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1           **Oligocene-Early Miocene topographic relief generation of**  
2                           **southeastern Tibet triggered by thrusting**

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19       **Key Points:**

- 20           • The Jianchuan basin experienced 2.3-3.2 km of exhumation at a rate of 0.57-
- 21           0.80 km/Myr at ~28-20 Ma.
- 22           • Exhumation of the Jianchuan basin was accomplished prior to *ca.* 20 Ma.
- 23           • Topographic relief in southeastern Tibet is partly produced by thrusting along
- 24           the Yulong thrust belt during the Oligocene-Early Miocene.
- 25

26 **Abstract**

27 The timing and mechanisms of uplift in southeastern Tibet remain disputed. To address  
28 this debate, we conducted structural and morphological analyses of the Yulong thrust-  
29 belt; we also reconstruct the cooling and exhumation history of the Jianchuan basin in  
30 the hanging wall of the thrust system using inverse thermal modeling of apatite fission-  
31 track and (U-Th)/He thermochronology data. Our results provide evidence for 2.3-3.2  
32 km of rapid exhumation in the Jianchuan basin between ~28 and ~20 Ma, followed by  
33 limited exhumation of less than 0.2 km since then. The magnitude of basin exhumation  
34 is consistent with the present-day topographic step of 1.8-2.4 km across the Yulong and  
35 Chenghai thrust belts, as shown by morphometric analysis. We thus infer that the  
36 present-day morphology of the southeastern margin of Tibet results partly from  
37 thrusting along the Yulong thrust belt during the Late Oligocene-Early Miocene. This  
38 structure may be the southwest continuation of the Longmen Shan thrust belt, offset by  
39 the Xianshuihe fault in the Late Miocene. On a regional scale, the approximate  
40 synchronicity of exhumation in the hanging walls of the Yalong-Yulong and Longmen  
41 Shan thrust systems indicates that widespread crustal shortening and thickening took  
42 place in southeastern Tibet during the Late Oligocene-Early Miocene.

## 43 **1 Introduction**

44 Southeastern Tibet is characterized by widespread high-elevation ( $\geq 4000$  m a.s.l.), low-  
45 relief surfaces (Clark et al., 2005a; Liu-Zeng et al., 2008) and a transition towards lower  
46 elevations in the southeast (Figure.1A). Understanding the origin of this landscape is  
47 critical to decipher between two end-member models for the tectonic evolution of this  
48 area: block extrusion (e.g., Tapponnier et al., 1982, 2001) and lower crustal flow (e.g.,  
49 Royden et al., 1997; Clark and Royden, 2000). The former model predicts large-scale  
50 lateral block escape along major strike-slip faults together with crustal shortening on  
51 the margins of the plateau, while the latter foresees distributed crustal thickening in the  
52 plateau interior followed by propagation of the high altitudes toward the southeast,  
53 resulting in a continuous gentle topographic slope. In addition, other models emphasize  
54 that a significant part of the topography may be inherited from crustal deformation prior  
55 to the India-Asian collision (e.g., Kapp et al., 2007; Rohrmann et al., 2012). The  
56 temporal and spatial links between crustal deformation (i.e., shortening) and building  
57 of topography are thus key to distinguish between these competing models.

58

59 The timing of topographic growth of southeastern Tibet remains controversial. Incision  
60 of the Jinsha-Yangtze River and its major tributaries, dated at  $\sim 13-9$  Ma by low-  
61 temperature thermochronology, has been interpreted as a proxy for the onset of uplift  
62 driven by lower crustal flow (Clark et al., 2005a; Ouimet et al., 2010). However, much  
63 older incision ages of  $\sim 22-15$  Ma and  $\sim 18-9$  Ma recorded by low-temperature

64 thermochronology (Tian et al., 2014) and cosmogenic nuclides (McPhillips et al., 2015)  
65 have been proposed for the paleo-Jinsha River, suggesting that the pattern of uplift may  
66 be more complex. Moreover, it has recently been proposed that Mid-Miocene river  
67 incision in southeastern Tibet may respond to a climatic rather than a tectonic-uplift  
68 trigger (Nie et al., 2018). Stable-isotope paleoaltimetry results indicate that western  
69 Yunnan probably attained its present-day elevation of ~3.3 km in the Late Eocene  
70 (Hoke et al., 2014). Paleoaltimetry data from the Shuanghe Formation (Fm.) in the  
71 Jianchuan basin were initially interpreted to indicate that the basin had reached an  
72 elevation of ~2.6 km in the Early Miocene (Li et al., 2015). However, Gourbet et al.  
73 (2017) have subsequently demonstrated that the Shuanghe Fm. is in fact Late Eocene  
74 in age, and re-evaluated the same data to indicate a lower elevation of  $\sim 1.2 \pm 1.2$  km at  
75 that time.

76

77 Since the Eocene, southeastern Tibet has been affected by the Oligocene-Miocene  
78 Ailao Shan-Red River (ASRR) left-lateral shear zone, the kinematics of which is well  
79 documented (Leloup et al., 1995, 2001; Replumaz et al., 2001; Figure 1): 700±200 km  
80 of initial left-lateral offset were followed by reversal to right lateral strike-slip as the  
81 Red River fault system. Although local uplift/exhumation along the ASRR may be  
82 linked to these kinematics (Leloup et al., 2001), they do not provide a viable mechanism  
83 for regional uplift of southeastern Tibet as the fault strikes perpendicular to the  
84 topographic margin. Thus, regional uplift is attributed either to lower-crustal channel

85 flow (Schoenbohm et al., 2006), or to crustal thickening along several thrust systems,  
86 such as the Yulong thrust belt (YTB), Muli thrust, Jinghe-Qinhe thrust belt (JQTB) and  
87 Chenghai thrust (CHT) (Liu-Zeng et al., 2008; Perrineau, 2010; Figure 1). However,  
88 the kinematics of these thrust belts and their relationships with exhumation and relief  
89 production are still poorly constrained.

90

91 In this paper, we reconstruct the cooling and exhumation history of the Jianchuan basin,  
92 located in the hanging wall of the YTB, using inverse thermal modeling of apatite  
93 fission-track (AFT) and (U-Th)/He (AHe) thermochronology data. These results enable  
94 us to link significant relief generation of southeastern Tibet during the Oligocene-Early  
95 Miocene to regional thrusting in the context of crustal compression.

96

## 97 **2 Geological setting**

98 Southeastern Tibet is divided into several tectonic blocks (e.g., the Chuandian and  
99 Indochina blocks) by large-scale strike-slip faults (Figure 1A). Its high-elevation  
100 plateau topography is dissected by a distinctive parallel, southeast-flowing river  
101 network. Along the eastern plateau margin, the Longmen Shan represents a steep  
102 topographic barrier adjacent to the Sichuan Basin and records two major phases of  
103 exhumation, from ~30 to 25 Ma and ~15 to 10 Ma, respectively (E. Wang et al., 2012).  
104 The earlier episode of exhumation is interpreted to be related to thrusting along the  
105 Longmen Shan thrust belt (E. Wang et al., 2012). In contrast, Miocene exhumation of

106 the Longmen Shan has been linked to similar cooling phases in southeastern Tibet  
107 (Figure 1A) and has been interpreted to be related either to lower-crustal flow (Clark et  
108 al., 2005a; Ouimet et al., 2010) or to continued thrusting.

109

110 To the southwest of the Longmen Shan, across the Xianshuihe left-lateral strike-slip  
111 fault, the margin of the plateau corresponds to the Yalong-Yulong thrust belt  
112 comprising the Muli, Yulong, Chenghai and Jinhe-Qinghe thrust belts (Figure 1). This  
113 fault system coincides with a series of topographic steps along which elevation  
114 decreases from ~4.2 km to ~1.8 km over a distance of 200-250-km (Liu-Zeng et al.,  
115 2008). The Muli thrust and JQTB were interpreted to represent the southward  
116 continuation of the Longmen Shan thrust belt (Wang et al., 1998) and thus to have  
117 possibly accumulated a few tens of kilometers of shortening during Oligocene-Miocene  
118 times (Burchfiel et al., 1995), which may have induced ~2 km of surface uplift (Clark  
119 et al., 2004). Based on geological cross sections, Perrineau (2010) estimated ~12 km of  
120 Cenozoic shortening across the JQTB and ~3.5 km of uplift in its hanging wall. For the  
121 Muli thrust, Cenozoic shortening is estimated at  $\geq 22.5$  km and the magnitude of uplift  
122 at ~3.5 km (Perrineau, 2010). AFT data interpreted to come from the hanging wall of  
123 the JQTB revealed an increase of the apparent exhumation rate at  $17 \pm 2$  Ma, which was  
124 interpreted to be related to initial thrusting while the fault presumably acted as a  
125 transpressive termination of the Xianshuihe fault (S. Wang et al., 2012). Others have  
126 proposed that the Xianshuihe fault in this area initiated at ~9 Ma, and displaced former

127 thrusts by ~60 km (Zhang et al., 2017). The N-S-striking Yulong and Chenghai thrusts  
128 crosscut Eocene deposits (BGMRY, 1990), and thus postdate the Eocene. About 20 km  
129 west of the YTB, the Yulong anticline lies in the hanging wall of the fault, with a fold  
130 axis parallel to the fault (Figure 2). A  $^{40}\text{Ar}/^{39}\text{Ar}$  K-feldspar plateau age from a mica-  
131 schist sample suggests that folding took place at  $\sim 17 \pm 3.5$  Ma (Lacassin et al., 1996).

132

133 These folds and thrusts are affected by N-S striking active normal faults that bound  
134 Pliocene-Quaternary basins (Figure 2). These faults constitute the Lijiang pull-apart  
135 system between the active Zhongdian and Red River faults (Leloup et al., 1995). The  
136 YTB and CHT are not found across the Red River fault, which roughly follows the  
137 trace of the Oligocene-Miocene ASRR (Figure 1A). The onset timing for sinistral  
138 shearing of the ASRR remains debated, ranging from ~34 to 28 Ma (Cao et al., 2011;  
139 Leloup et al., 1995, 2001; Palin et al., 2013). Left-lateral shear probably ceased at ~17  
140 Ma (Leloup et al., 2001). Reactivation of the Red River fault in a dextral sense occurred  
141 at ~10-5 Ma and ~25 km offset has accumulated since then (Leloup et al., 1993;  
142 Replumaz et al., 2001).

143

144 The Late Eocene Jianchuan basin is bounded by the Qiaohou thrust belt to the west and  
145 the Jianchuan fault to the east (Figures 2 and 3). Thrusting along the Qiaohou thrust  
146 belt induced folding of the basin interior in the Late Eocene or later (Gourbet et al.,  
147 2017). In contrast, the Jianchuan fault, part of the Red River fault system, probably



148 initiated in a normal sense synchronous with dextral strike-slip of the main fault in the  
149 Late Miocene (Leloup et al., 1995; Replumaz et al., 2001), which likely controls the  
150 Pliocene-Quaternary Dianwei pull-apart basin (Leloup et al., 1995; Wang et al., 1998).  
151 The Jianchuan basin contains >5.5 km of Paleogene fluvial-lacustrine and volcanic  
152 deposits (Figures 2 and 3) and records intensive magmatism at ~35-36 Ma (Gourbet et  
153 al., 2017; Lu et al., 2012). Robust zircon U-Pb geochronologic dating on igneous rocks  
154 crosscutting the lower part of the Paleogene fluvial-lacustrine sediments (i.e., E<sub>1m</sub>, E<sub>2b</sub>,  
155 E<sub>2jz</sub>) and interstratified within the upper part of the Paleogene volcanic sediments (i.e.,  
156 E<sub>2s</sub>, E<sub>2jc</sub>) indicates that the Cenozoic formations within the basin are mostly Eocene in  
157 age, and particularly that Oligocene-Miocene sediments are absent (Gourbet et al.,  
158 2017; Figures 2 and 3).

159

### 160 **3 Structural and morphometric analysis**

#### 161 3.1 The Yulong thrust belt (YTB)

162 The YTB consists of several branches and runs for over ~160 km from south of Heqing  
163 to the east of the Yulong Xue Shan range (Figure 2A). The fault trend changes from  
164 NNE-SSW in the south to N-S in the north (BGMRY, 1990; Figure 2A). The southern  
165 portion of the main fault extends along the eastern margin of the Heqing basin and has  
166 been locally obscured by later normal faulting. Structural investigation at five sites  
167 (JC46, CD101, CD305, CD306 and CD357; Figure 2) allowed us to characterize the  
168 kinematics of these brittle faults. At sites CD101, CD305 and CD357, the fault-damage

169 zone is characterized by intense brittle deformation, with unsolidified to semi-solidified  
170 fault breccias and cataclasite (Figures 4A and 4B). The thrust faults strike NNE-SSW  
171 and dip between 35 and 80° to the west (Figures 2B and 2C). The lense-shaped breccias,  
172 fractures and slickensides in the fault zones indicate reverse motion with a minor strike-  
173 slip component (Figures 2B, 2C, 4C, 4D and 4E). At a larger scale, the principal fault  
174 of the YTB is a thrust that locally places Triassic sediments over Eocene conglomerates  
175 equivalent to the basal rocks of the Baoxiangsi Fm. (E<sub>2b</sub>) in the Jianchuan basin  
176 (Figures 4C and 4E). Another possible splay of the YTB brings Permian basalts and  
177 Paleozoic metamorphic rocks on top of Triassic sediments between the Heqing and  
178 Jianchuan basins (Figures 2A and 2E).

179

180 In the north, the Yulong anticline is located in the hanging wall of the YTB, ~20 km  
181 west of the main thrust. Its fold axis trends N 175° (Lacassin et al., 1996), parallel to  
182 the thrust, suggesting that these two structures are genetically related. The timing of  
183 folding is estimated to be 17±3.5 Ma (Lacassin et al., 1996). Within the Jianchuan basin,  
184 Gourbet et al. (2017) have shown that Late Eocene sediments of the Shuanghe (E<sub>2jc</sub>)  
185 and Jiuziyan Fms. (E<sub>2jz</sub>) are folded with an axis trending N 7°, parallel to the YTB  
186 (Figure 2A). To the east of the Pliocene-Quaternary Heqing basin, Eocene  
187 conglomerates are crosscut by the NNW-trending thrust faults of the YTB (Figures 3C,  
188 3D and 4). Geological mapping shows a Triassic sliver lying on top of the Eocene in  
189 that area (BGMRY, 1990; Figure 2). These observations imply that the YTB initiated

190 after the Late Eocene (~35 Ma). The YTB thrusts are cut by steep N-S-striking normal  
191 faults bounding the Pliocene-Quaternary Heqing basin to the east (Figures 2A, 2D, 2E  
192 and 3). Assuming that these normal faults initiated at ~5 Ma, as suggested by the timing  
193 of onset of the Dali normal fault located 90 km south of Heqing (Leloup et al., 1993),  
194 the YBT could have been active after ~35 Ma and prior to ~5 Ma ago.

195

### 196 3.2 Topography of the southeastern Tibet margin

197 A topographic swath across the Jianchuan basin, the YTB and the CHT shows a marked  
198 decrease in elevation from west to east, with two steps broadly coinciding with the  
199 Yulong (from ~3.5 km to ~2.7 km a.s.l.) and Chenghai (from ~2.7 km to ~1.6 km a.s.l.)  
200 thrust belts (Figure 1B). West of the first topographic step, in the hanging wall of the  
201 YTB, an area with a mean elevation of ~3.5 km encompasses most of the Jianchuan  
202 basin. The present-day landscape is characterized by relict low-relief surfaces as  
203 defined by Clark et al. (2006) and Liu-Zeng et al. (2018), but is locally controlled by a  
204 set of normal faults bounding the Pliocene-Quaternary Dianwei and Heqing basins  
205 (Figures 2, 3, 4G, 4H and 4I). Between the YTB and the CHT-JQTB, the mean  
206 elevation is ~2.7 km and the landscape is shaped by incision of the Jinsha River and  
207 normal faults bounding the Chenghai Lake. The mean elevation increases gradually to  
208 the east close to the CHT-JQTB, which defines a prominent topographic step from ~2.7  
209 km to ~1.6 km, suggesting significant control of thrusting on relief production. In the  
210 footwall of the CHT-JQTB, the topography decreases gradually to ~1.6 km (Figure 1B).

211

## 212 **4 Methodology and sampling**

213 Apatite fission track (AFT) and apatite (U-Th)/He (AHe) are the two main low-  
214 temperature thermochronometers that allow placing constraints on thermal histories of  
215 upper crustal rocks related to faulting and/or erosion (Ehlers, 2005; Reiners and  
216 Brandon, 2006). They are sensitive to cooling at crustal levels of between 1 to 5 km  
217 depth, corresponding to their closure temperatures ranging from 40 to ~120 °C,  
218 depending on holding time and composition (Reiners and Brandon, 2006). To constrain  
219 the timing and rate of Jianchuan basin exhumation, we collected thirteen samples from  
220 Late Eocene syenitic plutons, two from Proterozoic gneiss and one from Eocene  
221 sandstone along two elevation transects (i.e., Laonjun Shan and Shamao Shan; Figures  
222 2 and 5; Table 1) for AFT analysis. AHe dating for the Laojun Shan has been reported  
223 by Shen et al. (2016); we included these data in our inverse modeling. Two samples  
224 from the Shamao Shan were analyzed for AHe (Table 1). Apatite crystals were  
225 concentrated using standard mineral separation procedures, including crushing, sieving,  
226 magnetic and heavy-liquid separation.

227

### 228 4.1 AFT

229 AFT analyses were accomplished at Apatite to Zircon, Inc., Viola, Idaho, USA. All  
230 samples were analyzed using the LA-ICP-MS approach to determine U-content. The  
231 procedures and methods for sample preparation are outlined in Donelick et al. (2005).

232 Apatite aliquots were mounted in epoxy and polished, and then etched in a 5.5 M HNO<sub>3</sub>  
233 solution at 21 °C for 20 s. U contents were acquired using a New Wave Neodymium-  
234 YAG 213 nm laser ablation system coupled to a Finigan Element II Magnetic Sector  
235 ICP-MS at a 12 µm spot and a 5 Hz repetition rate with the laser set in constant energy  
236 mode. Analyses were corrected by <sup>43</sup>Ca as an internal standard for variations in ablation  
237 volume.

238

#### 239 4.2 AHe

240 AHe analyses were performed at the University of Arizona, USA. Typically, 3-5 clear,  
241 intact and euhedral apatite crystals were selected. The dimension of each grain was  
242 measured and photographed. Only grains larger than 60 µm in both length and width  
243 were accepted for (U-Th)/He analysis. The apatite grains were wrapped into Nb foil  
244 tubes and degassed by laser heating, and then analyzed for He using <sup>3</sup>He isotope  
245 dilution, cryogenic purification and quadrupole mass spectrometry. The U, Th and Sm  
246 concentrations of each dissolved aliquot were subsequently measured on a sector  
247 inductively coupled plasma-mass spectrometer. (U-Th)/He ages were corrected for α-  
248 ejection using the equations from Farley (2002). Standard Fish Canyon Tuff zircon and  
249 Durango apatite fragments were analyzed together with unknowns to validate age  
250 determinations, age reproducibility and measurement accuracy.

251

#### 252 4.3 Thermal modeling

253 The thermal histories of the Laojun Shan and Shamao Shan samples were modeled  
254 using the QTQt inverse modeling code (Gallagher, 2012), which allows inferring  
255 thermal histories from multiple samples including different thermochronologic systems  
256 collected along age-elevation profiles. We built two sets of models for comparison  
257 between different input data sets. The first set only includes AFT ages, track length  
258 distributions and kinetic parameters. The second set considers not only the AFT data  
259 but also acceptable single-grain AHe ages, apatite crystal dimensions and U, Th and  
260 Sm concentrations (Table 3). Fission-track annealing and He diffusion algorithms used  
261 for the inverse modeling are from Ketcham et al. (2007) and Gautheron et al. (2009),  
262 respectively.

263

264 For the first set of models, we imposed two time-temperature constraints. An initial  
265 constraint at a temperature of  $750\pm 50$  °C was set up at  $35\pm 2$  Ma, based on the  
266 emplacement ages of the plutons ranging from 33 to 37 Ma (Gourbet et al., 2017; Lu et  
267 al., 2012). A second constraint at a temperature of  $90\pm 30$  °C was set up at  $30\pm 3$  Ma  
268 based on two considerations: first, the rapid thermal equilibration of igneous rocks  
269 emplaced at shallow crustal level ( $< 200$  °C) (Annen, 2011); second, the existence of an  
270 AFT PAZ as inferred from the age-elevation relationship in the Laojun Shan profile  
271 (see below). For the second set of models, we also fixed two time-temperature  
272 constraints. The first constraint is similar to that of the first set of models, while the  
273 second constraint was extended to  $30\pm 5$  Ma and  $90\pm 50$  °C in order to cover the closure

274 temperatures of both the AFT (120-60°C) and AHe (80-40°C) systems, resulting in a  
275 wider range of possible cooling histories.

276

## 277 **5. Results and interpretation**

### 278 5.1 AFT

279 All samples yielded grains that could be satisfactorily analyzed (Table 2). AFT ages  
280 range from 18±5 to 37±4 Ma in the Laojun Shan, and from 21±3 to 35±5 Ma in the  
281 Shamao Shan. All ages pass the  $\chi^2$  test with very low dispersion values, suggesting  
282 single age populations (Galbraith and Green, 1990). Mean track lengths range from  
283 13.8 to 15.1  $\mu\text{m}$ , and show little variation (Figures 5A and 5B; Table 2).

284

285 The Laojun Shan transect includes two groups of samples (Figure 3). One group (JC22  
286 to JC29) was collected along a ~10-km-distance elevation profile downward the Laojun  
287 Shan. The other group (JC30 to JC33) was collected near the village of Shuhe, ~15 km  
288 to the north. The sampled intrusive rocks have a similar age and facies (Lu et al., 2012),  
289 suggesting a similar origin and emplacement depth. The plutons intrude  
290 unmetamorphosed sediments and show a narrow zone with hypovolcanic textures at  
291 their margin, indicative of shallow emplacement. There is little evidence for faulting  
292 between the Laojun Shan and the Shuhe area (Figures 2b and 3). Eocene sediments of  
293 the Jianchuan basin are folded at the contact with magma intrusions and are affected by  
294 N-S folds (Gourbet et al., 2017). However, the Late Eocene Jianchuan Fm. (E<sub>2</sub>jc),

295 which comprises the youngest strata in the basin and was deposited synchronous to the  
296 emplacement of the plutonic rocks, dips monotonically by 15 to 20° to the east (Gourbet  
297 et al., 2017). This implies that there was negligible N-S tilting after ~35 Ma between  
298 the Laojun Shan and Shuhe transects. This is corroborated by samples JC31 (Shuhe)  
299 and JC29 (Laojun Shan), which are located at similar elevations but ~20 km apart, and  
300 have similar AFT cooling ages (Figures 3 and 5A). This similarity suggests little  
301 variation in exhumation depth and geothermal gradient between the two locations. We  
302 therefore integrated the two groups of samples in a single age-elevation transect (Figure  
303 5A).

304

305 This integrated transect has ten samples spanning ~1800 m of elevation (Figures 3 and  
306 5A). The four highest samples (JC22, JC23, JC24 and JC26, between 3500 and 4100 m  
307 elevation) yield pooled AFT ages between  $37.4 \pm 4.1$  Ma and  $31.4 \pm 3.1$  Ma, overlapping  
308 within error the magma intrusive ages of  $35.4 \pm 0.2$  Ma and  $35.3 \pm 0.4$  Ma, as dated by  
309 zircon U-Pb geochronology (Gourbet et al., 2017; Lu et al., 2012; Figure 2). These are  
310 interpreted to record rapid cooling following pluton emplacement at shallow depth. At  
311 elevations between 3500 and 2850 m, AFT ages between  $33.1 \pm 3.4$  and  $20.3 \pm 2.4$  Ma  
312 show a positive correlation between age and elevation with a slope of  $\sim 0.05 \pm 0.02$   
313 km/Myr (Figure 5A; Tables 1 and 2). Mean track lengths (13.8-14.6  $\mu\text{m}$ ) are relatively  
314 long, with standard deviations of 1.1-1.3  $\mu\text{m}$  (Figure 5A; Table 2). , A distinct break in  
315 the slope of the age-elevation relationship, anchored by sample JC29, occurs at an



316 elevation of 2850 m. Below that elevation, AFT ages of  $21.3\pm 4.4$  to  $18.0\pm 5.3$  Ma define  
317 a steep age-elevation trend, but fail to yield a well-constrained apparent exhumation  
318 rate due to large errors (Figure 5A; Table 2). These samples should be fully reset based  
319 on their long AFT track lengths, and narrow, unimodal distribution pattern, which are  
320 consistent with rapid cooling rates (Fitzgerald et al., 1995; Gleadow et al., 1983). The  
321 prominent break in age-elevation slope at  $\sim 20\pm 5$  Ma in the Laojun Shan AFT data thus  
322 suggests the onset of exhumation of a fossil AFT PAZ at that age.

323

324 The Shamao Shan transect has six samples (CD114 to CD118 & CD193) spanning a  
325 limited elevation range between 2276 and 2610 m (Figures 2, 3 and 5B; Table 2).  
326 Crystallization of the Shamao Shan pluton is dated between  $35.0\pm 0.1$  Ma (Schärer et  
327 al., 1994) and  $35.6\pm 0.3$  Ma (Lu et al., 2012). Initial cooling was probably rapid, as a  
328 nearby dyke yields an  $^{40}\text{Ar}/^{39}\text{Ar}$  phlogopite age of  $35.5\pm 1$  Ma, corresponding to a  
329 closure temperature of  $\sim 450\pm 50^\circ\text{C}$  (Gourbet et al., 2017). Similar to the Laojun Shan  
330 pluton, the Shamao Shan pluton was emplaced at shallow depth, but these two plutons  
331 are separated by a series of normal faults (Figures 2 and 3; Gourbet et al., 2017).

332

333 Sample CD115, from an elevation of 2460 m, has an AFT age of  $34.9\pm 4.6$  Ma. This  
334 age overlaps the pluton emplacement age and probably records rapid cooling following  
335 emplacement at shallow depth. The other AFT ages range between 32.5 and 21.0 Ma,  
336 and exhibit a gentle age-elevation trend with a slope of  $\sim 0.03\pm 0.02$  km/Myr (Figure

337 5B; Table 2). These samples have similar track-length distributions to those in the upper  
338 part of the Laojun Shan transect, and thus are interpreted identically. The lowest sample  
339 (CD118, 2276 m) has an age of  $21.0 \pm 3.2$  Ma, close to that of the Laojun Shan profile  
340 at a comparable height (sample JC30). The lack of samples below 2276 m does not  
341 allow detecting if a break in slope exists in the Shamao Shan transect, but a comparison  
342 of the elevation of the interpreted PAZ between the two transects suggests  $\geq 600$  m of  
343 differential uplift between them after  $\sim 20$  Ma. This could be caused by a component of  
344 down-to-the-east movement along normal faults that are parallel to the Jianchuan fault  
345 in between these two profiles (Figures 2 and 3).

346

## 347 5.2 AHe

348 Single-grain AHe ages were obtained from samples CD114 and CD116 in the Shamao  
349 Shan profile (Table 3). Sample CD114 yielded three discordant single-grain ages  
350 between  $34.0 \pm 0.4$  Ma and  $43.4 \pm 0.6$  Ma. These ages were rejected because they are  
351 much older than the corresponding AFT age of  $28.8 \pm 4.6$  Ma, and two of them are older  
352 than the intrusive age of the Laojun Shan pluton ( $35.6 \pm 0.3$  Ma; Lu et al., 2012). The  
353 lower-elevation sample CD116 yielded three single-grain ages between  $26.2 \pm 0.3$  Ma  
354 and  $33.5 \pm 0.4$  Ma (Figure 5B) as well as an outlier at  $91.0 \pm 0.9$  Ma. The  $33.5 \pm 0.4$  Ma  
355 age overlaps the crystallization age of the Shamao Shan pluton and may represent rapid  
356 cooling during shallow emplacement of the pluton. The other ages overlap nearby AFT  
357 ages of samples CD114 and CD117, and record post-intrusion exhumation of the pluton.

358

### 359 5.3 Thermal modeling

360 Based on (U-Th)/He data sampled along the same elevation transect from the Laojun  
361 Shan (Figure 2), Shen et al. (2016) inferred an exhumation episode between 30 and 20  
362 Ma with rates of  $\sim 0.10\text{-}0.18$  km/Myr. However, most of these data yield scattered ages,  
363 with several grain ages older than the timing of magma intrusion (Figure 5A).  
364 Excluding these ages  $>35$  Ma, the other single-grain ages of Shen et al. (2016) are  
365 somewhat younger than our AFT ages at a comparable elevation for high-elevation  
366 samples ( $>3500$  m) and overlap with them at lower elevations (Figure 5A). This  
367 relationship suggests rapid cooling around 20-30 Ma (e.g., Murray et al., 2016), while  
368 the scatter in single-grain AHe ages could be due to variable eU content and/or zoning  
369 of the grains (Shen et al., 2016).

370

371 Modeling results using QTQt (Gallagher, 2012) are presented in Figure 6A-E for AFT  
372 data only, and Figure 6E-H for combined AFT and AHe data, allowing assessment of  
373 the impact of including the AHe data in the thermal history models. The first set of  
374 models, which do not take the AHe data into account, predict best-fit cooling curves for  
375 the Laojun Shan profile that show a four-stage cooling history (Figure 6A-B). Initial  
376 rapid cooling between 35-30 Ma ( $\sim 100$  °C/Myr) reflects thermal equilibration for a  
377 pluton emplaced at shallow crustal levels ( $<200$  °C). Simple conductive cooling  
378 calculations suggest that a pluton emplaced at depths between 5 and 10 km should

379 thermally equilibrate within <1 to ~4 Myr (Braun et al., 2006). This is supported by the  
380 fact that AFT ages of high-elevation samples overlap with pluton-emplacement ages of  
381 ~35 Ma (Figure 5A). Subsequently, the rocks stayed at temperatures ~100 °C for ~5  
382 Myr. We interpret the following rapid cooling between ~24 and ~20 Ma at a rate of ~20  
383 °C/Myr to record rapid exhumation of the rocks, followed by a protracted period of  
384 extremely slow cooling at a rate of <1 °C/Myr (Figure 6A). The predicted AFT ages  
385 and mean track lengths (MTL) fit the observed data (Figure 6B). The predicted ages  
386 show a positive correlation with elevation, but do not clearly show the break-in-slope  
387 inferred from the AFT data (Figure 6B).

388

389 In contrast, modeling results for the Shamao Shan present a three-stage cooling history  
390 (Figure 6C). A first stage of cooling between 35 and 28 Ma is interpreted to result from  
391 thermal equilibration after pluton emplacement, as for the Laojun Shan. The rocks  
392 subsequently experienced cooling between ~28 and ~24 Ma at a rate of ~20 °C/Myr.  
393 The last episode shows extremely slow cooling at a rate of <1 °C/Myr since ~25 Ma,  
394 similar to the Laojun Shan results. The predicted ages and MTL calculated for these  
395 cooling histories reproduce the AFT data reasonably well, even though the predicted  
396 age-elevation gradient is steeper than the observed one (Figure 6D).

397

398 The models taking into account selected AHe data predict best-fit cooling paths for the  
399 Laojun Shan that suggest a three-phase thermal history (Figure 6E). A first stage of

400 cooling between 35-27 Ma ( $\sim 90$  °C/Myr) reflects the same process of thermal  
401 equilibration of the Laojun Shan pluton as in the first set of models (Figure 6A). The  
402 second cooling stage, during  $\sim 27$ -22 Ma at a rate of  $\sim 24$  °C/Myr, is interpreted to result  
403 from rapid exhumation of the rocks, which were brought to near-surface temperatures  
404 at  $\sim 22$  Ma. At that time, the cooling rate decreased dramatically to  $< 0.5$  °C/Myr.  
405 Modeling results for the Shamao Shan pluton (Figure 6G) present similar cooling  
406 histories to the first set of models, but rapid cooling related to rock exhumation is  
407 restricted to a very short time span from  $\sim 29$  to  $\sim 26$  Ma, at a rate of  $\sim 20$  °C/Myr. The  
408 best-fit models including AHe data reproduce the AFT data equally well as those  
409 without, and predict single-grain AHe that lie within the wide range of observed ages  
410 (Figures 6F and 6H).

411

412 In summary, both sets of inverse models show a first-stage of very rapid cooling ( $> 90$   
413 °C/Myr) during 35-30 Ma and 35-28 Ma, which we interpret as recording thermal  
414 equilibration of the Laojun Shan and Shamao Shan plutons, respectively, followed by  
415 rapid exhumational cooling between  $\sim 28$ -20 Ma and residence at surface temperatures  
416 since then. The main difference between the AFT-only models and the models  
417 including AHe data is the timing of the rapid exhumation phase, which takes place  
418 somewhat later ( $\sim 24$ -20 Ma and  $\sim 28$ -24 Ma in the Laojun Shan and Shamao Shan,  
419 respectively) for the AFT-only models than in the models including AHe data ( $\sim 27$ -22  
420 and  $\sim 29$ -26 Ma in the Laojun Shan and Shamao Shan, respectively). However, all

421 models consistently predict ~4 Myr of rapid Late Oligocene-Early Miocene cooling for  
422 both the Laojun Shan and Shamao Shan, at rates of ~20 °C/Myr. Considering  
423 reasonable geothermal values (30±5 °C/km), this corresponds to exhumation rates of  
424 ~0.57-0.80 km/Myr or ~2.3-3.2 km of total exhumation during this time. Both profiles  
425 show exhumation rates lower than ~0.01 km/Myr since ~20 Ma, suggesting less than  
426 0.2 km of exhumation of the Jianchuan basin since the Early Miocene. Rapid Late  
427 Oligocene-Early Miocene basin exhumation is consistent with the absence of coeval  
428 sedimentation within the basin, as recently evidenced by Gourbet et al. (2017).

429

## 430 **6 Discussion**

### 431 6.1 Mechanisms for rapid exhumation of the Jianchuan basin

432 It has been hypothesized that the remnant landscapes of southeastern Tibet correspond  
433 to an erosion surface formed close to sea level that has been passively uplifted by lower-  
434 crustal flow originating from the over-thickened crust of central Tibet (e.g., Clark et al.,  
435 2005b; Royden et al., 1997). The timing of uplift is assumed to correspond to a phase  
436 of accelerated incision of the main rivers that are entrenched in the plateau. It was  
437 inferred that exhumation related to incision started between ~13 and 9 Ma based on  
438 low-temperature thermochronology data (Clark et al., 2005a; Ouimet et al., 2010).  
439 However, other studies suggest that Miocene exhumation related to river incision  
440 started earlier at ~18-9 Ma (McPhillips et al., 2015) or ~22-15 Ma (Tian et al., 2014).  
441 In addition, more local Late-Miocene exhumation events are associated with faulting,

442 as for instance the initiation of the left-lateral transtensive Litang fault system at ~6 Ma  
443 (Zhang et al., 2015), and that of the Xianshuihe fault at ~9 Ma in the Gongga Shan  
444 (Zhang et al., 2017).

445

446 Our thermochronological data and modeling results suggest ~2.3 to 3.2 km of  
447 exhumation of the Eocene Jianchuan basin in the Late Oligocene-Early Miocene  
448 (between ~28 and ~20 Ma). A key question is to decipher the mechanism(s) that drove  
449 basin exhumation. The Jianchuan basin is bounded to the west by the Qiaohou thrust  
450 belt (Figure 2A). These thrusts dip to the west and the Jianchuan basin is located in  
451 their footwall; movement along these thrusts would thus have induced subsidence and  
452 burial of the basin rather than exhumation. Bounding the basin to the east, the Jianchuan  
453 fault shows normal motion with a possible left-lateral component, that could have  
454 induced exhumation of the basin. However, this normal fault is linked to the Lijiang  
455 pull-apart zone that initiated probably at ~5 Ma (Leloup et al., 1993), and in any case  
456 after the end of left-lateral shear along the ASRR at ~17 Ma (Leloup et al., 2001),  
457 incompatible with the ~28-20 Ma cooling/exhumation episode. Within the basin,  
458 several faults trends parallel to the Jianchuan fault (Figure 3) and show both strike-slip  
459 and normal sense of shear (Figure 4G). Mapping of the faults shows that most of them  
460 dip steeply to the ESE and cause downward motion of the eastern compartments  
461 (Figures 2D, 2E, 3 and 4G; Gourbet et al., 2017). Taking the limestone of the Jiuziyan  
462 Fm. (E<sub>2jz</sub>) as a reference bed, we estimated the amount of vertical throw at 400 to 840

463 m (3120/2680 m-2280 m). These values are broadly consistent with the  $\geq 600$  m  
464 vertical throw estimated from the offset of the fossil PAZ between the Laojun Shan and  
465 Shamao Shan. We interpret this as an evidence for a normal component of motion along  
466 NNE-SSW-striking and east-dipping faults in the eastern Jianchuan basin after 20 Ma,  
467 in good accordance with the hypothesis that the Jianchuan fault could be younger than  
468 17 Ma and likely  $\sim 5$  Ma. The offset of the Jianchuan bounding fault is not known, but  
469 appears too small ( $\leq 3$  km) to have brought to the surface in its footwall the post-20  
470 Ma AFT PAZ. The Qiaohou and Jianchuan faults now bounding the basin thus do not  
471 appear responsible for Late Oligocene-Early Miocene exhumation of the Jianchuan  
472 basin.

473

474 Alternatively, Shen et al. (2016) proposed that Late Oligocene-Early Miocene basin  
475 exhumation, at a relatively slow rate of  $\sim 0.10$ - $0.18$  km/Myr as inferred from their AHe  
476 data, was linked to river incision related either to early lower-crustal flow or to  
477 transpressional deformation in southeastern Tibet. However, these authors did not  
478 elucidate how the river incision was genetically linked with evolution of local rivers  
479 (e.g., Jinsha River) and which transpressional structure(s) could account for the  
480 exhumation. Whether the ancient Jinsha River flowed through the Jianchuan basin is  
481 largely disputed (e.g., Clark et al., 2004; Wei et al., 2016; Wissink et al., 2016). Eocene  
482 fluvial sediments of the Baoxiangsi Fm. (E2b; Figure 2) indicate that a large braided  
483 river flowed through the Jianchuan basin before  $\sim 36$  Ma (Gourbet et al., 2017) but this



484 predates basin exhumation by more than 10 Ma. Recent cosmogenic nuclide studies on  
485 cave sediments near the first bend of the modern Jinsha River (Figure 2) suggest ~1 km  
486 river incision during 18-9 Ma (McPhillips et al., 2015), thus postdating Jianchuan basin  
487 exhumation. Our new data show that major exhumation of the Jianchuan basin took  
488 place during the Late Oligocene-Early Miocene, with extremely low exhumation of  
489 <0.2 km since then ruling out southward flow of a large river across the basin in the  
490 Neogene. Therefore, neither the paleo ( $\geq 35$  Ma) nor modern ( $\leq 20$  Ma) Jinsha river  
491 may have been responsible for the Late Oligocene-Early Miocene (~28-20 Ma)  
492 exhumation of the Jianchuan basin. In contrast, the timing of river diversion is broadly  
493 compatible with exhumation of the basin and could be genetically related to it.

494

495 Another possibility is that thrusting of the N-trending, W-dipping YTB may have  
496 triggered exhumation of the Jianchuan basin. Crosscutting relationships indicate that  
497 thrusting took place between ~35 Ma and ~5 Ma. The timing of folding of the Yulong  
498 anticline, estimated at  $17 \pm 3.5$  Ma (Lacassin et al., 1996), is roughly compatible with  
499 the age of the YTB. This age encompasses within uncertainties that of rapid exhumation  
500 of the Jianchuan basin. Therefore, we argue that exhumation of the Jianchuan basin was  
501 probably related to thrusting along the YTB. Associated folding and uplift in the YTB  
502 and Yulong anticline could have been responsible for diversion of the Jinsha River to  
503 its modern course, consistent with a major change in composition of Red River-derived  
504 sediments in the Hanoi basin  $\geq 24$  Ma (Clift et al., 2006).

505

506 Based on their morphologic analysis, Liu-Zeng et al. (2008) proposed that the steep  
507 topographic step of ~1.8-2.4 km between the Yunnan highlands and southeastern Tibet  
508 (Figure 1) was possibly linked to Cenozoic thrusting. AFT ages of ~27-100 Ma with  
509 relatively short track lengths (Wilson and Fowler, 2011; Figure 1) suggest that rocks in  
510 the hanging wall of these thrusts (i.e., YTB and CHT) have been less exhumed than  
511 those in the footwall, as for example in the Jianchuan basin. Our estimate of ~2.3-3.2  
512 km of Late Oligocene-Early Miocene rapid rock exhumation in the hanging wall of the  
513 YTB would broadly correspond to the present-day ~1.8-2.4 km of topographic step  
514 across the YTB and CHT-JQTB, notwithstanding that the topography has later been  
515 disturbed by normal faulting that locally created Pliocene-Quaternary basins (Figures  
516 1B and 3). Such an amount of basin exhumation is roughly compatible with the  
517 magnitude of Oligocene-Miocene shortening and rock uplift across the YTB and CHT-  
518 JQTB (Clark et al., 2004; Perrineau, 2010).

519

520 However, our evidence for Late Oligocene-Early Miocene rapid exhumation of the  
521 Jianchuan basin does not exclude the possibility that substantial crustal thickening and  
522 corresponding elevation gain in southeastern Tibet occurred prior to the Oligocene or  
523 even the India-Asian collision. For example, Lacassin et al. (1996) documented an early  
524 phase of deformation in the Yulong anticline at ~36 Ma, which they interpreted as a  
525 phase of crustal thickening predating initiation of left-lateral shear along the ASRR.

526 Tapponnier et al. (2001) interpreted significant Eocene thickening of southeastern Tibet  
527 as a first stage of building of the Tibetan plateau. Recently, a multiple-  
528 thermochronometer study revealed two periods of rapid rock exhumation during the  
529 Middle to Late Cretaceous and Early Cenozoic for the low-relief areas in southeastern  
530 Tibet (Liu-Zeng et al., 2018). These two exhumation events are broadly consistent with  
531 rapid exhumation in central Tibet between 85-45 Ma (Rohrmann et al., 2012) and  
532 probably resulted from significant crustal shortening during the collision between the  
533 Lhasa and Qiangtang terranes (e.g., Kapp et al., 2005, 2007). Such early thickening  
534 could have triggered moderate surface uplift recorded by paleoaltimetry analyses (Hoke  
535 et al., 2014; Li et al., 2015; Tang et al., 2017) and erosion of parts of the eastern and  
536 southern Tibetan plateau, clasts from which were deposited in Eocene basins such as  
537 the Jianchuan basin. Our data only document exhumation of the Jianchuan basin after  
538 basin infilling, and thus neither confirm nor preclude the existence of Cretaceous to  
539 Eocene crustal shortening that could have partly shaped the landscape of the margins  
540 of southeastern Tibet.

541

## 542 6.2 Regional tectonic implications

543 Exhumation of the Jianchuan basin at ~28-20 Ma is broadly coeval with other  
544 exhumation events around the southeastern Tibet (Figure 1A), suggesting a regional  
545 cause for exhumation. The Longmen Shan thrust belt could have extended southward,  
546 merging with the YTB prior to offset by the Xianshuihe fault (Burchfiel et al., 1995;

547 Wang et al., 1998; Yan and Lin, 2015). In this case, upper crustal shortening and  
548 thickening probably affected a large area from the Longmen Shan to the Laojun Shan  
549 in the Oligocene-Early Miocene (Figure 1A), and would be responsible for the  
550 generation of similar topographic relief above major thrust faults along the margins of  
551 southeastern Tibet. However, Oligocene-Miocene sediments are pervasively absent in  
552 the footwalls of the Yalong-Yulong and Longmen Shan thrust belts (BGMRY, 1990;  
553 Deng et al., 2017). This is also the case for some large basins in southeastern Tibet, as  
554 for instance the Sichuan, Xichang and Chuxiong basins (Deng et al., 2017; Figure 1A).  
555 One possible explanation is that southeastern Tibet was not a closed system for water  
556 and sediments (Richardson et al., 2008); large amounts of eroded sediments may have  
557 been transferred by large rivers and eventually deposited into the peripheral seas. Rapid  
558 exhumation in the hanging walls of the thrusts led to accelerating surface erosion and  
559 ultimately may have contributed significantly to the peak in sediment fluxes observed  
560 in southeast Asia seas during Oligocene-Miocene times (Clift, 2006).

561

562 At a regional scale, Late Oligocene-Early Miocene crustal shortening and thickening  
563 coincides with strong left-lateral shearing along the ASRR (Leloup et al., 2001), as well  
564 as with activity of the Jiali (Lee et al., 2003; Lin et al., 2009) and Chongshan (Zhang et  
565 al., 2012) shear zones. These kinematics indicate SE-NW regional compression related  
566 to convergence between the northwest corner of the India plate and the Asian plate at  
567 this time. The end of this episode of crustal shortening generally predated the onset of

568 the left-lateral Kunlun strike-slip fault (Duvall et al., 2013; Jolivet et al., 2003), Ganzi-  
569 Xianshuihe-Xiaojiang fault (Wang et al., 2009; Zhang et al., 2017), Litang fault (Zhang  
570 et al., 2015) and dextral strike slip of the Gaoligong fault (Lin et al., 2009; Zhang et al.,  
571 2010). Overall, the synchronicity of major crustal deformations favours a Late  
572 Oligocene-Early Miocene tectonic configuration in which a southward extruded block  
573 was bounded by the Jiali fault-ASRR to the southeast (e.g., Lin et al., 2009; Zhang et  
574 al., 2010), with the YTB, Chenghai, Muli, Jinghe-Qinghe and Longmen Shan thrust  
575 belts further north that created topographic relief on the margins of southeastern Tibet  
576 (Figure 7).

577

## 578 **7 Conclusions**

579 In order to unravel the timing and mechanisms of uplift of southeastern Tibet, this study  
580 presents structural and morphological analyses of the YTB, and reconstructs the cooling  
581 and exhumation history of the Jianchuan basin through thermal modeling of AFT and  
582 AHe thermochronology data. Structural analysis along the YTB provides evidence for  
583 post-Eocene thrusting, coincident with a present-day topographic step of 1.8-2.4 km  
584 detected by morphometric analysis. AFT and AHe thermochronology assisted by  
585 thermal modeling reveals 2.3-3.2 km of rapid exhumation in the Jianchuan basin in the  
586 hanging wall of the YTB in the Late Oligocene-Early Miocene (~28-20 Ma) at a rate  
587 of ~0.57-0.80 km/Myr. Exhumation of the Jianchuan basin since ~20 Ma is limited to  
588 <0.2 km. These results suggest that activity of the YTB occurred during the Late

589 Oligocene-Early Miocene, synchronous with and related to thrusting in the Longmen  
590 Shan, and that drainage rearrangement and topographic relief development on the  
591 margins of southeastern Tibet could have been mostly generated by thrusting at that  
592 time.

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608 (<https://figshare.com/s/69ecce70ba9a99443b22>).

Table 1. Sample information in the Jianchuan basin, western Yunnan.

Sample	Lithology	Era	Longitude (°E)	Latitude (°N)	Elevation (m)	Dating method
JC22	Syenite	35.4 ± 0.3 Ma <sup>a</sup>	99.7043	26.6302	4045	AFT
JC23	Syenite	35.4 ± 0.3 Ma <sup>a</sup>	99.7128	26.6320	3953	AFT
JC24	Syenite	35.4 ± 0.3 Ma <sup>a</sup>	99.7302	26.6433	3832	AFT
JC26	Sandstone	Eocene	99.7683	26.6451	3491	AFT
JC27	Porphyry	35.4 ± 0.3 Ma <sup>a</sup>	99.7807	26.6607	3317	AFT
JC28	Porphyry	35.4 ± 0.3 Ma <sup>a</sup>	99.8009	26.6595	3058	AFT
JC29	Porphyry	35.4 ± 0.3 Ma <sup>a</sup>	99.8150	26.6561	2848	AFT
JC30	Porphyry	35.7 ± 0.2 Ma <sup>a</sup>	99.7718	26.7779	2130	AFT
JC31	Gneiss	Proterozoic	99.8125	26.8224	2724	AFT
JC33	Gneiss	Proterozoic	99.8153	26.7891	2019	AFT
CD114	Porphyry	35.6 ± 0.3 Ma <sup>a</sup>	99.9087	26.5874	2531	AFT, AHe
CD115	Porphyry	35.6 ± 0.3 Ma <sup>a</sup>	99.9100	26.5877	2460	AFT
CD116	Porphyry	35.6 ± 0.3 Ma <sup>a</sup>	99.9111	26.5883	2394	AHe
CD117	Porphyry	35.6 ± 0.3 Ma <sup>a</sup>	99.9115	26.5887	2342	AFT
CD118	Porphyry	35.6 ± 0.3 Ma <sup>a</sup>	99.9132	26.5891	2276	AFT
CD193	Porphyry	35.6 ± 0.3 Ma <sup>a</sup>	99.9069	26.5844	2610	AFT

<sup>a</sup> SHRIMP zircon U-Pb age for magma intrusion from Lu et al. (2012).



Table 2. Apatite fission-track results in the Jianchuan basin, western Yunnan.

Sample	Spontaneous tracks						Length, $D_{\text{par}}$ and $D_{\text{per}}$				
	$N_g^a$	No.	Density ( $10^5 \text{ cm}^{-2}$ )	U <sup>b</sup> (ppm)	$P(\chi^2)^c$ (%)	Disper sion (%)	Pooled age <sup>d</sup> $\pm 1\sigma$ (Ma)	Length <sup>e</sup> $\pm 1\sigma$ ( $\mu\text{m}$ )	$N_l^f$	$D_{\text{par}}$ ( $\mu\text{m}$ )	$D_{\text{per}}$ ( $\mu\text{m}$ )
Laojun Shan transect											
JC22	38	359	7.93	21.31	55	0.03	$37.4 \pm 4.1$	$14.14 \pm 1.17$	56	2.22	0.43
JC23	40	464	12.21	8.51	100	0.00	$31.4 \pm 3.1$	$14.56 \pm 1.23$	143	2.28	0.44
JC24	40	439	11.22	7.35	42	0.36	$32.3 \pm 3.3$	$14.11 \pm 1.37$	164	2.16	0.40
JC26	37	450	11.22	11.12	62	0.00	$33.1 \pm 3.4$	$14.14 \pm 1.33$	150	1.99	0.40
JC27	39	214	6.19	4.72	90	0.00	$28.5 \pm 4.1$	$14.23 \pm 1.33$	131	2.09	0.39
JC28	35	127	4.65	3.99	58	0.01	$27.0 \pm 5.2$	$14.19 \pm 1.13$	151	1.93	0.37
JC29	32	313	12.74	9.45	95	0.00	$20.3 \pm 2.4$	$14.17 \pm 1.13$	162	2.05	0.36
JC30	40	97	3.76	2.66	44	0.25	$21.3 \pm 4.4$	$13.97 \pm 1.19$	101	1.80	0.34
JC31	29	81	3.43	3.11	26	0.56	$19.5 \pm 4.4$	$13.83 \pm 1.15$	153	1.99	0.35
JC33	22	51	2.35	5.91	68	0.00	$18.0 \pm 5.3$	$14.00 \pm 0.68$	19	1.94	0.36
Shamao Shan transect											
CD114	24	165	4.75	6.68	41	0.01	$28.8 \pm 4.6$	$14.41 \pm 1.07$	151	2.04	0.37
CD115	25	258	6.09	6.87	39	0.03	$34.9 \pm 4.6$	$14.71 \pm 0.94$	156	1.95	0.36
CD117	30	226	7.11	10.67	25	0.66	$26.2 \pm 3.6$	$14.57 \pm 1.63$	161	1.98	0.38
CD118	30	187	7.36	10.67	47	0.02	$21.0 \pm 3.2$	$14.13 \pm 1.27$	156	1.96	0.36
CD193	40	411	10.44	6.60	64	0.01	$32.5 \pm 3.4$	$15.06 \pm 1.04$	172	2.28	0.43

<sup>a</sup> Number of grains dated.

<sup>b</sup> Mean uranium content of all crystals measured using LA-ICP-MS.

<sup>c</sup> Probability obtaining Chi-square value for  $\nu$  degrees of freedom ( $\nu=N-1$ ).

<sup>d</sup> Pooled ages of all grains.

<sup>e</sup> Track length measured after  $^{252}\text{Cf}$  irradiation, original mean track length.

<sup>f</sup> Number of track length measured.

Table 3. Apatite (U-Th)/He results from the Shamao Shan in the Jianchuan basin, western Yunnan.

Sample	Aliq.	Th/U	Grain mass ( $\mu\text{g}$ )	Ejection corr. ( $F_T238$ )	Ejection corr. ( $F_T235$ )	Ejection corr. ( $F_T232$ )	Grain length ( $\mu\text{m}$ )	Grain width ( $\mu\text{m}$ )	$R_s$ ( $\mu\text{m}$ )	4He (ncc)	U (ppm)	Th (ppm)	Sm (ppm)	eU (ppm)	Uncorr. He age (Ma)	$F_T$ -Corr. He age (Ma)	$1\sigma$ (Ma)
CD114	*a1	18.27	11.02	0.82	0.799	0.799	289.8	159.0	83.4	0.06	4.25	75.73	194.37	22.05	<del>34.99</del>	<del>43.43</del>	<del>0.55</del>
	*a2	10.32	12.55	0.84	0.813	0.813	277.1	176.0	89.6	0.07	6.59	66.32	244.61	22.18	<del>32.22</del>	<del>39.24</del>	<del>0.45</del>
	*a3	6.50	9.40	0.82	0.792	0.792	251.1	156.7	80.1	0.06	12.69	80.47	242.75	31.60	<del>27.34</del>	<del>34.04</del>	<del>0.37</del>
CD116	a1	7.67	15.43	0.84	0.821	0.821	88.6	349.3	94.3	0.12	12.59	94.14	247.85	34.71	27.79	33.46	0.37
	a2	7.21	43.30	0.89	0.873	0.873	349.3	177.2	134.5	0.26	11.69	82.16	379.33	31.00	25.92	29.45	0.31
	a3	7.23	15.68	0.85	0.833	0.833	408.0	265.4	101.3	0.09	11.79	83.08	178.31	31.32	22.02	26.16	0.28
	*a4	5.94	34.16	0.87	0.856	0.856	306.2	200.1	118.2	0.56	12.85	74.43	311.91	30.34	<del>78.68</del>	<del>90.95</del>	<del>0.94</del>

\* Ages were deemed outliers and not used for weighted mean age calculation and inverse modeling because they are older than zircon U-Pb ages of sampled igneous rocks.

609 **FIGURE CAPTIONS**

610 Figure 1. (A) simplified geology and topography of southeastern Tibet, with major  
611 Cenozoic faults, modified from Leloup et al. (1995) and E. Wang et al. (2012). The  
612 inset shows location within Asia. Abbreviations: AFT PAZ–Apatite fission-track  
613 partial annealing zone, ASRR–Ailao Shan-Red River shear zone, CD–Chuandian  
614 block, CHT–Chenghai thrust, CSSZ–Chongshan shear zone, JQTB–Jinhe-Qinghe  
615 thrust belt, RRF–Red River fault, YTB–Yulong thrust belt. White stars denote  
616 accelerated exhumation phases constrained by thermochronology in southeastern Tibet,  
617 with black numbers indicating the duration: 0–This study, 1–E. Wang et al. (2012), 2–  
618 Tian et al. (2015), 3–Clark et al.(2005a) and Ouimet et al. (2010), 4–Godard et al.  
619 (2009), 5–Xu and Kamp (2000), 6–Zhang et al. (2017), 7–S. Wang et al. (2012), 8–  
620 Tian et al. (2014), 9–Zhang et al. (2016), 10–Lacassin et al. (1996), 11–Yang et al.  
621 (2017), and 12–Wilson and Fowler (2011). Blue numbers indicate paleoaltimetry  
622 estimates: 13–Hoke et al. (2014), 14–Li et al. (2015), 15–Gourbet et al. (2017), 16–  
623 Tang et al. (2017). Ages for the onset of major active faults appear in red: 0-YTB (this  
624 study), a–western and eastern portions of the Kunlun fault (Duvall et al., 2013; Jolivet  
625 et al., 2003), b–Longmen Shan thrust belt, c–Xianshuihe-Xiaojiang (Zhang et al.,  
626 2017), d–Ganzi fault (Wang et al., 2009), e–Litang fault (Zhang et al., 2015), f-JQTB  
627 (S. Wang et al., 2012). Ages for the duration of major faults appear in red: g-sinistral  
628 shear of the RRF during ~34-17 Ma (Leloup et al., 2001) and kinematic reversal at  
629 ~10/5-0 Ma (Leloup et al., 1995; Replumaz et al., 2001), h–Jiali fault (Lin et al., 2009),

630 i–Parlung fault (Lee et al., 2003), j–Gaoligong fault (Lin et al., 2009; Zhang et al.,  
631 2012), k–Chongshan shear zone (Zhang et al., 2010). **(B)** morphotectonic cross section  
632 superimposed on topographic swath (black dotted box in Figure 1A) generated from  
633 30-m resolution ASTER GDEM across the YTB and CHT-JQTB in western Yunnan.  
634 Vertical exaggeration: 10x. Main faults have the same legend as Figure 1A.

635

636 Figure 2. **(A)** Simplified geological map of the Lijiang-Jianchuan area based on  
637 BGMRY (1990), Gourbet et al. (2017) and our new observations. **(B)** and **(C)** stereo  
638 plots (lower hemisphere projection) of brittle faults in the YTB at site CD357, and sites  
639 JC46, CD101, CD305 and CD306, respectively. **(D)** and **(E)** Geological cross sections  
640 through the YTB and the Jianchuan basin, showing contact relationships between  
641 different structural and lithological units and sampling strategies for AFT and AHe.  
642 Vertical exaggeration 2.5x.

643

644 Figure 3. Geological map of the Jianchuan basin, showing locations of  
645 geochronological and thermochronological samples and ages. For lithological and  
646 structural legends, see Figure 2.

647

648 Figure 4. Representative field photos of brittle deformation in the YTB to the east of  
649 the Jianchuan basin. **(A)** thrust fault cutting across Eocene conglomerates at site  
650 CD101, with slickensides and striations on fault planes showing right-lateral/reverse

651 motion (see trend and kinematics in Figure 2B). **(B)** semi-solidified fault breccias and  
652 cataclasites within the fault zone at site CD305, within which slickensides and striations  
653 indicate thrusting (see trend and kinematics in Figure 2B). **(C)** a series of minor faults  
654 within the Yulong thrust displacing Eocene conglomerates and juxtaposing Triassic  
655 siltstone and Eocene sediments at site CD357. **(D)** at the same locality CD357,  
656 slickensides and striations on the fault planes indicate early thrusting and normal  
657 faulting at a later stage. **(E)** Detail of lense-shaped breccias within the fault zone  
658 showing reverse motion at site CD357 (see location in Figure 4D). **(F)** Detail of  
659 striations and slickensides on the fault plane indicative of normal motion (see location  
660 in Figure 4D). **(G)** Fault in the Baoxiangsi Fm. to the northwest of the Shamao Shan  
661 pluton, showing slightly oblique striations with a normal apparent motion trending  
662 N150°.

663

664 Figure 5. AFT and AHe age-elevation relationships in the Jianchuan basin, western  
665 Yunnan. AFT and AHe ages are plotted against elevation for the Laojun Shan **(A)** and  
666 Shamao Shan **(B)** profiles, respectively. Black symbols represent samples with AFT  
667 ages that correspond to post-emplacement pluton cooling, while blue symbols are  
668 samples record later exhumation. Age-elevation relationship for this sample is given  
669 with corresponding correlation coefficient ( $R^2$ ). A clear break-in-slope occurs at  $\sim 20 \pm$   
670 5 Ma in the Laojun Shan profile; red symbols correspond to samples from below the  
671 break in slope that suggest very rapid exhumation. Confined track-length distributions

672 for each sample are shown in the insets. Grey dots correspond to single-grain AHe ages  
673 from the Laojun Shan transect reported by Shen et al. (2016); light grey data have not  
674 been used in QTQt inversions. Black dots represent AHe data from the Shamao Shan  
675 transect from this study used in the QTQt models, while white dots denote AHe data  
676 excluded from the models.

677

678 Figure 6. Thermal histories of the Jianchuan basin, western Yunnan. Cooling histories  
679 of the Laojun Shan and Shamao Shan **are** derived from QTQt inverse modeling based  
680 on AFT data (A, C) and AFT in combination with AHe data (E, G). (B), (D), (F) and  
681 (H) **show the** fits of the predicted **and** observed data. The thermal history of the  
682 uppermost sample is **shown in** blue, with the 95% confidence interval in cyan, while  
683 the thermal history of the lowermost sample is **shown in** red, with the 95% confidence  
684 interval in magenta. Thermal histories for samples **at** intermediate **elevations** are in  
685 grey. These reflect the combined uncertainty in the inferred thermal history and the  
686 offset parameters.

687

688 Figure 7. Late Oligocene-Early Miocene tectonic scenario for southeastern Tibet in the  
689 framework of India-Asian convergence, highlighting SE-NW-directed compression  
690 leading to a large-scale southeastward-extruded crust block accommodated by the  
691 ASRR along the southwest and thrust faults that are responsible for relief generation in  
692 the southeastern front (see details in discussion). Abbreviations: ASRR–Ailao Shan-  
693 Red River shear zone, CSSZ–Chongshan shear zone, JQTB–Jinhe-Qinghe thrust belt,  
694 RRF–Red River fault, YTB–Yulong thrust belt.

Figure 1.

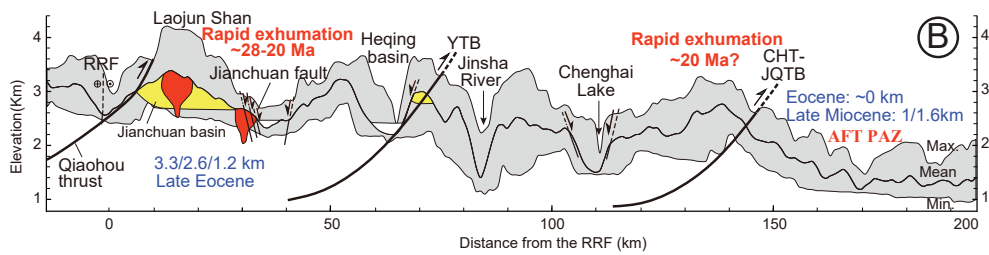
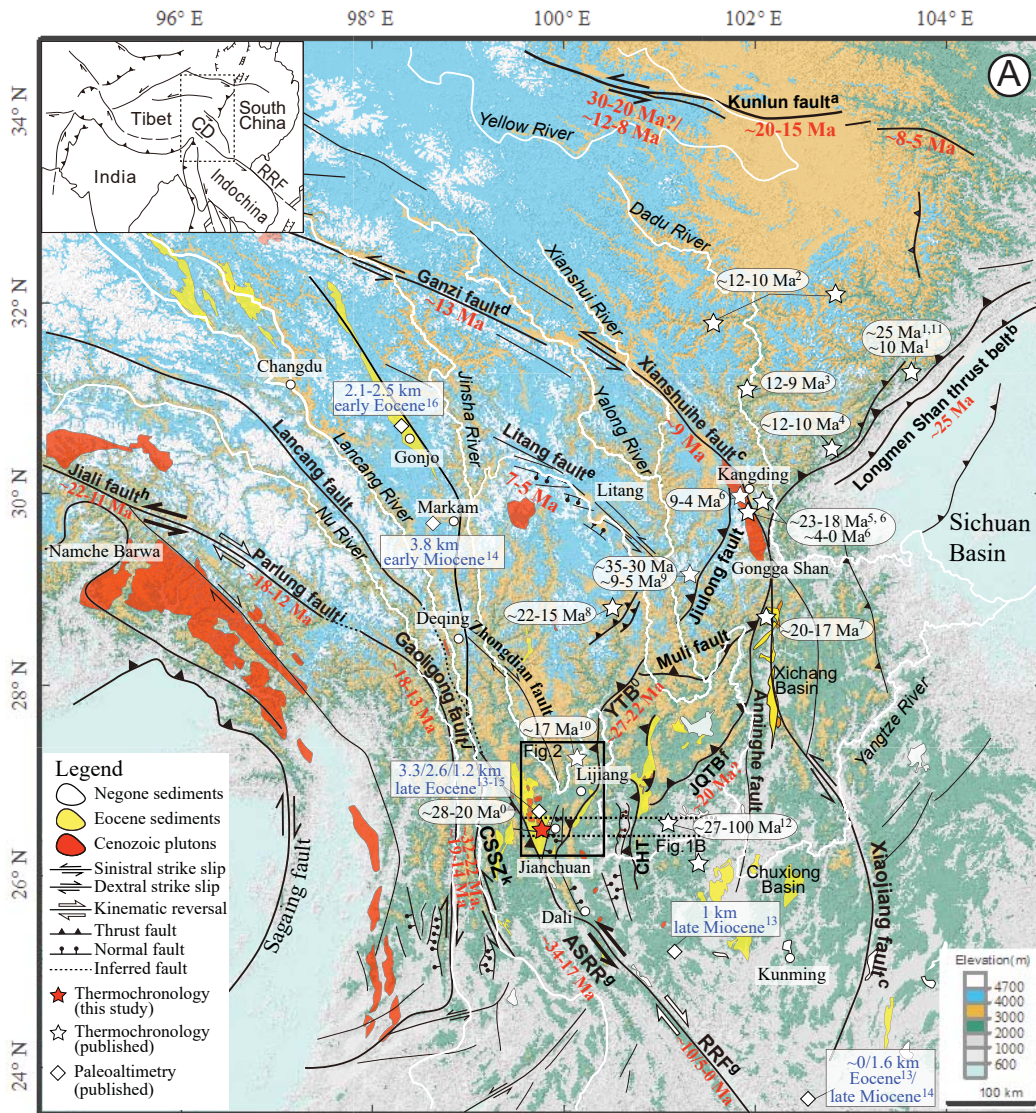




Figure 2.

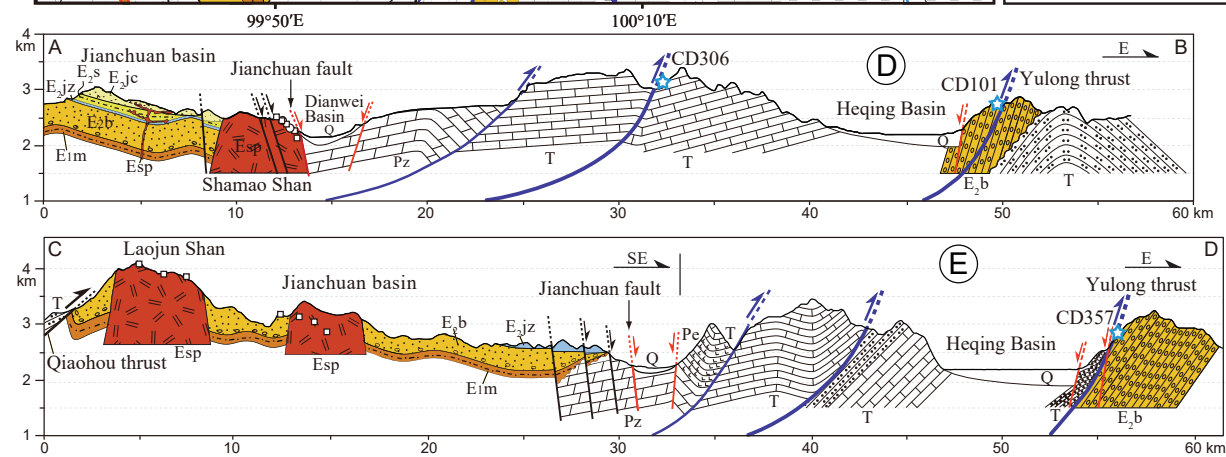
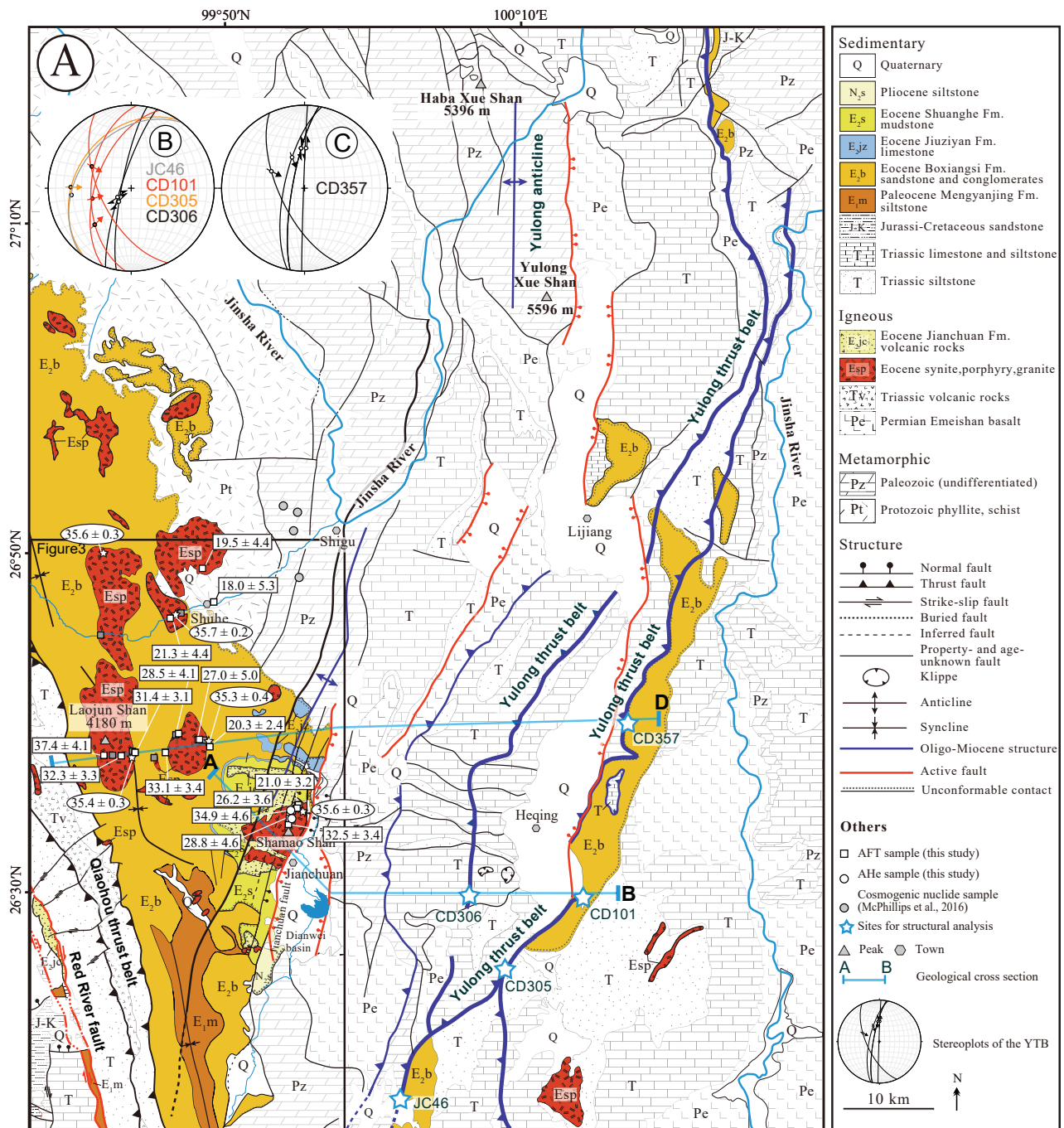
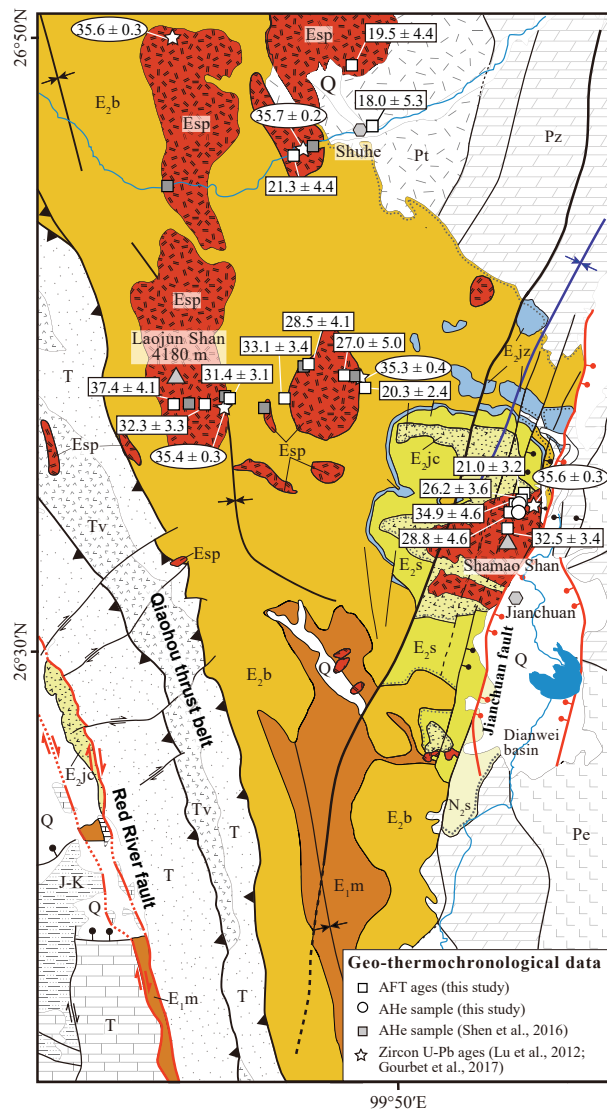


Figure 3.



99°50'E

Figure 4.

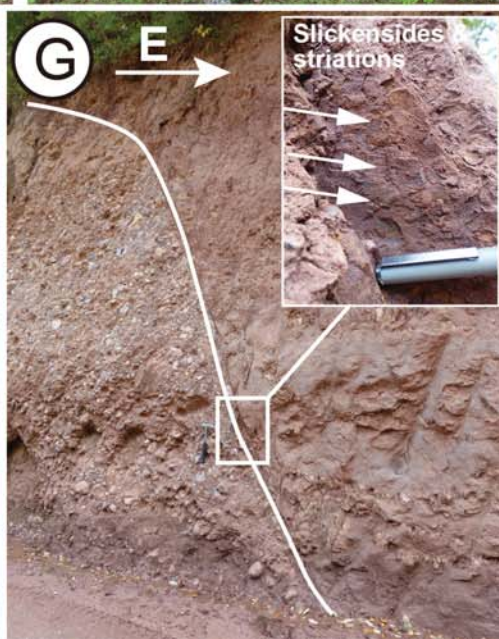
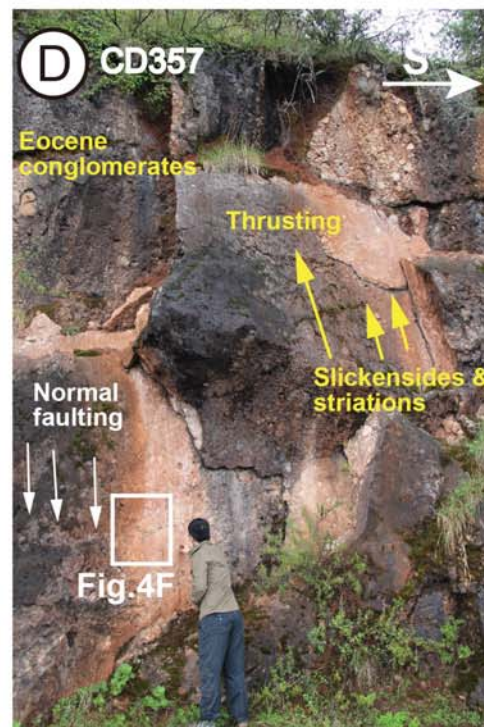
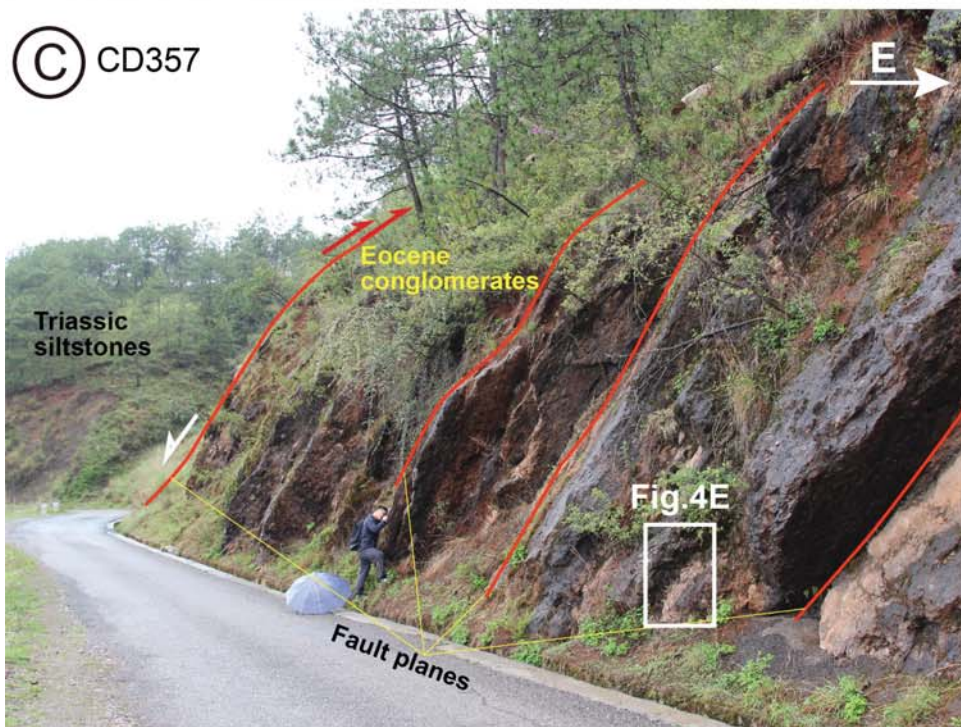
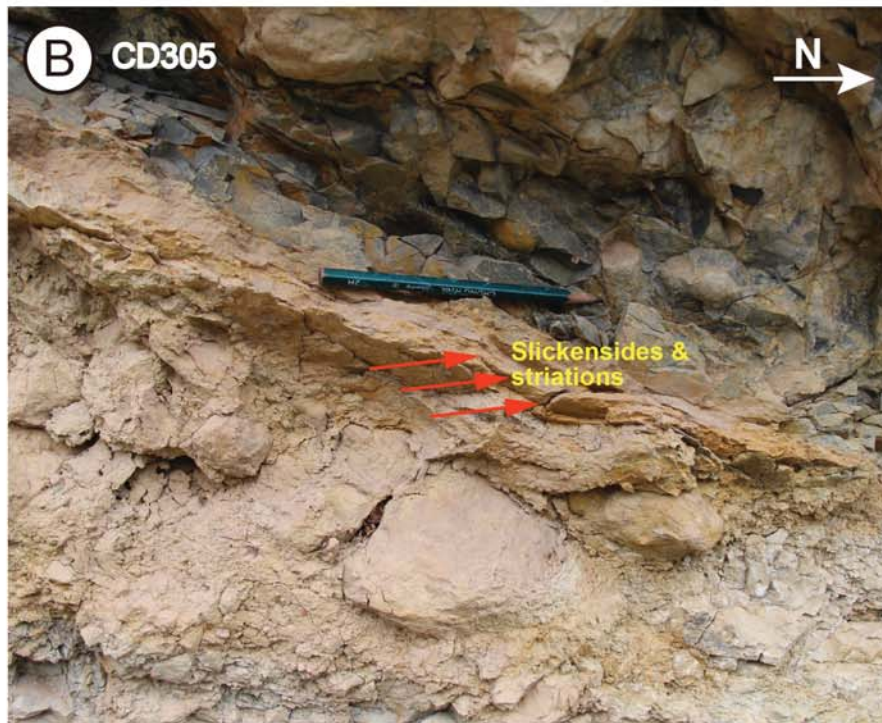


Figure 5.

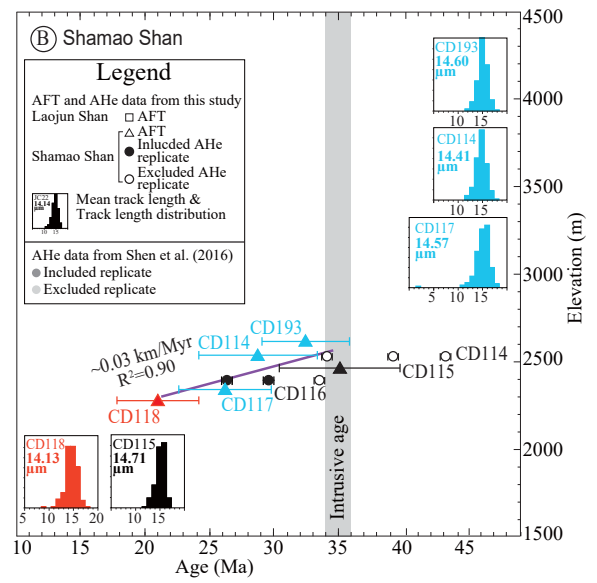
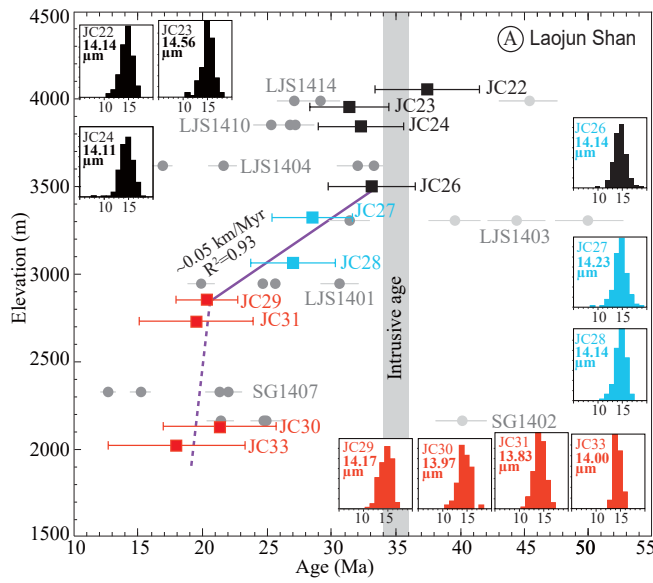
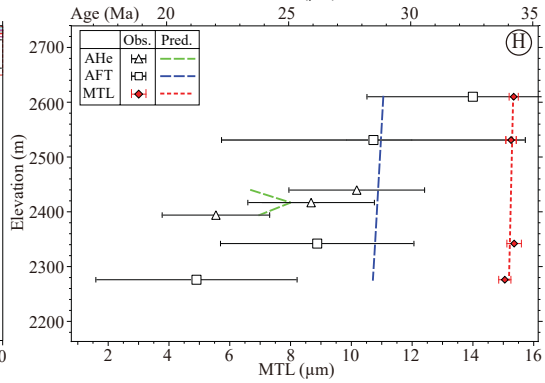
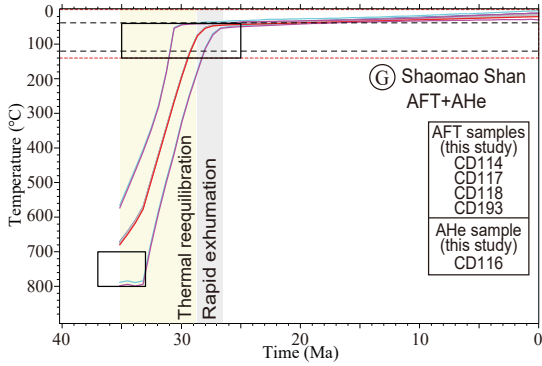
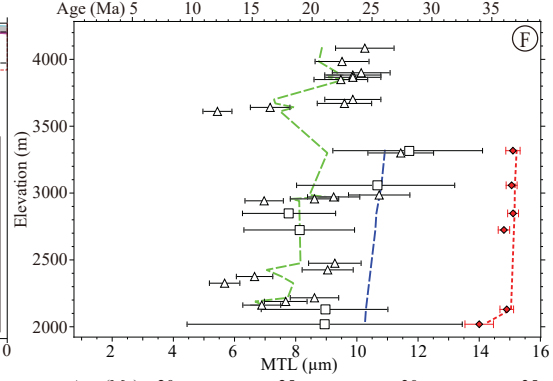
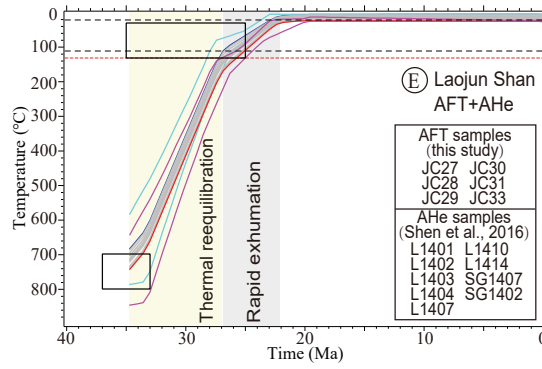
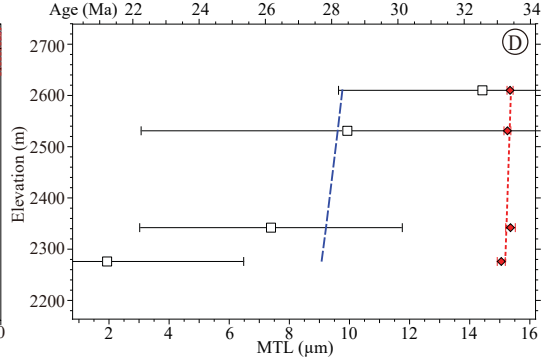
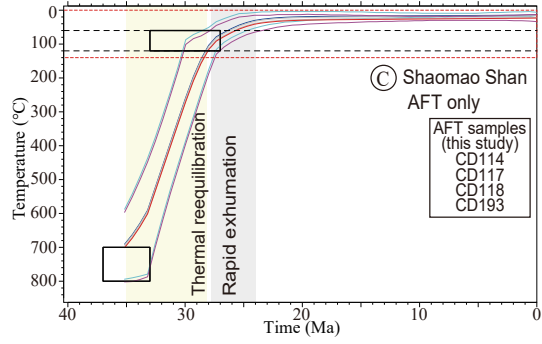
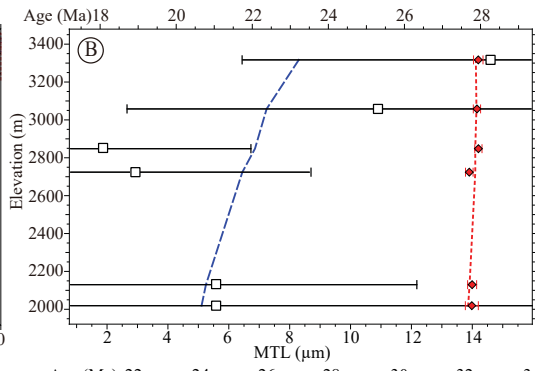
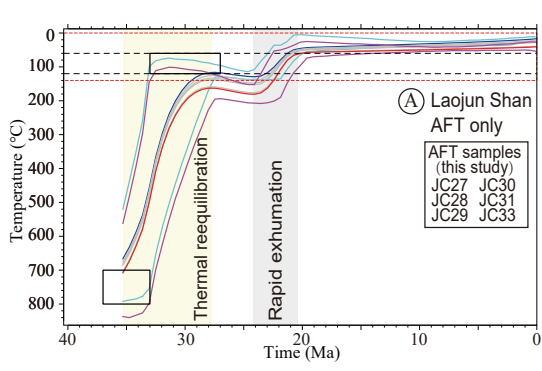
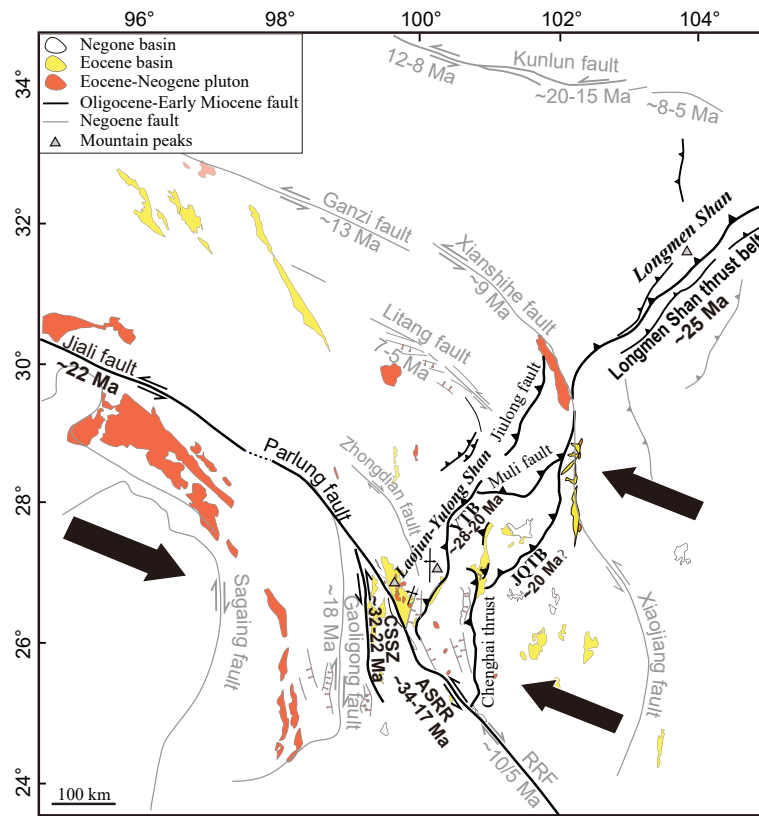




Figure 6.



**Figure 7.**



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