Inversion of thermochronological age–elevation profiles to extract independent estimates of denudation and relief history — II: Application to the French Western Alps

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A B S T R A C T

Thermochronologic data collected along age–elevation profiles are commonly interpreted as recording temporally variant but spatially constant exhumation rates. However, thermochronologic age–elevation relationships are known to be perturbed by topographic effects and potential changes in relief, which are neglected in the inherently 1-D interpretation commonly applied. Such data thus potentially record both the denudation and relief history of the sampled region but extracting this information is challenging. In a companion paper, we develop a methodology for rigorously interpreting thermochronologic age–elevation profiles in terms of exhumation rates and relief development through time, and to independently quantify the resolution of these constraints. Here we test this approach using a thermochronological dataset consisting of apatite and zircon fission-track and (U–Th)/He data, collected at La Meije Peak in the Pelvoux-Ecrins massif (French Western Alps). Our data and models suggest a three-phase exhumation history in the Pelvoux–Ecrins massif, including a pulse of rapid exhumation at ∼6–5.5 Ma, preceded and followed by more moderate rates of denudation in the order of 0.3–0.4 km Myr−1. This rapid exhumation event appears to occur coevally in other external crystalline massifs in the Alps but is not detected by qualitative inspection of the age–elevation relationships. Both our synthetic results and inversion of the La Meije data strongly suggest that apatite fission-track age–elevation relationships alone cannot resolve both denudation and relief histories independently and that multiple thermochronometers are required. Combining apatite fission-track and (U–Th)/He ages and, particularly, including fission-track-length data greatly improves the resolution of the inferred exhumation histories. Although denudation rates through time and the timing of rate changes are generally well resolved, our data have insufficient resolution to satisfactorily constrain the relief history. Synthetic results reported in the companion paper suggest that the reason for this limitation is that relief increase through valley carving has been insufficient with respect to the regional denudation rates to be unambiguously extracted from the data.

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1. Introduction

One of the key questions in the debate on the causal links between late Cenozoic climate change and the uplift of mountain belts is whether the Late Pliocene–Quaternary climate, characterised by high-frequency oscillations between glacial and interglacial conditions and significantly increased global denudation rates (Zhang et al., 2001; Molnar, 2004), can lead to isostatic uplift of mountain peaks (Molnar and England, 1990). Such climate-induced mountain-peak uplift requires isostatic rebound to outstrip erosion on the peaks (Montgomery, 1994; Small and Anderson, 1998; Champagnac et al., 2007). Erosion must therefore be concentrated in the valleys, increasing mountain-belt relief. It remains unclear if this is the case, particularly in response to the glaciation of mountain ranges. While several studies have indicated that glaciation leads to an increase in relief (Montgomery, 1994; Small and Anderson, 1995; Kirkbride and Matthews, 1997; Montgomery, 2002), theoretical considerations, numerical experiments and observations in the Himalaya suggest that increased glacial denudation rates may lead to a decrease in relief (Brozovic et al., 1997; Whipple et al., 1999; Tomkin and Braun, 2002). The development of methods enabling us to quantitatively assess paleo-relief in mountain belts is required to resolve this apparent controversy.

We explore the capacity of low-temperature (apatite and zircon fission-track and (U–Th)/He) thermochronometric data, in particular
thermochronological age–elevation profiles, to constrain the paleo-
relief of mountain belts. Thermochronological analyses have generally
considered the problem as one-dimensional (e.g., Fitzgerald et al.,
1995), neglecting potential effects of temporally varying topography
or laterally varying denudation rates on age–elevation profiles (Braun,
2002a). Only recently have some studies interpreted thermochrono-
logical age–elevation profiles in terms of relief development (Clark
et al., 2005; Schildgen et al., 2009; Richardson et al., 2010). In this
study, we quantify the extent to which such topographic effects may
be extracted from thermochronological datasets, and determine if it is
possible to differentiate regional changes in denudation rate from
relief development by analysing thermochronological age–elevation
profiles.

We use a recently developed inverse method that combines the
three-dimensional thermal-kinematic model Pecube (Braun, 2002a,
2003), with an inversion scheme based on the neighbourhood
algorithm (Sambridge, 1999a,b). We do not only search for best-
fitting model parameters (Braun and van der Beek, 2004; Braun and
Robert, 2005; Herman et al., 2007), but also derive Bayesian
probability–density functions for parameter values (Herman et al.,
in press). This approach allows best-fitting scenarios for denudation
and relief histories to be extracted from the data and their resolution
to be assessed. In a companion paper (Valla et al., 2010), we fully
describe the inverse method and use synthetic data from imposed
denudation and relief histories to quantitatively assess the constraints
on denudation rates, timing of rate changes and relief evolution that we
can extract from typical low-temperature thermochronological datasets.
Here, we apply this method to a new thermochronological
(apatite and zircon fission-track and (U–Th)/He) dataset collected
along an age–elevation profile in the French western Alps (La Meije
peak; Pelvoux–Ecrins massif), a region that has experienced modest
tectonic activity but intense glaciation during the last few million
years. We aim to quantify both the timing of denudation and relief
development in this massif, in particular to detect the potential
topographic effect of Quaternary glaciations (i.e. relief increase due to
glacial erosion) on the cooling histories derived from the thermo-
chronological dataset.

In the following, we first introduce the study area and then present
the thermochronological data and their qualitative interpretation
regarding the evolution of exhumation rates through time. We briefly
summarize our modelling approach, employ it to extract the
resolvable denudation and relief histories from the data, and discuss
its implications for our understanding of the tectonic and climatic
controls on this history.

2. The Pelvoux–Ecrins Massif

The “External Crystalline Massifs” (ECM) of the western and
central Alps consist of blocks of European crystalline basement
exhumed from ~15 km depth along crustal-scale thrusts since
Oligocene–Early Miocene times (Schmid and Kissling, 2000; Leloup
et al., 2005; Simon-Labric et al., 2009). The ECM are characterised by
some of the highest topography and relief of the Alpine orogen, with
many ~4000-m-high peaks, although the main Alpine drainage divide is
located more internally within the belt. Several recent studies of the
denudation history of these massifs have suggested peak
exhumation rates of ~1 km Myr \(^{-1}\) around 6–7 Ma, followed by
Pliocean–Quaternary rates of 0.5–1 km Myr \(^{-1}\), e.g., in the Argentiere
(Bigot-Cormier et al., 2006), Mont Blanc (Leloup et al., 2005;
Glotzbach et al., 2008) and Aar (Vernon et al., 2009) massifs, although
countering denudation histories have been inferred for the latter
(e.g., Reinecker et al., 2008; Glotzbach et al., in press). In contrast,
sediment flux to the peri-Alpine basins (Kuhlemann et al., 2002), and
apatite fission-track (AFT) data from the North Alpine Foreland Basin
(Cederbom et al., 2004) suggest significantly increased erosion of the
belt since ~3 Ma. However, neither the history of relief development
nor the potential effect of widespread glaciations on the relief history
has been studied in detail.

We focus on the Pelvoux–Ecrins Massif in southeastern France
(Fig. 1). This ECM is made up of several basement blocks with
intervening inverted Mesozoic basin remnants. Basement blocks have
been thrust up along steeply dipping faults with variable trends,
which result from a complex polyphase history during both Early
Mesozoic rifting and Alpine convergence phases (Ford, 1996; Dumont
et al., 2008). Morphologically, the massif forms a NNW–SSE oriented
delonated dome that has been deeply incised by tributaries of the
Romanche, Drac and Durance rivers to the north, west, and southeast,
respectively (Fig. 1). Glacial imprints on the morphology are widespread
(Montjuvent, 1974; van der Beek and Bourbon, 2008; Valla et al., 2010) and
consist of numerous hanging valleys, valley steps and overdeepenings.
However, Miocene fluvial deposits surrounding the massif demonstrate
that the planform drainage pattern is pre-glacial (Montjuvent, 1978).

Paleomagnetic, Ar–Ar and zircon fission-track (ZFT) data suggest
that denudational cooling of the Pelvoux–Ecrins massif started
~24 Ma from Alpine syn-tectonic temperatures of ~300 °C (Crouzet
et al., 2001; Simon-Labric et al., 2009). AFT ages from the massif and the
contiguous Grandes Rousses (Fig. 1) are between ~3 and ~14 Ma
(Sabil, 1995; Seward et al., 1999), showing relatively large scatter and
no clear age–elevation relationships (although neither study system-
atically sampled age–elevation profiles). The youngest AFT ages are
encountered at valley bottoms in the centre of the massif and require
several kilometres of denudation since the Late Pliocene. Geodetic
measurements suggest present-day uplift rates of up to 1 mm yr
\(^{-1}\) (with respect to the foreland) within the Belledonne Massif to the
north of the study area (Jouanne et al., 1995). However, these massifs are
currently seismically inactive, except for modest transpressive
activity within the Belledonne Massif (Thouvenot et al., 2003), and
continuous GPS measurements suggest minimal present-day defor-
mation (Calais et al., 2002; Delacou et al., 2004).

3. Thermochronology data

Samples were collected in the upper Romanche valley and along
a roughly north–south transect up the north-western flank of La
Meije peak, between 1310 and 3215 m elevation (Fig. 2). La Meije
peak consists of basement rocks (gneiss, schist and granite) thrust
northwards over Mesozoic sediments that crop out at the base of the
profile. Samples were collected every ~100 m along the profile where
possible. Samples were initially prepared for AFT and ZFT thermo-
chronology, following standard laboratory procedures (as described,
for instance, in Tricart et al., 2007). 15 samples yielded sufficient
apatite for AFT analysis and 6 proved suitable for ZFT analysis (Table 1).
Samples with high yields of good-quality apatite and zircon were
prepared for (U–Th)/He analysis on apatite (AHe, 4 samples) and
zircon (ZHe, 3 samples), following procedures outlined previously
(Persano et al., 2002; Foeken et al., 2006; Dobson et al., 2009).

3.1. Apatite fission-track data

AFT ages vary between 3.2 ± 0.8 and 8.0 ± 1.0 Ma (±2σ, Table 1;
Table S1). Ages correlate reasonably well with elevation (Pearson
correlation coefficient r = 0.73). The slope of the age–elevation profile
(Fig. 3) is 542±31 \(\mu\)m Myr \(^{-1}\), as given by the inverse of the weighted
least-squares regression (Williamson, 1968), where the variation in the
slope represents the 1 – σ error in the estimate. In detail, however, the
data show relatively large scatter, with several samples lying
outside the age–elevation relationship at the 1 – σ level (Fig. 3). The
data appear to form two parallel age–elevation relationships, with
samples M1, M5, M9, M11 and M16 defining the younger trend. Etch-
pit widths parallel to the C-axis (\(D_p\)) can be used to monitor the
annealing kinetics of apatite (Carlson et al., 1999; Barbarand et al.,
2003); in our samples $D_{par}$ varies between 1.08 and 1.66 μm (standard deviations of 0.2–0.3 μm, Table S1), indicating F-rich apatite that is not very resistant to annealing, and little compositional variation within individual samples. There is no systematic variation between $D_{par}$ and AFT age of a sample at a given elevation; it is therefore unlikely that compositional control, leading to variable annealing kinetics, accounts for the observed trends. Two samples contained sufficient confined tracks to permit measuring statistically significant confined track-length distributions (Fig. 3b). Both show relatively long mean track lengths (MTL) indicative of rapid cooling. M5 has a MTL of 13.5 μm.
and mean $D_{\text{par}}$ of $1.36 \pm 0.03 \mu m$, whereas M7 has a MTL of $14.4 \mu m$ and mean $D_{\text{par}}$ of $1.66 \pm 0.03 \mu m$. The difference between the MTL distributions and the younger age of M5 with respect to M7, despite its higher elevation, may reflect slightly different annealing kinetics of these samples.

3.2. Zircon fission-track data

ZFT ages increase monotonously with elevation from $13.0 \pm 2.0$ Ma at $1310$ m (M17) to $27.2 \pm 2.4$ Ma at $3065$ m (M2) (Table 1; Table S2). The age–elevation correlation is very good (Pearson correlation coefficient $r = 0.94$) and the slope of the age–elevation profile is $158 \pm \frac{19}{9} \text{ Myr}^{-1}$; significantly less steep than for the AFT data (Fig. 3). Single-grain ZFT ages for the upper three samples (M2, M6, and M7) show very low dispersions ($D \ll 1\%$; $P(\chi^2) > 98\%$). In contrast, the lower three samples (M13, M16, and M17) have dispersed single-grain ages ($D > 12\%$) and two of these fail the $\chi^2$-test, suggesting that these samples have been exhumed from within the ZFT partial annealing zone, and that the lower three ZFT ages should be interpreted with caution. Binomial peak-fitting (Stewart and Brandon, 2004) of the single-grain ages from these three samples (a combined total of 38 dated zircon grains) suggests they contain a young age population of $12.2 \pm 1.1$ Ma, made up by $65\%$ of the grains, with the rest of the grains defining a population of $19.3 \pm 1.8$ Ma.

Fig. 2. Topographic map of the sampling region (elevation contours from IGN 50-m resolution digital topography) overlain on orthorectified aerial photo mosaic from the Institut Géographique National Géoportal website (http://www.geoportail.fr), showing sample locations. Eastings and northings follow the IGN Lambert-III grid, in kilometres. Inset shows topography (no vertical exaggeration) and sample locations projected onto a N027E profile across the sampling sites.


3.3. Apatite (U-Th)/He data

Of the four samples analysed, two have AHe ages that are consistent with the AFT ages, whereas two have AHe ages that are significantly older than the corresponding AFT ages (Table 1, Table S3; Fig. 3b) even though replicate measurements lie within the 8% standard-age reproducibility. M2 yields a weighted-mean AHe age of 12.0±1.0 Ma (12.0±0.7 Ma). In contrast, M6 yields a weighted-mean AHe age of 18.0±1.3 Ma (18.0±1.3 Ma). The fact that two samples have AHe ages older than the corresponding AFT ages, and that all samples replicate only moderately well, leads us to consider the AHe ages with care. All samples were thoroughly screened for inclusions; however minute U and Th bearing inclusions may cause a problem of excess He in these relatively young samples. The AHe ages might be expected to vary significantly with U and Th concentrations, which may affect the AHe ages in these young samples.

3.4. Zircon (U-Th)/He data

Two replicate single-grain age determinations were run for each of the 3 samples selected for ZHe analysis (Table 1, Table S4). Weighted-mean ages of all 3 samples are within error, varying from 12.5±1.5 Ma to 13.7±1.6 Ma, even though two samples (M2 and M7) were collected close to the top of the profile, and the third (M17) at its base. Samples M7 and M17 replicate within the subalpine thrust belts to the northwest of the ECM (Beck et al., 2006) to predict AFT ages and mean fission-track age determinations provided in Supplementary Tables S1 to S4. We use the annealing algorithm of Stephenson et al. (2006) to predict AFT ages and mean fission-track age determinations provided in Supplementary Tables S1 to S4.

Apatite (AFT) and zircon (ZFT) fission-track ages are central ages (Callbraith, 2005); Apatite (AHe) and zircon (ZHe) (U-Th)/He ages are weighted-mean averages from 2 to 4 duplicate measurements; the reported error is either the standard deviation of the sample, or the reproducibility of the age standard, whichever is greater. AHe ages given in parentheses are not used in inversion. Eastings and Northings are in Institut Géographique National Lambert-III reference frame. Details for age determinations are provided in Supplementary Tables S1 to S4.

Table 1

Thermochronology data from La Meije peak, French western Alps.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Elev. (m)</th>
<th>Easting (m)</th>
<th>Northing (m)</th>
<th>AHe Age ± 1σ (Ma)</th>
<th>AFT Age ± 1σ (Ma)</th>
<th>MTL ± 1σ (μm)</th>
<th>ZHe Age ± 1σ (Ma)</th>
<th>ZFT Age ± 1σ (Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>3215</td>
<td>284,413</td>
<td>4,987,425</td>
<td>6.3 ± 0.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M2</td>
<td>3065</td>
<td>284,325</td>
<td>4,988,150</td>
<td>7.7 ± 0.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M3</td>
<td>3005</td>
<td>284,575</td>
<td>4,988,225</td>
<td>7.8 ± 0.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M4</td>
<td>2920</td>
<td>284,600</td>
<td>4,988,388</td>
<td>8.0 ± 0.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M5</td>
<td>2805</td>
<td>284,638</td>
<td>4,988,653</td>
<td>5.3 ± 0.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M6</td>
<td>2715</td>
<td>284,725</td>
<td>4,988,838</td>
<td>7.0 ± 0.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M7</td>
<td>2610</td>
<td>284,752</td>
<td>4,989,217</td>
<td>6.2 ± 0.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M9</td>
<td>2360</td>
<td>285,450</td>
<td>4,989,475</td>
<td>4.7 ± 0.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M10</td>
<td>2200</td>
<td>285,413</td>
<td>4,989,963</td>
<td>6.0 ± 0.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M11</td>
<td>1900</td>
<td>285,888</td>
<td>4,990,552</td>
<td>3.5 ± 0.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M12</td>
<td>1800</td>
<td>285,730</td>
<td>4,990,614</td>
<td>5.7 ± 0.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M13</td>
<td>1720</td>
<td>285,588</td>
<td>4,990,647</td>
<td>6.8 ± 0.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M14</td>
<td>1480</td>
<td>287,600</td>
<td>4,991,025</td>
<td>4.3 ± 0.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M15</td>
<td>1400</td>
<td>285,038</td>
<td>4,991,488</td>
<td>3.2 ± 0.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M16</td>
<td>1310</td>
<td>283,588</td>
<td>4,990,975</td>
<td>4.0 ± 0.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M17</td>
<td>1210</td>
<td>283,588</td>
<td>4,990,975</td>
<td>4.4 ± 0.5</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

Apatite and zircon (ZFT) fission-track ages are central ages (Callbraith, 2005); Apatite (AHe) and zircon (ZHe) (U-Th)/He ages are weighted-mean averages from 2 to 4 duplicate measurements; the reported error is either the standard deviation of the sample, or the reproducibility of the age standard, whichever is greater.

3.5. Qualitative interpretation

At face value, the variable slopes of the different age–elevation relationships (AER) can be interpreted as reflecting a pulsed exhumation history. The ZFT data suggest relatively slow denudation from within or below the ZFT partial annealing zone (around 200–240 °C) for α-damaged zircon (Brandon et al., 1998) between ~27 and ~13 Ma, at a rate of ~160 m Myr⁻¹. Timing of this initial cooling is consistent with earlier estimates from Ar–Ar (Simon-Labric et al., 2009) and paleomagnetic (Crouzet et al., 2001) data obtained to the west and south of our profile. The steeper age–elevation relationship from the AFT data implies an increase in regional denudation rates to ~500 m Myr⁻¹ sometime between ~13 and ~8 Ma. Varying denudation rates are also suggested by the ZHe data, which could be interpreted as implying a phase of rapid denudation (~1 km Myr⁻¹) at around 13 Ma (Fig. 3), even though the ZHe data must be interpreted with caution because of the small number of samples and relatively low reproducibility of ZHe ages. The ZHe and AFT data together may indicate a regional increase in exhumation rate that started ~13 Ma, as also suggested by the relatively young age population (~12 Ma) within the lowermost ZFT samples (see Section 3.2). This timing correlates with the onset of deformation within the subalpine thrust belts to the northwest of the ECM (Beck et al., 1998; Burkhard and Sommaruga, 1998). Finally, the partial overlap between AFT and AHe ages could indicate rapid final cooling to surface temperatures at ~4–6 Ma.

This interpretation is, however, inherently one-dimensional and neglects the possible effects of surface topography on underlying isotherms, which could explain, for instance, part or all of the difference in slope between the high-temperature ZFT and low-temperature AFT AERs (e.g., Braun, 2002a). It also neglects the possible effects of relief development. In the following, we will analyse our data more quantitatively using the inverse approach developed in Valla et al. (2010), in order to analyse to what extent we can extract quantitative information on exhumation and relief history from this age–elevation profile.

4. Inverse modelling of thermochronological data

A full description of the numerical methodology combining Pecube with the inverse algorithm NA is provided in the companion paper (Valla et al., 2010). Thermo-kinematic and elastic parameters used for modelling are identical to those used by Valla et al. (2010, see their Table 1). We use the annealing algorithm of Stephenson et al. (2006) to predict AFT ages and mean fission-track
lengths (MTL), the annealing model of Tagami et al. (1998) for ZFT ages and the diffusion models of Farley (2000) and Reiners et al. (2004) for AHe and ZHe ages, respectively. More sophisticated age-prediction models have been proposed in recent years, which take into account kinetic effects due to chemical variability for AFT annealing (e.g., Ketcham, 2005) and radiation damage for AHe diffusion (e.g., Flowers et al., 2009; Gautheron et al., 2009). However, given the chemical composition of our samples (F-rich apatite, U-content $\sim 30–90$ ppm) and the expected cooling rates $\geq 10^\circ$C Myr$^{-1}$ through the AFT and AHe closure temperatures, these effects are expected to lead to only minor deviations from the predictions used by our models.

4.1. Numerical approach

NA constitutes a two-stage inversion method (Sambridge, 1999a,b): the first or sampling stage involves an iterative search in the multidimensional parameter space in order to find sets of input parameters that minimize the misfit between the modelled and observed data, based on a weighted least-squares function:

$$\psi = \sqrt{\sum_{j=1}^{N} \sum_{i=1}^{M} \left( \frac{\alpha_{i,mod} - \alpha_{i,dat}}{\sigma_i} \right)^2}$$

where $N$ is the number of datasets (up to 5 in our case, see below), $M$ is the number of samples in each dataset, $\alpha_{i,mod}$ and $\alpha_{i,dat}$ are the predicted and observed values, respectively, and $\sigma_i$ is the error on the data. During the second or appraisal stage, the model ensemble is resampled to provide Bayesian measures of marginal probability-density functions (PDFs) for all parameters, allowing a quantitative assessment of the extent to which these parameters are resolved (see Valla et al., 2010, for full details).
We have an extended thermochronological dataset consisting of AFT and AHe ages and MTL measurements, as well as ZFT and ZHe ages. In order to evaluate to what extent apatite data alone can provide estimates of denudation and relief histories, and to determine what supplementary constraints zircon data impose on the tectonic-geomorphic history, we run models with the apatite data alone before the ZFT and ZHe data is incorporated. This allows us to interpret denudation and relief evolution since ∼10 Ma before investigating a longer period (since ∼30 Ma). The apatite-only scenario (hereafter referred to as Scenario Ap) was run over 15 Myr and describes a two-stage exhumation and relief history. This model combines four parameters: (1) denudation rate during the first phase ($E_1$: 0–4000 m Myr$^{-1}$); (2) denudation rate during the second phase ($E_2$: 0–2000 m Myr$^{-1}$); (3) transition time ($T$: 1–14 Ma); and (4) relief factor ($R$: 0–2). The relief factor $R$ is defined as: $R = \Delta h_1 / \Delta h_2$; for Scenario Ap, relief is constant during the first phase ($\Delta h_1$) and then linearly evolves towards $\Delta h_2$ (the present-day relief; extracted from a 90-m Digital Elevation Model) at the end of the second phase. In our models, relief changes through valley incision; i.e. peaks remain at constant elevation (see Valla et al., 2010 for details).

For all parameters, this specified range will be considered as a uniform prior distribution during the appraisal stage (see Valla et al., 2010 for details). Four numerical inversions used AFT ages alone, AFT + AHe ages, AFT + MTL and finally all apatite data, allowing quantitative assessment of the combination of low-temperature thermochronometers that provides the tightest constraints on denudation rates and/or relief evolution through time.

The second scenario (hereafter referred to as Scenario Ap+Zr) includes both apatite and zircon data. This was run over 40 Myr, in order to assure that all points that end up at the surface cool through the ZFT closure temperature during the model run, and includes three phases with seven associated parameters (again assuming uniform

![Fig. 4. Scatter diagrams showing results of NA inversions for Scenario Ap. Each dot corresponds to a forward model; its colour is proportional to the value of the reduced misfit between predictions and data ($\psi$ reduced by the number of data; blue to green corresponds to low misfits, red corresponds to mean misfits larger than the mean standard error on the data). Each diagram is the projection onto a plane defined by two of the four parameters (denudation rates $E_1$ and $E_2$; transition time $T$ and relief factor $R$); horizontal and vertical axes define the parameter space. Results are only shown for end-member inversion experiments with 15 AFT ages only (a–b) and 15 AFT + 2 AHe ages combined with 2 MTL measurements (c–d).](image-url)
prior distributions within the specified ranges): (1) denudation rate during the first phase \((E_0; 0–2000 \text{ m Myr}^{-1})\); (2) denudation rate during the second phase \((E_1; 0–4000 \text{ m Myr}^{-1})\); (3) denudation rate during the third phase \((E_2; 0–2000 \text{ m Myr}^{-1})\); note that these phases are numbered so as to be comparable to those of Scenario Ap; (4) transition time between first and second phase \((T_1; 1–39 \text{ Ma})\); (5) transition time between second and third phase \((T_2; 1–39 \text{ Ma})\); with \(T_1 > T_2\); (6) relief factor of the first phase \((R_1; 0–2)\); and (7) relief factor at the end of the second phase \((R_2; 0–2)\), the relief tending linearly toward the modern value \((R = 1)\) during the third phase.

4.2. Quantitative interpretation of apatite data (Scenario Ap)

Inversion results using AFT ages only as well as the full apatite dataset (AFT ages, MTL and AHe ages) are reported in Fig. 4. The inversion based on the AFT ages alone (Fig. 4a, b) does not resolve a unique set of parameters for either denudation rates \((E_1 \approx 300–4000 \text{ m Myr}^{-1}; E_2 \approx 300–1800 \text{ m Myr}^{-1})\), timing \((T \approx 2–6 \text{ Ma})\) or relief evolution \((R \approx 0.3–1.8)\). The plots suggest significant tradeoff between parameters and show that the AFT ages alone do not have the resolution to independently predict denudation or relief development. Addition of the two AHe ages and two MTL measurements significantly improves model convergence (Fig. 4c, d) and the sampling stage suggests high denudation rates \((E_1 > 1500 \text{ m Myr}^{-1})\) before 6.5–5 Ma followed by much slower denudation rates \((E_2 < 300 \text{ m Myr}^{-1})\) until present. The time of change is well constrained \((T \approx 5–6.5 \text{ Ma})\) and predictions for relief evolution suggest between 10 and 100% relief increase between the two phases \((R \leq 0.9; \text{Fig. 4d})\). Note that this optimum history deduced from the NA sampling stage differs significantly from that inferred qualitatively in the previous section: exhumation rates before 5 Ma are higher than inferred from the AFT AER and decrease sharply after that, which was not obvious from inspection of the AER. Furthermore, NA results provide independent information on relief evolution, suggesting that during this slow denudation phase, relief has dramatically increased.

Posterior probability-density functions (PDFs) for parameter values, derived from the appraisal stage, confirm most of these estimates (Fig. 5). The most important data for model convergence are the MTL measurements, especially for predictions of denudation rates \((E_1 \text{ and } E_2)\) and timing \((T)\). While predictions for \(E_1 \text{ and } E_2\) from the AFT ages or AFT + AHe inversions are \(600 \pm 600 \text{ and } 700 \pm 200 \text{ m Myr}^{-1}\) respectively, the inclusion of the MTL data yields values of \(2400 \pm 900 \text{ and } 130 \pm 130 \text{ m Myr}^{-1}\) (Fig. 5a, b; the quoted numbers are the mode and \(1 - \sigma\) dispersion around the mode of the PDF). The timing of change \((T)\) is also better constrained, improving from \(9.0 \pm 3.3 \text{ Ma}\) (AFT + AHe) to \(5.1 \pm 0.9 \text{ Ma}\) when the MTL measurements are included (Fig. 5c). The Bayesian predictions for relief evolution, in contrast, are not improved by adding AHe and/or MTL data to the AFT ages (Fig. 5d); parameter PDFs show that our data has insufficient resolution to constrain the relief-ratio parameter \((R = 1.1 \pm 0.6); \text{since the distribution has no clear mode this value corresponds to its weighted mean})\). We thus have good constraints on both denudation

![Fig. 5. Posterior PDFs for Scenario Ap parameters, obtained from the NA appraisal stage: (a) denudation rate of the first exhumation phase \((E_1)\); (b) denudation rate of the second exhumation phase \((E_2)\); (c) transition time between the two exhumation phases \((T)\); and (d) relief factor between the paleo-relief and the present-day relief \((R)\). Each line defines an inversion experiment with a given set of thermochronological data (see key in panel d).](image-url)
rates and timing but not on relief development: our apatite data strongly suggest a sharp change from high \( (E_1 = 2400 \pm 900 \text{ m Myr}^{-1}) \) to moderate \( (E_2 < 310 \text{ m Myr}^{-1}) \) denudation rates at 5.1 ± 0.9 Ma. However, although the inversion suggests that relief may have increased since this time, the apatite data do not resolve relief evolution over the last ~15 Myr. The fit to both the AFT and AHe AERs for this “most probable” model is illustrated in Fig. 8a and shows how the inversion attempts to simultaneously optimise the fit to the relatively scattered AFT ages and the overlapping AHe ages.

4.3. Quantitative interpretation of apatite + zircon data (Scenario Ap + Zr)

Sampling-stage results using all the data (Fig. 6) complete the results from Scenario Ap. The inversions suggest that moderate denudation rates \( (E_2 < 700 \text{ m Myr}^{-1}; \text{Fig. 6b}) \) during the last 3–7 Ma (Fig. 6c) were preceded by a phase of rapid denudation \( (E_1 \approx 1200–2500 \text{ m Myr}^{-1}; \text{Fig. 6a}) \) between 5–11 and 3–7 Ma (Fig. 6c). Addition of the zircon data enables us to constrain an older phase of relatively low denudation rates \( (E_0 < 500 \text{ m Myr}^{-1}; \text{Fig. 6a}) \) from 30 to 5–11 Ma. Relief predictions are quite different from Scenario Ap; they suggest an increase in relief before 5–11 Ma \( (R_1 < 1; \text{Fig. 6d}) \) but a decrease since that time \( (R_2 > 0.8; \text{Fig. 6d}) \), even though again the relief parameters do not seem to converge very well.

Parameter PDFs derived from the appraisal stage confirm that the exhumation history may be divided into 3 contrasting phases: moderate denudation rates \( (E_0 = 400 \pm 300 \text{ m Myr}^{-1}; \text{Fig. 7a}) \) between 30 and 6.0 ± 3.3 Ma \( (T_1; \text{Fig. 7e}) \); a pulse of rapid denudation \( (E_1 = 2600 \pm 1100 \text{ m Myr}^{-1}; \text{Fig. 7b}) \) between 6.0 ± 3.3 and 5.5 ± 3.3 Ma \( (T_2; \text{Fig. 7f}) \); and finally moderate denudation rates \( (E_2 = 600 \pm 300 \text{ m Myr}^{-1}; \text{Fig. 7c}) \) from 5.5 ± 3.3 Ma to the present. Relief-parameter predictions remain relatively unconstrained and do not show a clear indication for relief increase (Fig. 7d), although relief before ~6.0 Ma may have been lower than today \( (R_1 = 0.03 \pm 0.03) \) and the inferred pulse of rapid denudation may have been associated with higher relief \( (R_2 = 1.98 \pm 0.97) \). However, these estimates are not better resolved than the priors, implying that our data do not have sufficient resolution to constrain the relief history.

Fig. 6. Scatter diagrams showing results of the NA inversion for Scenario Ap + Zr. Same plots as Fig. 4 but for seven parameters (denudation rates \( E_0, E_1 \) and \( E_2 \); transition times \( T_1 \) and \( T_2 \); relief factors \( R_1 \) and \( R_2 \)); horizontal and vertical axes define the parameter space for given parameters. Note misfit function \( \psi \) is reduced by the number of data (i.e., 28); blue to green corresponds to low misfits; yellow corresponds to acceptable misfits (mean misfit smaller than the mean standard error on the data), and red corresponds to high misfits (larger than the mean standard error on the data).
5. Discussion

Our quantitative analysis of thermochronological data from an elevation profile at La Meije has important implications, both for the exhumation and relief history of the western Alps, and more generally for the interpretation of thermochronology data, in particular age–elevation relationships.

Our initial qualitative and inherently 1-dimensional interpretation of the data suggested slow exhumation of $\sim 150 \text{ m Myr}^{-1}$ from $\sim 30$ to $\sim 13 \text{ Ma}$ (from the ZFT AER), increasing to $\sim 540 \text{ m Myr}^{-1}$ after $\sim 8 \text{ Ma}$ (from the AFT AER). Depending on how much confidence one places in the ZHe data, a phase of rapid exhumation may have intervened and the AHe ages that overlap with AFT ages suggest rapid exhumation around $\sim 4 \text{ Ma}$ (Fig. 9). In contrast, the inversions suggest a sharp decrease in exhumation rate at $\sim 5 \text{ Ma}$ and Scenario Ap+Zr implies a rapid pulse of exhumation between $6.0 \pm 3.3$ and $5.5 \pm 3.3 \text{ Ma}$. Relief evolution remains essentially unconstrained, although an inversion using all data would suggest that the pulse of exhumation was associated with relief increase. A similar conclusion was recently reached by Vernon et al. (2009), who compared

**Fig. 7.** Posterior PDFs for Scenario Ap+Zr parameters, obtained from the NA appraisal stage: (a) denudation rate of the first exhumation phase ($E_0$); (b) denudation rate of the second exhumation phase ($E_1$); (c) denudation rate of the third exhumation phase ($E_2$); (d) relief factor for the first ($R_1$, solid line) and the second ($R_2$, dashed line) exhumation phases; (e) transition time between the first and second exhumation phases ($T_1$); and (f) transition time between the second and third exhumation phases ($T_2$).
qualitative and forward-modelled exhumation and relief histories derived from two age–elevation profiles in the central Alps.

Best-fit scenarios from the inversions fit the age–elevation relationships reasonably well (Fig. 8), although there is significant scatter in the AFT age–elevation relationship (AER) as discussed previously, and the models have difficulty in simultaneously fitting the gentle slope of the ZFT AER, the very steep slope of the ZHe AER and the overlapping AFT and AHe ages. The overall fit to the data may appear disappointing; the “most probable” inversion scenarios fit the AERs less well than simple linear regressions. However, in contrast to the direct approach, the inversion does attempt to fit the entire dataset using an internally consistent and physically-based model. The model results can therefore be used not only to infer a regional exhumation history from the dataset (Fig. 9), but also to identify potentially problematic data and limits to the model. In our case, exclusion of the potentially suspect ZHe data did not significantly change the inversion outcome. However, potential improvements to the approach could be provided by more sophisticated age-prediction models or more realistic relief-evolution scenarios (instead of simple linear valley carving as imposed here).

In a regional context, our data support a major pulse of exhumation in the Pelvoux–Ecrins massif around 6.0–5.5 Ma. This event appears to be regionally significant, as exhumation phases that overlap in timing have recently been reported in the Argentera (Bigot-Cormier et al., 2006), Mont Blanc (Glotzbach et al., 2008) and Aar (Vernon et al., 2009) massifs. The transient nature of the erosion and relief signal may suggest it is climatically controlled (e.g., Whipple, 2009); its timing is consistent with Messinian climate change as recently proposed by Willett et al. (2006). However, the fairly low resolution in timing (±3.3 Ma) does not allow ruling out other proposed climatic mechanisms, such as onset of Gulf Stream circulation at ~4.6 Ma (Cederbom et al., 2004) or alpine glaciation since ~3 Ma (e.g., Champagnac et al., 2007). Nor do these results rule out a possible tectonic control. In effect, underplating of normal-

![Fig. 8. Comparison of observed (symbols) and predicted (lines) age–elevation relationships (AERs) for the different datasets (circles: AFT; diamonds: ZFT; squares: AHe; inverted triangles: ZHe). Note that weighted-mean ages are plotted for the He data. (a) Zoom on the AFT and AHe AER's for “most probable” model of Scenario Ap (i.e. a model defined by a combination of parameters corresponding to the modes of the posterior parameter PDF's; $E_1 = 2.4 \text{ km Myr}^{-1}; E_2 = 0.13 \text{ km Myr}^{-1}; T = 5.1 \text{ Ma}; R = 1.28$); (b) AER's for all data. Predicted data are from the “most probable” model of Scenario Ap + Zr ($E_0 = 0.4 \text{ km Myr}^{-1}; E_1 = 2.6 \text{ km Myr}^{-1}; E_2 = 0.6 \text{ km Myr}^{-1}; T_1 = 6.0 \text{ Ma}; T_2 = 5.5 \text{ Ma}; R_1 = 0.03; R_2 = 1.98$).]
thickness continental crust below the ECM (as opposed to previously thinned continental margin), coincident with deformation stepping out into the Jura fold-and-thrust belt and aided by rapid exhumation is believed to have occurred sometime between ~12 and ~5 Ma (e.g., Burkhard and Sommaruga, 1998; Bonnet et al., 2007). A full understanding of the late Miocene–Pliocene evolution of the Alps, and its overriding tectonic and climatic controls, therefore appears beyond the current resolution of thermochronology data.

The data presented here cannot resolve the significant recent increase in Alpine relief that has been suggested from morphological analyses and linked to major Quaternary glaciations (Champagnac et al., 2007; Haeuselmann et al., 2007, van der Beek and Bourbon, 2008). Perhaps this is not surprising: in the companion study, Valla et al., 2010 show that in order for relief increase to be detected, rates of local valley carving should be 2–3 times greater than background denudation rates, which would require recent rates of valley carving >1500 m Myr$^{-1}$ in the Ecrins–Pelvoux massif.

More generally, our analysis supports the finding of the companion paper (Valla et al., 2010) that an AFT age–elevation profile alone does not provide sufficient resolution to independently constrain denudation and relief histories. Potential reasons for this include (1) the large relative uncertainty often associated with AFT ages; (2) the non-unique nature of AFT ages: similar ages may result from widely varying cooling histories; and (3) the complex interplay between regional exhumation and relief development in setting local denudation and cooling histories. Adding AHe data and especially track-length measurements is required if tightly constrained exhumation scenarios are to be obtained from age–elevation profiles. Unfortunately, track-length data are not easily obtained in young and/or low-U samples because of low track numbers, although Cf-irradiation may help to limit this problem (Donelick and Miller, 1991).

Relief development is hard to constrain using thermochronological age–elevation profiles. The relief ratio is clearly the least resolved parameter in all of the inversions we have run (both using synthetic and real data). There are several potential reasons for this: (1) on the scale of the topography studied here, the temperatures affected by relief development are below the thermal sensitivity of the thermochronometers used, even though relief is significant in both amplitude (~3 km) and wavelength (~15 km); (2) the age–elevation sampling scheme employed, in which topography was sampled at a single, relatively short wavelength, is not optimal for constraining relief change (cf. Braun, 2002b). Consequently, more promising approaches would be to employ recently developed thermochronometers that are sensitive to lower temperatures (e.g., $^{4}$He/$^{3}$He thermochronometry; Shuster et al., 2005) and/or to sample topography at variable wavelengths along a transect (e.g., House et al., 2001; Foeken et al., 2007; Herman et al., 2007; Glotzbach et al., 2008). Such data can be analysed using either the approach developed here or by direct spectral analysis (Braun, 2002b; Herman et al., 2007). In a recent study (Glotzbach, C., Spiegel, C. and van der Beek, P.A., Episodic exhumation of the Mont Blanc massif, Western Alps: constraints from numerical modelling of thermochronology data, manuscript in preparation), we show that a similar analysis of data collected along a transect across the Mont Blanc massif allows detecting a recent increase in relief. In that case, our analysis is helped by the fact that relief change is very recent (~1 Ma) and rapid, largely outpacing the background denudation rate in the massif.

6. Conclusions

We have developed a novel methodology to interpret thermochronological age–elevation profiles in terms of denudation and relief histories, and have applied this approach to a dataset collected in the Pelvoux–Ecrins massif, French Western Alps. Our results have both regional and more general implications. Our data and models suggest a three-phase exhumation history in the Pelvoux–Ecrins massif including a pulse of rapid exhumation between 6.0 ± 3.3 and 5.5 ± 3.3 Ma, which appears consistent with inferences from other external crystalline massifs in the Alps (Aar, Mont Blanc, Argentera). This rapid exhumation event was preceded and followed by more moderate rates of denudation, in the order of 0.3–0.4 km Myr$^{-1}$. The potential tectonic and/or climatic controls on these denudation histories remain unclear and need to be studied further. We have not obtained sufficient resolution on the history of relief development in the massif; the synthetic results reported in the companion paper suggest that the reason for this is that potential relief increase through valley carving has been insufficient with respect to the regional denudation rates to be unambiguously extracted from the data. Thus, other sampling schemes and/or thermochronometers that are sensitive to lower temperatures are required to constrain the relief history in this case. Finally, both our synthetic results and inversion of the La Meije data strongly suggest that AFT ages alone have insufficient resolution for resolving the exhumation history from age–elevation relationships and that multiple thermochronometers are required. Combining AFT and AHe ages and, particularly, including track-length data greatly improves the resolution of the inferred exhumation histories.

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