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► To cite this version:

Gaétan Milesi, Pierre G Valla, Philippe Münch, Damien Huyghe. Tectono-geomorphological evolution of the Eastern Pyrenees: Insights from thermo-kinematic modeling. *Tectonophysics*, 2023, 866, pp.230057. 10.1016/j.tecto.2023.230057. hal-04232140

HAL Id: hal-04232140

<https://hal.science/hal-04232140>

Submitted on 7 Oct 2023

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1 Tectono-geomorphological evolution of the Eastern
2 Pyrenees: insights from thermo-kinematic modeling

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15

16

17 **ABSTRACT**

18 Constraining the tectono-geomorphological evolution of the Pyrenees is still a
19 major challenge, especially in the Eastern Pyrenees where late Neogene exhumation
20 history and topographic evolution appear contrasted and have been debated. In this study,
21 we performed thermo-kinematic (Pecube) modeling using a relatively dense spatial
22 compilation of previously-published low-temperature thermochronological data for the

23 Eastern Pyrenees, and quantified the late-Neogene exhumation history based on different
24 topographic evolution models reconstructed from literature constraints. Our modeling
25 outcomes suggest a major decrease in the regional exhumation rate between 37-35 Ma,
26 associated to an early-end contractional tectonics for the Eastern Pyrenees. Two main
27 periods of the Têt fault normal activity have been characterized, with the existence of
28 pluri-kilometric (2-3 km) post- Oligocene-Miocene displacement along the western
29 segment of the Têt fault. The different topographic evolution models show relatively
30 similar results for the regional exhumation since ca. 35 Ma and for the most recent (mid
31 to late-Miocene) tectonic event recorded along the Têt fault. Conversely, inversion results
32 obtained for pre-35 Ma regional exhumation rates, and more importantly for the
33 Oligocene-Miocene activity of the Têt fault appear contrasted between the investigated
34 topographic scenarios. Overall, this study confirmed a mid to late Miocene significant
35 extensional tectonic event for the Eastern Pyrenees, which may have had a non-negligible
36 role in late-stage relief evolution for this part of the orogen. However, deciphering the
37 long-term evolution of topographic relief through thermo-kinematic modeling appears
38 still challenging for slowly-exhuming mountain ranges given the limited resolution of
39 low-temperature thermochronological data to topographic changes.

40

41 **KEYWORDS**

42 Eastern Pyrenees, Low-temperature thermochronology, Tectonics, Thermo-kinematic
43 models, Topographic evolution, Exhumation

44 **1. INTRODUCTION**

45 The Earth's surface evolution is controlled by the combination of tectonic, erosion
46 and climate processes (e.g. Beaumont 1981; Willett, 1999; Dadson et al., 2003; Braun,
47 2010; Herman et al., 2013; Jamieson and Beaumont, 2013; Thieulot et al., 2014). The
48 existence of feedbacks amongst these mechanisms (Whipple, 2009) constitutes one of the
49 major difficulties to deconvolute the impact of each individual forcing on landscape
50 dynamics (Braun, 2012). In the upper crust, isotherm shapes and wavelengths are
51 especially controlled by the overlying topography and its evolution (Stüwe et al., 1994;
52 Mancktelow and Grasemann, 1997; Braun, 2002; Foeken et al., 2007; Valla et al., 2010),
53 therefore the upper-crust thermal evolution is influenced by rock exhumation and can be
54 impacted by (i) major topographic changes or (ii) fault motion and associated isotherm
55 advection (Batt and Braun, 1997; Ehlers and Chapman, 1999; Ehlers and Farley, 2003).
56 Low-temperature (low-T) thermochronology coupled with 3D thermo-kinematic
57 modeling provides a quantitative way to assess the crustal long-term thermal evolution
58 and has the main advantage to investigate the respective contributions of the regional
59 topographic evolution and/or the tectonic component(s) in rock exhumation (e.g. Farley,
60 2002; Ehlers and Farley, 2003; Glotzbach et al., 2011; Braun et al., 2012).

61

62 Thermo-kinematic 3D modeling based on low-T thermochronology data has been
63 widely used in active mountain ranges to constrain the topographic evolution and fault-
64 activity history, especially in mountain ranges with rapid changes in either topographic
65 relief or tectonic forcing like for instance the Himalayas (e.g. Coutand et al., 2014; Zhang
66 et al., 2015; Wang et al., 2016; Grujic et al., 2020; Pitard et al., 2021; Shen et al., 2022),

67 the Andean Cordillera (e.g. Schildgen et al., 2009, 2022; Avdievitch et al., 2018;
68 Bermúdez et al., 2021; Gérard et al., 2021; Zapata et al., 2021) or the European Alps (e.g.
69 Vernon et al., 2009; van der Beek et al., 2010; Valla et al., 2011, 2012; Beucher et al.,
70 2012). However, only few 3D thermo-kinematic modeling studies have been devoted to
71 the evolution of mountain ranges with limited or slow long-term topographic relief and
72 tectonic evolution like the Pyrenees (i.e. Gibson et al., 2007; Fillon and van der Beek,
73 2012; Erdős et al., 2014; Curry et al., 2021; Capaldi et al., 2022). This approach is
74 particularly challenging in mountain ranges formed by long tectonic histories with
75 multiple phases since (1) overall exhumation rates can be relatively low between the
76 different tectonic phases (<0.1 km/Ma; e.g. Braun and Robert, 2005), and (2) the
77 topographic and tectonic settings and their long-term evolutions are complex. Therefore,
78 it remains difficult to disentangle these two components in rock exhumation through low-
79 T thermochronology in slowly-exhuming mountain range settings.

80

81 In the Pyrenees, regional 3D thermo-kinematic modeling has been focused on the
82 central (Gibson et al., 2007; Erdos et al., 2014; Capaldi et al., 2022) and southern (Fillon
83 and van der Beek, 2012) parts of the orogen. Recent study of Curry et al. (2021) has
84 provided new quantitative constraints for the western and central part of the Axial Zone
85 to evaluate thrust sheet-controlled exhumation as well as along-strike exhumation
86 differences in the Pyrenees. Moreover, these previous studies have been particularly
87 focused on the Paleogene Pyrenean contractional phase. The Eastern Pyrenees have a
88 specific evolution, reflected by a complex tectonic history with an Eocene contractional
89 phase (Laumonier, 2015; Ternois et al., 2019; Calvet et al., 2021; Ford et al., 2022)

90 followed by 2 significant post-orogenic periods: i) a transtensional phase associated
91 with the opening of the West European Rift (Angrand and Mouthereau, 2021; Milesi et
92 al., 2022), and ii) an Oligocene-Miocene extensional phase associated to the Gulf of Lion
93 opening (Calvet et al., 2021; Jolivet et al., 2020, 2021; Romagny et al., 2020; Séranne et
94 al., 2021; Taillefer et al., 2021; Milesi et al., 2022). The Têt normal fault is the most
95 prominent tectonic structure in the Eastern Pyrenees, and localizes high-relief massifs in
96 such as the Mont-Louis (hanging wall), and the Canigou and Carança (footwall) massifs.
97 The development of these high topographic reliefs has been related to normal faulting
98 during the Oligocene-Miocene period (Maurel et al., 2008, Milesi et al., 2022). However,
99 the topographic evolution of the area is still highly debated (e.g. Augusti et al., 2006;
100 Gunnell et al., 2008, 2009; Suc and Fauquette, 2012; Calvet et al., 2014; Huyghe et al.,
101 2018, 2020). The potential links between the topographic and tectonic evolutions of the
102 Eastern Pyrenees are also not entirely clear due to their location between the
103 contractional Pyrenean domain and the extensional area of the Gulf of Lion. Finally, the
104 long-term topographic evolution of the Eastern Pyrenees (Huyghe et al., 2012, 2020)
105 appears to differ significantly from the topographic evolution model proposed for the
106 western and central parts of the Pyrenees (Curry et al., 2019; 2021).

107

108 In this study, we present the first 3D thermo-kinematic modeling outcomes for the
109 Eastern Pyrenees, based on a large synthesis of previously-published (U-Th)/He on apatite
110 (AHe) and zircon (ZHe), and apatite fission-track (AFT) data (Gunnell et al., 2009;
111 Maurel et al., 2002, 2008; Milesi, et al., 2019, 2020a, 2020b, 2022). We also investigate 3
112 different models for the topographic evolution of the Eastern Pyrenees, with the objective

113 to integrate topographic evolution in 3D thermo-kinematic modeling and quantification
114 of rock exhumation. By independently prescribing the long-term topographic evolution,
115 we aim to provide constraints on the timing and rates of the Cenozoic to modern regional
116 rock uplift as well as on the tectonic deformation along the Têt fault. Based on these
117 results, we discuss the onset and timing of the contractional tectonic record in the Mont-
118 Louis massif, and the late-Cenozoic extensional period(s) along the Têt fault in the
119 Canigou and Carança massifs.

120

121 **2. GEOLOGICAL SETTING**

122 **2.1 Topographic and tectonic evolution of the Pyrenees**

123 In the Pyrenees, collision and orogen building occurred from the Late Cretaceous
124 to the Middle Miocene (e.g. Roure et al., 1989; Muñoz, 1992; Vergés et al., 2002;
125 Mouthereau et al., 2014; Ford et al., 2022), and formed a double-wedged mountain range.
126 The Axial Zone (Fig. 1) is composed of a stack of crustal nappes formed during the main
127 Eocene-early Oligocene orogenic build up and linked to the maximum of shortening and
128 exhumation (Sinclair et al., 2005; Bosch et al., 2016a; Jolivet et al., 2007; Labaume et al.,
129 2016; Mouthereau et al., 2014; Vacherat et al., 2016; Waldner et al., 2021). During the
130 Lutetian (lower Eocene), the paleo-elevation of the Pyrenees has been estimated to
131 around 2 ± 0.5 km (Huyghe et al., 2012), which is associated with the main phase of the
132 Pyrenean orogen starting around 50 Ma (Fitzgerald et al., 1999; Sinclair et al., 2005;
133 Vacherat et al., 2014, 2016; Ternois et al., 2019, 2021). Crustal flexural models (Curry et
134 al., 2019) suggest topographic growth from 56 to 23 Ma and a sharp increase in
135 topography at 38 Ma that is in contradiction with the more progressive topographic

136 growth deduced from stable isotope data (Huyghe et al., 2012). Flexural models showed a
137 minor decay of overall Pyrenean topography from 23 Ma to present-day. On the contrary,
138 the topographic model for the Eastern Pyrenees deduced from stable isotope analyses
139 (mammal teeth from the Cerdanya basin; Huyghe et al., 2020) suggests a slow relief
140 development since the Miocene (Fig. 2).

141

142 The exhumation history of the Pyrenees is marked by a southward propagation of
143 the orogenic-wedge deformation (Fitzgerald et al., 1999; Sinclair et al., 2005;
144 Mouthereau et al., 2014). The Pyrenean orogen has developed diachronously, from East
145 to West due to spatially-variable pre-orogenic crustal extension (e.g., Puigdefàbregas et
146 al., 1992; Whitchurch et al., 2011), some authors also proposed a role of major base-level
147 changes on the timing and rates of post-orogenic exhumation (Coney et al., 1996; Fillon
148 and van der Beek, 2012). Recent thermo-kinematic study from Curry et al. (2021) has
149 focused on the western and central part of the Pyrenees (Fig. 1) and, based on a large
150 compilation of low-T thermochronological data, their outcomes confirm a first-order
151 westward propagation of rock uplift and exhumation since the Eocene. This observed
152 propagation of tectonic deformation and exhumation may be explained by the inherited
153 crustal configuration rather than differential onset of shortening along strike (Teixell et
154 al., 2018; Muñoz, 2019). On the other hand, southward propagation of the deformation
155 (Fitzgerald et al., 1999; Sinclair et al., 2005; Metcalf et al., 2009) has been confirmed by
156 low-T thermochronology in the central part of the Pyrenees, while only geological
157 evidences support southward propagation of the deformation in the Western Pyrenees
158 (Teixell et al., 2016).

159

160 The post-orogenic tectonic evolution in the western and central Axial Zone has
161 not been well constrained. AHe ages from middle to late Miocene (15–6 Ma) are
162 interpreted in many ways, such as: (i) the result of a distinct tectonic event (Jolivet et al.,
163 2007; Bosch et al., 2016a; Fillon et al., 2021), (ii) the erosional response to major
164 drainage changes with the connection of the foreland Ebro Basin to the Mediterranean
165 Sea (Coney et al., 1996; Fitzgerald et al., 1999; Fillon and van der Beek, 2012), (iii)
166 large-scale erosion resulting from Pliocene climate changes, as proposed for the
167 European Alps (Cederbom et al., 2004), or (iv) a lithological control on post-orogenic
168 erosion with lower erosion rates for Variscan metamorphic lithologies in the eastern part
169 of the Axial Zone compared to unmetamorphosed lithologies in the western part (Bernard
170 et al., 2019). A recent thermochronological study in the Ebro basin (South Pyrenean
171 Zone) evidenced also a potential long-wavelength tectonic event at ~ 10 Ma, linked to the
172 cessation of slab retreat in the Western Mediterranean domain (Rat et al., 2022).

173

174 **2.2 Topographic and tectonic evolution of the Eastern Pyrenees**

175 The eastern part of the Axial Zone is characterized by the emplacement of south-
176 verging nappes rooted in the northern part (Laumonier et al., 2015; Sibuet et al., 2004;
177 Vergès et al., 1995; Teixell et al., 2016). Balanced cross-sections (Ternois et al., 2019)
178 suggest an Eocene thrusting of the Aspres-Mont-Louis massifs onto the Canigou massif
179 as already proposed by Maurel et al., (2008) based on low-T thermochronology. In
180 addition, the eastern part of the Pyrenees (east of $\sim 1^\circ\text{E}$) underwent post-orogenic crustal
181 thinning (Chevrot et al., 2018; Diaz et al., 2018). This crustal-thinning phase has been

182 explained by regional extensional episodes associated to the (re-)activation of major
183 orogenic structures as normal faults in response to the Gulf of Lion opening from the end
184 of the Priabonian to the Quaternary (e.g. Calvet et al., 2021; Taillefer et al., 2021, Milesi
185 et al., 2022). In the study area (Fig. 1b), two main crustal tectonic structures are
186 identified: the Têt and Py faults. The most prominent tectonic structure, the Têt fault, is a
187 crustal-scale NE-SW fault with pluri-kilometric (~3 km) displacement associated to the
188 main opening stage (25-20 Ma) of the Gulf of Lion during the Oligocene-Miocene
189 (Maurel et al., 2008; Milesi et al., 2022). The Py fault delimits the Canigou and Carança
190 blocks in the footwall of the Têt fault (Fig. 1b), and recent thermochronological data
191 suggest a late Priabonian to early Rupelian (35-32 Ma) activity of this fault associated to
192 at least 2 km displacement (Milesi et al., 2022).

193

194 A major debate exists on the geomorphological evolution of the Eastern Pyrenees,
195 related to the formation timing and relative elevation of Oligocene-early Miocene high-
196 elevation low-relief surfaces (Bosch et al., 2016b; Monod et al., 2016; Calvet et al.,
197 2021). Some authors proposed the formation of these low-relief surfaces at low
198 elevations, followed by a major uplift event (~2 km) since the early Miocene (Gunnell et
199 al., 2008; 2009). Another model proposed the development of these low-relief surfaces at
200 high elevations due to the smoothing of the relief before the Late Miocene, associated to
201 a limited surface uplift of around 400 m since then (Babault et al. 2005; Bosch et al.,
202 2016b). Rock exhumation associated to late-Miocene normal faulting is considered to
203 have played a subordinate role, although significant exhumation events have been
204 proposed by (i) NW-SE fault activity (Taillefer et al., 2021) and (ii) thermal modeling in

205 the Carança massif, with predicted rock cooling between 12 to 9 Ma, interpreted as the
206 normal motion of the western segment of the Têt fault (Milesi et al., 2022).

207

208 A paleo-elevation reconstruction for the whole Eastern Pyrenees, based on stable-
209 isotope data coupled with regional geological constraints, has been proposed by Huyghe
210 et al. (2020). This model suggests that the topographic uplift in the Eastern Pyrenees is a
211 long-term process initiated in the Late Burdigalian (~20 Ma, Fig. 2) in response to the
212 pre-breakup uplift in the Gulf of Lion. The Burdigalian period is considered as the end of
213 the main rifting period for the western part of the Gulf of Lion. During this period, the
214 topographic conditions in the Eastern Pyrenees were proposed to be close to sea level
215 (Bache et al., 2010; Huyghe et al., 2020). The post-Burdigalian period in the Eastern
216 Pyrenees is still debated, with a proposed uplift of ~1 km since the Tortonian to
217 Messinian (i.e. since around 10 to 6 Ma) based on palynological constraints (Agusti et al.,
218 2006; Suc and Fauquette, 2012). Stable-isotope data obtained from the analyses of small
219 mammal teeth (Huyghe et al., 2020) complete these palynological data and suggest an
220 uplift estimate of around 500 m since the Messinian (ca. 6 Ma). On the contrary, Tosal et
221 al. (2021) recently proposed, from the study of leaf taxa, that the Cerdanya Basin was
222 located at an elevation comprised between 1100 and 1500 m already during the
223 Tortonian, although this estimate may reflect local conditions and should be confirmed
224 by additional taxa analyses.

225

226 **3. THERMO-KINEMATIC MODELING**

227 **3.1 Low-temperature thermochronology data in the Eastern Pyrenees**

228 We focused our 3D thermo-kinematic modeling on the South Mérens, Carança and
229 Canigou blocks. The North Mérens block is not included due to the sparse low-T
230 thermochronological record in this area (Milesi et al., 2022). We compiled AHe, AFT,
231 ZHe ages and mean track lengths (MTL) from previously-published datasets (Gunnell et
232 al., 2009; Maurel et al., 2002, 2008; Milesi, et al., 2019, 2020a, 2020b, 2022). For our
233 study, we used only samples issued from crustal basement that record long-term rock
234 exhumation and were not affected by recent geothermal anomalies or hydrothermal
235 circulations (41 samples in total, Fig. 1b). In the Têt fault footwall, samples have been
236 selected in the first 5-km distance to the fault, since the cooling history of farther samples
237 may have been potentially impacted by other local faults. Details of the selected samples
238 and associated low-T thermochronological ages are available in the Supplementary Table
239 S1.

240

241 **3.2 Modeling approach**

242 Inverse modeling has been performed using the thermo-kinematic modeling code
243 Pecube v4.0, based on a finite-element method to solve the heat transport equation in 3D
244 (Braun, 2003; Braun et al., 2012), and coupled with the neighborhood algorithm (NA)
245 inversion method (Sambridge 1999a, 1999b). The detailed model setup is fully described
246 with all modeling parameters and our inversion approach in the Supplementary
247 Information.

248

249 We explored the 3 crustal blocks separately to constrain their respective rock
250 exhumation patterns: the South Mérens, Carança and Canigou blocks. No activity on the

251 Têt fault has been defined when modeling the South Mérens exhumation history (hanging
252 wall of the Têt fault), only exhumation in response to regional uplift has been considered
253 (Milesi et al., 2022). We modeled a two-stage regional exhumation model based on low-
254 T thermochronological age-elevation relationships (Milesi et al., 2022) using AHe, ZHe
255 AFT and MTL data (Supplementary Table S1). The model runs for 60 Myr, with a
256 transition event between the two exhumation phases called “transition time” and ranging
257 from 60 to 0 Ma. Each phase is associated to exhumation rates during the first (V1) and
258 second (V2) phases, which range from 0 to 2 km/Ma and from 0 to 1 km/Ma,
259 respectively. The output exhumation scenario obtained for the South Mérens block is thus
260 considered as the regional exhumation scenario and used for subsequent modeling.

261 The Carança and Canigou blocks have been then investigated with prescribing an
262 activity on the Têt fault. For the Canigou block, a single activity phase for the Têt fault
263 has been tested following the work of Milesi et al. (2022). This approach is based on low-
264 T thermochronological age-elevation relationships, which suggest a simple exhumation
265 history for this area using AHe, ZHe AFT and MTL data. To further test this hypothesis,
266 we have run an exhumation scenario with 2 activity phases for the Têt fault, however
267 output results show poor inversion convergence for the tested parameters on the Têt fault
268 activity (see Supplementary Figure S1). In the single-phase scenario, the model runs for
269 60 Myr, with a regional background exhumation fixed by best-fitting output results
270 obtained in Section 4.1 (South Mérens block). The Têt fault activity is allowed between
271 35 and 5 Ma, with the onset time ranging from 35 to 25 Ma, and the ending time from 25
272 to 5 Ma. The fault slip rate ranges from 0 to 6 km/Ma.

273 For the Carança block, two potentially distinct activity phases for the Têt fault
 274 have been tested following the proposed thermal history of Milesi et al. (2022) using
 275 AHe, ZHe AFT and MTL data. The model runs for 60 Myr, with a regional background
 276 exhumation fixed by best-fitting output results obtained in Section 4.1 (South Mérens
 277 block). The first fault-activity phase is allowed between 35 and 15 Ma, with the onset
 278 time ranging from 35 to 25 Ma, and the ending time from 25 to 15 Ma. The fault slip rate
 279 during this first phase ranges from 0 to 6 km/Ma. The second fault-activity phase is
 280 allowed between 15 and 5 Ma, with the onset time ranging from 15 to 11 Ma, and the
 281 ending time from 11 to 5 Ma. The fault slip rate during the second phase ranges from 0 to
 282 4 km/Ma.

283

284 Three main topographic evolution models (TEMs, Fig. 4) have been tested for the
 285 different crustal blocks: (1) a model without topographic change and a constant
 286 topography since 56 Ma which is similar to the present-day topography (Fig. 1b); (2) a
 287 Global Pyrenees model based on the topographic outcomes from Curry et al. (2019); and
 288 (3) an Eastern Pyrenees model (Fig. 2) based on the mean paleo-elevation curve proposed
 289 by Huyghe et al. (2020) and the maximum paleo-elevations defined by palynological
 290 constraints (Agusti et al., 2006; Suc and Fauquette, 2012). Due to the lack of continuous
 291 record for the maximum paleo-elevations, a conservative hypothesis has been established
 292 when no data is available. At 56 Ma, topographic parameters for the Eastern Pyrenees
 293 have been inferred from the literature, lower mean relief and topography have thus been
 294 implemented based on the lack of detrital material in adjacent basins, and the absence of
 295 alluvial cone/delta at that time (Calvet et al., 2021). All the parameters considered are

296 available in the Supplementary Table S2, and the mean paleo-elevation curves for the
297 three models, together with resulting topographies and associated topographic
298 amplification factor/offset, are illustrated in Figure 4.

299

300 **4. RESULTS**

301 **4.1 Hanging wall of the Têt fault: the South Mérens block**

302 Inversion results (Table 1) demonstrate that regardless of the considered TEM, the
303 1D probability density functions (PDFs) show no statistical convergence for the output
304 exhumation rates V1. However, we can note that all output values are above 0.2 km/Ma
305 and that a maximum of probability is reached for exhumation rates between 0.3 and 0.6
306 km/Ma for the Eastern Pyrenees TEM (Fig. 5). For the Global Pyrenees and No
307 topographic change TEMs, V1 is highly variable with a more pronounced probability
308 towards high exhumation rates (>0.5 km/Ma, Fig. 5).

309

310 The output transition time is well constrained and concordant for all three TEMs.
311 Inversion results for the transition time show a continuous probability distribution (40-30
312 Ma range), with a maximum probability between 37 and 35 Ma (Fig. 5).

313

314 The exhumation rate V2 is also well constrained for all three TEMs and varies
315 only slightly between them. The output PDFs for V2 are close to a Gaussian distribution,
316 with exhumation rates of 0.04 ± 0.03 km/Ma, 0.06 ± 0.01 km/Ma and 0.09 ± 0.03 km/Ma
317 for the No topographic change, the Global Pyrenees and Eastern Pyrenees TEMs,

318 respectively. Overall, the regional exhumation scenario for the different TEMs is very
319 well constrained between ~35 Ma and present day.

320

321 The best-fitting parameters obtained for each TEM have subsequently been used
322 in a forward Pecube model to predict low-T thermochronological ages and time-
323 temperature paths (Fig. 6). Low-T thermochronological ages modeled for the South
324 Mérens block are close to observed data, except for ZHe ages that are underestimated for
325 all considered TEMs (Fig. 6a). Modeled AHe ages with the Eastern Pyrenees TEM are
326 slightly younger for the top samples compared to the two other TEMs. Between 1600 and
327 2100 m, AHe ages are not well reproduced for all TEMs. However, it must be noted that
328 the observed AHe ages are older than AFT ages obtained at similar elevations. The
329 general trend of the AFT elevation profile is generally well reproduced with slightly older
330 modeled than observed ages. Predicted MTLs are relatively consistent between the used
331 TEMs, but overall overestimated the observed data except for mid-elevation samples
332 (~1600 m elevation, Fig. 6a).

333

334 Best-fitting predicted thermal histories (Fig. 6b) show similar overall trends, with
335 rapid cooling until ~35 Ma followed up by slow cooling until present day. Some
336 differences are observed between the considered TEMs: (i) before 35 Ma, the output
337 cooling rates are close to 17, 14 and 23 °C/Ma for the No topographic change, Eastern
338 Pyrenees and Global Pyrenees TEMs, respectively. Output cooling rates for this period
339 must be considered carefully when considering the large output PDFs and thus high
340 uncertainties obtained for V1 (Fig. 5d), with the better statistical estimate being given by

341 the Eastern Pyrenees TEM. (ii) Cooling rates after 35 Ma are more impacted by the
342 choice of the TEM. For the No topographic change TEM, the output cooling rate is
343 constant (~ 1 °C/Ma). The Global Pyrenees TEM yields a very low cooling rate between
344 35 and 23 Ma (~ 0.3 °C/Ma) which increased towards present day (1 °C/Ma). Finally, the
345 Eastern Pyrenees TEM yields a gradual decrease in cooling rate from 2.8 °C/Ma between
346 34 and 23 Ma to around 0.7 °C/Ma since 23 Ma.

347

348 **4.2 Eastern footwall of the Têt fault: the Canigou block**

349 Inversion results for the Têt fault activity (Table 1) slightly differ according to the
350 used TEMs. For the No topographic change and Global Pyrenees TEMs, the Têt fault
351 activity is limited in time with maximum probabilities from 26-25 to 24.5 Ma (Fig. 7a)
352 and from 28-26 to 24.5 Ma (Fig. 7b), respectively. Inversions based on the Eastern
353 Pyrenees TEM do not well constrain the fault-activity onset time but suggest a longer
354 activity period between >28 and 23.5 ± 1.5 Ma. These output differences are also marked
355 for the output fault slip rates (Fig. 7d). This parameter is not well constrained for the No
356 topographic change and Global Pyrenees TEMs, all inversions yielding high slip rates
357 above 1.0 and 1.5 km/Ma, respectively. In contrast, inversions with the Eastern Pyrenees
358 TEM show a maximum probability for output slip rate at 1 ± 0.5 km/Ma, significantly
359 lower than for other TEMs (Fig. 7d).

360

361 Predicted AHe ages are close for the No topographic change and Eastern Pyrenees
362 TEMs (Fig. 8a), and consistent with observed ages for elevation >1400 m. AHe ages
363 predicted with the Global Pyrenees TEM are younger than for the two other TEMs and

364 also compared to observed ages for elevation >1800 m. Observed AFT ages for top
 365 samples (>2000 m) are well reproduced by numerical inversions with all the considered
 366 TEMs (Fig. 8b). Only inversions with the Global Pyrenees TEM show predicted AFT
 367 ages in agreement with observed ages for elevation <1600 m. Predicted MTLs differ
 368 between the considered TEMs and samples: for most samples, the Global Pyrenees and
 369 Eastern Pyrenees TEMs provided similar MTL predictions except for the low-elevation
 370 sample for which predicted MTL differ for the Global Pyrenees TEM. The No
 371 topographic change TEM predicted relatively short MTLs (<14 μm) and close to
 372 observed data for most of samples, while the Global Pyrenees TEM produced shorter
 373 MTL and close to observations for the low-elevation sample (Fig. 8a). The only ZHe age
 374 in the Canigou block cannot be properly reproduced by numerical inversions whatever
 375 the considered TEM, which all predict too young ZHe ages (Fig. 8a).

376

377 Best-fitting output thermal histories (Fig. 8b) show differences essentially due to
 378 the contrasted timing and slip rate of the Têt fault activity (Fig. 7d). At around 25 Ma,
 379 high cooling rates (~ 130 $^{\circ}\text{C}/\text{Ma}$) are observed for the No topographic change TEM, while
 380 slower cooling is predicted for the Global Pyrenees and Eastern Pyrenees TEMs (around
 381 70 and 40 $^{\circ}\text{C}/\text{Ma}$, respectively). Posterior to this fault-activity phase, predicted cooling
 382 rates are lower and consistent between all TEMs (2-4 $^{\circ}\text{C}/\text{Ma}$, Fig. 7d).

383

384 **4.3 Western footwall of the Têt fault: the Carança block**

385 Inversion results for the first fault-activity phase (Table 1) differ according to the
 386 used TEM (Fig. 9). For the No topographic change TEM (Fig. 9a), the first phase is

387 similar but slightly shorter compared to the Canigou block, i.e. from 26-25 to 25-24 Ma,
388 and associated with a high slip rate (maximum of probability at 5.5-6 km/Ma). The
389 Global Pyrenees TEM (Fig. 9b) suggests a longer fault activity between 28 ± 2 and
390 around 25-24 Ma. The output slip rate is not well constrained. For inversions based on
391 these 2 TEMs (No topographic change and Global Pyrenees), the first phase of the
392 Carança block appears similar to the predicted fault activity of the Canigou block.
393 Inversions based on the Eastern Pyrenees TEM suggest a longer fault activity, with a
394 maximum probability for the onset time at 32 ± 1 Ma and ending time at around 15 Ma.
395 For this TEM, the end of first fault-activity phase is thus suggested later than for the
396 Canigou block. Inversions based on the Eastern Pyrenees TEM yield a well-constrained
397 slip rate of <1 km/Ma that is lower than for the other TEMs (Fig. 9d) but consistent with
398 output slip rate for the Canigou block (Fig. 7d).

399

400 The inversion outcomes for the second fault-activity phase (Table 1 and Fig. 10)
401 are similar whatever the considered TEM. Inversion results show a maximum probability
402 for the fault-activity duration between around 15 and 11 Ma. The PDFs for the slip rate
403 are close to Gaussian distributions, with a maximum probability in the range of 0.7-0.8
404 km/Ma (Fig. 10d).

405

406 Predicted AHe ages are close for the 3 considered TEMs but they overall
407 underestimate the observed AHe ages. Output AHe ages are rather consistent with
408 observed low-elevation ages (1050-1250m, Fig. 11a). Predicted AFT ages are consistent
409 or very close to the observed ages for all considered TEMs. Predicted ZHe ages are

410 different according to the used TEMs, being increasingly younger for inversions based on
411 the Global Pyrenees, Eastern Pyrenees and No topographic change TEMs, respectively.
412 Modeled ZHe ages with the Global Pyrenees TEM are close to observed ages for the base
413 of the elevation profile (900-1000 m) whereas predictions with the No topographic
414 change TEM are more coherent with observed ages (1200-1400 m). Predicted MTLs are
415 well reproducing observed data for the different TEMs (Fig. 11a). All TEM models fail to
416 explain observed ZHe ages (>1600 m), and predict rather young ZHe ages compared to
417 observations (Fig. 11a).

418

419 Best-fitting output thermal histories (Fig. 11b) show differences between TEMs
420 that are essentially due to the contrasted duration and intensity of the first fault-activity
421 phase (Fig. 9d). The main differences are similar to those obtained for the Canigou
422 inversions (Section 4.2). For the first phase, high cooling rates are observed for the No
423 topographic change (~140 °C/Ma) and Global Pyrenees TEMs (~70 °C/Ma), while
424 slower cooling is predicted for the Eastern Pyrenees TEM (~10 °C/Ma). This first cooling
425 phase is followed by a decrease in cooling rate regardless of the TEM (<5 °C/Ma).
426 Output thermal histories show a similar pattern between 15 Ma and present day between
427 the three TEMs: output cooling at ~20 °C/Ma associated to the second fault-activity
428 phase between 15 and 11 Ma, followed by slow cooling (1-2° C/Ma, Fig. 11b).

429

430 **5. DISCUSSION**

431 **5.1 Pyrenean contractional stage**

432 Our inversion results allow reconstructing a two-stage regional exhumation
433 history for the South Mérens block (hanging wall of the Têt fault, Fig. 1), with a well-
434 constrained transition time between 37 and 35 Ma regardless of the considered TEM
435 (Fig. 5). Exhumation rates V1 are not well constrained, with a probability peak between
436 0.3 and 0.6 km/Ma for the Eastern Pyrenees TEM and >0.5 km/Ma for the global
437 Pyrenees and No topographic change TEMs. Exhumation rates V2 appear significantly
438 lower and are well constrained (close to Gaussian distributions) below 0.1 km/Ma for all
439 the TEMs. These results overall agree with thermal histories obtained with QTQt
440 modeling, showing rapid cooling between 40 and 35 Ma, followed by slow cooling since
441 35 Ma (Milesi et al., 2022, Fig. 12). The regional exhumation scenario for the different
442 TEMs is also very well constrained between ~ 35 Ma and present day, which is the main
443 period of interest for this study. More complex exhumation scenarios (e.g. considering a
444 three-phase exhumation history) have also been tested, without significant improvement
445 regarding low-T thermochronological age predictions (Milesi, 2020).

446 Best-fitting inversion models showed similar thermal-history predictions for the 3
447 TEMs, only slightly influenced by the topographic evolution after 35 Ma (Fig. 6).
448 Cooling rates associated to the first exhumation phase are between 15 and 20°C/Ma,
449 consistent at first order with QTQt outcomes. However, QTQt results (Milesi et al., 2022)
450 suggested an apparent two-stage cooling history before 35 Ma: a first phase between 50
451 and 38 Ma ($>5^\circ\text{C}/\text{Ma}$) followed by a second phase between 38 and 35 Ma ($\sim 30^\circ\text{C}/\text{Ma}$).
452 This two-stage history is not constrained in Pecube-derived thermal histories (Fig. 12),
453 which can be explained by both the relative simplicity of our implemented Pecube
454 exhumation scenarios (i.e. only two exhumation phases considered) but also by the lack

455 of low-T thermochronological data for the 50-38 Ma period (Fig. 6 and Table S1).
456 Indeed, most of ZHe and AFT data from high-elevation samples are not well reproduced
457 whatever the considered TEMs (Fig. 6).

458

459 Predicted cooling rates associated to the second exhumation phase showed slight
460 differences between the considered TEMs, but are overall quite low (up to 1°C/Ma,
461 except for the Eastern Pyrenees TEM with 2.8 °C/Ma between 34 and 23 Ma, Fig. 6).
462 Observed AHe and AFT data are well reproduced by our best-fitting Pecube models,
463 except for samples characterized by ages inversion (i.e. AHe ages are older than AFT
464 ages). Such an ages inversion cannot be reproduced by Pecube due to the relatively
465 simple AHe diffusion model used in this code (Braun et al., 2012), since for example it
466 does not consider apatite chemistry nor size effects on He diffusion (see Section 3.2; e.g.
467 Gautheron et al., 2009).

468

469 Predicted regional exhumation rates prior to ca. 35 Ma are all above 0.2 km/Ma,
470 with PDF peaks for rates >0.3 km/Ma from our inversion results (Figs. 5 and 12) that can
471 be related to the activity of major regional thrusts located further South of the Mérens
472 block (Fig. 1a), like the Cadi-Canigou thrust (Ternois et al., 2019). Regional thrusting in
473 the Eastern Pyrenees has been linked to the contractional phase of the orogen, associated
474 to the convergence between the Iberian and European plates during the Eocene
475 (Fitzgerald et al., 1999; Whitchurch et al., 2011; Rushlow et al., 2013; Mouthereau et al.,
476 2014; Bosch et al., 2016a; Labaume et al., 2016; Cruset et al., 2020). The end of this
477 contractional phase is well constrained in our inversion results between 37 and 35 Ma,

478 followed by a major decrease of exhumation rates (<0.1 km/Ma) for the eastern part of
479 the Axial Zone (Fig. 1), which contrasts with faster exhumation rates at 1.0 ± 0.1 km/Ma
480 proposed further West between 40 and 30 Ma (Curry et al., 2021). These exhumation
481 differences can first be explained by our model set-up, for which the transition time is an
482 inversion parameter and not constrained by an a priori prescribed time window (see
483 Section 4.1) as in Curry et al. (2021). In addition, we propose that this temporal
484 difference may reflect a first-order westward propagation of rock uplift and exhumation
485 starting in the eastern part of the Pyrenees (Whitchurch et al., 2011; Fillon et al., 2016;
486 Curry et al., 2021). The observed early end of the contractional event corresponds also to
487 the proposed period for the onset of extensional tectonics in the Eastern Pyrenees,
488 associated with the large-scale West European Rifting (Ziegler, 1992; Romagny et al.,
489 2020; Angrand and Mouthereau, 2021; Jolivet et al., 2021; Mouthereau et al., 2021;
490 Séranne et al., 2021; Milesi et al., 2022).

491

492

493 **5.2 Têt fault activity**

494 **5.2.1 The Canigou block**

495 Inversion results for the Têt fault activity differ according to the used TEM, but
496 overall our model outcomes reveal that the fault-activity duration is not well constrained
497 (Fig. 7). For the No topographic change and Global Pyrenees TEMs, the Têt fault activity
498 appears shorter in time (from 26-25 to 24.5 Ma and 28-26 to 24.5 Ma, respectively)
499 compared to the Eastern Pyrenees TEM (between >28 Ma and 23.5 ± 1.5 Ma).
500 Consistently, predicted fault slip rates are also not well constrained for the different

501 TEMs (Figure 7e) but they appear relatively high and unconstrained for the No
502 topographic change (1.0-6.0 km/Ma) and Global Pyrenees (1.5-6.0 km/Ma) TEMs, while
503 they seem slightly lower and more constrained for the Eastern Pyrenees TEM (1 ± 0.5
504 km/Ma). Output slip rates can be translated into vertical rock uplift/exhumation rates
505 using the implemented fault dip in Pecube models, with the following estimates: >0.85
506 km/Ma, >1.3 km/Ma and 0.85 ± 0.40 km/Ma for the No topographic change, Global
507 Pyrenees and Eastern Pyrenees TEMs, respectively. All these estimates are well higher
508 than output exhumation rates of 0.33 to 0.56 km/Ma derived from age-elevation
509 relationships for the same period (Milesi et al., 2022). However, our estimated
510 exhumation rates associated to the Têt fault activity are in the same order of magnitude
511 than exhumation rates obtained by thermochronological studies along other normal faults
512 worldwide (e.g. Fletcher et al., 2000; Ehlers et al., 2001). These differences of
513 exhumation rates can be explained by the simple diffusion models used in Pecube code
514 and modeling assumptions (see Section 3.2).

515

516 Best-fitting inversion models show a good agreement between model predictions and
517 observed low-T thermochronological ages (Fig. 8), with noticeable differences between
518 the No topographic change/Eastern Pyrenees TEMs and the Global Pyrenees TEM. The
519 main differences are illustrated by AHe and low-elevation AFT ages predicted for the
520 Global Pyrenees TEM, which are younger than for the two other TEMs. These
521 differences are also visible in output thermal histories, with a more pronounced cooling
522 event (~ 120 °C/Ma) for the Global Pyrenees TEM than for the two other TEMs (~ 90
523 °C/Ma). In contrast with the QTQt output Oligocene-Miocene cooling rates (~ 30 °C/Ma,

524 Fig. 12), Pecube thermal histories reveal faster cooling during that period. It is
525 particularly visible for Global Pyrenees and Eastern Pyrenees TEMs (Fig. 8b), with
526 prescribed Oligocene-Miocene cooling from 350°C to 120°C and 260°C to 30°C,
527 respectively. These important differences can be due to the potential combination of 2
528 independent cooling phases in our Pecube approach: a Priabonian cooling phase,
529 followed by a second Oligocene-Miocene phase, which are predicted for QTQt modeling
530 (Fig. 12, Milesi et al., 2022). Furthermore, these output thermal histories are reflecting
531 the complexity to properly model the observed ZHe age for the Canigou block (Fig. 8a)
532 and the MTL data from top-profile samples of the Canigou block (Fig. 8b). Performed
533 inversion models with 2 fault-activity periods tend to refine fault slip rates during the
534 Oligocene-Miocene phase rather than highlighting a Priabonian tectonic event, most
535 certainly due to the lack of data for this period (Supplementary Table S1 and Figure S1).
536 It is important to note that with the Eastern Pyrenees TEM, the output fault activity is
537 starting earlier (~28 Ma) which is closer to the observed ZHe age. Additional ZHe and
538 ZFT data in the Canigou area would allow to better constrain this early tectonic phase.
539 Considering our inversion results and the relatively good AHe/AFT model predictions, no
540 post Oligocene-Miocene activity of the Têt fault is required to explain low-T
541 thermochronological data in the Canigou block.

542

543 **5.2.2 The Carança block**

544 Inversion results for the first fault-activity phase differ according to the
545 considered TEM (Fig. 12). For the No topographic change TEM, this first phase appears
546 limited in time (from 26-25 Ma to 25-24 Ma). The Global Pyrenees TEM suggests a

547 slightly earlier onset of fault activity (28 ± 2 Ma) but close ending time (25-24 Ma),
548 similarly to the Canigou block (Section 5.2.1). Inversions based on the Eastern Pyrenees
549 TEM suggest a longer fault activity, between around 32 Ma and 15 Ma. Estimated fault
550 slip rates are high (5.5-6 km/Ma) for the No topographic change TEM, these are much
551 lower for the Eastern Pyrenees TEM (<1 km/Ma) and not well constrained for the Global
552 Pyrenees model (Fig. 10d). These differences in quantitatively constraining fault slip
553 rates can be explained by the major differences in the low-T thermochronological dataset
554 for the Carança block compared to the Canigou block, with a complete ZHe age-elevation
555 profile and low-elevation AHe ages that record exhumation for the mid to late Miocene
556 period (Fig. 11a). Output Oligocene-Miocene cooling rates (Fig. 11) are relatively high
557 (>100 °C/Ma) for the No topographic change and Global Pyrenees TEMs, similar to the
558 Canigou block (Fig. 9), while slower cooling is predicted for the Eastern Pyrenees TEM
559 (~ 10 °C/Ma). However, the output cooling rate for the Global Pyrenees TEM has to be
560 considered cautiously and may not be representative due to the largely unconstrained
561 fault slip rate with this TEM (Fig. 10d). Finally, our results suggest the existence of
562 diachronism and magnitude differences for the Têt fault activity along its western
563 segment (i.e. Canigou vs. Carança block), confirming previous observations with QTQt
564 models (Fig. 12; Milesi et al., 2022).

565

566 Predictions for the second fault-activity phase are relatively similar whatever the
567 considered TEM. Inversion results for the fault duration show a maximum probability
568 between around 15 and 11 Ma, with an associated fault slip rate of 0.7-0.8 km/Ma (Fig.
569 10). These results indicate the existence of a major post Oligocene-Miocene activity of

570 the Têt fault along the Carança block, with associated rock exhumation (estimated using
571 slip-rate predictions and Têt-fault dip) above 0.6 km/Ma that is 5-10 times higher than the
572 regional exhumation rate recorded in the South Mérens block (see Section 5.1) over the
573 same period. Independently of the considered TEM, the low-T thermochronological
574 dataset for the Carança block cannot be only explained by large-scale change(s) in
575 topographic relief (Gunnell et al., 2008; Huyghe et al., 2020; Calvet et al., 2021). Output
576 cooling at about 20 °C/Ma is associated with this late-stage tectonic exhumation phase
577 between 15 and 11 Ma, and is consistent to first order with the previously recognized
578 cooling phase, but of lower magnitude (around 10 °C/Ma) and duration (between 11 and
579 9 Ma), in QTQt thermal models (Milesi et al., 2022). Observed differences between the
580 two modeling approaches (Pecube vs. QTQt) can be explained by (i) the relatively simple
581 He diffusion model used in Pecube (see Section 3.2), and (ii) the lack of topographic
582 evolution in QTQt modeling approach. Overall, our results indicate a major tectonic stage
583 during the middle to late Miocene, with kilometeric-scale (2-3 km) displacement inferred
584 on the Têt fault along the Carança block only, which cannot be reproduced for the
585 Canigou block (Supplementary Figure S1). This fault-displacement estimate is much
586 higher than the previously-proposed 150-500 m for this period and applied
587 homogeneously along the Têt fault (Pous et al., 1986; Réhault et al., 1987; Roca &
588 Desegaulx, 1992; Calvet, 1999; Carozza & Baize, 2004; Delcaillau et al., 2004; Agusti et
589 al., 2006). Our results are also consistent with a westward propagation of the deformation
590 along the Têt fault with a proposed more recent activity along the Carança block
591 compared to the Canigou block (Carozza & Delcaillau, 1999; Carozza & Baize, 2004;
592 Milesi et al., 2022), marked by the more recent activity along the Carança block

593 compared to the Canigou block, and the latest activity of the Têt fault further West, along
594 the Cerdanya Basin, during late Miocene times (Pous et al., 1986; Agustí et al., 2006).

595

596 The main differences between observed and predicted low-T thermochronological
597 ages (Fig. 11a) are essentially marked for high-elevation ZHe and AHe ages. ZHe age
598 differences may be linked to lateral variations in timing and exhumation rates associated
599 to the contractional deformation phase in the Eastern Pyrenees as it has been observed at
600 the scale of the whole Pyrenees (Curry et al., 2021). In addition, AHe ages located below
601 1400 m elevation show an important dispersion between 15 and 20 Ma. This observed
602 dispersion can be explained by (i) differences in apatite U-Th content and grain size
603 (Milesi et al., 2022), and/or (ii) additional activity of secondary NW-SE fault(s) between
604 20 and 15 Ma (Fig. 1b). These NW-SE faults are particularly well expressed in the
605 western part of the study area (Taillefer et al., 2021) and can create an important
606 segmentation of the Carança block, therefore resulting in slightly different cooling
607 histories within the different sub-blocks. The potential activity of such NW-SE faults
608 could also explain the local elevation increase of the Cerdanya basin documented by
609 Tosal et al. (2021) during late Miocene-Pliocene times.

610

611 **5.3 Tectono-geomorphological evolution of the Eastern Pyrenees**

612 The original approach of our study was to assess regional exhumation and
613 tectonic histories from 3D Pecube inversions using contrasted TEMs over the last around
614 60 Myr (Fig. 4). Figure 13 summarizes the three tested topographic evolution scenarios
615 along with the output key periods in exhumation/tectonic activity:

616 - (i) Prior to 37 Ma for the South Mérens block, inferred exhumation rates are
617 significantly higher for the Global Pyrenees or No topographic change TEMs (>0.5
618 km/Ma) compared to the Eastern Pyrenees TEM (0.3-0.6 km/Ma);

619 - (ii) since around 37-35 Ma, i.e. the end of the contractional phase, until present
620 day, inferred regional exhumation rates are very close (0.04-0.09 km/Ma, Fig. 12),
621 whatever the considered TEM;

622 - (iii) from 33 to 15 Ma, corresponding to the main Têt-fault activity period along
623 the Canigou and Carança blocks (phase 1), the Global Pyrenees and No topographic
624 change TEMs predict a shorter phase with much higher fault-slip rates compared to
625 inversions with the Eastern Pyrenees TEM (Fig. 12). As these differences are observed
626 for both the Canigou and Carança blocks, our results confirm that the topographic relief
627 evolution scenarios have had a significant impact on the thermochronology cooling ages
628 predicted by the model;

629 - (iv) between 15 and 11 Ma, a second fault-activity phase but only along the
630 Carança block is inferred from our Pecube inversions whatever the considered TEM.
631 Output fault-slip rates are also very consistent for the different TEMs, between 0.7 and
632 0.8 km/Ma (Fig. 10d).

633

634 Overall, these results show that it remains difficult to use low-T
635 thermochronological data from the Eastern Pyrenees to quantitatively assess the long-
636 term topographic evolution of the area, even if the proposed topographic evolution
637 models since ca. 60 Ma are very contrasted (Fig. 13). We suggest the possible following
638 reason for this limitation: topographic relief changes for the Eastern Pyrenees, even if

639 they appear important in amplitude, are spread out over tens of millions of years, limiting
640 their impact on the crustal thermal structure and rock exhumation compared to the
641 regional rock uplift and local fault activity (Valla et al., 2010; 2011).

642

643 Despite the lack of quantitative information on the robustness of the different
644 TEMs from low-T thermochronology, this approach allowed us to highlight and quantify
645 the main extensional tectonic events that have affected the Eastern Pyrenees. Our results
646 confirm a major Oligocene-Miocene displacement (pluri-kilometric) along the Têt fault,
647 confirming previously-proposed interpretations for the Canigou massif (Maurel et al.,
648 2008; Milesi et al., 2022). This major tectonic phase may be related to the opening of the
649 Gulf of Lion (e.g. Séranne, 1999; Mauffret et al., 2001; Maillard et al., 2020; Romagny et
650 al., 2020; Jolivet et al., 2021). Our new results moreover highlight some differences in
651 fault timing and slip rates for this extensional phase between the Carança and Canigou
652 blocks, even though these results must be considered carefully, in particular for the
653 Canigou block, due to the potential contribution of an earlier fault-activity phase during
654 the Priabonian. One major outcome of this study is the characterization of a second, post
655 Oligocene-Miocene, extensional tectonic event between 15 and 11 Ma, with kilometric
656 displacement associated along the Têt fault but restricted to its western segment (i.e. the
657 Carança block). Even if this episode is less important in magnitude than the Oligocene-
658 Miocene one, this has been triggering important displacement along the western part of
659 the Têt fault, and can have significantly contributed to the regional relief changes
660 recorded in the Eastern Pyrenees (Gunnell et al., 2008; Huyghe et al., 2020; Calvet et al.,
661 2021). This tectonic event may have been recorded at the scale of the whole Pyrenees, as

662 recent thermochronological evidence in the Ebro basin (South Pyrenean Zone) have
663 highlighted a long-wavelength tectonic event at ~10 Ma (Rat et al., 2022) similar to what
664 was also proposed for the western part of the Pyrenees (Fillon et al., 2021). Our study
665 provides further evidence for large-scale lithospheric and sub-lithospheric processes,
666 particularly well expressed in the Eastern Pyrenees, that coincide with the cessation of
667 slab retreat in the West Mediterranean Sea (Jolivet et al., 2021).

668

669 **CONCLUSIONS**

670 3D Pecube thermo-kinematic inversions, using different topographic evolution
671 models for the Eastern Pyrenees, reveal a major decrease in regional exhumation rates
672 between 37-35 Ma. This change is associated to an early end of the contractional tectonic
673 period in the Eastern part of the orogen, while deformation and rock exhumation
674 propagated to the West. The detailed investigation of the Têt fault activity along the
675 Canigou and Carança blocks has been favored by the dense existing low-T
676 thermochronological datasets. Our inversion results highlight two main period of normal-
677 fault activity with (i) a major Oligocene-Miocene phase recorded in the Canigou and
678 Carança blocks, (ii) a secondary mid- to late-Miocene phase with, however, kilometeric
679 displacement (2-3 km) restricted along the western segment of the Têt fault (Carança
680 block), and (iii) no latest Miocene or Pliocene major phase that could have been recorded
681 by low-T thermochronometers. These outcomes confirmed the presence of significant
682 extensional tectonics in the Eastern Pyrenees that may have had a non-negligible role in
683 the late-stage construction of the topographic relief. Finally, our approach and results
684 highlight the benefits of integrating long-term topographic evolution models at a regional

685 scale to further constrain the exhumation and tectonic histories from low-T
686 thermochronological data and inverse 3D thermo-kinematic modeling.

687

688 **ACKNOWLEDGMENTS**

689 This research received funding from the program TelluS of the Institut National
690 des Sciences de l'Univers, CNRS. Thanks for technical support with Pecube code go to J.
691 Braun and B. Gérard. G.M acknowledges D. Whipp and I. Kukkonen for the organization
692 of the short course on low temperature thermochronology 2017 and first steps with
693 Pecube modeling at the University of Helsinki. P.G.V. acknowledges funding from the
694 French ANR-PIA program (ANR-18-MPGA-0006). We thank M.E. Curry and F.
695 Mouthereau for their positive and constructive reviews that clearly helped improving our
696 manuscript.

697

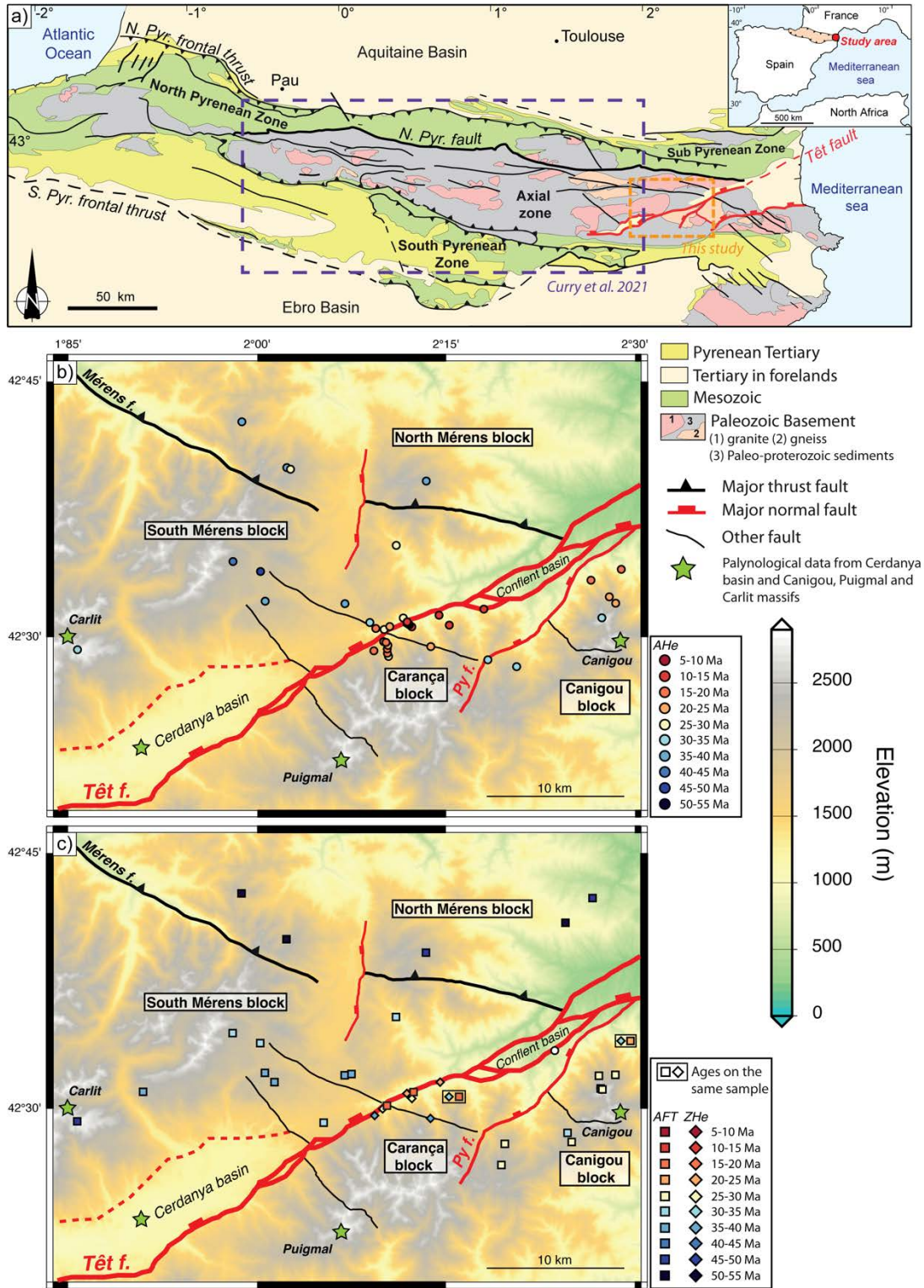
698 **Supplementary Information**

699 Supplementary Information to this article can be found online at ...

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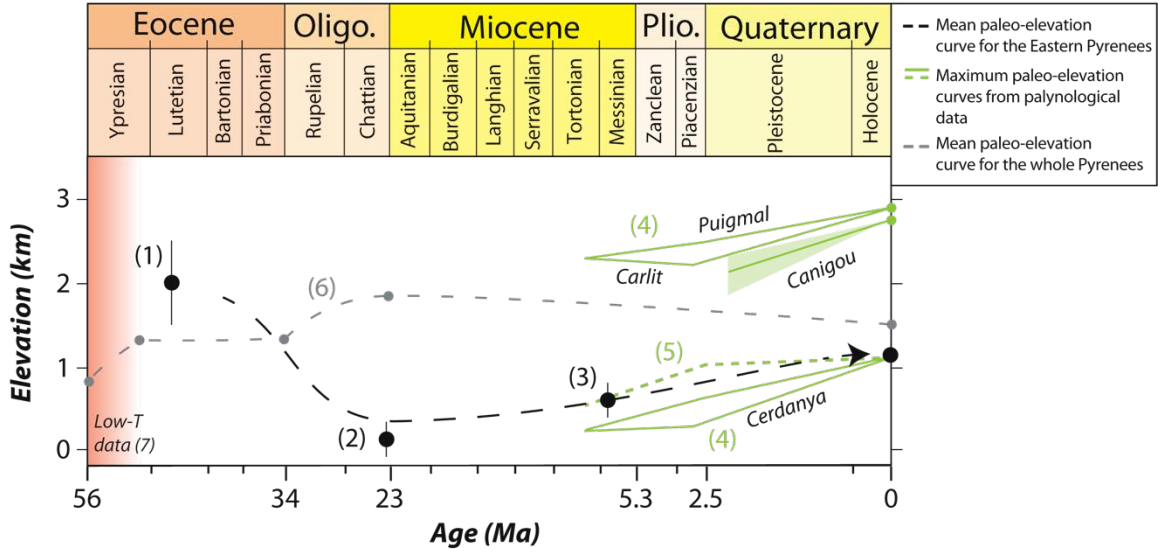
FIGURES AND CAPTIONS



702

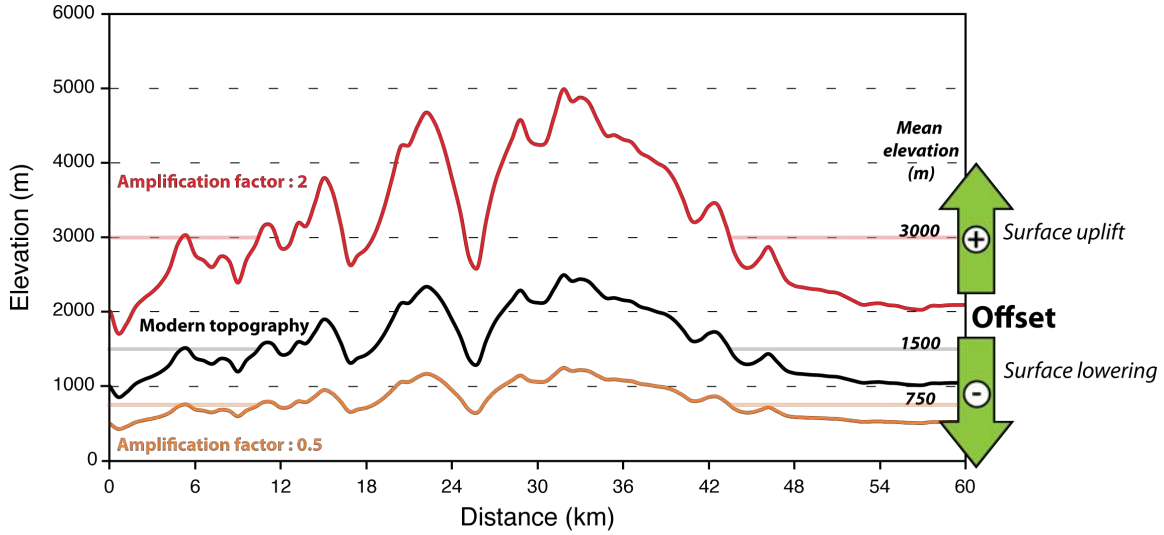
703 Figure 1. a) Geological map showing the main structural domains of the Pyrenees
 704 (modified after Taillefer et al., 2017). The main Neogene normal faults of the Eastern

705 Pyrenees are reported in red. The area delimited for 3D thermo-kinematic modeling from
706 Curry et al. (2021) is outlined with a purple-dashed box, and our study area with an
707 orange-dashed box. b) Location of AHe ages and c) AFT and ZHe ages (literature data,
708 see text for details) projected on SRTM1s DEM under GMT (Wessel et al., 2019). The
709 different crustal blocks (South and North Mérens in the Mont Louis massif, Carança and
710 Canigou) are delimited by regional major faults (bold italics, modified after Milesi et al.,
711 2022), while secondary faults and main basins (Cerdanya, Conflent) are also indicated.
712 Location of palynological data discussed in the main text are indicated by green stars in
713 panels b-c.



714

715 Figure 2. Topographic relief evolution for the Eastern Pyrenees since Ypresian times
 716 (modified after Huyghe et al., 2020). Mean paleo-elevation curve for the Eastern
 717 Pyrenees is based on studies from (1) Huyghe et al. (2012); (2) Bache et al. (2010); (3)
 718 Huyghe et al. (2020). Maximum paleo-elevation curves are issued from palynological
 719 data from (4) Suc and Fauquette (2012) and (5) Agusti et al. (2006), Mean paleo-
 720 elevation curve for the whole Pyrenees is issued from (6) flexural model outputs from
 721 Curry et al. (2019), and (7) low-T thermochronological studies from Fitzgerald et al.
 722 (1999); Sinclair et al. (2005); Vacherat et al. (2014, 2016) and Ternois et al. (2019,
 723 2021).



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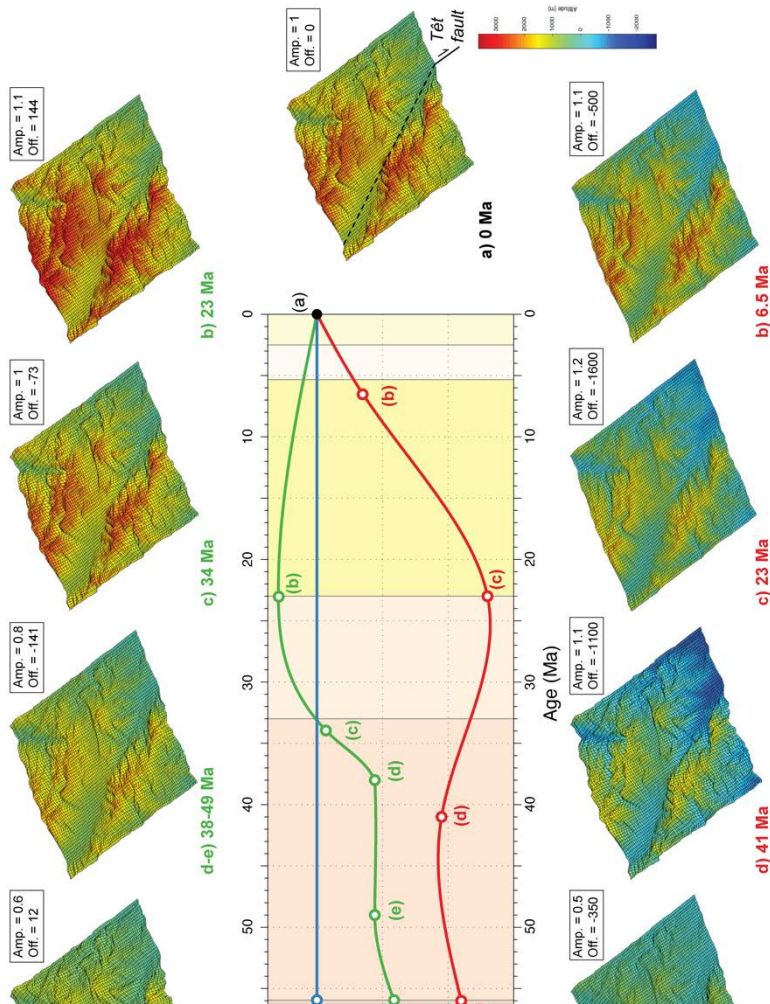
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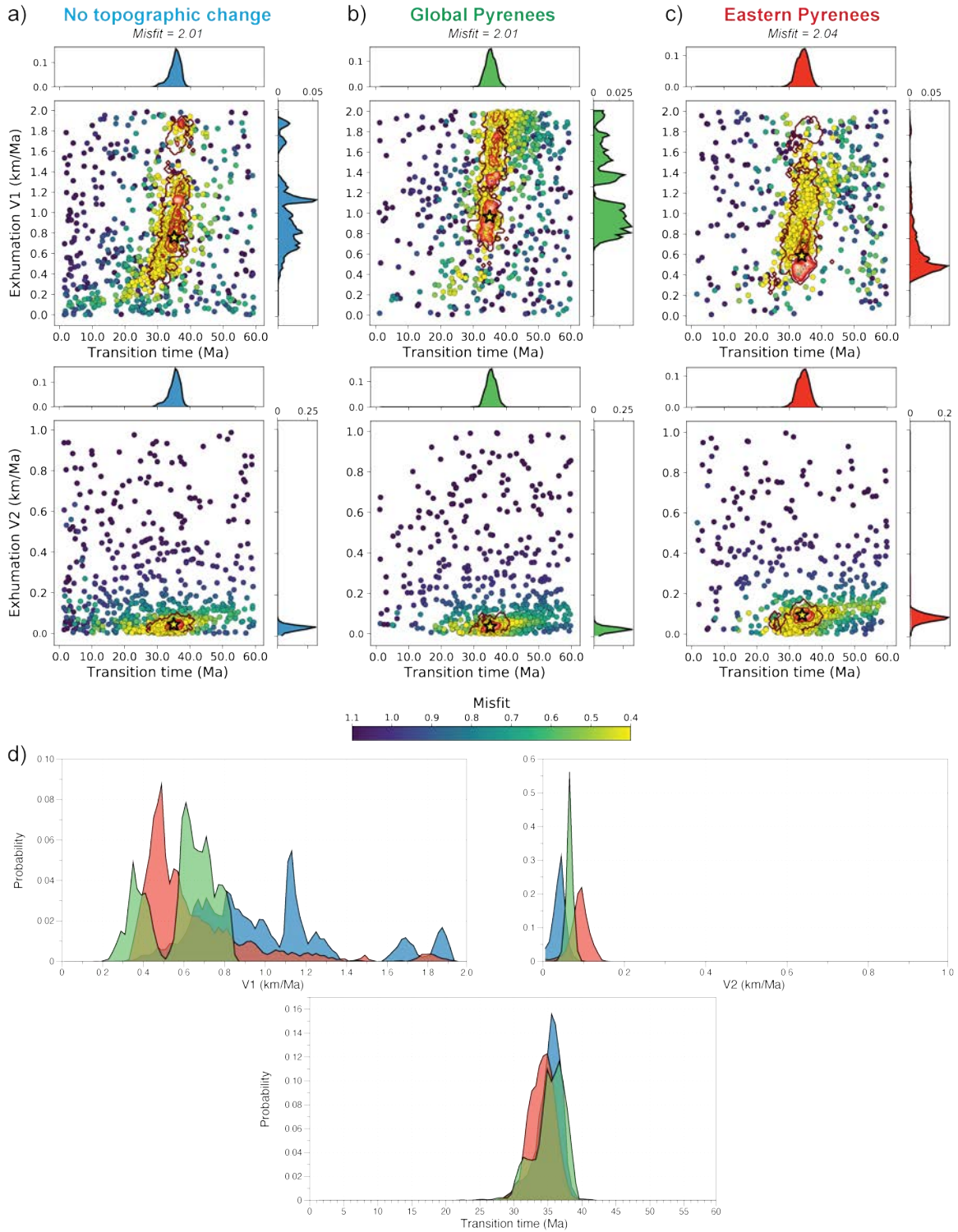
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Figure 3. Topographic profile of the Canigou massif to schematically illustrate the impact of the amplification factor and offset parameters used to describe topographic changes in Pecube modeling. Different scenarios are considered with (1) an amplification factor of 2 and offset of 1500 m (red line) and (2) an amplification factor of 0.5 and offset of -750 m (orange line). The modern topography (amplification factor 1 and offset 0 m) is shown by the black line.



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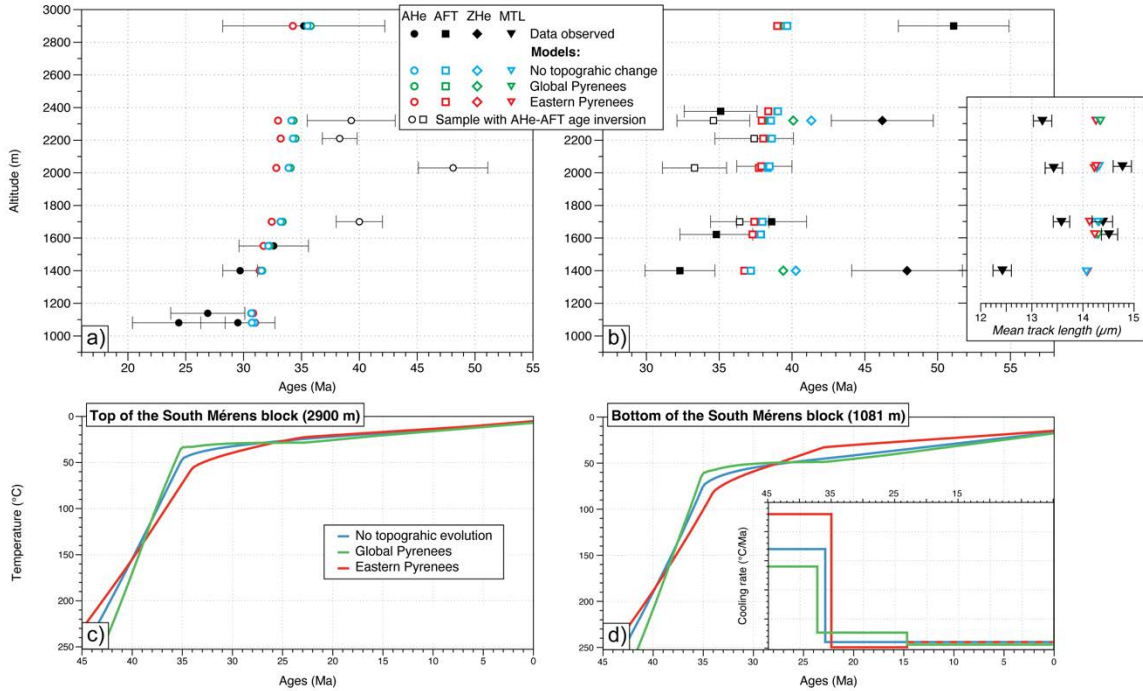
732 Figure 4. Three topographic evolution models (TEMs) used for Pecube thermo-kinematic
 733 modeling. In blue is represented the TEM for the No topographic change. In green is
 734 shown the TEM for the Global Pyrenees issued after Curry et al. (2019). Finally, in red
 735 appears the TEM for the Eastern Pyrenees (after Huyghe et al., 2020; see Section 3.3 for
 736 further details). The resulting DEM for each evolution step is presented (upper: Global
 737 Pyrenees; lower: Eastern Pyrenees) with associated values of amplification factor (Amp.)
 738 and offset (Off.) in meters (see Section 3.2 and Supplementary Table S2 for full details).
 739 The surface trace of the normal Têt fault implemented in Pecube models is represented in
 740 the modern DEM (dashed black line).



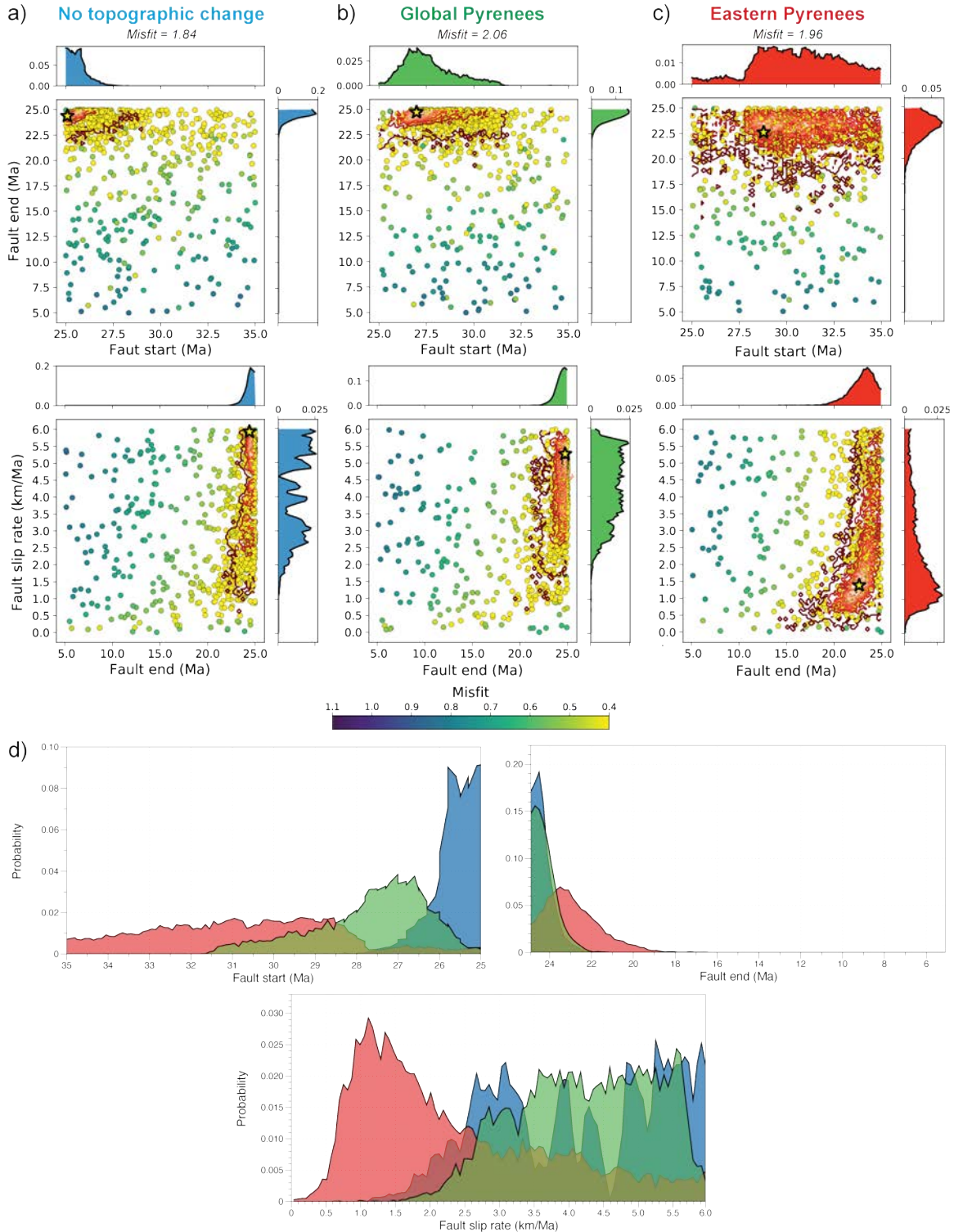
741

742 Figure 5. 3D Pecube inversion results for the South Mérens block, using the 3 TEMs: (a)
 743 No topographic change, (b) Global Pyrenees, (c) Eastern Pyrenees. In these model runs, 3
 744 parameters are inverted: exhumation rates V1 and V2, and the transition time between the
 745 two exhumation phases. Scatter diagrams show results of Pecube and NA inversion with

746 the probability density function (PDF) adjacent to the axes for each parameter. Each dot
747 corresponds to a forward model; its color is proportional to the value of the reduced
748 misfit between model predictions and the observed low-T thermochronological data.
749 Note that violet corresponds to high misfits and yellow to low misfits. The yellow stars
750 are the best-fitting model (values given on top for each TEM). Red and black lines are 2D
751 posterior marginal probability density functions (PDFs) with 2σ (black) and 1σ (red)
752 confidence contours. d) Probability density function (PDF) results for the 3 inverted
753 parameters and three considered TEMs (blue: No topographic change, green: Global
754 Pyrenees, and red: Eastern Pyrenees).
755

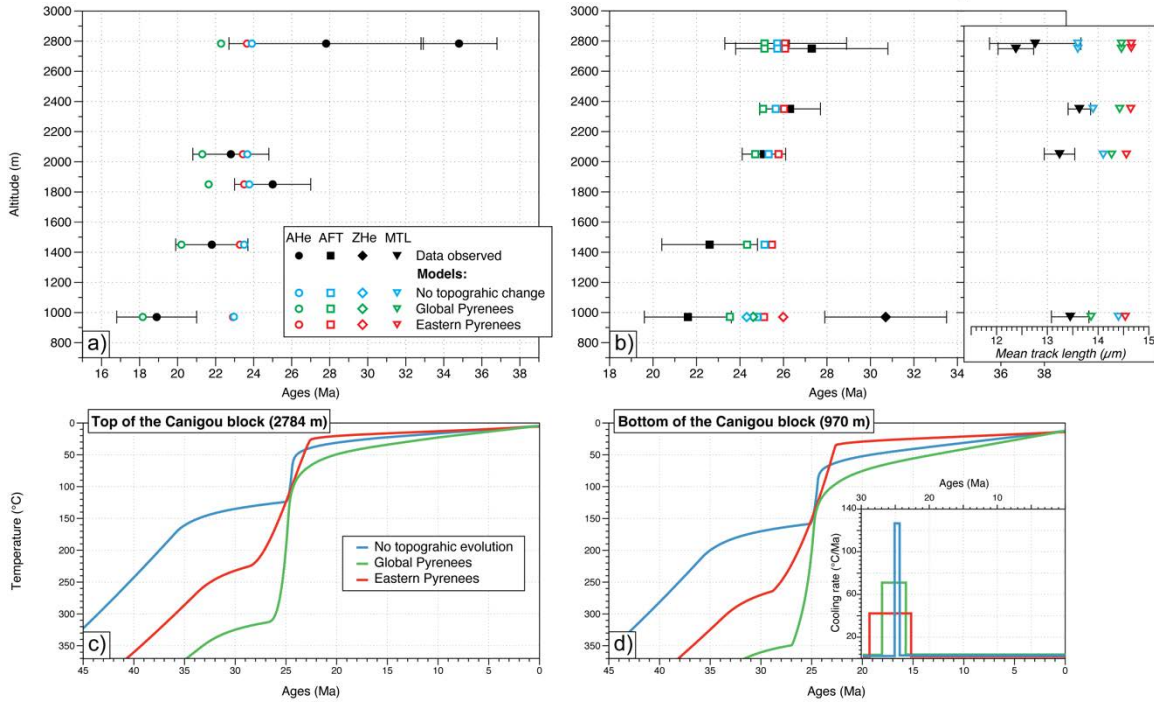


756
 757 Figure 6. Age-elevation profiles with best-fitting predicted vs. observed AHe, AFT and
 758 ZHe ages and MTLs, and output thermal histories from the South Mérens block. a-b)
 759 Black dots (AHe, a), squares (AFT, b), diamonds (ZHe, b) and triangle (MTL, subplot in
 760 b) are observed data and associated uncertainties. Colored dots, squares, diamonds and
 761 triangles are predicted data for the 3 TEMs. c-d) Best-fitting output thermal histories for
 762 top (c) and bottom (d) samples of the South Mérens block, considering the 3 different
 763 TEMs. Inset plot shows the predicted cooling rates for the 3 TEMs.



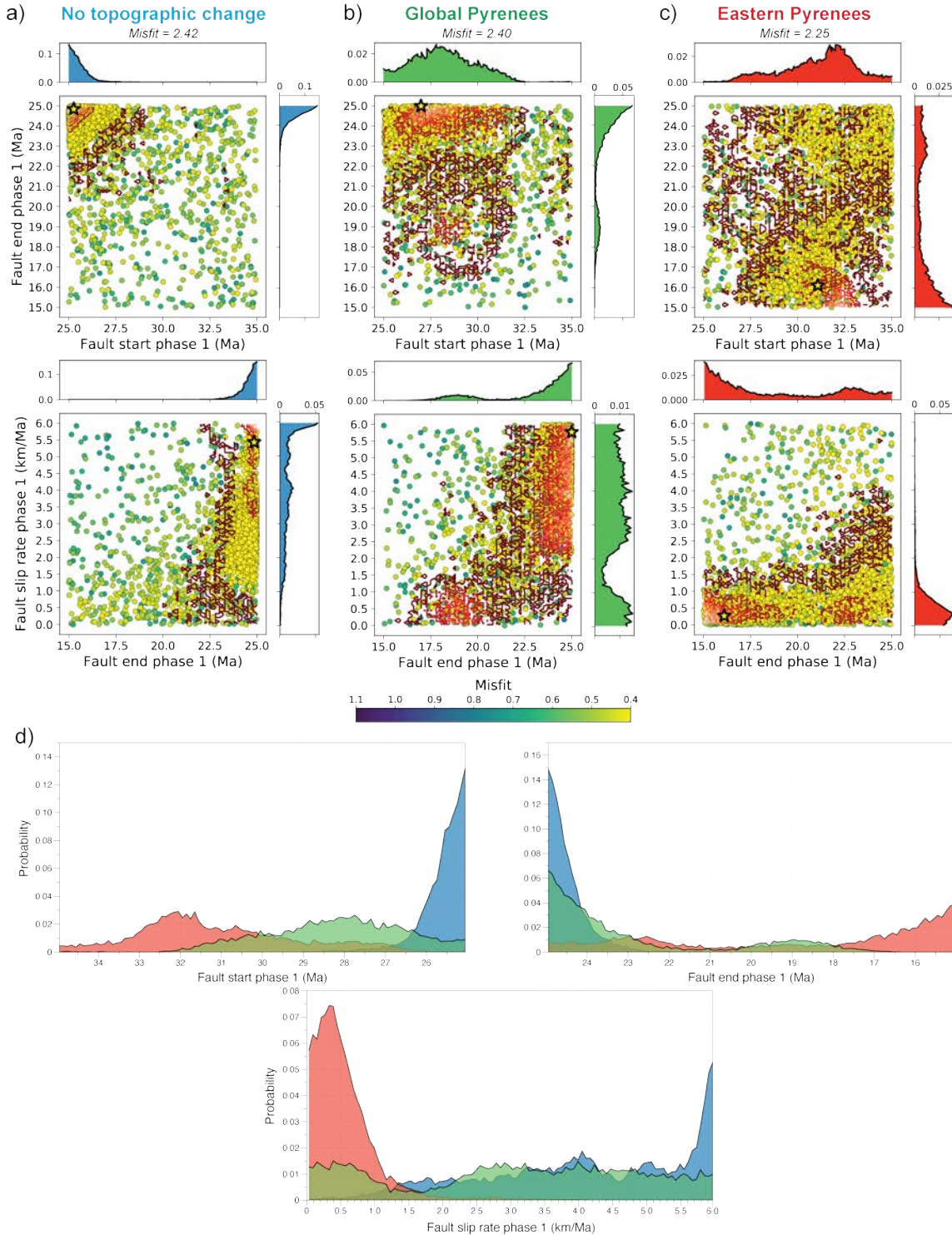
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 765 Figure 7. 3D Pecube inversion results of the Têt fault activity for the Canigou block,
 766 using the 3 TEMs: (a) No topographic change, (b) Global Pyrenees, (c) Eastern Pyrenees.
 767 In these model runs, 3 parameters are inverted: the Têt fault start and end times, and the
 768 slip rate on the fault. Scatter diagrams show results of Pecube and NA inversion with the
 769 probability density function (PDF) adjacent to the axes for each parameter. Each dot

770 corresponds to a forward model; its color is proportional to the value of the reduced
771 misfit between model predictions and the observed low-T thermochronological data.
772 Note that violet corresponds to high misfits and yellow to low misfits. The yellow stars
773 are the best-fitting model (values given on top for each TEM). Red and black lines are 2D
774 posterior marginal probability density functions (PDFs) with 2σ (black) and 1σ (red)
775 confidence contours. d) Probability density function (PDF) results for the 3 inverted
776 parameters and three considered TEMs (blue: No topographic change, green: Global
777 Pyrenees, and red: Eastern Pyrenees).



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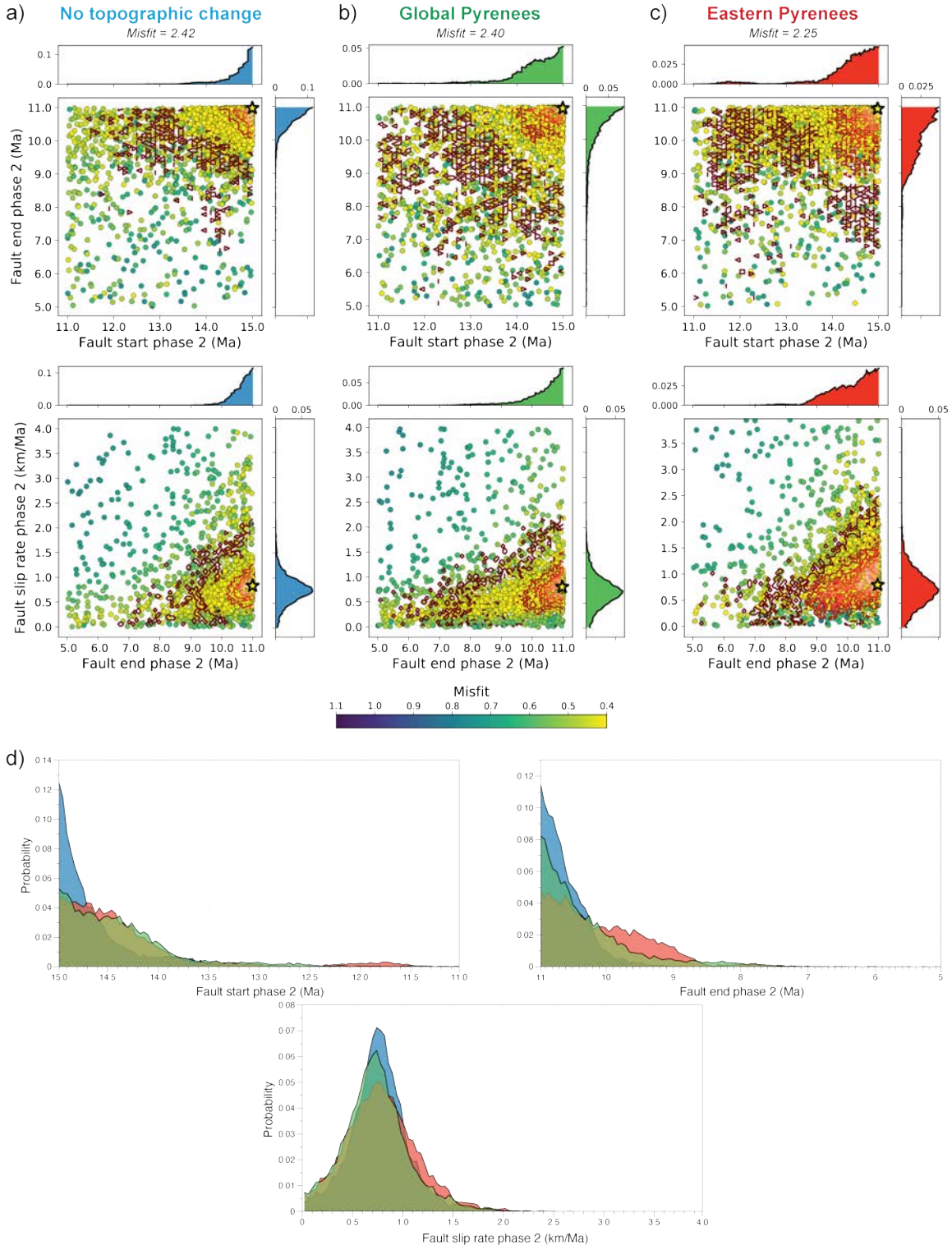
779 Figure 8. Age-elevation profile with best-fitting predicted vs. observed AHe, AFT and
 780 ZHe ages and MTLs, and output thermal histories from the Canigou block. a-b) Black
 781 dots (AHe, a), squares (AFT, b), diamonds (ZHe, b) and triangle (MTL, subplot in b) are
 782 observed data and associated uncertainties. Colored dots, squares, diamonds and triangles
 783 are predicted data for the 3 TEMs. c-d) Best-fitting output thermal histories for top (c)
 784 and bottom (d) samples of the Canigou block, considering the 3 different TEMs. Inset
 785 plot shows the predicted cooling rates for the 3 TEMs.



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Figure 9. 3D Pecube inversion results of the first phase of the Têt fault activity for the Carança block, using the 3 TEMs: (a) No topographic change, (b) Global Pyrenees, (c) Eastern Pyrenees. In these model runs, 6 parameters are inverted: the Têt fault start and end times, and the slip rate on the fault for the 2 phases of fault activity. Scatter diagrams show results of Pecube and NA inversion with the probability density function (PDF)

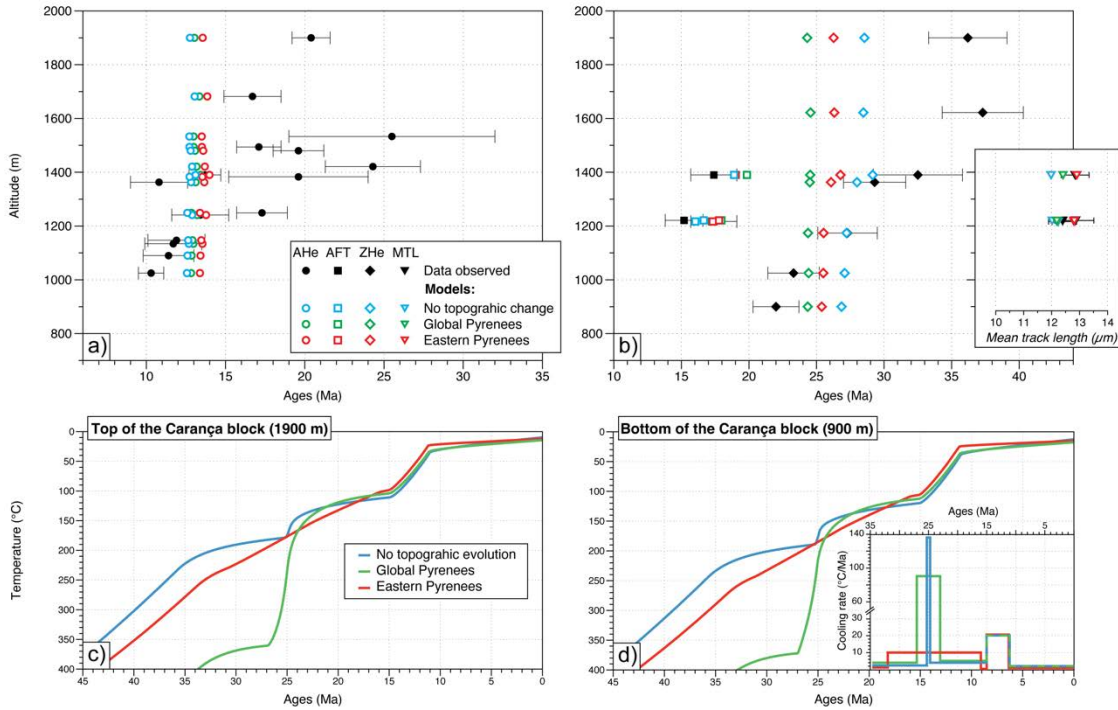
792 adjacent to the axes for each parameter. Each dot corresponds to a forward model; its
793 color is proportional to the value of the reduced misfit between model predictions and the
794 observed low-T thermochronological data. Note that violet corresponds to high misfits
795 and yellow to low misfits. The yellow stars are the best-fitting model (values given on top
796 for each TEM). Red and black lines are 2D posterior marginal probability density
797 functions (PDFs) with 2σ (black) and 1σ (red) confidence contours. d) Probability density
798 function (PDF) results for the 3 inverted parameters and three considered TEMs (blue:
799 No topographic change, green: Global Pyrenees, and red: Eastern Pyrenees).



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Figure 10. 3D Pecube inversion results of the second phase of the Têt fault activity, using the 3 TEMs for the Carança block: (a) No topographic change, (b) Global Pyrenees, and (c) Eastern Pyrenees. In these model runs, 6 parameters are inverted: the Têt fault start and end times, and the slip rate on the fault for the 2 phases of fault activity. Scatter diagrams show results of Pecube and NA inversion with the probability density function

806 (PDF) adjacent to the axes for each parameter. Each dot corresponds to a forward model;
807 its color is proportional to the value of the reduced misfit between model predictions and
808 the observed low-T thermochronological data. Note that violet corresponds to high
809 misfits and to low misfits. The yellow stars are the best-fitting model (values given on top
810 for each TEM). Red and black lines are 2D posterior marginal probability density
811 functions (PDFs) with 2σ (black) and 1σ (red) confidence contours. d) Probability density
812 function (PDF) results for the 3 inverted parameters and three considered TEMs (blue:
813 No topographic change, green: Global Pyrenees, and red: Eastern Pyrenees).



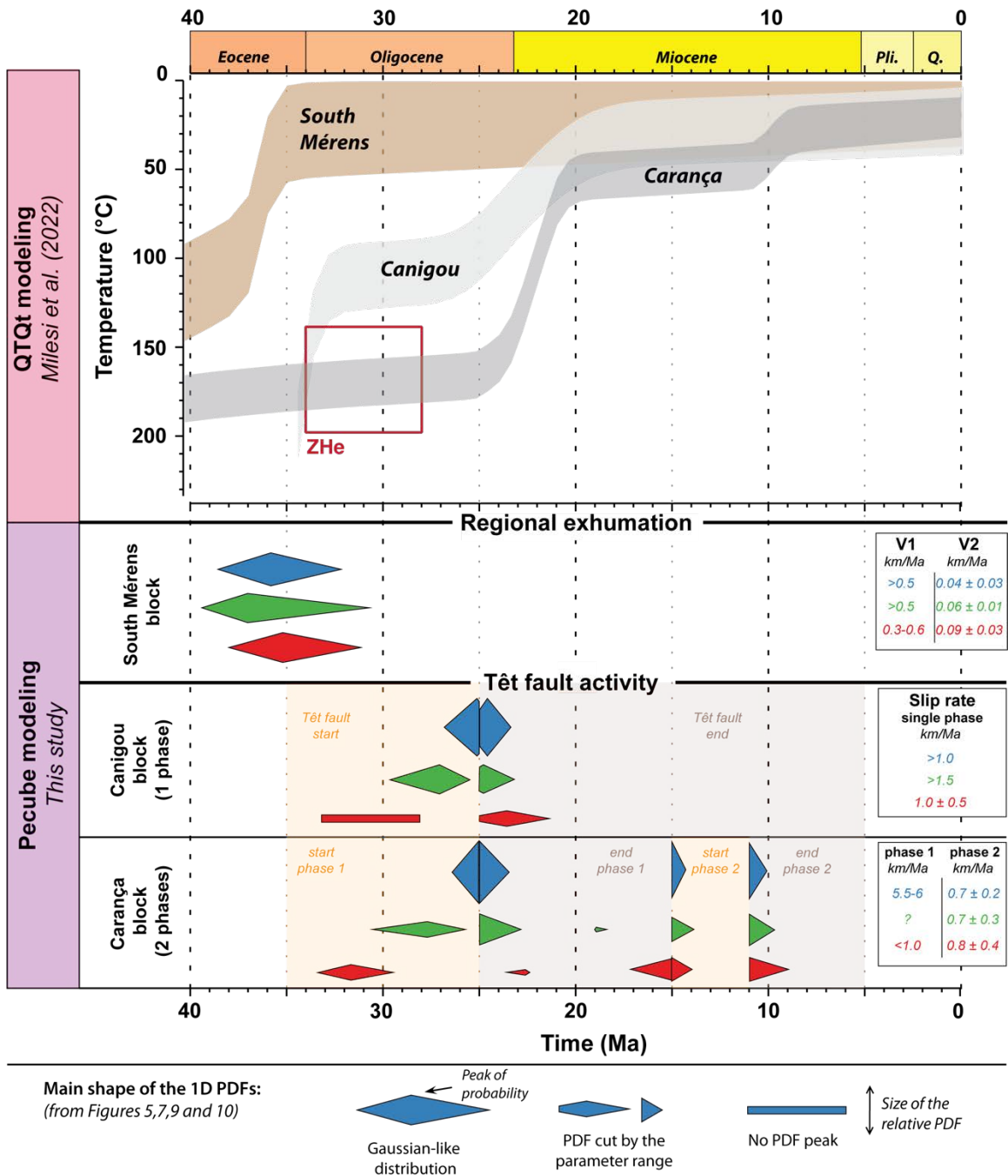
814

815 Figure 11. Age-elevation profiles with best-fitting predicted vs. observed AHe, AFT and
 816 ZHe ages and MTLs, and output thermal histories from the Carança block. a-b) Black
 817 dots (AHe, a), squares (AFT, b), diamonds (ZHe, b) and triangle (MTL, subplot in b) are
 818 observed data and associated uncertainties. Colored dots, squares, diamonds and triangles
 819 are predicted data for the 3 TEMs. c-d) Best-fitting output thermal histories for top (c)
 820 and bottom (d) samples of the Carança block, considering the 3 different TEMs. Inset
 821 plot shows the predicted cooling rates for the 3 TEMs.
 822

823 Table 1. Synthesis of Pecube inversion results

Parameters	Range	Pecube inversion results		
		<i>South Merens block</i>		
		<i>No topographic change</i>	<i>Global Pyrenees</i>	<i>Eastern Pyrenees</i>
Transition time (Ma)	0-60	36.0 ± 1.5	37.0 ± 2.1	35.2 ± 1.8
V1 (km/Ma)	0-2	>0.5	>0.5	0.3-0.6
V2 (km/Ma)	0-1	0.04 ± 0.03	0.06 ± 0.01	0.09 ± 0.03
		<i>Canigou block</i>		
		<i>No topographic change</i>	<i>Global Pyrenees</i>	<i>Eastern Pyrenees</i>
Têt fault start (Ma)	25-35	26-25	28-26	>28
Têt fault end (Ma)	25-5	24.5	24.5	23.5 ± 1.5
Slip rate (km/Ma)	0-6	>1.0	>1.5	1.0 ± 0.5
		<i>Carança block</i>		
		<i>No topographic change</i>	<i>Global Pyrenees</i>	<i>Eastern Pyrenees</i>
Têt fault start phase 1 (Ma)	35-25	26-25	28.0 ± 2.0	32 ± 1.0
Têt fault end phase 1 (Ma)	25-15	25-24	25-24	15
Slip rate phase 1 (km/Ma)	0-6	5.5-6	-	<1.0
Têt fault start phase 2 (Ma)	11-15	15	15	15
Têt fault end phase 2 (Ma)	5-11	11	11	11
Slip rate phase 2 (km/Ma)	0-4	0.7 ± 0.2	0.7 ± 0.3	0.8 ± 0.4

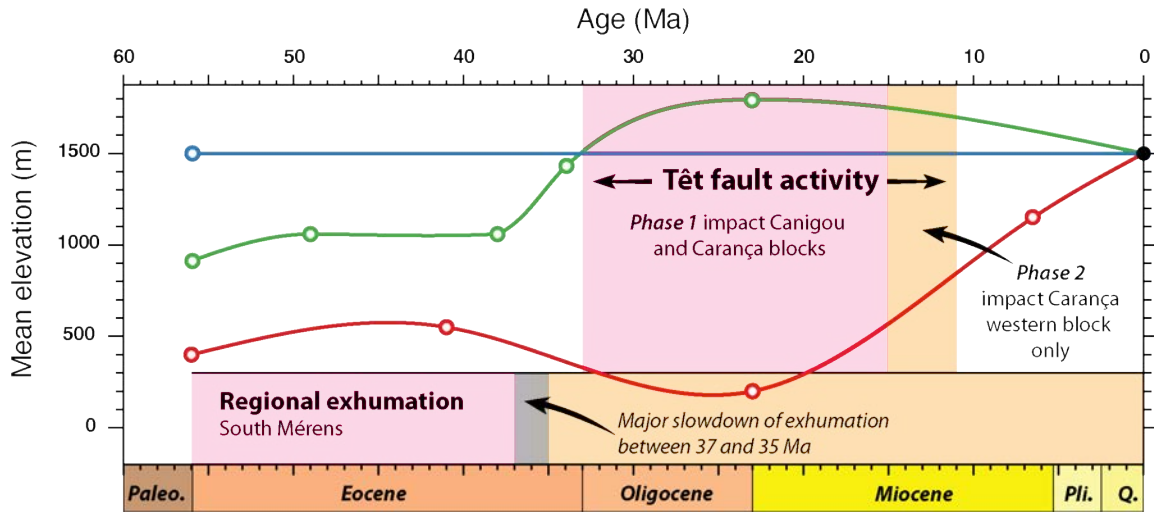
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826 Figure 12. Summary results of QTQt thermal modeling (modified after Milesi et al.,
 827 2022; red box indicates prescribed time-temperature constraint from ZHe data used in
 828 QTQt modeling) and 3D Pecube inversions from this study, using 3 different TEMs
 829 (blue: No topographic change, green: Global Pyrenees, and red: Eastern Pyrenees).
 830 Diamonds schematically (see legend for details) represent the probability density
 831 functions (PDFs) for the timing of the different exhumation or fault-activity phases: PDF
 832 values >0.2 are considered for South Mérens inversion, and >0.1 for Canigou and
 833 Carança inversions. Output exhumation and fault-slip rates are indicated (bottom right).

834 Time ranges explored for the start and the end of the Têt fault activity are indicated in
835 light orange and light grey colors, respectively.



836

837 Figure 13. Summary information of the three topographic evolution models (TEMs) used
 838 in Pecube thermo-kinematic modeling (blue: No topographic change; green: Global
 839 Pyrenees; red: Eastern Pyrenees, see Section 3.3 for further details). The temporal
 840 windows highlighted in light pink (i.e. 55-37 Ma for the regional exhumation and 33-15
 841 Ma for the Têt fault activity) and light orange (i.e. 35-0 Ma for the regional exhumation
 842 and 15-11 Ma for the Têt fault activity) represent divergent and convergent Pecube
 843 inversion results (Fig. 12) between the different TEMs, respectively. See text for details.

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