Late- to post-orogenic exhumation of the Central Pyrenees revealed through combined thermochronological data and modelling

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ABSTRACT
Apatite (U–Th)/He and fission track thermochronometry have been combined with 3D thermal modelling to constrain the late- to post-orogenic exhumation history of the Central Pyrenees, Spain. Data from four massifs immediately north and south of the present drainage divide of the mountain belt reveal a diachronity in the transition from syn- to post-orogenic forcing of exhumation. Immediately south of the drainage divide, rapid exhumation of \( \sim 1.5 \text{ mm year}^{-1} \) decelerated after \( \sim 30 \text{ Ma} \) to \( \sim 0.03 \text{ mm year}^{-1} \). A similar transition occurred immediately north of the drainage divide at the same time. Further south, in the core of the Axial Zone antiformal stack of the Pyrenees, rapid\( (\sim 1 \text{ mm year}^{-1}) \) syn-orogenic exhumation continued to \( \sim 20 \text{ Ma} \), but slowed to \( \sim 0.1–0.2 \text{ mm year}^{-1} \) soon after that time. This order of magnitude decrease in exhumation rates across the orogen records the diachronous transition into a post-orogenic state for the mountain belt. These data do not record rejuvenation of exhumation in Late Miocene or Pliocene times driven either by large-scale base-level change or an evolution to more erosive climatic conditions.

INTRODUCTION
Understanding the factors that govern the decay of high-relief topography within post-orogenic environments, and the associated late-stage exhumation history of orogens, remains at the forefront of deciphering long-term landscape evolution (Pazzaglia & Brandon, 1996; Baldwin et al., 2003; Reiners et al., 2003). Rock cooling histories obtained through the application of low-temperature mineral thermochronometers can be used as a proxy for exhumation and provide quantitative constraints on the temporal and spatial variability of erosional denudation (Föken et al., 2003; Reiners et al., 2003; Spotila et al., 2004). In tectonically inactive mountain systems this enables the geomorphic response to changing environmental parameters, or particular geological events, to be accurately assessed without the ambiguity of a combined tectonically driven forcing.

Empirical and theoretical models for the decay of high-relief topography indicate that post-orogenic erosion occurs over protracted time periods at steady, slow rates and may decline exponentially through time as topographic relief is progressively reduced (Pazzaglia & Brandon, 1996; Baldwin et al., 2003; Reiners et al., 2003). However, recent studies indicate that external forces acting on tectonically inactive mountainous topography, such as climatic changes, palaeoceanographic aberrations or fluvial reorganisations, may exert sufficient influence on the rates of erosional denudation to induce nonmonotonic patterns of exhumation (Baldwin et al., 2003; Föken et al., 2003; Reiners et al., 2003; Cederbom et al., 2004).

The Pyrenees of western Europe (Fig. 1) represent an Alpine-age collisional mountain belt that has experienced approximately 20 Myr of post-orogenic decay (Fitzgerald et al., 1999; Sinclair et al., 2005). Apatite fission track studies in the Central Pyrenees are interpreted to record rapid exhumation of the Axial Zone during Late Eocene to Early Oligocene times, followed by abrupt deceleration and cessation of exhumation processes at \( \sim 30–32 \text{ Ma} \) (Fitzgerald et al., 1999). Localised exhumation has also been recorded in the western Central Pyrenees up to \( \sim 20 \text{ Ma} \) linked to the youngest phase of structural activity within the core of the orogen (Sinclair et al., 2005). The decline of erosional denudation is regarded to coincide with the termination of major compressional tectonics and with a rise in fluvial base levels and reduction of local relief (Fitzgerald et al., 1999). This rise in base level has been interpreted as the result of closure and infilling of the Ebro foreland basin and the onlap of alluvial sediments onto the southern flank of the range (Coney et al., 1996; Fitzgerald et al., 1999). Forward modelling of the fission track length distributions predicts that a ‘post-orogenic’ rejuvenation of rapid exhumation rates may have occurred after a period of thermal quiescence of more than 20 Myr (Fitzgerald et al., 1999).
Importantly, as there is no structural or metamorphic evidence to suggest the Central Pyrenees has experienced any significant tectonic denudation (footwall exhumation during normal faulting) during the Neogene, a rejuvenation of exhumation requires accelerated rates of erosional denudation.

It has been postulated that such a late-stage rejuvenation of exhumation in the Pyrenees may be linked to the re-excavation of the Ebro foreland Basin on the southern flank of the Pyrenees, possibly during the Messinian salinity crisis at 5.97 Ma (Coney et al., 1996; Fitzgerald et al., 1999; Krijgsman et al., 1999). Equally plausible is that the Pyrenees have experienced an acceleration in erosion during Early Pliocene times as recorded in the European Alps where climate change has been proposed as the driving mechanism (Cederbom et al., 2004). Such a Pliocene climatic signal is advocated by Babault et al. (2005) as a mechanism to explain the partial preservation of high-elevation ‘peneplains’ in the Pyrenees. Accelerations in Pliocene erosion are also recorded in the Sierra de Guadarrama of central Spain (de Bruijne & Andriessen, 2002).

Here, we compare the exhumation histories of the north and south sides of the Central Pyrenees and test for
the presence of accelerated post-orogenic exhumation using apatite (U-Th)/He (hereafter referred to as AHe) thermochronology. This chronometer can be used to determine the timing of rock cooling between 80 and 35 °C, for rapid cooling (10^6 °C Myr^-1 cooling rate; 80 μm effective crystal radius) a closure temperature of ~70 °C can be considered (Zeitler et al., 1987; Wolf et al., 1996; Farley, 2000). New AHe ages are combined with existing and new apatite fission track data and numerical modelling of thermal histories to test whether the Pyrenees has undergone slow and steadily declining erosion, as predicted for areas of progressively reducing high relief (Pinet & Souriau, 1988; Baldwin et al., 2003) or by a punctuated erosional history as predicted by previous thermochronology (Fitzgerald et al., 1999), or by accelerated erosion linked to climate change (Zhang et al., 2001; Cederbom et al., 2004).

**GEOLOGIC AND GEOMORPHIC SETTING**

The Pyrenean mountain belt extends over 1500 km from the Mediterranean Sea in southwest France to the Cantabrian platform in northern Spain, and separates the Iberian peninsula from the rest of the European continent. The range forms a ~150 km-wide west-northwest to east-southeast trending linear zone of high topography and relief with the main drainage divide running down the axis of the orogen (Fig. 1). Elevation and local relief is intimately linked to lithologic variation, with highest mean and peak elevations associated with metamorphic basement lithologies of the Axial Zone and a number of crystalline massifs distributed across the Central orogen.

The Pyrenees formed by Afro-Iberian and European plate convergence, initiated during Late Cretaceous times determined by the opening of the Central Atlantic and the rotation of Iberia to open the Bay of Biscay (Roest & Srivastava, 1991). The ECORS deep seismic profile (Choukroune, 1989) and seismic tomography data (Souriau & Granet, 1995) indicate the Iberian plate was partially subducted below the European plate during active convergence. Analysis of Iberian plate kinematics indicate convergence had ceased by Early Miocene times as Iberia had begun to move as part of the Eurasian plate, with its southern boundary along the Azores–Gibraltar Fracture Zone (Srivastava et al., 1990; Roest & Srivastava, 1991). This is consistent with the youngest age-constrained compressive deformation in the South Pyrenean fold and thrust belt (Meigs et al., 1996; Meigs & Burbank, 1997) and in the Iberian and Catalan Coastal Range (Guimera, 1984).

The mountain belt comprises an Axial Zone of dominantly Palaeozoic meta-sediments and Hercynian-age crystalline massifs (Fig. 1), flanked to the north and south by folded and thrusted Mesozoic and Cenozoic sedimentary cover rocks (Zwart, 1979; Muñoz, 1992). The Central Axial Zone is characterised by a complex antiformal duplex structure of stacked thrust nappes which accommodated a significant component of the estimated 165 km of overall tectonic shortening (Muñoz, 1992; Beaumont et al., 2000). Rapid rates of exhumation during Upper Eocene and Lower Oligocene times, on the southern flank of the range, have been linked to temporally variable, tectonically driven rock uplift, associated with internal deformation in the upper crust below the basement antiformal stack (Muñoz, 1992; Fitzgerald et al., 1999; Sinclair et al., 2005). South of the Axial Zone is the South Pyrenean Thrust Belt that comprises a deformed Mesozoic succession overlain by syn-orogenic Tertiary sediments (Verges & Munoz, 1990). Sandwiched between the South Pyrenean Thrust Belt and the Axial Zone is a 2–5 km wide zone of Carboniferous, Permian and Triassic strata termed the Nogueres Zone (Seguret & Vergely, 1969). Importantly for this study, the volcanic rocks of the Carboniferous succession yield apatites for thermochronology.

The Ebro foreland basin, to the south of the mountain belt, formed by flexural subsidence in response to crustal loading primarily associated with the growth of the Pyrenees, but also due to the development of the Catalan Coastal Range and Iberian Range (Fig. 1) to the southeast and southwest, respectively (Riba et al., 1983; Zoetemeijer et al., 1990; Puigdefàbregas et al., 1992). During Late Eocene times, the western seaward connection of the basin was closed through Pyrenean and Iberian range tectonism (Riba et al., 1983). This marked the onset of a period of endorheic (internal) drainage for all fluvial catchments draining into the basin. During this time accelerated sediment yield from the mountain belt (Sinclair et al., 2005) progressively infilled the basin and onlapped across the low relief topography of the south Pyrenean fold and thrust belt (Coney et al., 1996). Sedimentation in the Ebro Basin continued up to at least ~14 Ma, as documented by the presence of magneto-stratigraphically dated lacustrine and alluvial sediments in the geographic centre of the basin (Pérez-Rivaréres et al., 2002). Present day exposures of these sediments are preserved, undeformed, at up to ~800 m elevation; these have been deeply incised by fluvial systems down-cutting since basin capture. This incision has been interpreted to be a consequence of fall in base-level upon the reconnection of the Ebro Basin to the Mediterranean Sea (Riba et al., 1983; Coney et al., 1996).

The timing of the reopening and excavation of the Ebro Basin has not been established but has been tentatively linked to sediment overfilling and eventual capture, or piracy, by streams that drained into the Mediterranean Sea during Miocene times (Riba et al., 1983; Serrat, 1992). It has been postulated that the combination of Miocene rifting offshore of the Catalan Coastal Ranges and the drop in sea level associated with the Messinian salinity crisis at 597 Ma (Krijgsman et al., 1999) may have triggered the capture of the Ebro drainage and exhumation of the southern end of the Pyrenean mountain chain as a whole (Coney et al., 1996; Dañobeitia et al., 1999). This was supported by the modelling of apatite fission tracks in the Axial Zone that suggested a Late Miocene rejuvenation of cooling (Fitzgerald et al., 1999). Conversely, the presence of large-scale siliciclastic progradations into the Valencia Trough from the Ebro Delta (Johns et al., 1989; Bartrina et al., 1999).
analysed in duplicate or triplicate. Variation of grain dia-

magnification for mineral inclusions, structural defects,

Baseline fall in the Ebro Basin. Proﬁle localities was applied.

THERMOCHRONOLOGY

Samples and methodology

Four sub-vertical proﬁles were sampled from high-relief Hercynian-age granodioritic massifs (Barruera, Maladeta, Arties and Marimáña) from coherent structural blocks within the Central Axial Zone (Fig. 1). All samples were fresh, unweathered bedrock located at least 100 m from hy-
drothermal veins or systems or from evidence of small-scale fault or shear structures. The Barruera and Maladeta pro-
files are located south of the modern Pyrenean watershed within the hinterlands of catchments entering the south-
ern modern Ebro drainage system. The Arties and Marimáña profiles are located immediately north of the main Pyrenean watershed within a catchment draining into the Aquitaine Basin. This sampling distribution is intended to distinguish between potential contrasting exhumational histories between the northern and southern margins of the mountain belt that may be indicative of mechanisms involving base-level fall in the Ebro Basin. Profile localities were chosen to sample the maximum local vertical topo-

U, Th and He ages before and after \( \alpha \)-ejection correction are summarised in Table 1. Several aliquots yielded AHe ages that are signiﬁcantly older than the sample apatite fission track age and we do not consider them here. Most apatite duplicate or triplicate He ages re-
produce within analytical uncertainty. This is commonly regarded as a demonstration of the quality of AHe ages (Ehlers & Farley, 2003). However, the reproducibility of several samples is poorer (e.g. Mal-00/2250 and MM-00/ 2030) than is usually obtained on rapidly cooled samples using this analytical protocol (± 8%) (Persano et al., 2002). Grain size variations, undetected parent element zonation, variability in kinetic parameters, adjacent U- and/or Th-rich minerals, and the presence of sub-micro-

microscopic U- or Th-rich mineral or ﬂuid inclusions may affect

The Aquitaine Foreland Basin to the north of the Pyre-
nees was initiated during late Early Cretaceous times, with thick accumulations of deep-water siliciclastics (Bour-
rouilh et al., 1995). Throughout Palaeocene and Early Eo-
cene times, calcareous turbidites and marls accumulated in the North Pyrenean trough. An abrupt change took place in Middle Eocene times when shallowing and the de-
position of thick conglomerates along the southern fringes of the Aquitaine Basin took place. The conglomerates (Poudinges de Palassou) are intercalated with nodular mudstones and sandstones, and suggest ﬂuvial settings with periodic marine transgressions (BRGM 1973). Molasse sedimentation continued in the southern Aqui-
taine Basin up to Pliocene times.

Results

U, Th and He concentrations and He ages before and after \( \alpha \)-ejection correction are summarised in Table 1. Several aliquots yielded AHe ages that are signiﬁcantly older than the sample apatite fission track age and we do not consider them here. Most apatite duplicate or triplicate He ages re-
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microscopic U- or Th-rich mineral or ﬂuid inclusions may affect

Apatite crystals were separated from crushed rocks using standard magnetic and gravimetric techniques. Crystals were screened under polarised light at \( \times 218 \) magniﬁcation for mineral inclusions, structural defects, morphology and size. Inclusion-free crystals were mea-
ured and packed into stainless-steel capsules. Where en-
ough inclusion-free apatite was recovered, samples were analysed in duplicate or triplicate. Variation of grain dia-

meter was minimised within individual aliquots to reduce the standard deviation of the recoil correction within each population to ± 0.5% (Farley, 2002). Samples were heated in a double-walled resistance furnace at 950 °C for 35 min. The gas released was puriﬁed on TiZr getters and a liquid nitrogen-cooled charcoal trap and \(^{4}\)He abundances were measured relative to a 999% pure \(^{4}\)He spike in a Hiden HAL3F quadrupole mass spectrometer. Samples were checked for quantitative degassing of \(^{4}\)He by re-heating. All ratios were referenced to measurements of a manome-
trically determined \(^{4}\)He standard. The reproducibility of the \(^{4}\)He standards measured during the analytical period averages better than 0.5%. After \(^{4}\)He extraction the capsules were retrieved from the furnace and the samples were dis-
solved in 5% nitric acid and spiked with 3 ng \(^{230}\)Th and 1.3 ng \(^{238}\)U in Teflon beakers. U and Th concentrations were measured by VG PlasmaQuad 2 inductively coupled plasma mass spectrometer (ICPMS). The analytical uncertainty on age determinations of all samples is ± 6%, governed by uncertainty in spike concentrations, repro-
cibility of standard measurements and ICPMS back-
ground corrections (Balestrieri et al., 2005). All He ages are corrected for the effects of \( \alpha \)-ejection following Farley (2002). Durango apatites analysed during the analytical period yielded a mean age of 32.7 ± 2.3 Ma.

Apatite fission track data for the proﬁles Barruera, Ma-
adeta, Marimáña and Nogueres are published (Sinclair et al., 2005). New apatite fission track data from Arties and Nogueres were acquired using procedures reported in Sinclair et al. (2005). The apatite fission track data are com-
bined with the AHe ages to better constrain the thermal history of the mountain belt. Several etched apatite fission track slides were used to characterise the distribution of U (and by inference Th) in crystals from the samples used for AHe analysis in order to assess the effect that parent element zonation may have on measured AHe ages if un-
detected and unaccounted for during the recoil correction (Meesters & Dunai, 2002). No signiﬁcant U zonation was observed and no correction for parent element zonation was applied.
Late- to post-orogenic exhumation of the Central Pyrenees

Apatite fission track data is from Sinclair et al. (2005). AFT ages (Table 2), against elevation in Figs 2 and 3, respectively. AFT ages of the four Arties samples range from 30.6 to 37.7 Ma and show a small increase with altitude (Fig. 3). These ages are generally within error, as noted for the Marímaña profile, show a slight increase with altitude (Fig. 3). These ages are generally within error, although often slightly lower than, the AFT ages. Duplicates display more age scatter than the Marímaña samples but the uppermost and lowermost samples reproduce well giving us confidence that the age profile records a similar rapid exhumation event. In contrast to the AHe age profiles from north of the drainage divide, the AHe of the lowermost sample at Maladeta is approximately 5 Myr younger than the corresponding AFT age; this corresponds to a trend of shortening mean fission track lengths from the top (14.27 ± 0.15 mm) to the bottom (13.73 ± 0.18 mm) of the profile. This indicates that cooling of the Maladeta Massif slowed after 30 Ma, and that the southern side of the Axial Zone is more deeply exhumed since this time than the north.

AFT ages (28–36 Ma) and moderate to high mean track lengths (13.73 μm at 1750 m, 14.27 μm at 2870 m) from the Maladeta profile (Fig. 3) reflect the same Late Eocene–Early Oligocene cooling event recorded by the Axial Zone north of the drainage divide. AFT ages from the Maladeta profile range from 35.4 to 20.4 Ma and, as noted for the Marímaña profile, show a slight increase with altitude (Fig. 3). These ages are generally within error, although often slightly lower than, the AFT ages. Duplicates display more age scatter than the Marímaña samples but the uppermost and lowermost samples reproduce well giving us confidence that the age profile records a similar rapid exhumation event. In contrast to the AHe age profiles from north of the drainage divide, the AHe of the lowermost sample at Maladeta is approximately 5 Myr younger than the corresponding AFT age; this corresponds to a trend of shortening mean fission track lengths from the top (14.27 ± 0.15 mm) to the bottom (13.73 ± 0.18 mm) of the profile. This indicates that cooling of the Maladeta Massif slowed after 30 Ma, and that the southern side of the Axial Zone is more deeply exhumed since this time than the north.

AFT ages from between 1150 and 1750 m at Barruera (Sinclair et al., 2005) suggest that exhumation continued up to at least 20 Ma in the core of the antiformal stack of the Axial Zone. Two samples from the Barruera profile have AHe ages (15.9–10.5 Ma) that are 5–10 Myr younger than the AFT ages (Fig. 3). Despite the sparsity of data it is clear that the Barruera Massif records markedly different cooling history from the other granite massifs in the Axial Zone. As with the Maladeta profile, the contrasting AFT and AHe ages is accompanied by relatively short mean...
fission track lengths in the low-elevation sample (13.18 ± 0.15 μm). The AHe ages record the cooling of the Barruera massif through the PRZ at 15-10 Ma following a period of rapid exhumation where the massif had passed through the PAZ at approximately 20 Ma.

New AFT ages from the Erill Castell volcanics (24.4 ± 27.6 Ma; Table 2) confirm the earlier work (Sinclair et al., 2005) demonstrating that the Nogueres Zone cooled slightly later than the Axial Zone immediately south of it (i.e. the Barruera massif). Mean track lengths (13.75–13.99 μm) are shorter than in the Axial Zone and reflect the slowing of cooling that appears in the lowermost Maladeta samples. Suitable apatites for He dating from the volcanic rocks were rare. Only the lowermost sample yielded enough apatite for one aliquot. The AHe age (23.6 Ma), un-supported by replication, is broadly consistent with the cooling history predicted by the AFT data, and is considerably older than the Barruera massif.

### NUMERICAL MODELLING OF COOLING HISTORIES

**Methodology**

The AHe data from south of the Pyrenean drainage divide provide the best constraints on the late to post-orogenic cooling history of the Central Pyrenees due to the availability of a significant elevation range (1110 m) from a single, structurally undisturbed sample set on the Maladeta Massif, thus permitting a significant statistical fit to the
regression line. Here, we report the results of numerical modelling that was performed on these data in order to verify our qualitative interpretations of the cooling and exhumation histories. The same approach was applied to the Barruera Massif in order to assess the implications of the clear contrasts in ages between the Maladeta and Barruera Massifs, both south of the drainage divide. In a second series of experiments, we allow the topography to evolve with time in order to assess the possible influence of increasing and decreasing topography on the AHe age–elevation relationship.

Synthetic AHe ages have been generated for different thermal histories and for varying topographic histories using the finite-element code ‘Pecube’ (Braun, 2003). Time–temperature (t–T) histories of specific rock particles, defined by delineating specific nodes on the imposed topographic surface, are generated for a given exhumation history. These t–T paths are input into thermostchronometer-specific software – AFTSolve (Ketcham et al., 2000) and Decomp (Dunai et al., 2003)—in order to predict cooling ages (Braun, 2002, 2003). AHe ages are calculated for apatite crystal sizes of 66–130 μm diameter. These modelled cooling ages are iteratively compared with the recorded AHe age–elevation relationships (Figs 2 and 3) until a best-fit solution is obtained.

The depth to, and the temperature at, the base of the lithosphere during the last ~50 Myr are unknown, and so values for the present crustal structure were used. These have been interpreted using a variety of geophysical techniques and surface heat flow measurements yielding a value of ~30 km for the depth of the lower crust at a temperature of ~600 °C (Zeyen & Fernandez, 1994). The surface temperature is set at 0 °C and a lapse rate is not enforced. The thermal diffusivity of 31.5 km2 Myr−1 (Türcotte & Schubert, 1982) and heat production of 15.8 °C Myr−1 is based on lithology, crustal thickness and temperature at the base of the crust. At the start of each experiment, isotherms are distributed uniformly with depth. During exhumation isotherms are advected towards the cooling surface (Brown & Summerfield, 1997) temporarily increasing geothermal gradients up to 35 °C km−1. During exhumation isotherms are advected towards the cooling surface (Brown & Summerfield, 1997) temporarily increasing geothermal gradients up to 35 °C km−1. During exhumation isotherms are advected towards the cooling surface (Brown & Summerfield, 1997) temporarily increasing geothermal gradients up to 35 °C km−1.

Results – exhumation histories

Seventeen experiments were run for both data sets in attempting to iterate towards the observed data, three experimental results for the Maladeta Massif are illustrated.

Table 2. Apatite fission track data for unpublished samples from the Pyrenees; all other data plotted are published in Sinclair et al. (2005)

<table>
<thead>
<tr>
<th>Sample</th>
<th>ψs (Ns)</th>
<th>ps (Ni)</th>
<th>ρd (Nd)</th>
<th># crystals</th>
<th>Q</th>
<th>Dpar (μm)</th>
<th>Pooled age (Ma)</th>
<th>Tracks</th>
<th>Mean length (μm)</th>
<th>SD (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nogueres</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Col-00/1540</td>
<td>0.131 (66)</td>
<td>0.977 (494)</td>
<td>3.985 (4146)</td>
<td>39</td>
<td>0.87</td>
<td>2</td>
<td>30.2 ± 4.1</td>
<td>28</td>
<td>13.62 ± 0.33</td>
<td>1.73</td>
</tr>
<tr>
<td>Coll-00/1490</td>
<td>0.142 (65)</td>
<td>1.163 (533)</td>
<td>3.988 (4146)</td>
<td>40</td>
<td>0.354</td>
<td>2.27</td>
<td>27.6 ± 3.7</td>
<td>94</td>
<td>13.80 ± 0.22</td>
<td>2.15</td>
</tr>
<tr>
<td>Esc-02/1250</td>
<td>0.172 (83)</td>
<td>1.321 (639)</td>
<td>3.486 (4176)</td>
<td>25</td>
<td>0.05</td>
<td>0.24</td>
<td>25.5 ± 31.8</td>
<td>84</td>
<td>13.83 ± 0.19</td>
<td>1.71</td>
</tr>
<tr>
<td>Sas-02/1580</td>
<td>0.1725 (60)</td>
<td>1.257 (453)</td>
<td>3.447 (4176)</td>
<td>25</td>
<td>0.245</td>
<td>2</td>
<td>25.9 ± 3.6</td>
<td>26</td>
<td>13.85 ± 0.28</td>
<td>1.4</td>
</tr>
<tr>
<td>Sas-02/1490</td>
<td>0.259 (157)</td>
<td>1.685 (1020)</td>
<td>3.477 (4176)</td>
<td>25</td>
<td>0.435</td>
<td>2.16</td>
<td>30.1 ± 27.3</td>
<td>133</td>
<td>14.16 ± 0.14</td>
<td>1.59</td>
</tr>
<tr>
<td>Arties</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ART/03/1315</td>
<td>1.392 (407)</td>
<td>7.583 (2218)</td>
<td>2.986 (4078)</td>
<td>22</td>
<td>0.037</td>
<td>1.76</td>
<td>30.2 ± 19</td>
<td>125</td>
<td>14.21 ± 0.15</td>
<td>1.63</td>
</tr>
<tr>
<td>ART/03/1555</td>
<td>1.243 (552)</td>
<td>6.952 (3088)</td>
<td>2.910 (4078)</td>
<td>23</td>
<td>0.216</td>
<td>1.77</td>
<td>29.4 ± 16</td>
<td>127</td>
<td>14.81 ± 0.10</td>
<td>1.12</td>
</tr>
<tr>
<td>ART/03/1880</td>
<td>0.459 (179)</td>
<td>2.398 (936)</td>
<td>2.901 (4078)</td>
<td>24</td>
<td>0.476</td>
<td>1.77</td>
<td>31.5 ± 2.7</td>
<td>125</td>
<td>14.58 ± 0.16</td>
<td>1.73</td>
</tr>
<tr>
<td>ART/03/2164</td>
<td>0.548 (282)</td>
<td>3.032 (1560)</td>
<td>2.903 (4078)</td>
<td>24</td>
<td>0.014</td>
<td>1.90</td>
<td>29.8 ± 2.1</td>
<td>126</td>
<td>14.64 ± 0.15</td>
<td>1.69</td>
</tr>
</tbody>
</table>
in Fig. 4. The two best-fit scenarios (Fig. 4b and c) start with constant exhumation of 0.3 mm yr$^{-1}$ between 50 and 31 Ma, consistent with the 50 Ma zircon fission track age from the Maladeta Massif (Sinclair et al., 2005). Exhumation accelerates from 31 to 29 Ma at 1.5 and 1.0 mm yr$^{-1}$ then slows from 29 Ma to present day at a rate of 0.03 and 0.09 mm yr$^{-1}$, respectively. This protracted history of continuous late-stage exhumation is intended to represent a simplified modelling analogy for that predicted for post-orogenic settings (Pinet & Souriau, 1988; Pazzaglia & Brandon, 1996; Baldwin et al., 2003; Reiners et al., 2003). However, as the cooling rate should decrease exponentially through time (e.g. Pinet & Souriau, 1988), the model ages are minima which would be greater for exponential decay. Model ages for the Maladeta Massif are presented as three age-elevation profiles, corresponding to the AHe ages predicted for the maximum (130μm) and minimum (66μm) apatite crystal analysed and apatite.

Fig. 4. Four modelled cooling histories and equivalent age elevation profiles plotted against measured thermochronological data for the Maladeta profile (a–c), and the Barruera profile (d). Modelled grey line is for the apatite fission track data, the solid black line is for the apatite Helium data with grain sizes equating to 66μm, and the dashed line if for grain sizes of 133μm. The model run shown in c is considered the best-fit out of 17 experiments for the Maladeta profile. The model run d is the best-fit out of 17 for the Barruera profile. Clear circles are AFT data points, black circles are AHe data points. Modelled erosion rates are labelled next to the cooling curves.
fission track ages. The best-fit occurs when the rapid exhumation rate is $1.5 \text{ mm year}^{-1}$ (Fig. 4c). In this case the lower part of the profile does not exhume fully through the PRZ by the time exhumation slows. The best-fit solution to the data requires a post-29 Ma exhumation rate of 0.03 mm year$^{-1}$.

The best-fit thermal history for the Barruera Massif AHe ages starts with slow exhumation ($0.13 \text{ mm year}^{-1}$) up to 21 Ma, followed by an increase to $1 \text{ mm year}^{-1}$ between 21 and 19 Ma, followed by a gradual slowing that requires an exhumation rate of $0.2 \text{ mm year}^{-1}$ until 9 Ma, followed by $0.1 \text{ mm year}^{-1}$ from 9 Ma to present (Fig. 4d).

By integrating the modelled geothermal gradients of 30–35 °C with the age data for the Marimana/Arties profiles to the north, we can evaluate an exhumation history for this region without recourse to further modelling. Similar to the Maladeta Massif, this region must have experienced a rapid exhumation of at least $1.5 \text{ mm year}^{-1}$ to have exhumed through both the AFT partial annealing zone and the AHe partial retention zone. Since 29 Ma, the amount of exhumation cannot have exceeded 2 km, at an average rate of $<0.03 \text{ mm year}^{-1}$. This slightly slower rate than to the south reflects the fact that it had passed right through the AHe partial retention zone during rapid cooling.

Results — topographic evolution

Experiments were also run in order to explore the influence of deformation and advection of the isotherms during uplift of rock towards the surface. Each experiment ends with the present day topography derived from the digital elevation model, but varies the initial topography at 50 Ma among (i) flat, (ii) twice the present day relief, and (iii) unchanged from today. Model age–elevation profiles were generated for each scenario at the appropriate nodes for the Maladeta and Barruera profiles. The results show that the maximum impact on ages in the profiles was <1 Myr, and hence within the error of the technique. This demonstrates limited influence of topographically induced isothermal perturbation and thermal advection imposed on the AHe ages and derived $t$–$T$ histories. Consequently, no additional corrections are necessary and it can be assumed that the interpreted age–elevation relationships from the profiles are likely to be a singular function of the exhumation history.

DISCUSSION

The results demonstrate that the last rapid exhumation events that occurred during Late orogeny were diachronous across the Pyrenees (Fig. 5). The Axial Zone massifs located near the present day drainage divide (Maladeta and Marimana/Arties) record rapid exhumation at approximately 30 Ma that is followed by a dramatic slowing. This records the rapid growth and unroofing of the northern margin of the Axial Zone antiformal stack of the Central Pyrenees at this time (Fitzgerald et al., 1999; Sinclair et al., 2005). This same signal is also observed on the southern margin of the antiformal stack in the Nogueres profile. In contrast, the Barruera Massif in the core of the antiformal stack, records a pulse of rapid differential exhumation that occurred at ca. 20 Ma followed by a distinct slowing. The deceleration of differential exhumation records the termination of structural-induced uplift of these Massifs. Hence, the results demonstrate the diachronity across the mountain belt of the termination of structural activity during transition from a syn- to a post-orogenic state. This contrasts with the abrupt termination of structural induced uplift incorporated into models of post-orogenic decay (Baldwin et al., 2003). In other words, the final pulses of activity are localised and punctuated as recent models predict (Naylor & Sinclair, 2007).

The prime intention of this study was to discriminate between several possible alternative exhumation histories for the post-orogenic evolution of the Pyrenees. The combined AFT–AHe data and the numerical models do not record any acceleration in erosional exhumation during Late Neogene times that can be linked to a drop in base-level or climatic rejuvenation. Instead, the simplest explanation for the data is a slow down in exhumation following syn-orogenic structural forcing in the Axial Zone north and south of the modern drainage divide. The dominance of syn-orogenic AHe cooling ages in the Axial Zone granites immediately north of the drainage divide places constraints on the amount of post-orogenic exhumation in this region. For a geothermal gradient of 35 °C km$^{-1}$, approximately 2 km of crustal must have been removed in the last 30 Myr at an average exhumation rate of $\sim0.03 \text{ mm year}^{-1}$. However, the details of how exhumation rate varied around the mean during this post-orogenic stage are not determined by the thermochronometry, and it is possible that exhumation slowed through time as predicted for a tectonically inactive region with decreasing relief (e.g. Pinet & Souriau, 1988; Baldwin et al., 2003; Reimers et al., 2003). It is also possible that for short periods exhumation rates accelerated but that the changes were insufficient to be recorded by AFT or AHe analysis. The requirement of at least 2 km of rock exhumation in both the Axial Zone and Nogueres Zone since 30–20 Ma means it is highly unlikely that these regions preserve peneplain surfaces of Palaeogene age (Babault et al., 2005).

CONCLUSIONS

Combined AFT and AHe thermochronometric data and modelling from the Central Pyrenees yields insight into the late- to post-orogenic exhumation history of the mountain belt. Age–elevation profiles from south of the modern drainage divide (Maladeta Massif) record rapid exhumation through the AFT partial annealing zone, and then partially through the AHe partial retention zone at a rate of $\sim1.5 \text{ mm year}^{-1}$. After 30 Ma, these samples slowed in their passage to the surface at a rate of $\sim0.03 \text{ mm year}^{-1}$. A similar exhumation history is recorded from north of the drainage divide (Arties and Marimana profiles), but with
Fig. 5. Summary of exhumation rates across the Pyrenees at ~30, 20, and post 20 Ma. Note the diachrony of termination in thrust induced, localised high erosion rates from 30 to 20 Ma, and the subsequent order of magnitude reduction in exhumation rates since then.
complete exhumation through both the partial annealing and partial retention zones, implying a rate >1.5 mm year$^{-1}$ at 30 Ma, followed by a slower passage to the surface since then of <0.03 mm year$^{-1}$.

The youngest evidence for accelerated differential exhumation (i.e. syn-orogenetic) is at ~20 Ma from AFT data in the Barruera Massif located in the axis of the Axial Zone antiformal stack. The AHe data for this profile again fit with an interpretation of slowly decelerating cooling since then at a time-averaged rate of ~0.2–0.1 mm year$^{-1}$. Therefore, these post-orogenic rates of exhumation reveal a progressive slowing from the present day locations south of the drainage divide in the core of the antiformal stack, to locations immediately north of the drainage divide.

The transition from syn- to post-orogenic exhumation was diachronous across the mountain belt, with the last evidence coming from the termination in growth of the axial zone antiformal stack in the Pyrenees on the southern side of the orogen. There is no evidence from the low temperature thermochronometry of a rejuvenation of exhumation (i.e. syn-orogenic) is at 20 Ma from AFT data.

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