We have adapted the Brandon et al. (1998) model to simultaneously estimate closure temperatures and depths for both the ZFT and AFT systems (cf. Braun et al., 2006 and van der Beek et al., 2006 for details), using values for the kinetic parameters as estimated by Brandon et al. (1998): AFT: $E_a = 186.4$ kJ mol$^{-1}$, $D_0/a^2 = 3.64 \times 10^{10}$ s$^{-1}$; ZFT: $E_a = 208.2$ kJ mol$^{-1}$, $D_0/a^2 = 3.70 \times 10^6$ s$^{-1}$. Other parameter values used in the model are: surface temperature $T_s = 15 - (6 \times \text{elevation (km)})$ °C, initial (non-perturbed) geothermal gradient $G = 25$ °C km$^{-1}$, model thickness $L = 25$ km, thermal diffusivity $\kappa = 25$ km$^2$ Myr$^{-1}$. The model predicts initial and final exhumation rates that are consistent with both ages; the ratio between the final and initial rates indicates whether the average exhumation rate accelerated or decelerated after closure of the AFT
system. An interpolated map of this ratio is plotted in Figure 4. Absolute values of predicted exhumation rates are affected by the assumed initial geothermal gradient, which is largely unknown and may vary spatially. However, the ratio between final and initial rates is not sensitive to this parameter, providing the geothermal gradient does not change through time, other than through advective perturbation.

4.3. Reconstruction of isoage surfaces

Apatite fission-track isoage surfaces join all rocks predicted to have cooled through the AFT closure temperature at the same time (Figure 5). They are obtained by interpolation in map view between the elevations of points having the same AFT age. Providing the assumption that the depth of the AFT closure isotherms is only moderately affected by changes in exhumation rate, the latter can be estimated using the vertical distance between two successive isoage surfaces. In this respect, isoage surfaces may be viewed as a 3-D generalization of the 1-D age-elevation profile concept, allowing the same information on denudation history to be extracted on a regional scale and potentially recording spatial variations in denudation rates through time.

Regional variability in geothermal gradient, cooling history and/or apatite annealing kinetics may cause the closure temperature and depth to vary spatially between samples from different tectonic units, thus potentially imposing secondary effects on the spatial variation in elevation of isoage surfaces. However, as for age-elevation profiles, the denudation rate inferred from the elevation difference between successive isoage surfaces is independent of the absolute closure temperature and depth, as long as these remain constant through time. Temporal variations in exhumation rates may affect the AFT closure temperature (Dodson, 1973) as well as the geometry of near-surface isotherms (e.g., Braun, 2002; Stüwe et al., 1994). These
two factors tend respectively toward over- or under-estimation of the exhumation rate in the case of an increase in exhumation rate. Nevertheless, the characteristic diffusive timescales are rather large (e.g., Braun et al., 2006) so that these variations will be relatively small over the 1 Myr time span separating two isoage surfaces. In any case, the latter effect significantly outweighs the former (e.g., Braun et al., 2006), so that estimated exhumation rates during a period of increase before reaching a thermal steady-state are likely to be minimum estimates.

4.3.1. Production of arrays of isoage points

The most obvious way to obtain x, y, z coordinates of isoage points is to use the elevation of isoage contours, which, by definition, are the lines of intersection between isoage surfaces and the Earth’s surface. We extracted the elevation of each isoage contour traced on the maps of interpolated AFT ages (Figure 3-a) by projection on the Digital Elevation Model (DEM). The spatial resolution of the DEM (90 m) is much higher than the resolution of the isoage contours (controlled by interpolated points often separated by several kilometers). Therefore, the elevation of any segment of an isoage contour has a high pixel-to-pixel variability (or noise) due to the short-wavelength topography sampled. Nevertheless, the average local value should accurately reflect the elevation of the intersection between an isoage surface and the topography.

We added a second series of isoage points to the array, based on local estimates of AFT age-elevation relationships (AER) in the neighborhood of data points where the correlation between these two parameters was statistically significant (Figure 6). The aim is to document areas where the AER are well correlated and use them to interpolate the elevation of isoage surfaces. We used a subset of 660 AFT samples with an age younger than 35 Ma for this approach. Sample elevation values that had to be derived from the DEM were found to
introduce too much noise in the calculation of regression coefficients for age-elevation relationships and were therefore rejected. We did include, however, data points with non-unique ages, as they comply with the requirements to estimate age-elevation relationships. The condition of sample ages younger than 35 Ma aims to avoid introducing samples that are manifestly partially reset, such as those with Mesozoic ages from the Southern Alps (cf. Figure 3-a), into the calculation of AER regression lines.

For our semi-automated AER analysis, we first selected the neighbors of every point in the database, included in a circle of increasing radius (from 3 to 15 km). For every selection containing more than 4 points, we calculated a regression line between age (dependent variable) and elevation (independent variable), together with its correlation coefficient. The AER was judged significant and was retained if the correlation coefficient for the regression was higher than the critical Pearson’s product-moment coefficient at 95 % confidence level for the appropriate number of degrees of freedom (cf. Figures 6-b and 6-c). When the initial selection around a data point (3 km radius) failed this statistical test, we incrementally increased the search radius by 2 km steps to a maximum of 15 km. This maximum presents a characteristic distance between adjacent valleys: for larger search radii, the samples selected may belong to adjacent valleys with distinct exhumation histories. We used the regression equations calculated from the set of points selected within the smallest successful search radius possible, because they constitute the closest equivalent to a vertical profile and therefore carry the smallest risk for the AER to be affected by either large-scale tilting (Rahn et al., 1997) or the deflection of isotherms in large Alpine valleys (e.g., Braun, 2002; Stüwe et al., 1994).
The local AER is described by the simple linear equation $z = A_0 + (A_1 \times t)$, where $A_0$ is the elevation of the zero-age intercept, and $A_1$ is the slope of the AER (with $z$: elevation [m]; $t$: age [Ma]). Statistically significant AERs extracted from the data are used to interpolate the elevations of isoage surfaces at the location of the center of the search radius, limiting the extrapolation to between 1 Myr before the oldest and 1 Myr after the youngest age in the neighborhood selection. This limitation is imposed in order to avoid extrapolating age-elevation trends into periods during which they are not locally documented. In case of a slightly kinked AER (i.e. change in exhumation rate with time), the slope $A_1$ would be averaged; if the kink is more pronounced the linear correlation coefficient will be insignificant and the neighborhood selection rejected. Given that this study is aimed at testing for changing exhumation rates through time, the rejection of kinked AERs in the generation of isoage data points is conservative, and will downplay any signal.

4.3.2. Interpolation of isoage point arrays

We constructed isoage surfaces by natural-neighbor interpolation applied to the elevations of the points constituting each isoage array (Figure 6d). In order to remove unconstrained parts of the surfaces, which have been interpolated far from any point of the isoage arrays, a mask is applied at 15 km around the point arrays. The oldest isoage surfaces have been eroded from large parts of the study area, while the youngest surfaces remain buried in other areas, resulting in a heterogeneous scatter of each array of isoage points. The result is a series of thirteen maps showing isoage surfaces between 14 and 2 Ma where they can be reconstructed with reasonable accuracy; a representative selection of six isoage surfaces is reported in Figure 7.
4.4. Estimation of exhumation rates

The vertical distance between two isoage surfaces corresponds, in principle, to the amount of exhumation during the time period separating them, with the same caveats that apply to the interpretation of 1-D age-elevation profiles, notably the effect of topography on the AER slope (Braun, 2002). In the crystalline massifs of the Western Alps, geomorphic data suggest a significant recent increase in relief (e.g., Champagnac et al., 2007; van der Beek and Bourbon, 2008) so that we expect topographic effects to be limited and the distance between successive isoage surfaces to provide a reliable estimate of exhumation.

After being clipped by the 15 km mask, each isoage surface covers only a limited portion of the Western Alps, and two successive surfaces are never completely superposed. Therefore, it is not possible to calculate the total volume exhumed over the entire surface of the Western Alps during any time period. Instead, we focused on eight specific areas characterized by several million years of continuous isoage surface coverage (Figure 8).

The difference in elevation between successive isoage surfaces is calculated for all 1.2 km$^2$ pixels of each study area and the average distance constitutes our estimate of exhumation during the corresponding time period. Some pixels show negative differences, i.e. the younger isoage surface lies above the older one. These correspond either to artefacts introduced by our treatment of the data or to local areas of strong recent relief decrease. We decided to exclude these pixels from our calculation of the average distance between isoage surfaces, as two isoage surfaces cannot cross each other in an exhuming massif. To illustrate pixel value distributions, Figure 9 presents the values measured between the surfaces aged 5 and 4 Ma for the Mont Blanc area. Plotted against time, the average distances between isoage surfaces enable quantifying the temporal evolution of exhumation rates over each area (Figure 10).
Samples that underwent slow cooling through the partial annealing zone may lead to apparent AERs that do not correspond to the exhumation rate (e.g., Gallagher et al., 1998). The mean track lengths can be used to monitor whether this is the case, as samples that cooled slowly through the partial annealing zone are characterized by mean track length $\leq \sim 12.5 \, \mu m$. Most areas covered by our constructed isoage surfaces are characterized, in contrast, by sample mean track length $\geq 13 \, \mu m$ (compare Figures 3-c and 8), with the exception of the Bergell and the Aar-Leventina (areas 1 and 6 in Figure 8).

5. Results

5.1. Main features of the fission-track age patterns

Young AFT ages ($< 10 \, Ma$) appear in the axial region of the Western Alps (Figure 3-a) and particularly over the Argentera, Ecrins - Mont-Blanc, and Aar External Crystalline Massifs. Very young ages ($< 5 \, Ma$) are also found in the Chur region, between the eastern Aar and the Silvretta nappe, and in the western Lepontine dome, east of the Simplon fault. In contrast, the internal crystalline massifs (Gran Paradiso, Dora Maira) as well as the Austroalpine units are characterized by early Miocene or older AFT ages ($> 10 \, Ma$). An inverse relationship between AFT age and mean track length appears, with ages $< 10 \, Ma$ generally characterized by mean track length $> 13 \, \mu m$ (compare Figures 3-a and 3-c). The only exception to this pattern is a band of short mean track lengths extending from the central Aar massif to the SSE (Figure 3-c). Young ZFT ages ($< 15 \, Ma$) characterize the Aar, Mont-Blanc, Belledonne and Lepontine massifs (Figure 3-b). Extensive regions of both the external and internal parts of the orogen show early Alpine ZFT ages (20-35 Ma), whereas two orogen-parallel bands (an external band covering the frontal parts of the Mont-Blanc and Aar massifs and an internal
band running from the eastern Ecrins across the Southern Alps) show ZFT ages that were not reset by the Alpine orogeny (i.e., ZFT age ≥ 35 Ma).

The AFT and ZFT age patterns run parallel to two major Alpine tectonic lineaments: the Penninic thrust, bordering the External Crystalline Massifs, and the Simplon fault. Both areas show younger ages in their footwalls (Figures 3-a and 3-b), which suggests that a component of tectonic exhumation may affect the age patterns, as previously suggested in more local studies (Fügenschuh and Schmid, 2003; Seward and Mancktelow, 1994; Tricart et al., 2007).

5.2. Variation in exhumation rate from paired AFT and ZFT ages

A pattern of recent accelerated exhumation, dominantly affecting the external side of the belt (and the External Crystalline Massifs in particular), is evidenced in Figure 4. This map demonstrates an overall acceleration in exhumation rate along the northern and western borders of the orogen, since these areas crossed the AFT closure temperature of ~120 °C. AFT ages in the region showing accelerated denudation are mostly ≤ 8 Ma (compare Figures 3-a and 4). However, exhumation rates used in this ratio calculation are average values for initial cooling between the ZFT and AFT closure temperatures and final cooling between the AFT closure temperature and the surface, and do not enable us to resolve when the acceleration occurred.

5.3. Description of isoage surfaces

The elevation of isoage surfaces generally increases with age (see legend on each map of Figure 7), which is consistent with the assumption that isoage surfaces are mainly controlled by the effect of denudation on isotherms (Figure 5). The overall shape of the isoage surfaces is that of arcuate domes, the axes of which are roughly superposed with the External
Crystalline Massifs (Aar, Mont-Blanc and Ecrins, see Figure 2) for the younger surfaces, and
with more internal massifs (Lepontine Alps, Dent-Blanche) for older surfaces. Young isoage
surfaces are defined mostly by points from high-relief areas with young fission-track ages in
the valleys, whereas old isoage surfaces are controlled by locally old fission-track ages
encountered on topographic peaks and the elevation of isoage contours in the periphery of the
orogen.

5.4. Spatial and temporal evolution of exhumation rates

The difference in elevation of AFT isoage surfaces was used to estimate exhumation rates
between 13.5 and 2.5 Ma over the Western Alps (Figures 7-10). Comparing curves of
exhumation rate against time for different sub-areas (Figure 10) highlights a series of eight
overlapping segments from 9.5 to 2.5, 9.5 to 4.5, 13.5 to 10.5 and 13.5 to 4.5 Ma, which all
share a similar trend. The estimates of exhumation rate vary between 200 and 700 m/Myr,
with an acceleration centered around 5 Ma, which is in surprisingly good agreement with peri-
alpine sedimentation rates and inferred alpine denudation rates reported by Kuhlemann and
coworkers (Kuhlemann, 2000; Kuhlemann et al., 2002). While we are mostly interested in
the pattern of denudation rates at the orogen scale, regional variations in the exhumation
history demonstrate the localization of denudation (Figure 10). The exhumation rates
estimated in the Bergell and Valais-Sesia areas (curves 1 and 2) are similar and indicate a
denudation rate of ~300 m/Myr between 13.5 and 10.5 Ma. The Ecrins and Mont-Blanc
massifs (curves 3 and 4) share a similar pattern of increase in exhumation rate between 5.5
and 4.5 Ma, with recent rates reaching 500 m/Myr. Further east, the Aar-Leventina area
(curve 6) shows a slightly earlier increase in exhumation rate (~6 Ma). However, the
occurrence of short mean track lengths in the Aar-Leventina and the Bergell areas (cf. section
4.4) may lead us to overestimate recent exhumation. In contrast, the onset of the acceleration
in the Simplon and Chur areas (curves 5 and 7) appears to be younger than 3.5 Ma, with recent denudation rates reaching over 600 m/Myr. The sub-area with the longest continuous coverage in isoage surfaces (area 8 on Figure 8) combines a suite of small areas in the Western Alps. The values of exhumation rate it provides between 13.5 and 4.5 Ma (curve 8 on Figure 10) are included within the range of the seven other sub-areas.

6. Discussion

6.1. Conditions of use of isoage surfaces

The use of isoage surfaces to calculate exhumation rates through time requires that the surfaces have not been significantly deformed. Therefore, actively deforming thrust belts would need to be treated with caution. Locations undergoing relief reduction are also to be avoided because age-elevation relationships would provide overestimates of exhumation rates (Braun, 2002). The optimal conditions are met in orogens where relief is either steady or increasing, and tectonic activity is insufficient to significantly deform the isoage surfaces. The Western Alps are a successful candidate because relief appears to have increased recently due to glaciations (Champagnac et al., 2007; van der Beek and Bourbon, 2008), whereas present-day tectonic activity is limited (e.g., Calais et al., 2002). Moreover, the European Alps are covered by an exceptional density of existing AFT ages, allowing us to use the approach developed here.

6.2. Errors affecting exhumation rate calculations

Several types of error potentially affect the calculation of exhumation rates from isoage surfaces: (1) uncertainties affecting the ages, elevations and coordinates of samples in the database used to compute isoage surfaces, (2) heterogeneous scatter of the interpolated data points, and (3) geological factors such as the composition of apatites (defining their precise
While errors of type 1 can be estimated on a sample per sample basis, propagating these into an uncertainty in isoage surface elevation cannot be done rigorously, although a Monte Carlo approach in which the surfaces are created thousands of times while varying the input data within error could be envisaged. Whereas uncertainties of type 2 (role of sampling density and scatter) are generally assessed using kriging techniques, these are limited for geological applications because of strong assumptions on spatial continuity and statistics of the data. Alternatively such errors may be evaluated using calculation-intensive boot-strap techniques. Uncertainties of type 3, however, are practically impossible to quantify. Moreover, the weight of these three types of errors within the final uncertainty in exhumation rates is unknown. Therefore, we chose to present the estimates of exhumation rates as such, without the addition of an inherently partial and, therefore, misleading error.

6.3. Comparison between exhumation rates and the volume of sediment deposited through time

The exhumation rates calculated from the AFT isoage surfaces over the Western Alps (Figure 10) are of the same order (200-600 m/Myr) as those calculated from the sedimentary record (Kuhlemann, 2000; Willett et al., 2006). They are also, more expectedly, comparable with denudation rates obtained from local thermochronological studies (e.g., Michalski and Soom, 1990; Schär et al., 1975; Schlunegger and Willett, 1999; Tricart et al., 2007). Thus, both the sedimentary record and the in-situ thermochronological record show a similar increase in exhumation rates around 5 Ma. However, the thermochronometric estimates of denudation rates are overall slightly higher than those obtained from the sedimentary record (Figure 10). This small offset may be explained by the fact that areas with the most complete isoage surface coverage, which are used in the calculations, are biased toward the more rapidly
eroding massifs with young AFT ages in the valleys, and therefore do not constitute a representative sampling of the entire Western Alps. Other explanations could be an overestimation of exhumation rates obtained from age-elevation relationships (Braun, 2002) or a general bias in the calculation of sediment volume, which, for instance, does not take chemical weathering or sediment recycling into account.

6.4. Possible causes for increased recent exhumation

Over the last 14 Myr, the shift of the apex of isoage surface domes through time from the inner Alps to the External Crystalline Massifs (Figure 7) suggests a shift of the most actively exhuming regions during late Miocene and Pliocene times. This idea is in agreement with the map of the ratio of final / initial exhumation rates (Figure 4), where acceleration of exhumation is observed after AFT closure in the External Crystalline Massifs.

Within this general frame, we observe a broad increase in exhumation rate in the Western Alps centered around 5 Ma, with local variations in the timing of this increase (Figure 10). Assuming that these variations are significant compared to the unquantified uncertainty, they suggest that the rise in Alpine denudation described as happening around 5 Ma (e.g. Cederbom et al., 2004; Kuhlemann, 2000), actually varied considerably, taking place between 6.5 and 2.5 Ma depending on local tectonic and structural conditions. A clear expression of regional diversity within a general trend of exhumation increase is found in the Simplon and Chur areas (Figures 8 and Figure 10). The resent surge in exhumation rates in these areas can be linked spatially to present-day high rock-uplift rates in the western and eastern Aar massif (e.g., Persaud and Pfiffner, 2004). Although a significant part of present-day rock uplift rates could be due to the isostatic response to erosional unloading (Champagnac et al., 2007; Schlunegger and Hinderer, 2001), this spatial link may suggest that these two locations are
characterized by high rock uplift rates since at least the time of AFT closure. Furthermore, this pattern suggests that current exhumation of the Aar massif is concentrated on its western and eastern borders, and has been so for several million years.

Based on the approximate temporal coincidence between Mio-Pliocene acceleration of exhumation in the Western Alps, and the closure of the Panama isthmus and subsequent reorganization of Atlantic Ocean currents, Cederbom et al. (2004) proposed that the increase in exhumation around 5 Ma was externally controlled by increased precipitation over Europe. An alternative, and more global mechanism, is that the increased variability of climate witnessed by the ocean oxygen isotope record forced accelerated erosion rates, although the data suggest that this happened between 4 and 3 Ma (e.g., Molnar, 2004; Zhang et al., 2001). Although this explanation remains difficult to confirm, it is seducing as a cause on a global, or at least a continental, scale could explain the simultaneous increase in exhumation in other orogens (e.g., Molnar, 2004; Zhang et al., 2001). Uplift of the Western Alps followed by widespread exhumation may also be controlled by a deep-seated event such as slab detachment; however, no evidence exists to tie such an event down at this particular time.

7. Conclusions

Our analysis of the complete fission-track thermochronology database in the Western Alps leads to the following general conclusions:

1) Although different regions of the Western Alps show a variable absolute amount of exhumation since 13.5 Ma, they share a common trend of doubling in exhumation rates at approximately 5 Ma. Providing assumptions on error values, it is possible to distinguish between areas where the rise in Alpine denudation took place at different periods within a 6.5 to 2.5 Ma time frame.
2) The overall consistency between estimated denudation rates using sediment volumes (Kuhlemann, 2000), and bedrock thermochronology (this study) demonstrates that, although both records are fragmentary and error-prone, they are appropriate to describe the general exhumation history at the orogen scale since at least 13.5 Ma.

3) The maps of zircon and apatite fission-track ages share a pattern of young ages over an arc linking the External Crystalline Massifs, as well as in the area of the Lepontine Alps, suggesting that these areas underwent the strongest recent denudation in the Western Alps. The observed longer mean AFT lengths in the areas with young fission track ages further supports this conclusion.

4) This pattern fits with the trend of accelerated exhumation rates calculated from samples with paired zircon and apatite fission-track ages. This trend indicates that most of the Western Alps, in particular the external side of the arc, was on average exhumed faster after AFT closure than between the times of ZFT and AFT closure.

Acknowledgements

This study is supported by an INSU-CNRS “Reliefs de la Terre” program grant to PvdB. AV is supported by a University of Edinburgh PhD teaching scholarship and an international student mobility (MIRA) grant of the Rhône-Alpes region. We are grateful to M. Ford and D. Seward for permission to use unpublished AFT ages. L. Keller, P. Leloup, S. Schwartz and P. Tricart kindly provided complementary details on their published material. The manuscript benefited from thorough and constructive reviews by Kerry Gallagher and an anonymous reviewer.
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Figure captions

Figure 1. Evolution of sedimentation rates through time, reconstructed from the preserved volume of sediments originating from the Western and the Eastern Alps, respectively (modified from Kuhlemann et al., 2002).

Figure 2. (a) Simplified geologic map of the Western Alps (modified from Schmid et al., 2004). The study area (shown by bold outline) covers the geological units with the highest density of fission track ages (cf. Figure 3), limited to the east by the Austroalpine Silvretta nappe boundary at about 9°55' E. (b) Cross-section following north-south transect A-B across the central Swiss Alps (modified from Schmid et al., 1996).

1979; Weh 1998; as well as unpublished ages provided by M. Ford, D. Seward and our own data.

Figure 3-b. Map of 296 interpolated ZFT ages from the Western Alps. Numbers are as in Figure 3-a. ZFT data are compiled from Bernet et al. 2001; Bigot-Cormier 2002; Bürgi and Klötzli 1990; Carpéna 1992; Carpéna et al. 1986; Ciancaleoni 2005; Flisch 1986; Fügenschuh and Schmid 2003; Fügenschuh et al. 1999; Giger 1991; Hunziker et al. 1992; Hurford and Hunziker 1985; Hurford and Hunziker 1989; Hurford 1986; Hurford et al. 1991; Keller et al. 2005; Michalski and Soom 1990; Rahn 1994; Schwartz 2000; Seward and Mancktelow 1994; Seward et al. 1999; Soom 1990; Vance 1999; Weh 1998; as well as unpublished ages provided by M. Ford, D. Seward and our own data.

Figure 3-c. Interpolated map of 258 mean apatite fission-track lengths (µm) from the Western Alps. Short mean lengths (< 13 µm) indicate slow passage of the sample through the AFT partial annealing zone, indicative of a slow exhumation rate. Long mean track lengths, in contrast, indicate rapid exhumation. Note the strong spatial overlap between mean track lengths >13 µm and AFT ages <~10 Ma (Figure 3-a), particularly in the Simplon and Chur areas, as well as more generally in the Mont-Blanc-Ecrins and the Argentera massifs. Numbers are as in Figure 3-a. Apatite fission-track lengths compiled from Bigot-Cormier 2002; Bürgi and Klötzli 1990; Ciancaleoni 2005; Giger 1991; Hunziker et al. 1992; Hurford and Hunziker 1989; Hurford 1986; Hurford et al. 1991; Knaus 1990; Malusà et al. 2005; Michalski and Soom 1990; Pawlig 2001; Rahn et al. 1997; Sabil 1995; Seward and Mancktelow 1994; Seward et al. 1999; Soom 1990; Vance 1999; Weh 1998; as well as our own unpublished data.
Figure 4. Variation of exhumation rate (Er) through time, calculated from samples with paired AFT and ZFT ages. Samples with both ages younger than 35 Ma (i.e., Alpine cooling ages) are used to calculate an initial rate during the time between closure of the ZFT and AFT thermochronometers and a final rate for the time since closure of the AFT system (see text for details). The color scale presents the ratio between final and initial exhumation rates and enables to distinguish between localities where average exhumation rates have accelerated (ratio > 1), remained steady (ratio ≈ 1) or decelerated (ratio < 1) after AFT closure. Data points are labeled by their AFT age. Data origin is given in the legends of Figure 3-a and 3-b.

Figure 5. Generic sketch of AFT isoage surface concept. (a) Denudation (i.e., removal of material) occurring between times t₁ and t₂ over the present day topography is reflected by the migration of shallow isotherms, downwards with respect to the exhuming rock mass such that a rock particle is cooled during exhumation (see definitions in Ring et al., 1999). The 120 - 60 °C AFT partial annealing zone is shifted downwards, and so are the AFT closure temperature (the temperature at which the first track is recorded) and the AFT closure surface (the surface linking all samples crossing the closure temperature at a given moment). (b) Former closure surfaces become isoage surfaces, younging downwards and intersecting the topography.

Figure 6. Steps toward the interpolation of isoage surfaces. A neighborhood search of significant age-elevation relationships (AER) is performed within 3 km around each data point (a, b). If the correlation coefficient between age and elevation is not statistically significant at the 95 % confidence level (b), the radius for selection of points is increased stepwise up to a maximum of 15 km (c). The $A₀$ and $A₁$ parameters defining the regression lines are used to interpolate the elevation of isoage surfaces between 1 Myr before the oldest age selected ($A_{min}$) and 1 Myr after the youngest age selected ($A_{max}$). Finally, isoage surfaces
are obtained by interpolation of isoage point arrays combining the results of neighborhood
AER search and the elevation of isoage contours (d). The figure shows a zoom of the
Lepontine area and the sources of data points are as in Figure 3a.

**Figure 7.** Six examples of isoage surfaces among the 13 obtained between 14 and 2 Ma.

Following a natural-neighbor interpolation between isoage points, the grid is clipped with a
mask at 15 km to reduce the number of pixels located far from any source of information. The
color scale represents the elevation in meters above sea level (note that the scale is different
for each panel). The overall elevation of old isoage surfaces (e.g., 11 Ma; 14 Ma) is higher
than the elevation of younger isoage surfaces (2 Ma; 4 Ma) which is in agreement with the
generic sketch in Figure 5.

**Figure 8.** Areas with continuous isoage surface coverage. Eight areas with isoage surfaces
covering 4 to 10 Myr were obtained by comparing the area covered by the 13 isoage surfaces
obtained between 14 and 2 Ma (Figure 6). Different periods of time are documented in
different areas, as indicated in the legend, depending on the ages accessible at outcrop.

**Figure 9.** Calculation of denudation rate from the elevation difference of isoage surfaces. (a)
Map of the elevation difference between the 5 and 4 Ma isoage surfaces. (b) In this example,
values of elevation difference are extracted from the area of continuous isoage surface
coverage located on the Mont-Blanc massif (area 4 in Figure 8), and plotted in a frequency
histogram. The pixels with a negative value (in black on the map) cannot be used to infer
denudation rates and are discarded. The average distance between isoage surfaces is
calculated over the remaining histogram and considered to be equivalent to the amount of
exhumation affecting the Mont-Blanc area during the corresponding period.
Figure 10. Comparison between the estimates of average denudation rate (recorded in sediment volume) and exhumation rate (using AFT isoage surfaces, this study) over the Western Alps. The average Western Alps denudation rate calculated by Kuhlemann (2000) is the ratio between the peri-Alpine sedimentation rates (Figure 1) and the provenance area. The exhumation rate was estimated over 8 regions of the Western Alps by the isoage surface technique (Figures 5 to 9). Both the envelope of exhumation trend and the denudation curve show an increase centered around 5 Ma. See sections 6.3. and 6.4. for a discussion of the features observed in exhumation rate trends.
Figure 1
Figure 3-a
Figure 3-b
Figure 3-c
Figure 4
Figure 5
Figure 6
Figure 7
Figure 9
Figure 10

Denudation rate calculated over the Swiss and western Alps from the volume of sediments preserved (Kuhlmann, 2000).

Envelope of exhumation trends obtained from AFT isogae surfaces (this study).

Exhumation and denudation rates