

 Open access • Journal Article • DOI:10.1144/JGS2012-051

## Oligocene–Miocene burial and exhumation of the Southern Pyrenean foreland quantified by low-temperature thermochronology — [Source link](#)

[Charlotte Fillon](#), [Cécile Gautheron](#), [Pieter van Beek](#)

**Institutions:** [Joseph Fourier University](#), [University of Paris-Sud](#)

**Published on:** 01 Jan 2013 - [Journal of the Geological Society](#) (Geological Society of London)

**Topics:** [Thermochronology](#) and [Foreland basin](#)

Related papers:

- [Evolution of a continental collision belt: ECORS-Pyrenees crustal balanced cross-section](#)
- [Asymmetric exhumation across the Pyrenean orogen: implications for the tectonic evolution of a collisional orogen](#)
- [Placing limits to shortening evolution in the Pyrenees: Role of margin architecture and implications for the Iberia/Europe convergence](#)
- [Asymmetric growth of the Pyrenees revealed through measurement and modeling of orogenic fluxes](#)
- [Transdimensional inverse thermal history modeling for quantitative thermochronology](#)

Share this paper:    

View more about this paper here: <https://typeset.io/papers/oligocene-miocene-burial-and-exhumation-of-the-southern-1c39hrcwq5>



**HAL**  
open science

# Oligocene-Miocene burial and exhumation of the Southern Pyrenean foreland quantified by low-temperature thermochronology

Charlotte Fillon, Cécile Gautheron, Pieter van der Beek

## ► To cite this version:

Charlotte Fillon, Cécile Gautheron, Pieter van der Beek. Oligocene-Miocene burial and exhumation of the Southern Pyrenean foreland quantified by low-temperature thermochronology. *Journal of the Geological Society*, Geological Society of London, 2013, 107, pp.67 -77. 10.1144/jgs2012-051 . hal-00772598

**HAL Id: hal-00772598**

**<https://hal.archives-ouvertes.fr/hal-00772598>**

Submitted on 10 Jan 2013

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1 **Oligocene-Miocene burial and exhumation of the Southern Pyrenean foreland**  
2 **quantified by low-temperature thermochronology**

3 Charlotte Fillon<sup>1\*</sup>, Cécile Gautheron<sup>2</sup> and Peter van der Beek<sup>1</sup>

4  
5 1. Institut des Sciences de la Terre, Université Joseph Fourier – Grenoble I, CNRS, BP 53,  
6 38041 Grenoble, France

7 2. UMR IDES – CNRS8148, Interactions et Dynamique des Environnements de Surface,  
8 Université Paris Sud, 91405 Orsay, France

9 cecile.gautheron@u-psud.fr

10 pvdbeek@ujf-grenoble.fr

11 **\* corresponding author: charlotte.fillon@ujf-grenoble.fr**

15 **Abstract**

16 The central Pyrenees experienced an episode of rapid exhumation in Late Eocene-Early Oligocene  
17 times. Erosional products shed from the range during this time were deposited in large paleovalleys of  
18 the southern flank of the Axial Zone, leading to significant sediment accumulation. A recent numerical  
19 modelling study of the post-orogenic exhumation and relief history of the central Axial Zone allowed  
20 us to constrain this valley-filling episode in terms of timing and thickness of conglomeratic deposits.  
21 This paper aims to test these results for the southern fold-and-thrust belt using apatite fission-track and  
22 (U-Th)/He analysis on detrital samples from the Tresp-Graus and Ager basins. Inverse thermal-  
23 history modelling of the low-temperature thermochronology data indicates that the fold-and-thrust belt  
24 was covered during the Late-Eocene to Miocene by 0.7 to 1.6 km of sediments and confirms the  
25 timing of re-exhumation of the valleys during the Miocene. A detailed analysis of the apatite (U-Th)/He  
26 results shows that the significant scatter in grain ages can be explained by the influence of alpha-recoil  
27 damage with varying eU content together with distinct pre-depositional thermal histories; the age  
28 scatter is consistent with initial exhumation of the sediment sources during the Triassic and Early  
29 Cretaceous.

30

31 **1. Introduction**

32

33 The southern central Pyrenees have figured prominently in studies of orogenic wedge building,  
34 thrusting sequences and interactions between tectonics and surface processes, in part because of the  
35 exceptional exposure of syn-tectonic strata (Puigdefàbregas and Souquet 1986; Vergés and Muñoz  
36 1990) and the quality of the ECORS seismic profile (ECORS Pyrenees Team 1988) shot through this  
37 area.

38

39 Low-temperature thermochronology (mainly apatite fission-track; AFT) data (Fitzgerald *et al.* 1999;  
40 Sinclair *et al.* 2005) provide evidence for a phase of rapid exhumation of the Axial Zone of the central  
41 Pyrenees during Late Eocene – Early Oligocene times, accompanied by the development of a crustal-  
42 scale duplex (Muñoz 1992; Beaumont *et al.* 2000). The conglomeratic erosional products of this phase  
43 of rapid exhumation were hypothesized to have buried the southern flank of the Axial Zone in a late  
44 orogenic stage of its evolution, and to have been removed ~20 Myr later as post-orogenic incision of  
45 the Ebro drainage system reached the area (Coney *et al.* 1996). Recent magnetostratigraphic studies  
46 (Beamud *et al.* 2003; 2011) have confirmed the depositional ages of these conglomerates, while the  
47 link to exhumation of the Axial Zone is clearly established by their sedimentology (Vincent 2001).  
48 However, the amount, extent and timing of excavation of these conglomerates have yet to be  
49 quantified in the foreland basin where low-temperature thermochronological data are scarce. The only

50 currently available data are AFT ages and track-length distributions from the conglomeratic deposits  
51 themselves (Beamud *et al.* 2011; Rahl *et al.* 2011), which confirm the timing of rapid erosional  
52 unroofing of the Axial Zone and suggest that the deposits were sufficiently thick to result in partial  
53 AFT annealing in samples from their base.

54

55 Two of us have recently constrained the thickness of the conglomerate deposits and the timing of their  
56 re-incision, using thermo-kinematic modelling constrained by the existing thermochronology dataset  
57 in the Southern Axial Zone (Fillon and van der Beek 2012). These models predict a thickness of the  
58 deposits of ~2 km on the southern flank of the Axial Zone, which was reached shortly after 30 Ma.  
59 Valley incision is predicted to have occurred from Late Miocene times (9 Ma) onward, which we link  
60 to the base-level drop resulting from opening of the Ebro Basin to the Mediterranean (Garcia-  
61 Castellanos *et al.* 2003; Urgelés *et al.* 2011). We thus have proposed a scenario of topographic  
62 evolution from Axial Zone data that we extrapolated to the southern Pyrenean foreland, but no data  
63 were available to test our model predictions.

64

65 Low temperature apatite fission-track (AFT) and (U-Th)/He (AHe) thermochronology provides a  
66 powerful tool to constrain the thermal history of the foreland. The AFT and AHe thermochronometers  
67 are sensitive to the 50-120 °C and 40-110 °C temperature ranges respectively (Farley 2000; Shuster  
68 and Farley 2009), therefore their combination can be used to constrain burial and exhumation in the  
69 fold-and-thrust belt from depths between ~1.5 and 3.5 km, depending on the local geothermal  
70 gradient.

71

72 We present new AFT and AHe data from Late Cretaceous-Palaeocene “Garumnian” sandstones  
73 collected in the Tremp-Graus and Ager basins of the southern central Pyrenees (Fig. 1), in order to  
74 provide direct estimates of the thickness and extent of the overlying conglomerate deposits, as well as  
75 to further constrain the timing of excavation of the basin. The AHe thermochronometer is very  
76 sensitive and requires high-quality samples, rendering the application of this method challenging in  
77 sedimentary samples. However, we will show that despite limited and relatively scattered AHe ages,  
78 we are able to obtain consistent Mesozoic to Cenozoic exhumation histories for three samples located  
79 in the north, centre and south of the fold-and-thrust belt. We use a new thermal-history inversion code  
80 (Gallagher 2012) that allows incorporation of variable AFT-annealing and AHe-diffusion kinetics.

81

## 82 **2. Tectono-sedimentary evolution of the South Central Pyrenees**

83

84 The south-central Pyrenean fold-and-thrust belt (also called South Central Unit, SCU) developed with  
85 the collision of the Iberian and European plates in the Late Cretaceous. Underthrusting of the Iberian  
86 plate below the European plate created a doubly-vergent Pyrenean wedge. The southern Pyrenees

87 evolved as the pro-wedge by inversion of Cretaceous extensional structures (Puigdefàbregas and  
88 Souquet 1986; Bond and McClay 1995) followed by in-sequence thrust propagation towards the south  
89 (Vergés and Muñoz 1990; Muñoz 1992; Vergés *et al.* 1995; Beaumont *et al.* 2000). The fold-and-  
90 thrust belt propagated further in the SCU, compared to the regions east and west of it, by sliding on a  
91 thick Triassic evaporite layer (Fig. 1c). Thrusting is in-sequence at first order, with activation of the  
92 Boixols thrust initiated in the Late Cretaceous, followed by the Montsec thrust, which transported the  
93 Tremp-Graus Basin in a piggy-back manner from Paleocene to Late Eocene times (Puigdefàbregas *et*  
94 *al.* 1992), and finally the frontal Sierras Marginales thrust sheet, active from Middle Eocene to Late  
95 Oligocene times (see Fig. 1 for locations).

96

97 From the ECORS seismic profile (ECORS Pyrenees Team 1988; Choukroune and ECORS Team  
98 1989), as well as modelling and thermochronological studies of the Southern Axial Zone (Beaumont *et*  
99 *al.* 2000; Sinclair *et al.* 2005; Fitzgerald *et al.* 2006; Gibson *et al.* 2007; Metcalf *et al.* 2009), rapid  
100 exhumation of the internal units (Nogueres, Orri and Rialp, Fig. 1c) is known to have occurred by  
101 vertical stacking (Muñoz 1992; Vergés *et al.* 1995) during Middle Eocene to Early Oligocene times.  
102 Thermo-kinematic modelling of the *in-situ* low-temperature thermochronology (AFT and AHe)  
103 dataset predicts exhumation rates of  $2.8 \pm 0.3$  km Myr<sup>-1</sup> between 37 and 30 Ma in that area (Fillon and  
104 van der Beek 2012). This rapid exhumation was associated with strong erosion of the southern Axial  
105 Zone, the products of which were deposited in pre-existing palaeo-valleys as a thick pile of  
106 conglomerates currently mainly exposed in the Sis, Gulp and La Pobla massifs (Fig. 1b). These  
107 palaeo-valleys probably represented sediment transfer zones, supplying the Huesca fan system  
108 (Vincent 2001), one of the main drainage systems of the Southern Central Pyrenees (with the Luna fan  
109 system to the West) during Oligocene-Miocene times. The link between exhumation of the internal  
110 massifs and deposition of the conglomerates has been confirmed by provenance studies (Vincent  
111 2001) and by AFT analysis of pebbles from the Sis conglomerates (Beamud *et al.* 2011; Rahl *et al.*  
112 2011), which both reveal unroofing of the Axial Zone and deposition of its erosional products in the  
113 basin.

114

115 Present-day remnants of these extensive syn- to post-tectonic conglomerate deposits include the  
116 Senterada and La Pobla basins (Beamud *et al.* 2003; Beamud *et al.* 2011), the Sis conglomerates  
117 (Vincent, 2001), the Oliana fan (to the east of the CSU; Burbank *et al.* 1992b) and the Huesca fan  
118 (southwest of our study area; Friend *et al.* 1996); they reach a maximum thickness of ~1000 m.  
119 Magnetostratigraphic studies constrain deposition of the Sis conglomerates at ~40 to 27 Ma (Beamud  
120 *et al.* 2003; Beamud *et al.* 2011), deposition of similar conglomerates to the east of the CSU, in the  
121 Oliana area, at ~40 to 36 Ma (Burbank *et al.* 1992a), and in the Sierras Marginales thrust sheet  
122 between 36.5 and 24.7 Ma (Meigs *et al.* 1996). The period of strong exhumation/erosion/deposition  
123 was synchronous with closure of the Atlantic connection of the Ebro foreland basin at 36 Ma (Costa *et*

124 *al.* 2009). The basin became endorheic at that time and remained so until Late Miocene times (Arenas  
125 and Pardo 1999; Garcia-Castellanos *et al.* 2003; Arche *et al.* 2010; Urgelés *et al.* 2011). During its  
126 endorheic phase, the basin was progressively filled by conglomeratic deposits at its borders, grading to  
127 lacustrine sediments in its centre, and developed into a large overfilled foreland basin.

128

### 129 **3. Mesozoic pre-depositional history**

130

131 Recently, two independent studies have reported zircon fission-track (ZFT), U-Pb and (U-Th)/He  
132 (ZHe) ages of samples from the SCU (Filleaudeau *et al.* 2011; Whitchurch *et al.* 2011). ZHe analysis  
133 of Garumnian sandstones of the Tresp Basin (sample ORC2; Filleaudeau *et al.* 2011) shows three  
134 main age populations (Triassic, Early Cretaceous and Late Cretaceous), interpreted to reflect distinct  
135 Mesozoic exhumation events affecting the source area(s). Whitchurch *et al.* (2011) applied detrital  
136 ZFT dating to Garumnian sandstones of the Ager basin and found the same Early and Late Cretaceous  
137 exhumation events, together with Carboniferous (Variscan) ZFT ages. A sample collected from the  
138 Aren formation (the stratigraphic unit just below the Garumnian in the Tresp Basin) presents Early  
139 Cretaceous and Carboniferous ZFT age peaks, lacking Late Cretaceous ages. The combination of these  
140 two datasets shows an important phase of Early Cretaceous source-area exhumation at  $134 \pm 15$  Ma (all  
141 uncertainties combined), with less well expressed events at  $\sim 80$  Ma,  $\sim 225$  Ma and 300-330 Ma. We  
142 will discuss later the imprint of these pre-depositional exhumation phases on our sample ages.

143

### 144 **4. Low-temperature thermochronology**

145

146 Five samples (AN01 to AN05) were collected along a N-S profile in Garumnian facies sandstones.  
147 These continental deposits of Maastrichtian-Middle Palaeocene (65-60 Ma) age crop out extensively  
148 throughout the fold-and-thrust belt (Fig. 1b). Other lithologies were also sampled, including Eocene  
149 sandstones, Santonian turbidites and volcanic rocks of the Nogueres zone, but none of these provided  
150 sufficient high-quality apatite grains for thermochronological analysis.

151

#### 152 **4.1. Apatite Fission-Track thermochronology**

153 Samples were prepared and analyzed at ISTERre (Grenoble, France). Apatite grains were separated  
154 from fine- to medium-grained sandstone samples using standard heavy-liquid and magnetic separation  
155 techniques. Apatite aliquots were mounted in epoxy, polished to expose internal crystal surfaces, and  
156 etched with 5.5 M HNO<sub>3</sub> for 20 s at 21 °C. Low-U muscovite sheets were fixed to the mounts, to be  
157 used as external detectors, and samples were irradiated in the FRM II Research Reactor at the  
158 Technische Universität München (Germany). Apatite samples were irradiated together with IRMM  
159 540R dosimeter glasses and Durango and Fish Canyon Tuff age standards. After irradiation, the mica

160 detectors of all samples and standards were etched for 18 minutes at 21 °C in 48% HF. The samples  
161 and standards were counted dry at 1250× magnification, using an Olympus BH2 optical microscope  
162 and the FTStage 4.04 system of Dumitru (1993). Due to the low yield of apatite grains, all datable  
163 grains were counted for each sample. Fission-track ages were calculated using the zeta-calibration  
164 method and the standard fission-track age equation (Hurford and Green 1983). The  $\chi^2$ -test and age  
165 dispersion (Galbraith and Green 1990; Galbraith and Laslett 1993) were used to assess the  
166 homogeneity of AFT ages. We were able to measure horizontal confined track lengths and the lengths  
167 of the track etch pits that outcrop on the etched internal surface ( $D_{par}$ ) in four samples.

168

#### 169 **4.2. Apatite (U-Th)/He analysis**

170 Apatite grains were carefully selected according to their morphology at ISTerre. Each grain was  
171 placed into a platinum basket for He-extraction at Paris-sud University (Orsay, France). Two to five  
172 replicates were analyzed per sample. The platinum baskets were heated using a diode laser to 1030±50  
173 °C during 5 minutes, allowing total He degassing; a reheat under the same conditions allowed  
174 checking for the presence of He trapped in small inclusions. The  $^4\text{He}$  content was determined by  
175 comparison with a  $1\text{-}2\times 10^{-7}$  ccSTP  $^3\text{He}$  spike. After He extraction, platinum baskets were placed into  
176 single-use polypropylene vials. Apatite grains were dissolved one hour at 90 °C in a 50  $\mu\text{l}$   $\text{HNO}_3$   
177 solution containing a known concentration of  $^{235}\text{U}$  and  $^{230}\text{Th}$ , and then filled with 1 ml of ultrapure  
178 MQ water. U and Th measurements followed a procedure similar to Evans *et al.* (2005). The final  
179 solution was measured for U and Th concentrations by quadrupole ICP-MS (series<sup>II</sup> CCT Thermo-  
180 Electron at LSCE, Gif-sur-Yvette, France). Analytical accuracy and reproducibility for U-Th isotope  
181 measurements by using ICP-QMS were better than  $\pm 0.5\%$  at  $2\sigma$  (Douville *et al.* 2010). The analysis  
182 was calibrated using internal and external age standards, including Limberg Tuff, Durango and FOR3,  
183 which provided mean AHe ages of 16.8±0.7 Ma, 31.8±0.5 Ma, and 110.7±7.0 Ma respectively. These  
184 values are in agreement with literature data, i.e. 16.8±1.1 Ma for the Limberg Tuff (Kraml *et al.* 2006),  
185 31.02±0.22 Ma for Durango (McDowell *et al.* 2005) and 112±10 Ma for the internal FOR3 standard.  
186 Individual ages were corrected by each grain's ejection factor  $F_T$ , determined using the Monte Carlo  
187 simulation technique of Ketcham *et al.* (2011); the equivalent-sphere radius has been calculated using  
188 the procedure of Gautheron and Tassan-Got (2010). The  $1\sigma$  error on AHe age should be considered at  
189 8%, reflecting the sum of errors in the ejection-factor correction and age dispersion of the standards.

190

### 191 **5. Results**

192

193 Apatite fission tracks were counted and measured in 4 samples located in the north (AN04), centre  
194 (AN03, AN02) and south (AN01) of the fold-and-thrust belt (see Fig. 1 for location); the results are  
195 reported in Fig. 2 and Table 1. Only sample AN01, collected south of the Montsec thrust (Fig. 1),



196 close to the Ager basin sample of (2011), shows a single age component ( $144\pm 11$  Ma). The other  
197 samples, for which more grains were counted, fail the  $\chi^2$ -test and have age dispersions  $>20\%$ , with  
198 central ages between  $64\pm 5$  and  $77\pm 6$  Ma. Individual samples contained insufficient dated grains to  
199 deconvolve the sample ages into age components. However, since the samples were collected in the  
200 same stratigraphic unit and show similar age structures, we calculated age components from the  
201 combined data, using the radial-plotter software of Vermeesch (2009). Three age peaks are found  
202 when pooling all single-grain ages: the major age component is Late Cretaceous in age ( $76.1\pm 3.7$  Ma),  
203 the second peak age is Late Paleocene (i.e., younger than the depositional age;  $51.7\pm 3.2$  Ma), and a  
204 minor Early Cretaceous peak age is found at  $142\pm 10$  Ma, with Early Cretaceous single-grain ages  
205 encountered in all samples (Fig.2).

206  
207 The youngest age population is clearly younger than the depositional age and single-grain ages  $<60$   
208 Ma are found in all samples except AN01, suggesting that they have been partially reset by post-  
209 depositional burial. Mean track lengths (MTL) are very short, ranging from  $10.1\ \mu\text{m}$  in AN01 to  $12.2$   
210  $\mu\text{m}$  in AN03 with standard deviations between  $1.0$  and  $2.2\ \mu\text{m}$ , indicating relatively slow long-term  
211 exhumation rates. Note, however, that only between 10 and 27 track lengths could be measured in  
212 these samples due to the low apatite yield.

213  
214 Apatite (U-Th)/He analyses were also performed on four samples: AN01, 02, 03 and AN05 (Fig. 3,  
215 Table 2). A striking feature of the AHe ages is their large scatter; single-grain ages vary from 3.9 to  
216 169 Ma. There appears to be some correlation between AHe ages and the effective uranium content  
217 ( $eU = [U] + 0.24 \times [\text{Th}]$ , expressed in ppm) of the grains, which varies between 4 and 25 ppm in samples  
218 AN01, 02 and 03 (Fig. 3a). The relationship between single-grain AHe ages and eU content reflects  
219 the increase of closure temperature as a function of the amount of  $\alpha$ -recoil damage, for which eU  
220 content is a convenient proxy (Shuster *et al.* 2006; Shuster and Farley 2009). Moreover, the rapidly  
221 increasing ages for  $eU > 15$  ppm, with less variation below this value (Fig. 3a), are consistent with a  
222 model in which He-retention increases non-linearly with the amount of  $\alpha$ -recoil damage (Shuster *et*  
223 *al.*, 2006; Flowers *et al.* 2009). Only sample AN05 does not fit this correlation; we suspect that this  
224 may be related to its very high eU content and, in particular, quite extreme Th concentration compared  
225 to the other samples. Thus, the AHe ages cannot be interpreted directly, but the Late Miocene-Pliocene  
226 ages measured in samples AN01, AN02 and AN03 imply post-depositional burial and exhumation of  
227 the basin. We will test the timing and amount of burial / exhumation through numerical inversion of  
228 the data in the next section.

229

## 230 **6. Thermal-history modelling**

231

232 In order to test what constraints the data provide on the post-depositional thermal history of the  
233 samples, we use an inversion model (Gallagher *et al.* 2009, Gallagher 2012) that allows extracting  
234 both optimal thermal histories and AFT annealing/AHe diffusion parameters by a Markov chain  
235 Monte Carlo (MCMC) sampling method. The inversion code incorporates recent kinetic models of He  
236 diffusion proposed by Flowers *et al.* (2009) and Gautheron *et al.* (2009), as well as the most recent  
237 multi-kinetic AFT annealing model of Ketcham *et al.* (2007). The modelling proceeds from an initial  
238 randomly chosen time-temperature path and set of kinetic parameters, for which a probability that the  
239 model fits the data is calculated. Then the parameters are slightly perturbed, the probability of fitting  
240 the data is recalculated and compared to the initial model. The model with the highest probability is  
241 retained. This procedure is repeated a large number of times (the number of iterations being chosen by  
242 the user), providing a large collection of models with their associated probabilities that allow  
243 calculating model statistics (probability distributions of model parameters, etc.). A full explanation of  
244 the modelling procedure is provided in Gallagher (2012).

245

### 246 **6.1. Model set-up**

247 The parameter space (time,  $t$  and temperature,  $T$ ) has been subdivided into three  $T$ - $t$  boxes: from 300  
248 Ma (beginning of the model run) to 70 Ma with temperatures between 140 °C and 0 °C, from 70 to 60  
249 Ma with a temperature of  $10 \pm 10$  °C (e.g. surface conditions), and finally from 60 Ma to present, with a  
250 temperature range of 140 °C to 0 °C. By doing this, the only constraint we impose on the model is the  
251 deposition time. The results are the product of 200,000 iterations, which is a sufficient amount to  
252 obtain a stable and robust solution (see discussion in Gallagher 2012). We present results of inversions  
253 for samples AN01, 02 and 03, which were analysed with both AFT and AHe thermochronology;  
254 samples AN04 and AN05, which come from the same structural position but for which only AFT  
255 (AN04) or AHe (AN05) measurements were available, were combined for a test model but do not  
256 provide sufficient thermal constraints to obtain a well-defined  $T$ - $t$  path.

257

258 As we use a multikinetic AFT annealing algorithm (Ketcham *et al.* 2007) in this study, the single  
259 grain-age counting data and track-length measurements were incorporated in the model and combined  
260 with the average  $D_{\text{par}}$  (i.e. we do not take potential intra-sample kinetic variation into account). We  
261 acknowledge that the number of track lengths measured in the samples is less than optimal for inverse  
262 thermal history modelling; however, this limitation is offset by the fact that we have both AFT and  
263 AHe data and exploit variable annealing and diffusion kinetics.

264

265 The He-diffusion models of Gautheron *et al.* (2009) and Flowers *et al.* (2009) were used to reproduce  
266 He-diffusion behaviour in apatite. These two models include the influence of  $\alpha$ -recoil damage and its

267 annealing on He-diffusion kinetics; in particular, they predict He retentivity to increase either linearly  
268 (Gautheron *et al.* 2009) or non-linearly (Flowers *et al.* 2009) with the amount of  $\alpha$ -recoil damage.  
269 Predicted AHe ages by the two models mainly differ for low eU contents (15-25 ppm), because this is  
270 the range where the amount of  $\alpha$ -recoil damage corresponds to the slope change in the diffusion law  
271 defined by natural and experimental data (Shuster *et al.* 2006; Shuster and Farley 2009). The  
272 simulations therefore predict slightly different thermal histories depending on which He-diffusion  
273 model is used; we will only present models using the Flowers *et al.* (2009) diffusion algorithm here;  
274 modelling results obtained using the Gautheron *et al.* (2009) diffusion algorithm are presented in  
275 Supplementary Figure 1.

276

277 The inversion procedure used here implicitly assumes that all grains share a single pre-depositional  
278 thermal history, whereas the zircon data discussed in Section 3 show that these sediments were derived  
279 from multiple sources with different pre-depositional histories. We will assess the effect of this  
280 simplification in the discussion (Section 7.2).

281

## 282 **6.2. Inferred thermal histories**

283 The models predict very similar  $T-t$  paths for all three samples (Fig. 4), in accordance with their  
284 similar stratigraphic and structural position, showing burial from their time of deposition until  
285 Miocene-Pliocene times, followed by exhumation until the present-day. The pre-deposition  $T-t$  path is  
286 poorly constrained for samples AN01 and AN02, in contrast to the model for sample AN03, which  
287 predicts a well-constrained pre-depositional history with linear cooling from the Early Cretaceous (130  
288 °C at 100 Ma) to the time of Garumnian sandstone deposition. For this sample, the model predicts  
289 burial to a temperature of ~70 °C reached between 11 and 5 Ma, before final exhumation.

290

291 Sample AN01 produced the widest range of single-grain AHe ages (7 Ma and 77 Ma); although the  
292 AFT age (144±11 Ma) suggests a single source age. The sample is also furthest from the preserved  
293 conglomeratic massifs. Nevertheless, the model predicts significant burial, to a maximum temperature  
294 of 80 °C, and an onset of Miocene exhumation between 20 and 10 Ma. The  $T-t$  path of sample AN02  
295 is quite similar, although this sample appears to have been buried most deeply, reaching a temperature  
296 of up to 95 °C. The predicted onset of final exhumation is well constrained at 7 Ma. Finally, we  
297 observe that the maximum Cenozoic burial temperatures predicted by the models are consistent with  
298 their corresponding AFT ages; maximum predicted burial temperatures are higher for samples with  
299 younger central AFT ages.

300

301 **7. Discussion**

302

303 **7.1. Sensitivity to eU variations**

304 To test the thermal histories provided by inverse modelling and the match with our AHe ages, the  
305 “expected” thermal histories (i.e. the weighted-average  $T-t$  path for the probability distributions shown  
306 in Fig. 4; cf. Gallagher 2012) for the three samples have been introduced in a forward model (Ketcham  
307 *et al.* 2005) to predict AHe ages for a grain size equal to the average size of our analysed crystals  
308 (equivalent-sphere radius of 57  $\mu\text{m}$ ) and eU contents varying from 5 to 30 ppm, using the He-diffusion  
309 model of Flowers *et al.* (2009). A comparison of predicted ages with our AHe data (Fig. 5) shows that  
310 both single-grain ages of sample AN02, as well as most single-grain ages of sample AN03 are in good  
311 agreement with the modelled path. Therefore, this test shows that the age scatter of these samples can  
312 be largely explained by their varying eU content. Conversely, some grains of samples AN01 and  
313 AN03 do not fit the modelled relationship between age and eU; therefore the measured ages could  
314 have been influenced by another parameter, such as a different pre-depositional history. We will test  
315 that possibility in the following section.

316

317 **7.2. Influence of the pre-depositional history**

318 The inverse modelling procedure we used cannot take into account variable pre-depositional histories  
319 of these detrital grains. However, the detrital ZFT and ZHe data of Whitchurch *et al.* (2011) and  
320 Filleaudeau *et al.* (2012) provide evidence for variability in timing and rates of source-area  
321 exhumation, as discussed in Section 3. We thus test to what degree such variable pre-depositional  
322 exhumation histories could explain the encountered dispersion of AHe ages.

323

324 The ZFT and ZHe data presented in Section 3 show pre-depositional exhumation ages between  $\sim 80$   
325 and  $\sim 300$  Ma. From this starting point, we tested the influence of the pre-depositional history and eU  
326 content by performing forward modelling (Ketcham 2005), using the AFT annealing model of  
327 Ketcham *et al.* (2007) and the AHe-diffusion model of Flowers *et al.* (2009), with the same parameter  
328 values as in Section 7.1. We imposed the post-depositional scenario from the inversion results  
329 presented previously and tested how the final AHe age varies as a function of eU, maximum post-  
330 depositional temperature ( $T_{\text{max}}$ ) and onset time of initial (pre-depositional) exhumation (Fig. 6a). The  
331 results are presented as contours of predicted AHe ages as a function of eU and onset time in Fig. 6b  
332 and 6c, for  $T_{\text{max}}$  of 70 and 80  $^{\circ}\text{C}$  respectively.

333

334 This forward modelling differs from the inverse modelling presented previously in two important  
335 aspects, therefore inducing somewhat different results: first, the forward models use fixed values for  
336 the diffusion parameters, whereas the inverse models allow varying these within the uncertainties

337 propagated from the original experiments (Gallagher 2012). Second, we fix  $T_{\max}$  as well as its timing  
338 and the overall shape of the thermal history path in the forward models, whereas these have more  
339 degrees of freedom in the inversions and show, for instance, clear tradeoffs between  $T_{\max}$  and timing  
340 of initial (pre-depositional) cooling. We use these forward models to illustrate the effects of variable  
341  $T_{\max}$ , eU and pre-depositional history on the measured AHe ages rather than to provide additional  
342 constraints on these parameters.

343

344 For the two burial temperatures tested, the modelling reveals the same patterns, in agreement with the  
345 relationship we expect between AHe age, eU content and  $T_{\max}$ . The modelled ages are older when  
346 initial exhumation starts earlier and for higher eU contents. The predicted ages are younger when  $T_{\max}$   
347 increases; the maximum modelled AHe ages are 155 and 120 Ma for  $T_{\max}$  of 70 and 80 °C,  
348 respectively. Moreover, for the same eU, the age scatter decreases with increasing  $T_{\max}$ . For example,  
349 for an eU of 16 ppm (the average eU value of our grains), modelled ages vary from 10 to 105 Ma as a  
350 function of onset time of initial exhumation for  $T_{\max} = 70$  °C, but only from 10 to 40 Ma for  $T_{\max} = 80$   
351 °C.

352

353 These forward models confirm the hypothesis that the pre-depositional history of the detrital grains  
354 can have a major effect on AHe age variations. With these results, we can also identify what  
355 variability in timing of pre-depositional exhumation would be required to explain the scatter in our  
356 AHe ages, by plotting the ages and eU values of our samples on the contour plots (Fig.7b). First of all,  
357 we note that the forward model with  $T_{\max} = 70$  °C provides the best fit to the combined data; this value  
358 is within the range of predictions of all inverse models. Secondly, when looking at the  $T_{\max} = 70$  °C  
359 plot, we can conclude that all grains except AN011 fit with a pre-depositional exhumation phase  
360 starting between 150 and 90 Ma, which is in good agreement with the ZHe and ZFT age distributions  
361 of Filleaudeau et al. (2012) and Whitchurch *et al.* (2011), which record a major Early Cretaceous  
362 (~120-150 Ma) exhumation phase and a less well-expressed phase in the Late Cretaceous (~80 Ma).  
363 These results are also in agreement with the expected model from the thermal-history inversion of  
364 AN02 and AN03, predicting an onset of initial exhumation before the Late-Cretaceous (i.e. >100 Ma).  
365 Only the age of AN011 is outside of this range and suggests Triassic initial cooling, consistent with  
366 the occurrence of Triassic ZHe ages, which may result from a major volcanic episode associated with  
367 the emplacement of the Central Atlantic Magmatic Province (Marzoli *et al.* 1999). Our previous  
368 observations showed that the age dispersion between the two grains of this sample could not be  
369 explained by their respective eU contents alone. We thus propose that variable pre-depositional  
370 exhumation histories, with at least one grain recording Triassic initial cooling, constitute another  
371 factor to explain the variable AHe grain ages.

372

373 To conclude, our forward modelling shows that the pre-depositional history of a detrital sample can  
374 considerably influence the measured AHe ages as well as the inferred temperature of burial. In our  
375 case, it seems that a combination of variable eU and variable timing of initial exhumation, consistent  
376 with higher-temperature detrital ZHe and ZFT data, can explain the scatter in AHe ages. Moreover, the  
377 forward models suggest that most apatite grains record an Early Cretaceous pre-depositional  
378 exhumation phase.

379

### 380 **7.3. Cenozoic Burial and exhumation scenario**

381 The inverse modelling results provide values for the amount and timing of Cenozoic burial heating  
382 that range from 70 to 95 °C, with final exhumation starting between 20 and 5 Ma. Even though the  
383 modelling predicts a variable range of maximum burial temperatures and associated timing, the first-  
384 order pattern of the  $T-t$  paths in all cases shows significant burial during post-Eocene times, with  
385 subsequent exhumation starting in the Late Miocene–Early Pliocene.

386

387 We interpret the burial recorded by the samples as being due to deposition of the Late Eocene-  
388 Oligocene conglomerates produced by rapid erosion of the Axial Zone, and explain the subsequent  
389 exhumation by excavation of the modern southern Pyrenean river valleys. In this scenario, we do not  
390 take into account any tectonic activity that could be responsible for late-stage exhumation of the SCU  
391 (*i.e.*, during Miocene times). The main reason for this choice is that there is no clear evidence for such  
392 tectonic activity in the SCU, mainly because no Miocene sediments are exposed in that area.  
393 Moreover, as shown in Fig. 7, our AFT and AHe ages and the corresponding burial estimates  
394 predicted by the thermal modelling are homogeneous for all samples, despite their provenance from  
395 different thrust sheets. A few very young (Middle Miocene) AFT and AHe ages were reported further  
396 west, in the Bielsa massif (Jolivet *et al.* 2007) and to the north of the study area in the Barruera massif  
397 (Gibson *et al.* 2007), which have been interpreted as recording Miocene out-of-sequence thrusting.  
398 However, it is unclear how these results could be extrapolated to the SCU.

399

400 Estimating the thickness of the conglomerate cover requires knowledge of the local geothermal  
401 gradient. A previous interpretation of AFT data from the SCU (Beamud *et al.* 2011) used a geothermal  
402 gradient of 30 °C km<sup>-1</sup>, as constrained by numerical modelling (Zeyen and Fernández 1994) supposing  
403 a value for the thermal conductivity of sediments of 2.5 W m<sup>-1</sup> K<sup>-1</sup>. According to Fernández *et al.*  
404 (1998), however, the average present-day geothermal gradient for the SCU is 22±4 °C km<sup>-1</sup>,  
405 significantly lower than the value for the Pyrenean Axial Zone (~33 °C km<sup>-1</sup>); this discrepancy is  
406 apparently due to the high thermal conductivity (2.47 to 3.22 W m<sup>-1</sup> K<sup>-1</sup>) measured in the sediments.  
407 As there is no consensus on the subject, we will use in the following a 30 °C km<sup>-1</sup> geothermal gradient  
408 to estimate the sediment thicknesses, thus providing a conservative estimate of the amount of burial.

409

410 Using this value for the geothermal gradient and a surface temperature of 20 °C, the minimum amount  
411 of burial required to reach the  $T_{\max}$  recorded by our Garumnian samples can be estimated at 2.3 km for  
412 sample AN03, 2.6 km for sample AN01 and to 3.2 km for sample AN02, with final exhumation rates  
413 of 0.13 to 0.5 km Myr<sup>-1</sup>. As the thickness of the Palaeocene-Middle Eocene sediments deposited in the  
414 Tremp-Graus Basin ranges from 1.2 km in the Montsec footwall area (sample AN01) to 1.6 km in the  
415 Tremp area (samples AN02 and AN03), our results imply a minimum thickness of post-Middle  
416 Eocene sediments of 700 m for sample AN03, 1.6 km for the sample AN02 and 1.4 km for sample  
417 AN01, as represented in Fig. 7. Note that, because the Late Eocene-Oligocene conglomerates are  
418 discordant on the Middle-Eocene and older sediments, it is difficult to estimate the exact thickness of  
419 the latter. Note also that for a lower geothermal gradient of 22 °C km<sup>-1</sup> (see paragraph above), inferred  
420 burial depths are significantly higher and require 1.6, 2.4 and 2.7 km of post-Middle Eocene  
421 sediments, respectively, for samples AN03, AN01 and AN02.

422

423 Thermo-kinematic modelling of the *in-situ* AFT and AHe dataset in the Axial Zone of the central  
424 Pyrenees (Fillon and van der Beek 2012) suggested that ~2 km of conglomeratic deposits once  
425 covered the southern flank of the central Axial Zone. The model also predicted re-incision and erosion  
426 of the conglomerates during the Tortonian (9.2±0.5 Ma), implying late-stage exhumation rates of ~0.3  
427 km Myr<sup>-1</sup> in the valley bottoms. The AHe ages confirm this interpretation and show continuous  
428 excavation of the basin from the Late Miocene-Pliocene to the present.

429

430 Finally, it is interesting to note that our inverse models do not reproduce an Eocene signal of  
431 exhumation linked to tectonic activity of the fold-and-thrust belt. However, the Late Eocene  
432 conglomerates rest unconformably on the earlier syn-tectonic sediments, implying an initial period of  
433 burial and unroofing between the Late Cretaceous and Late Eocene. We tested for this by forcing the  
434 thermal history models to reach near-surface temperatures in the Eocene but found that this did not  
435 affect the models to any significant extent. Therefore, if there was exhumation in the Eocene it could  
436 not have been very large (>1 km) otherwise the AFT and AHe systems would have recorded this  
437 event. Our modelling results thus support the idea of a strongly overfilled Ebro basin in the Oligocene-  
438 Miocene, characterised by up to 1.6 km of sediment aggradation at its northern edge.

439

#### 440 **7.4. Extent of late orogenic conglomerate deposits**

441 The inferred amounts of burial are consistent with what we expected for samples AN02 and AN03, as  
442 these were collected close to the remnant conglomeratic massifs and the Axial Zone. A more  
443 surprising result is obtained for sample AN01, which is located in another structural unit, south of the  
444 Montsec thrust, and quite far from the Axial Zone. The closest conglomeratic outcrops to this sample  
445 are located further east and have been dated by magnetostratigraphy at 40 to 36 Ma (Oliana  
446 conglomerates; Burbank *et al.* 1992a). Nevertheless, the inversion results for sample AN01 suggest

447 2.6 km of burial before an onset of final exhumation between 10 and 20 Ma. These values are  
448 comparable to those obtained for the northern samples. Thus, the Ager Basin, south of the Montsec  
449 thrust (Fig. 1), seems to record the same post-Eocene burial/exhumation history as the Tresp Basin,  
450 implying that infilling by the Huesca fan sediments extended to that basin. The burial of the Ager  
451 Basin, which is not drawn in most paleo-geographic reconstructions (see Jones 2004 for example),  
452 could result from an extension of the Huesca fan further to the east, or from extension of the Oliana  
453 fan towards the west.

454

## 455 **8. Conclusions**

456

457 We have succeeded in modelling our dataset of AFT and AHe ages of detrital apatites to obtain  
458 consistent  $T-t$  paths using He-diffusion kinetics that are a function of radiation damage and its  
459 annealing. Our models show that the significant AHe-age scatter can be explained by variable eU  
460 content together with variable pre-depositional exhumation histories, consistent with inferences from  
461 published higher-temperature ZFT and ZHe data. Modelling of three samples predicts burial from the  
462 Late-Cretaceous to the Miocene-Pliocene to reach maximum temperatures of 70 to 95 °C, requiring at  
463 least 0.7 to 1.6 km of Late Eocene-Oligocene overburden. The inferred timing for the onset of  
464 exhumation ranges from 20 to 5 Ma, with exhumation rates of 0.13 to 0.5 km Myr<sup>-1</sup>. These modelling  
465 results thus show similar post-orogenic burial and exhumation in the southern Pyrenean foreland as  
466 previously inferred for the southern Axial Zone and suggest a Late Miocene (pre-Messinian) onset of  
467 Ebro Basin incision. They confirm that several km of sediments covered the southern Pyrenean flank  
468 and filled the Ebro Basin, consequently to the onset of endorheism in the basin.

469

## 470 **Acknowledgements:**

471 This study was supported by INSU-CNRS through the European Science Foundation Topo-Europe  
472 programme “Spatial and temporal coupling between tectonics and surface processes during lithosphere  
473 inversion of the Pyrenean-Cantabrian mountain belt (PyrTec)”. It forms part of CF's PhD project at  
474 Université Joseph Fourier, supported by the French Ministry for Research and Higher Education.  
475 Vincent Bouvier, Rosella Pinna and Louise Bordier are thanked for AFT sample preparation, U-Th  
476 chemistry and help during ICP-MS measurement at LSCE (Gif sur Yvette), respectively. Eric Douville  
477 is thanked for providing access to the ICP-MS. AHe age measurements at Orsay were funded by the  
478 ANR-06-JCJC-0079 project granted to C. Gautheron. The fission-track lab at ISTerre is supported by  
479 Université Joseph Fourier and INSU-CNRS. We thank Kerry Gallagher for providing a pre-  
480 publication version of the QTQt thermal-history inversion code and for advise in running it.  
481 Constructive reviews by Hugh Sinclair and an anonymous reviewer, as well as comments by editor  
482 Andy Carter, significantly improved the manuscript.

483



- 486 Arche, A., G. Evans and E. Clavell (2010). "Some considerations on the initiation of the present SE  
487 Ebro river drainage system: Post- or pre-Messinian?" *Journal of Iberian Geology* **36**(1): 73-  
488 85.
- 489  
490 Arenas, C. and G. Pardo (1999). "Latest Oligocene-Late Miocene lacustrine systems of the north-  
491 central part of the Ebro Basin (Spain): sedimentary facies model and palaeogeographic  
492 synthesis." *Palaeogeography, Palaeoclimatology, Palaeoecology* **151**(1-3): 127-148.  
493
- 494 Beamud, E., M. Garcés, L. Cabrera, J. A. Muñoz and Y. Almar (2003). "A middle to late Eocene  
495 continental chronostratigraphy from NE Spain." *Earth and Planetary Science Letters* **216**:  
496 501-504.  
497
- 498 Beamud, E., J. A. Muñoz, P. G. Fitzgerald, S. L. Baldwin, M. Garcés, L. Cabrera and J. R. Metcalf  
499 (2011). "Magnetostratigraphy and detrital apatite fission track thermochronology in  
500 syntectonic conglomerates: constraints on the exhumation of the South-Central Pyrenees."  
501 *Basin Research* **23**(3): 309-331.  
502
- 503 Beaumont, C., J. A. Muñoz, J. Hamilton and P. Fullsack (2000). "Factors controlling the Alpine  
504 evolution of the central Pyrenees inferred from a comparison of observations and  
505 geodynamical models." *Journal of Geophysical Research* **105**: 8121-8145.  
506
- 507 Bond, R. and K. McClay (1995). Inversion of a Lower Cretaceous extensional basin, south central  
508 Pyrenees, Spain. *Basin Inversion*. J. Buchanan, Buchanan, P., Geological Society of London  
509 Special Publications. **88**: 415-431.  
510
- 511 Burbank, D. W., C. Puigdefàbregas and J. A. Muñoz (1992a). "The chronology of the Eocene tectonic  
512 and stratigraphic development of the eastern Pyrenean foreland basin, northeast Spain."  
513 *Geological Society of America Bulletin* **104**: 1101-1120.  
514
- 515 Burbank, D. W., J. Vergés, J. A. Muñoz and P. Benthams (1992b). "Coeval hindward- and forward-  
516 imbricating thrusting in the south-central Pyrenees, Spain: Timing and rates of shortening and  
517 deposition." *Geological Society of America Bulletin* **104**: 3-17.  
518
- 519 Choukroune, P. and ECORS Team (1989). "The ECORS Pyrenean deep seismic profile reflection data  
520 and the overall structure of an orogenic belt." *Tectonics* **8**: 23-39.  
521
- 522 Coney, P. J., J. A. Muñoz, K. R. McClay and C. A. Evnechick (1996). "Syntectonic burial and post-  
523 tectonic exhumation of the southern Pyrenees foreland fold-thrust belt." *Journal of the*  
524 *Geological Society, London* **153**(1): 9-16.  
525
- 526 Costa, E., M. Garcés, M. López-Blanco, E. Beamud, M. Gómez-Paccard and J. Cruz Larrasoña  
527 (2009). "Closing and continentalization of the South Pyrenean foreland basin (NE Spain):  
528 magnetochronological constrains." *Basin Research* **22**(6): 904-917.  
529
- 530 Douville, E., E. Sallé, N. Frank, M. Eisele, E. Pons-Branchu and S. Ayrault (2010). "Rapid and  
531 accurate U-Th dating of ancient carbonates using inductively coupled plasma-quadrupole  
532 mass spectrometry." *chemical geology* **272**(1-4): 1-11.  
533
- 534 Dumitru, T. A. (1993). "A new computer-automated microscope stage system for fission-track  
535 analysis." *Nuclear Tracks and Radiation Measurements* **21**(4): 575-580.  
536

- 537 ECORS Pyrenees Team (1988). "The ECORS deep seismic profile reflection survey across the  
538 Pyrenees." *Nature* **331**: 508-811.  
539
- 540 Evans, N. J., J. P. Byrne, J. T. Keegan and L. E. Dotter (2005). "Determination of uranium and  
541 thorium in zircon, apatite, and fluorite: Application to laser (U-Th)/He thermochronology."  
542 *Journal of Analytical Chemistry* **60**(12): 1300-1307.  
543
- 544 Farley, K. A. (2000). "Helium diffusion from apatite: general behavior as illustrated by Durango  
545 fluorapatite." *J. Geophys. Res.*(105): 2903–2914.  
546
- 547 Fernández, M., I. Marzan, A. Correia and E. Ramalho (1998). "Heat flow, heat production, and  
548 lithospheric thermal regime in the Iberian Peninsula." *Tectonophysics* **291**(1-4): 29-53.  
549
- 550 Filleaudeau, P. Y., F. Mouthereau and R. Pik (2012). "Thermo-tectonic evolution of the south-central  
551 Pyrenees from rifting to orogeny: insights from detrital zircon U/Pb and (U-Th)/He  
552 thermochronometry " *Basin Research* **24**(4): 401-417.  
553
- 554 Fillon, C. and P. van der Beek (2012). "Post-orogenic evolution of the southern Pyrenees: constraints  
555 from inverse thermo-kinematic modelling of low-temperature thermochronology data." *Basin  
556 Research* **24**(4): 418-436.  
557
- 558 Fitzgerald, P. G., S. L. Baldwin, L. E. Webb and P. B. O'Sullivan (2006). "Interpretation of (U-Th)/He  
559 single grain ages from slowly cooled crustal terranes: A case study from the Transantarctic  
560 Mountains of southern Victoria Land." *Chemical Geology* **225**(1-2): 91-120.  
561
- 562 Fitzgerald, P. G., J. A. Muñoz, P. J. Coney and S. L. Baldwin (1999). "Asymmetric exhumation across  
563 the Pyrenean orogen: implications for the tectonic evolution of a collisional orogen." *Earth  
564 and Planetary Science Letters* **173**: 157-170.  
565
- 566 Flowers, R. M., R. A. Ketcham, D. L. Shuster and K. A. Farley (2009). "Apatite (U-Th)/He  
567 thermochronometry using a radiation damage accumulation and annealing model." *Geochimica et Cosmochimica Acta* **73**(8): 2347-2365.  
568  
569
- 570 Friend, P. F., M. J. Lloyd, R. McElroy, J. Turner, A. Van Gelder and S. J. Vincent (1996). Evolution of  
571 the central part of the northern Ebro basin margin, as indicated by its Tertiary fluvial  
572 sedimentary infill. *Tertiary Basins of Spain*. P.F. Friend, C. J. Dabrio (eds.), Cambridge  
573 University press: 166-172.  
574
- 575 Galbraith, R. F. and P. F. Green (1990). "Estimating the component ages in a finite mixture." *Nuclear  
576 Tracks and Radiation Measurements* **17**(3): 197-206.  
577
- 578 Galbraith, R. F. and G. M. Laslett (1993). "Statistical models for mixed fission track ages." *Nuclear  
579 Tracks and Radiation Measurements* **21**(4): 459-470.  
580
- 581 Gallagher, K. (2012). "Transdimensional inverse thermal history modeling for quantitative  
582 thermochronology." *Journal of Geophysical Research* **117**(B2): B02408, doi:  
583 10.1029/2011jb008825.  
584
- 585 Gallagher, K., K. Charvin, S. Nielsen, M. Sambridge and J. Stephenson (2009). "Markov chain Monte  
586 Carlo (MCMC) sampling methods to determine optimal models, model resolution and model  
587 choice for Earth Science problems." *Marine and Petroleum Geology* **26**(4): 525-535.  
588
- 589 Garcia-Castellanos, D., J. Vergés, J. Gaspar-Escribano and S. Cloetingh (2003). "Interplay between  
590 tectonics, climate, and fluvial transport during the Cenozoic evolution of the Ebro Basin (NE  
591 Iberia)." *Journal of Geophysical Research* **108**(B7): 2347, doi: 10.1029/2002JB002073.

592  
593 Gautheron, C. and L. Tassan-Got (2010). "A Monte Carlo approach of diffusion applied to noble  
594 gas/helium thermochronology." *Chemical Geology* **273**: 212-224.  
595  
596 Gautheron, C., L. Tassan-Got, J. Barbarand and M. Pagel (2009). "Effect of alpha-damage annealing  
597 on apatite (U-Th)/He thermochronology." *Chemical Geology* **266**(3-4): 157-170.  
598  
599 Gibson, M., H. D. Sinclair, G. J. Lynn and F. M. Stuart (2007). "Late- to post-orogenic exhumation of  
600 the Central Pyrenees revealed through combined thermochronological data and modelling."  
601 *Basin Research* **19**(3): 323-334.  
602  
603 Hurford, A. J. and P. F. Green (1983). "The zeta age calibration of fission-track dating." *Chemical*  
604 *Geology* **41**: 285-317.  
605  
606 ICC (2002). Mapa geològic de Catalunya 1:250 000. Institut Cartogràfic de Catalunya.  
607  
608 Jolivet, M., P. Labaume, P. Monié, M. Brunel, N. Arnaud and M. Campani (2007).  
609 "Thermochronology constraints for the propagation sequence of the south Pyrenean basement  
610 thrust system (France-Spain)." *Tectonics* **26**: TC5007, doi: 10.1029/2006TC002080.  
611  
612 Jones, S. J. (2004). "Tectonic controls on drainage evolution and development of terminal alluvial  
613 fans, southern Pyrenees, Spain." *Terra Nova* **16**(3): 121-127.  
614  
615 Ketcham, R. A. (2005). Forward and reverse modeling of low-temperature thermochronology data.  
616 *Low-Temperature Thermochronology: Techniques, Interpretations and Applications*. P. W.  
617 Reiners, T. A. Ehlers (eds.), *Rev. Mineral. Geochem.* **58**: 275-314.  
618  
619 Ketcham, R. A., A. Carter, R. A. Donelick, J. Barbarand and A. J. Hurford (2007). "Improved  
620 modeling of fission-track annealing in apatite." *American Mineralogist* **92**: 789-798.  
621  
622 Ketcham, R. A., C. Gautheron and L. Tassan-Got (2011). "Accounting for long alpha-particle stopping  
623 distances in (U-Th-Sm)/He geochronology: Refinement of the baseline case." *Geochemica et*  
624 *Cosmochimica Acta* **75**: 7779-7791.  
625  
626 Kraml, M., R. Pik, M. Rahn, R. Selbekk, J. Carignan and J. Keller (2006). "A new multi-mineral age  
627 reference material for  $^{40}\text{Ar}/^{39}\text{Ar}$ , (U-Th)/He and fission track dating methods: The Limberg  
628 t3 tuff." *Geostandards and Geoanalytical Research* **30**(2): 73-86.  
629  
630 Marzoli, A., P. R. Renne, E. M. Picirillo, G. Bellieni and A. De Min (1999). "Extensive 200-million-  
631 year-old continental flood basalts of the central Atlantic magmatic province." *Science* **284**:  
632 616-618.  
633  
634 McDowell, F. W., W. C. McIntosh and K. A. Farley (2005). "A precise  $^{40}\text{Ar}/^{39}\text{Ar}$  reference age for  
635 the Durango apatite (U-Th)/He and fission-track dating standard." *Chemical Geology* **214**(3-  
636 4): 249-263.  
637  
638 Meigs, A. J., J. Verges and D. W. Burbank (1996). "Ten-million-year history of a thrust sheet."  
639 *Geological Society of America Bulletin* **108**(12): 1608-1625.  
640  
641 Metcalf, J. R., P. G. Fitzgerald, S. L. Baldwin and J. A. Muñoz (2009). "Thermochronology of a  
642 convergent orogen: Constraints on the timing of thrust faulting and subsequent exhumation of  
643 the Maladeta Pluton in the Central Pyrenean Axial Zone." *Earth and Planetary Science Letters*  
644 **287**(3-4): 488-503.  
645

- 646 Muñoz, J. A. (1992). Evolution of a continental collision belt: ECORS Pyrenees crustal balanced cross  
647 section. *Thrust Tectonics*. K. R. McClay (ed.). London, Chapman & Hall: 235-246.  
648
- 649 Puigdefàbregas, C., J. A. Muñoz and J. Vergés (1992). Thrusting and foreland basin evolution in the  
650 southern Pyrenees. *Thrust Tectonics*. K. R. McClay (ed.). London, Chapman & Hall: 247-254.  
651
- 652 Puigdefàbregas, C. and P. Souquet (1986). "Tecto-sedimentary cycles and depositional sequences of  
653 the Mesozoic and Tertiary from the Pyrenees." *Tectonophysics* **129**: 173-203.  
654
- 655 Rahl, J. M., S. H. Haines and B. A. van der Pluijm (2011). "Links between orogenic wedge  
656 deformation and erosional exhumation: Evidence from illite age analysis of fault rock and  
657 detrital thermochronology of syn-tectonic conglomerates in the Spanish Pyrenees." *Earth and  
658 Planetary Science Letters* **307**(1-2): 180-190.  
659
- 660 Shuster, D. L. and K. A. Farley (2009). "The influence of artificial radiation damage and thermal  
661 annealing on helium diffusion kinetics in apatite." *Geochimica et cosmochimica acta* **73**(1):  
662 183-196.  
663
- 664 Shuster, D. L., R. M. Flowers and K. A. Farley (2006). "The influence of natural radiation damage on  
665 helium diffusion kinetics in apatite." *Earth and Planetary Science Letters* **249**(3-4): 148-161.  
666
- 667 Sinclair, H. D., M. Gibson, M. Naylor and R. G. Morris (2005). "Asymmetric growth of the Pyrenees  
668 revealed through measurement and modeling of orogenic fluxes." *American Journal of  
669 Science* **305**: 369-406.  
670
- 671 Urgelés, R., A. Camerlenghi, D. Garcia-Castellanos, B. De Mol, M. Garcés, J. Vergés, I. Haslam and  
672 M. Hardman (2011). "New constraints on the Messinian sealevel drawdown from 3D seismic  
673 data of the Ebro Margin, western Mediterranean." *Basin Research* **23**(2): 123-145.  
674
- 675 Vergés, J., H. Millan, E. Roca, M. J. A., M. Marzo, J. Cites, T. Den Bezemer, R. Zoetemeijer and S.  
676 Cloetingh (1995). "Eastern Pyrenees and related foreland basins: pre-, syn- and post-  
677 collisional crustal-scale cross-sections." *Marine and Petroleum Geology* **12**(8): 893-915.  
678
- 679 Vergés, J. and J. A. Muñoz (1990). "Thrust sequences in the southern central Pyrenees." *Bulletin  
680 Société Géologique de France* **8**(2): 265-271.  
681
- 682 Vermeesch, P. (2009). "RadialPlotter: a Java application for fission track, luminescence and other  
683 radial plots." *Radiation Measurements* **44**(4): 409-410.  
684
- 685 Vincent, S. J. (2001). "The Sis palaeovalley: a record of proximal fluvial sedimentation and drainage  
686 basin development in response to Pyrenean mountain building." *Sedimentology* **48**(6): 1235-  
687 1276.  
688
- 689 Whitchurch, A. L., A. Carter, H. D. Sinclair, R. A. Duller, A. C. Whittaker and P. A. Allen (2011).  
690 "Sediment routing system evolution within a diachronously uplifting orogen: Insights from  
691 detrital zircon thermochronological analyses from the South-Central Pyrenees." *American  
692 Journal of Science* **311**(5): 442-482.  
693
- 694 Zeyen, H. and M. Fernández (1994). "Integrated lithospheric modeling combining thermal, gravity,  
695 and local isostasy analysis: Application to the NE Spanish Geotranssect." *Journal of  
696 Geophysical Research* **99**(B9): 18,089 - 18,102.  
697  
698  
699

Sample	position (lat/long)	Elevation (m)	no of grains	$\rho_s$ (Ns) ( $10^6 \text{ cm}^{-2}$ )	$\rho_i$ (Ni) ( $10^6 \text{ cm}^{-2}$ )	$\rho_d$ (Nd) ( $10^6 \text{ cm}^{-2}$ )	$P\chi^2$ (%)	D	Central age ( $\pm 1\sigma$ , Ma)	MTL ( $\mu\text{m}$ )	sd ( $\mu\text{m}$ )	no tracks	Dpar ( $\mu\text{m}$ )	sd ( $\mu\text{m}$ )	no Dpar
AN01	41.96/00.85	624	8	1.133 (489)	0.632 (273)	0.74 (4262)	32.34	0.02	$144 \pm 11$	10.1	1.0	10	2.2	0.4	24
AN02	42.16/00.89	436	20	0.7641 (999)	0.8513 (1113)	0.75 (4262)	$\ll 1$	0.26	$76.9 \pm 6.2$	11.3	1.4	19	2.1	0.2	36
AN03	42.18/00.89	504	22	1.264 (1639)	1.493 (1936)	0.75 (4262)	$\ll 1$	0.26	$64.2 \pm 4.6$	12.2	1.6	27	2.2	0.2	61
AN04	42.22/00.84	902	13	1.0715 (810)	1.205 (911)	0.75 (4262)	$\ll 1$	0.20	$74.1 \pm 7.6$	11.3	2.2	19	2.1	0.1	18

700

701 **Table 1** Apatite Fission-Track results.  $\rho_s$  and  $\rho_i$  are the spontaneous and induced track densities measured;  $\rho_d$  is the induced track density in the external  
702 detector, the number of tracks counted (Ns, Ni, Nd) are in brackets;  $P(\chi^2)$  is  $\chi^2$ -probability (in %), D is the single-grain age dispersion. A  $P(\chi^2) < 5$  and/or  $D >$   
703  $0.15$  indicates that the data distribution contains multiple age populations ; MTL is the mean track length, with sd its standard deviation; Dpar is the average  
704 etch-pit width measured parallel to the C-axis. Measurements were performed by CF with a  $\zeta$ -factor =  $217.9 \pm 3.5$  for IRMM-540 dosimeter glasses.

705

706

707

708

709

710

711

712

Lab ID	Sample	$F_T$	Weight (ng)	Length/ Width/ Thickness ( $\mu\text{m}$ )	$^4\text{He} \times 10^{-6}$ (cc/g)	U (ppm)	Th (ppm)	Th/U	eU (ppm)	Age (Ma)	Age corr. $\pm 1\sigma$ (Ma)
2486	AN011	0.76	2.9	128 101 95	122	12.9	19.2	1.5	17.5	58.0	<b>76.9 <math>\pm</math> 7.1</b>
2488	AN012	0.80	5.7	181 123 108	4.1	2.8	6.3	2.3	4.3	5.2	<b>6.5 <math>\pm</math> 0.6</b>
2493	AN022	0.76	3.4	146 106 92	9.4	9.9	11	1.1	12.5	6.2	<b>8.1 <math>\pm</math> 0.7</b>
2495	AN023	0.84	6.7	156 139 132	5.4	5.8	33.6	5.8	13.9	3.2	<b>3.9 <math>\pm</math> 0.3</b>
2499	AN031	0.76	3.9	187 100 85	48.5	9.8	39.6	4	19.3	20.9	<b>27.6 <math>\pm</math> 2.5</b>
2501	AN032	0.87	5.3	177 135 117	117	22.3	20.5	0.9	27.2	35.7	<b>41.0 <math>\pm</math> 3.8</b>
2548	AN033	0.69	10	151 77 67	120	12	54.9	4.6	25.2	39.6	<b>57.4 <math>\pm</math> 5.3</b>
1641	AN034	0.84	11.5	200 150 187	20.6	15.9	8.9	0.56	18	9.5	<b>11.3 <math>\pm</math> 1.0</b>
1643	AN035	0.80	5	150 125 112	6.2	4	14.2	3.55	7.4	6.9	<b>8.7 <math>\pm</math> 0.8</b>
2552	AN051	0.80	4.6	190 113 97	326	49.2	616.3	12.5	197.1	13.8	<b>17.2 <math>\pm</math> 1.6</b>
2554	AN052	0.80	5	147 120 112	224	27.9	362.4	13	114.9	16.3	<b>20.3 <math>\pm</math> 1.9</b>
1878	AN053	0.85	12.6	275 175 125	53.2	6.4	29.9	4.67	13.6	32.6	<b>38.5 <math>\pm</math> 3.5</b>
1880	AN054	0.80	12.8	262 162 162	335	10.6	36.5	3.43	19.4	144.0	<b>169.1 <math>\pm</math> 15.6</b>

713

714 **Table 2.** Apatite (U-Th)/He results. Lab ID is the Orsay sample identification number, which is the second replicate  $^3\text{He}$  spike pipette number,  $F_T$  is the  
715 geometric correction factor for age calculation; age corr. is the age corrected by the ejection factor  $F_T$ , the uncertainty  $1\sigma$  was fixed at 8 % of the age. eU is  
716 the effective uranium concentration.

717 **Figure captions**

718

719 **Figure 1.** a) Regional map of the Pyrenean range and its two foreland basins, the black box represents  
720 the study area shown in map b. NPZ: North Pyrenean Zone; SCU: South Central Unit. b) Simplified  
721 geological map of the southern central Pyrenees (modified from ICC 2002), with sample positions and  
722 location of cross-section shown in c. c) Geological cross-section drawn from the ECORS seismic  
723 profile (Muñoz 1992); sample positions have been projected on the section.

724

725 **Figure 2.** Radial-plot and histogram representations (Vermeesch 2009) of the AFT counting data of  
726 samples AN01, 02, 03, and 04 combined. The radial plot is centred on the central age of the combined  
727 samples (79 Ma); grey lines indicate peak ages and the black dashed line represents the depositional  
728 age (65 Ma). Samples are individualised by different grey-shading of the data points.

729

730 **Figure 3.** a) AHe ages plotted as a function of effective uranium content ( $eU = [U] + 0.24 \times [Th]$ ) for the  
731 four samples analysed; gray dashed line in a) represents exponential fit to the data. b) Sample AN05  
732 has been separated from the others due to its high eU content and lack of correlation between eU and  
733 AHe ages, which contrasts with the other samples.

734

735 **Figure 4.** Modelled  $T-t$  paths from joint AFT and AHe data for samples AN01, 02 and 03 (note  
736 variable timescales for these plots, constrained by the oldest single-grain AFT age). The black curves  
737 represent the expected model (weighted mean model) and its 95% confidence interval for the  $T-t$   
738 paths; the yellow curve is the maximum likelihood model (best data fit).  $T-t$  paths are coloured  
739 according to their probability (scale on the right-hand side, which varies between samples). The gray  
740 boxes represent the prior constraints on the explored parameter space (see text for discussion) and  
741 dotted gray lines refer to the values of  $T_{max}$  and burial time discussed in the text.

742

743 **Figure 5.** Sensitivity of AHe ages to eU variations. The curves represent predicted AHe ages as a  
744 function of eU for the  $T-t$  paths of the expected models (cf. Fig. 4), and for eU varying from 5 to 30  
745 ppm. The dots represent the AHe data shown in Fig. 3 and Table 2.

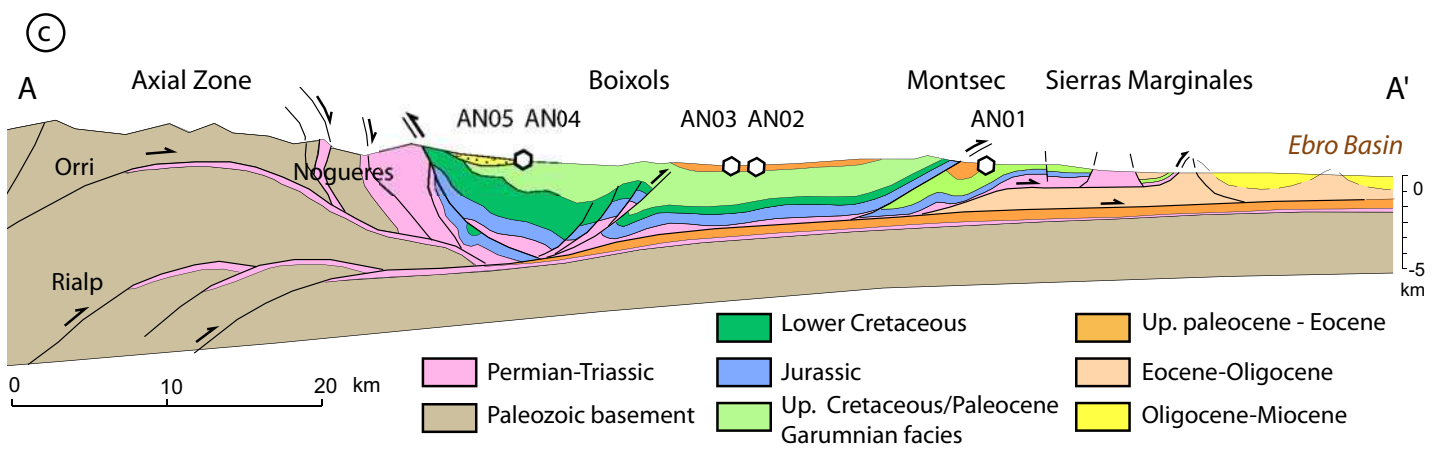
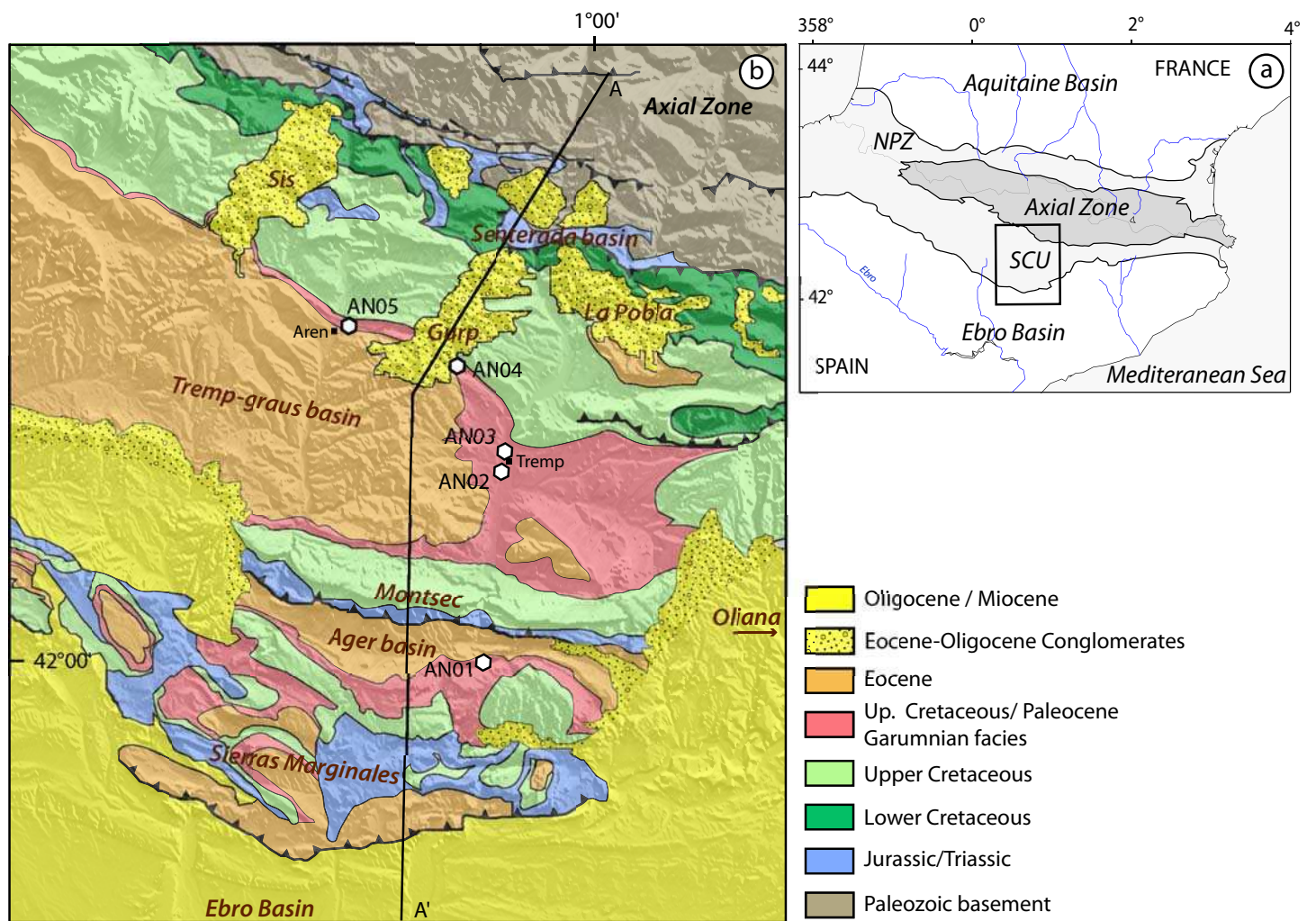
746

747 **Figure 6.** Effect of pre-depositional exhumation history on AHe ages. a) Forward model set up: AHe  
748 ages are predicted using the He-diffusion model of Flowers *et al.* (2009) for varying eU contents,  $T_{max}$   
749 and starting times of pre-depositional exhumation (“exhumation 1”). b) AHe ages modelled as a  
750 function of eU content and starting time of the pre-depositional phase of exhumation, for two different  
751 maximum burial temperatures ( $T_{max} = 70$  and  $80$  °C respectively). Measured ages of our samples are  
752 plotted as black squares, or represented as dashed lines when they do not resolve a starting time.

753

754 **Figure 7.** Topographic profile along the same transect as A-A' in Figure 1b, showing the inferred  
755 palaeo-elevation of the Oligocene-Miocene deposits inferred from thermal-history modelling of the  
756 AHe and AFT data for samples AN02, AN03 and AN01 (dashed line is best estimate, orange band is  
757 uncertainty), compared to the inferred maximum elevation over the southern Axial Zone from  
758 inversion of *in-situ* thermochronology data (Fillon & van der Beek 2012). Yellow shading in Sierra de  
759 Gulp represents current exposure of Late Eocene–Oligocene conglomerates. Locations of major thrust  
760 faults in the SCU fold-and-thrust belt are indicated for comparison to Fig. 1c.  
761





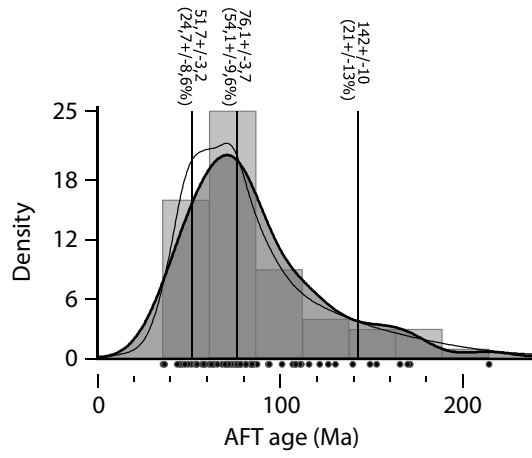
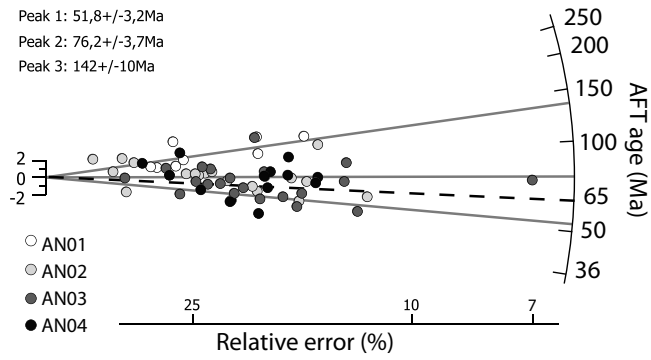
### AN01, AN02, AN03 and AN04 combined

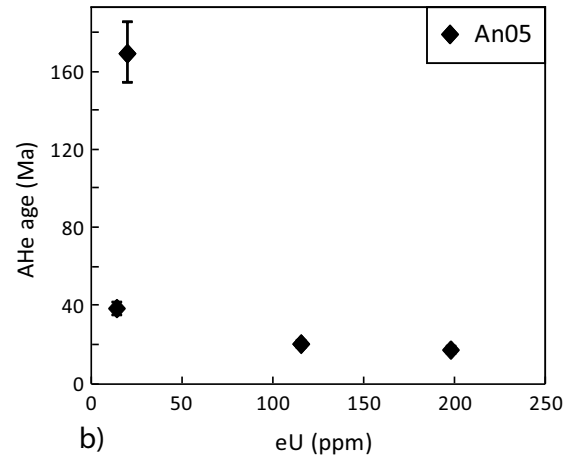
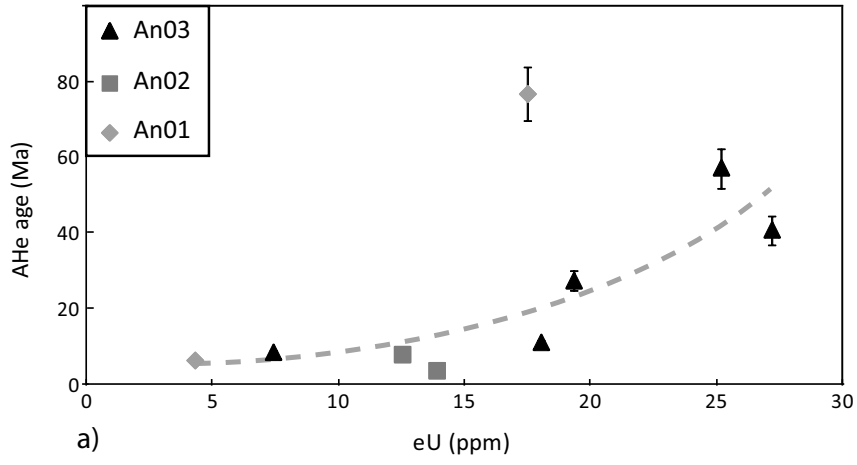
Central age = 79,3 +/- 7,9 Ma (2se)

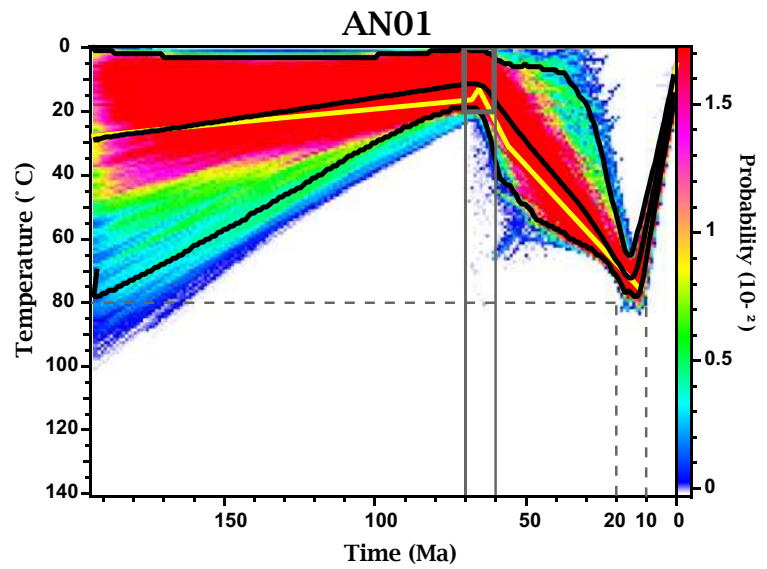
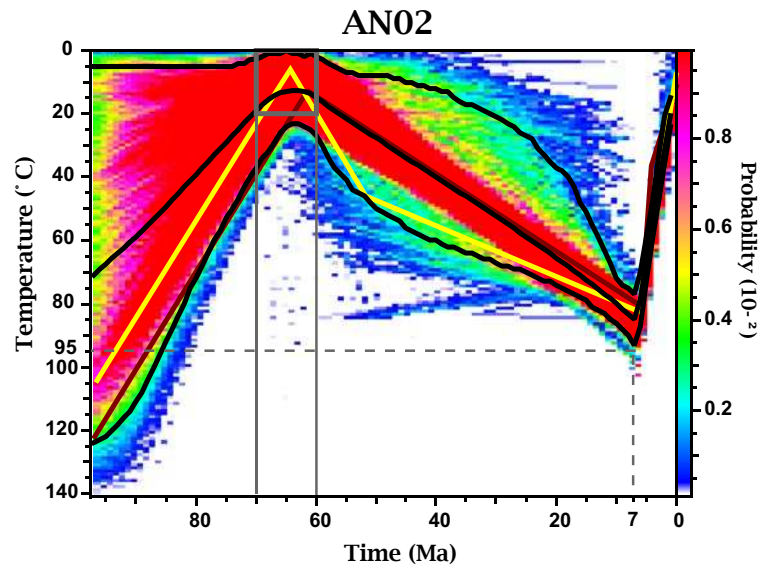
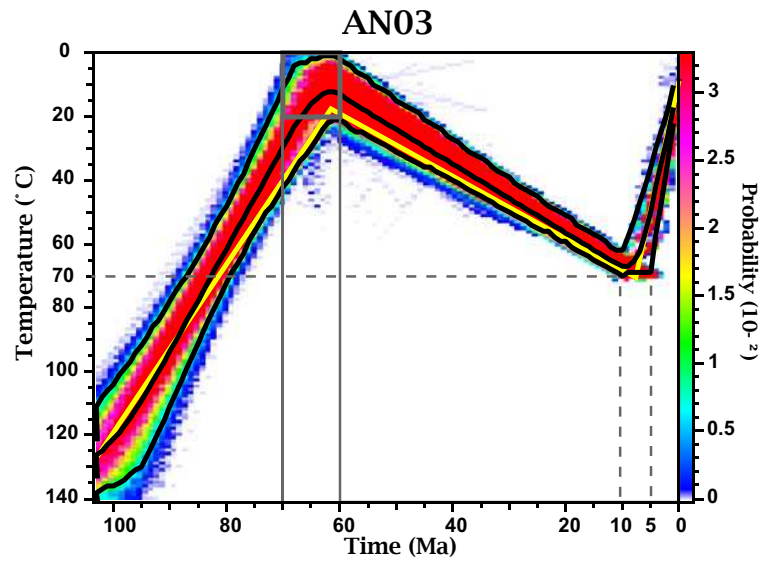
Peak 1: 51,8 +/- 3,2 Ma

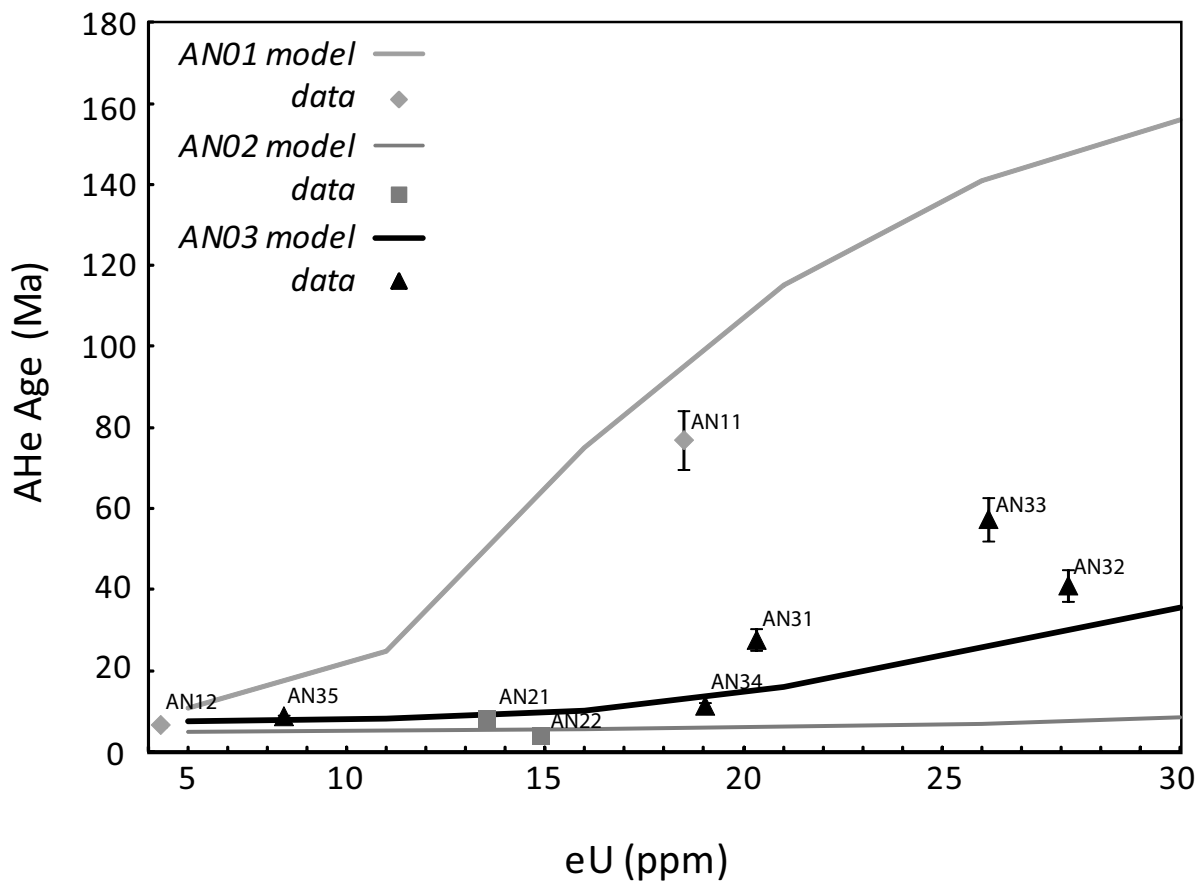
Peak 2: 76,2 +/- 3,7 Ma

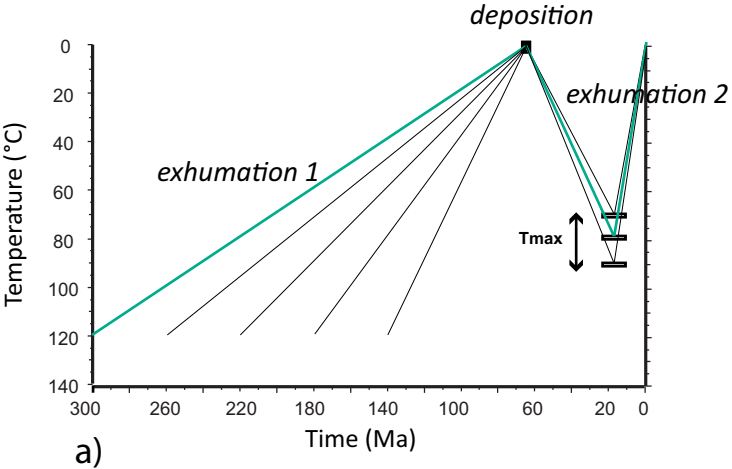
Peak 3: 142 +/- 10 Ma



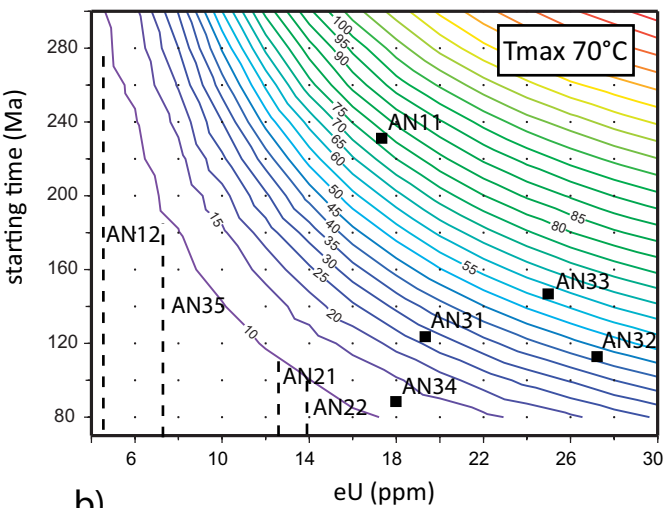




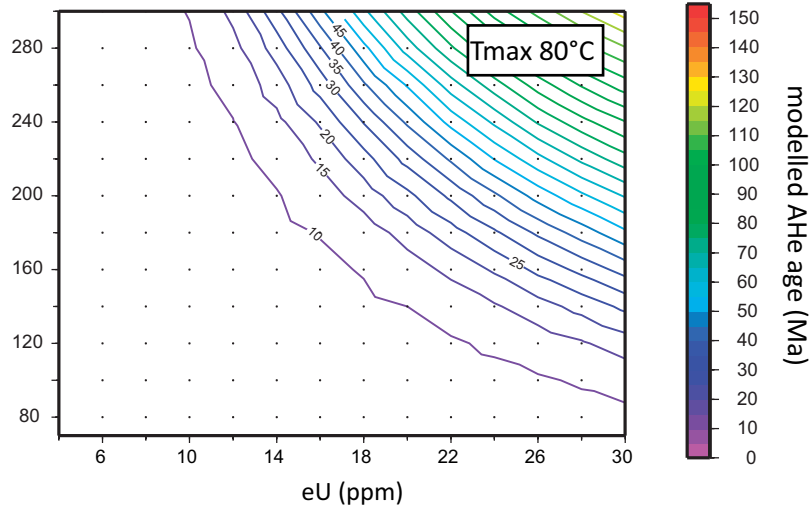




a)



b)



modelled AHe age (Ma)

