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4 **Thrusting, exhumation and basin fill on the western margin of the**  
5 **South China block during the India-Asian collision**

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20  
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23 **Abstract**

24 The pattern and timing of deformation in southeast Tibet resulting from the early stages of the India-  
25 Asian collision, are crucial to understand the growth of the Tibetan Plateau but remain poorly  
26 constrained. Detailed field mapping, structural analysis, geochronological and thermochronological  
27 data along a 120 km section of the Ludian-Zhonghejiang (LZ) fold-thrust belt bounding the Jianchuan  
28 basin in western Yunnan, China document the Early Cenozoic tectonic evolution of the conjunction  
29 between the Lanping-Simao and South China blocks. The study area is cut by two major southwest-  
30 dipping brittle faults named Ludian-Zhonghejiang fault and Tongdian fault from east to west. Numerous  
31 kinematic indicators and the juxtaposition of Triassic meta-sedimentary rocks on top of Paleocene strata  
32 indicate thrusting along the Ludian-Zhonghejiang fault. Similarly, structural analysis shows that the  
33 Tongdian fault is a reverse fault. Between these structures, fault-bounded Permo-Triassic and Paleocene  
34 rocks are strongly deformed by nearly vertical and upright southwest-vergent folds with axes that trend  
35 nearly parallel to the traces of the main faults. Zircon and apatite (U-Th)/He and apatite fission track  
36 data from a Triassic pluton with zircon U-Pb ages of 225-237 Ma in the hanging wall of the Ludian-  
37 Zhonghejiang fault assisted by inverse modeling reveal two episodes of accelerated cooling during 125-  
38 110 Ma and 50-39 Ma. The Cretaceous cooling event was probably related to crustal thickening during  
39 the collision between the Lhasa and Qiangtang terranes. The accelerated exhumation during 50-39 Ma  
40 is interpreted to record the lifespan of the fold-thrust belt. This timing is corroborated by the intrusive  
41 relationship of Eocene magmas of ~35-36 Ma dated by zircon U-Pb into the fold-thrust belt. Early  
42 Cenozoic activity of the deformation system controlled deposition of alluvial-fan and braided-river  
43 sediments in the Jianchuan basin evidenced by eastward and northeastward paleoflows and terrestrial  
44 clasts derived from the hanging wall of the Ludian-Zhonghejiang thrust. Since 39 Ma, decreasing  
45 cooling rates likely reflects cessation of the fold-thrust belt. Early Cenozoic compressive deformation  
46 on the western margin of the South China block, together with geological records of contraction in  
47 central, northern and eastern Tibet, document Eocene upper crustal shortening located in the Himalaya,  
48 Qiangtang terrane and northern plateau margins together with contractional basin development  
49 intervened by Lhasa, Songpan-Garze and Kunlun terranes, coevally with or shortly after the onset of  
50 the India-Asian collision. This suggests that moderate crustal shortening affected a large part of Tibet  
51 in a spaced way contrary to homogenous crustal thickening soon after the collision, prior to the main  
52 crustal thickening propagated progressively from south to north. This complex deformation pattern  
53 illustrates the complexity of the Asian crustal rheology that contrasts with what were assumed in the  
54 existing geodynamic models.

55  
56 **Keywords:** India-Asian collision, South China, Jianchuan basin, fold-thrust belt, low temperature  
57 thermochronology, lithospheric rheology

## 58 **1. Introduction**

59 The collision between India and Asia, which started since 60-50 Ma (Allègre et al., 1984; Ding et al.,  
60 2016; Hu et al., 2016; Najman et al., 2010; Rowley, 1996), has resulted in double-thickness crust and  
61 growth of the Tibetan Plateau that stands as a mean elevation of 5 km over a distance of ~2000 km north  
62 of the plate boundary. The reconstruction of the appropriate rheology of the Asian continental  
63 lithosphere as inferred from geodynamic models is crucial to understand the uplift and growth history  
64 of the Tibetan Plateau that have puzzled the earth scientists for a century (see reviews in Yin and  
65 Harrison (2000) and Kapp and Decelles (2019)). The prevailing models encompass 1) homogenous  
66 shortening and thickening distributed within Tibetan lithosphere analogue to a viscous sheet (Dewey  
67 and Burke, 1973; England and Houseman, 1986), 2) homogenous crustal thickening followed by flow  
68 of low-viscosity lower crust driven by topographic load (Bird, 1991; Clark et al., 2005; Clark and  
69 Royden, 2000; Royden et al., 1997), and 3) upper crustal shortening and oblique intracontinental  
70 subduction between coherent elasto-plastic lithospheric blocks (Meyer et al., 1998; Tapponnier et al.,  
71 1982, 1990). The first two models predict that uplift and deformation of the Tibetan plateau commenced  
72 throughout the plateau synchronously with or shortly after the India-Asian collision, while the third one  
73 predicts stepwise growth of the plateau from south to north and crustal deformation mostly localized  
74 along the boundaries of the lithospheric blocks. The discrimination of the three models largely depends  
75 on the quantification of the spatiotemporal evolution of intracontinental deformation resulting from the  
76 India-Asian collision and convergence. The middle-late Cenozoic extrusion of the crustal materials to  
77 the Tibetan sideways, inferred from plasticine analogue modeling, has been relatively well documented  
78 by structural analyses and geo-thermochronology (e.g., Tapponnier et al., 1976, 1982; Leloup et al.,  
79 1993, 1995, 2001; Cao et al., 2011; Lin et al., 2009; Zhang et al., 2010, 2011, 2014; Zhang et al., 2015,  
80 2017). In contrast, how the Tibetan plateau crust deformed in the early Cenozoic remains poorly  
81 constrained (e.g., Cao et al., 2013; Clark et al., 2010; Horton et al., 2002; Leloup et al., 2012; Spurlin  
82 et al., 2005; Staisch et al., 2016; Tong et al., 2017; Yin and Harrison, 2000). Quantitative data of the  
83 geometry and kinematics of the first-order structures that predated the occurrence of the crustal  
84 extrusion within the collision belt are lacking.

85  
86 Southeast Tibet is characterized by extrusion tectonics accommodated by large-scale strike-slip fault  
87 systems in middle-late Cenozoic times especially along the Ailao Shan-Red River shear zone (ASRR)  
88 and Red River fault (e.g., Tapponnier et al., 1976, 1982, 1990; Leloup et al., 1995, 2001) and is thus an  
89 ideal region to address the above question. However, the tectonic configuration of southeast Tibet prior  
90 to extrusion remains poorly understood. Deformed Paleogene sediments in southeast Tibet provide an  
91 opportunity to study Early Cenozoic sedimentation and deformation. The Jianchuan basin, one of the  
92 largest hinterland basins in southeast Tibet (Fig. 1), is proximal to the Red River fault and has been the  
93 subject of several recent studies pertaining to its age, deformation, exhumation and paleoelevation (Cao  
94 et al., 2019; Gourbet et al., 2017; Hoke et al., 2014; Li et al., 2015; Sorrel et al., 2017; Wei et al., 2016;  
95 Wissink et al., 2016; Wu et al., 2018; Yang et al., 2014). Despite its importance, the geodynamic  
96 context of its formation and the subsidence mechanisms are still poorly known.

97  
98 In this study, our field and analytical data provide first quantitative constraints on the geometry,  
99 kinematics and timing of the compressive deformation along a fault zone that we termed Ludian-  
100 Zhonghejiang fold-thrust belt (LZTB) on the western margins of the South China block, western Yunnan,  
101 which preceded sinistral motion of the ASRR. These results allow establishing casual links between  
102 Early Cenozoic thrusting-induced rock exhumation within the deformation zone and deposition in the  
103 Jianchuan basin. Accordingly, we provide mechanistic interpretations for tectonic deformation and  
104 sedimentation in southeast Tibet corresponding to the India-Asian collision.

## 105 **2. Geological setting**

### 106 **2.1 Regional tectonics**

107  
108 The southeast Tibetan Plateau comprises a collage of several major lithospheric fragments, including  
109 the Songpan-Garze, Lanping-Simao, Indochina and South China (Fig.1a). This region has experienced  
110 a protracted tectonic history from Paleozoic amalgamation to Mesozoic Tethys evolution (e.g.,  
111 Burchfiel and Chen, 2012; Deng et al., 2014a; Jian et al., 2009a, b; Metcalfe, 2006), overprinted by



112 significant Cenozoic intracontinental deformation under the compound effects of India-Asian  
113 convergence and Pacific-Indonesian subduction (e.g., Burchfiel and Chen, 2012; Deng et al., 2014b;  
114 Leloup et al., 1995; Yin, 2010). Paleozoic-Mesozoic orogenesis in southeast Tibet is largely related to  
115 the evolution of the Paleo-Tethys recorded by numerous NS-striking belts of Devonian-Permian  
116 ophiolites and accretionary mélangé complex (Burchfiel and Chen, 2012; Jian et al., 2009a, b). Large  
117 volume of Permo-Triassic plutonic and volcanic assemblages between the South China and Lanping-  
118 Simao blocks had been produced by westward subduction and final suturing of the Paleo-Tethys along  
119 the Jinsha-Ailao Shan suture zone (Burchfiel and Chen, 2012; Deng et al., 2014a; Faure et al., 2014;  
120 Jian et al., 2009a, b; Zi et al., 2012, 2013).

121  
122 Since initial collision of the India with Asia at 60-50 Ma (Allègre et al., 1984; Ding et al., 2016; Hu et  
123 al., 2016; Najman et al., 2010; Rowley, 1996), the eastern margin of the Tibetan Plateau was strongly  
124 deformed, with early Cenozoic crustal shortening (Tapponnier et al., 2001; Spurlin et al., 2005;  
125 Studnicki-Gizbert et al., 2008; Tong et al., 2017) followed by southward block extrusion and rotation  
126 via large-scale strike slip faults (e.g., the ASSR; Fig.1; Tapponnier et al., 1982, 1990; Cao et al., 2011;  
127 Leloup et al., 1993, 1995, 2001; Lin et al., 2009; Tong et al., 2016; Zhang et al., 2010, 2011, 2014;  
128 Zhang et al., 2015, 2017). Early Cenozoic crustal deformation in east Tibet has been recorded by  
129 magmatism (Spurlin et al., 2005; Wang et al., 2001; Zhang et al., 2010), tectonic activity of fold-thrust  
130 system (Horton et al., 2002; Spurlin et al., 2005), deposition of syn-tectonic Paleogene basins, such as  
131 the Yushu-Nangqian and Gonjo basins (Horton et al., 2002; Spurlin et al., 2005; Studnicki-Gizbert et  
132 al., 2008; Tang et al., 2017) and paleomagnetism (Tong et al., 2017; Zhang et al., 2018). Recent  
133 thermochronological results from two vertical profiles at Deqin and Weixi in southeast Tibet reveal two  
134 episodes of rapid exhumation during 120-80 Ma and 60-40 Ma to the northwest of the Jianchuan basin  
135 (Liu-Zeng et al., 2018).

136  
137 The middle-late Cenozoic crustal deformation in southeast Tibet is characterized by large-scale strike-  
138 slip fault system. Amongst them, the nearly-1000 km long ASRR extending from Vietnam to southeast  
139 Tibet defines a prominent crustal discontinuity and separates the South China to the northeast from  
140 Lanping-Simao/Indochina to the southwest. This shear zone comprises four narrow segments of  
141 strongly deformed metamorphic rocks: Day Nui Con Voi, Ailao Shan, Diancang Shan and Xuelong  
142 Shan from southeast to northwest (Fig. 1). The onset timing for left-lateral shear of the ASRR remains  
143 controversial, ranging between ~34 and 28 Ma (Cao et al., 2011; Leloup et al., 1995, 2001, 2007; Palin  
144 et al., 2013; Zhang et al., 2014) to ~25 Ma (Searle et al., 2010), or even later than 21 Ma (Searle, 2006).  
145 Cessation of its left-lateral deformation occurred at ~17 Ma (Leloup et al., 2001). Since ~10-5 Ma, the  
146 dextral Red River fault almost followed the trace of the ASRR (Leloup et al., 1995; Replumaz et al.,  
147 2001).

## 148 149 **2.2 Subsidence and uplift history of the Jianchuan basin**

150 The Jianchuan basin is a Paleogene intermontane basin in southeast Tibet on the South China block,  
151 mostly standing at an elevation of 3-4 km (Figs. 1 and 2). It is bounded to the west by the Qiaohou  
152 thrust belt (Gourbet et al., 2017). Paleogene sediments are strongly folded in the vicinity of the Ludian-  
153 Zhonghejiang fault, the eastern branch of the fold belt (Fig.2). To the northeast of the basin, basal  
154 sediments of the Paleogene Baoxiangsi Fm. ( $E_2b$ ) rest unconformably on the Proterozoic and Paleozoic  
155 basement rocks. To the southeast of the basin, Eocene sediments are bounded by the Jianchuan normal  
156 fault, which belongs to a releasing bend of the Red River fault system that probably initiated in the Late  
157 Miocene (Leloup et al., 1995; Replumaz et al., 2001). The Paleogene sediments in the Jianchuan basin  
158 and surrounding areas stand unconformably on folded Triassic and older basement rocks (Burchfiel and  
159 Chen, 2012). Basin stratigraphy was recently reappraised based on new results of geological mapping,  
160 geochronologic data and fossil assemblages (Gourbet et al., 2017; Wu et al., 2018). Revised stratigraphic  
161 sequences of the Paleogene basin consist of the Mengyejing Formation “(Fm.)” ( $E_{1m}$ ), Baoxiangsi Fm.  
162 ( $E_{2b}$ ), Jiuziyan Fm. ( $E_{2jz}$ ), Shuanghe Fm. ( $E_{2s}$ ) and Jianchuan Fm. ( $E_{2jc}$ ) from the bottom to the top  
163 (Fig. 3).

164  
165 The Mengyejing Fm. ( $E_{1m}$ ), outcropping in the southern part of the basin, is dominated by red  
166 mudstones and siltstones, with limited presence of sandstone and conglomerate layers (Fig. 2). These

167 sediments are interpreted to be a flood plain environment with local occurrence of alluvial-fan deposits  
168 (Gourbet et al., 2017). The Baoxiangsi Fm. ( $E_2b$ ) having a thickness of up to ~600 m is exposed parallel  
169 to the bounding Ludian-Zhonghejiang fault to the west and occupies the greatest volume of basin infill  
170 (Gourbet et al., 2017; Fig. 3). This formation can be subdivided into two units:  $E_2b1$  and  $E_2b2$ . The  
171 sediments of  $E_2b1$  are characteristics of basal conglomerates, filling an uneven paleo-relief carved  
172 within the Shigu metamorphic schists along the northeast basin margin (Studnicki-Gizbert, 2006),  
173 indicative of an angular unconformable contact of the Baoxiangsi Fm. ( $E_2b$ ) above the Proterozoic to  
174 Paleozoic metamorphic rocks (Fig. 2). This suite of sediments ( $E_2b1$ ) also locally appear along the  
175 Ludian-Zhonghejiang fault (e.g., at site CD522 and east of site CD144; Figs. 2 and 4). Contrary to what  
176 was described by Wei et al. (2016), there is no clear field evidence for an angular unconformity between  
177 the  $E_2b1$  and the underlying  $E_1m$  (Gourbet et al., 2017). Most of the Baoxiangsi Fm. ( $E_2b2$ ) consists of  
178 massive red siltstones interbedded with red sandstones, containing parallel and cross bedding and  
179 channel-fill conglomerates, consistent with a facies interpretation of a braided river system, while the  
180 base of the sedimentary succession is locally made of massive, well-sorted, thick multi-storey channel-  
181 fill sandstones. There is no precise age control for both the Mengyejing Fm. ( $E_1m$ ) and Baoxiangsi Fm.  
182 ( $E_2b$ ). The presence of Paleocene-Early Eocene ostracods in the Mengyejing Fm. ( $E_1m$ ), along with  
183 charophyte assemblages and Late Eocene mammalian faunas in the Baoxiangsi Fm. ( $E_2b$ ), allow  
184 roughly attributing Paleocene and Eocene ages to these two formations respectively (BGMRY, 1990).  
185 This timing assignment is supported by the cut-off relationships between 35-36 Ma old intrusive rocks  
186 and the sediments of the Mengyejing ( $E_1m$ ) and Baoxiangsi Fms. ( $E_2b$ ) (Fig. 3; Gourbet et al., 2017).

187  
188 The overlying deposits of the Jiuziyan Fm. ( $E_2jz$ ), Shuanghe Fm. ( $E_2s$ ) and Jianchuan Fm. ( $E_2jc$ ) appear  
189 to be restricted to the eastern part of the Jianchuan basin (Fig. 2). The 0-100 m-thick Jiuziyan Fm. ( $E_2jz$ )  
190 seems limited to the northeastern corner of the basin, mostly resting on the mountain top and isolated  
191 by incision of the river network (Fig. 2). The Jiuziyan Fm. ( $E_2jz$ ) is locally in an erosional basal contact  
192 above the red mudstones of the Mengyejing Fm. ( $E_1m$ ), while the sediments show a regular transition  
193 without any clear angular unconformity at some spots (Gourbet et al., 2017). It consists of multi-storey  
194 carbonate successions, including life-position stromatolites interbedded with massive matrix-supported  
195 conglomerates and argillaceous calcisiltites, indicative of a palustrine-lacustrine environment (Sorrel et  
196 al., 2017). The 0-200 m-thick Shuanghe Fm. ( $E_2s$ ), overlying conformably the Jiuziyan Fm. ( $E_2jz$ ), is  
197 composed of poorly consolidated yellow sandstones, interbedded with organic-rich coal levels, as well  
198 as few layers of lava, tuff and volcanoclastic sediments. The sediments are commonly cut by intrusions  
199 (mostly lamprophyres), often sills in the coals or along sandstones stratifications. The strata are folded  
200 under nearly EW-directed contraction (Gourbet et al., 2017). The 0-300 m thick Jianchuan Fm. ( $E_2jc$ )  
201 overlies the folded sediments of the Shuanghe Fm. ( $E_2s$ ). These strata are dominantly volcanoclastic  
202 and relates to Late Eocene intrusion of the Shamao Shan syenite (Gourbet et al., 2017). The deposition  
203 timing of the Shuanghe Fm. ( $E_2s$ ) and Jianchuan Fm. ( $E_2jc$ ) was recently refined to be at  $\sim 35.9 \pm 0.9$  Ma  
204 and  $35.4 \pm 0.8$  Ma respectively, from zircon U-Pb and  $^{40}\text{Ar}/^{39}\text{Ar}$  dating on interbedded and crosscutting  
205 igneous rocks (Fig. 3; Gourbet et al., 2017). This is supported by newly-discovered fossils of chara and  
206 ostracod (Wu et al., 2018). The age of the Shuanghe Fm. ( $E_2s$ ) is further corroborated by a jaw (found  
207 in coal deposits) of a large amynodontid that thrived during the Late Eocene Ergilian interval (37.2-  
208 33.9 Ma) (Gourbet et al., 2017).

209  
210 The elevation history of the Jianchuan basin remains highly debated. Paleoelevation reconstructions  
211 based on stable isotopes suggest an attainment of modern surface height of  $\sim 3.3 \pm 0.5$  km asl. in the Late  
212 Eocene for the Jianchuan basin (Hoke et al., 2014). Similar work on the Shuanghe Fm. ( $E_2s$ ) suggests  
213 that the Jianchuan basin had reached  $\sim 2.6$  km asl. close to modern surface elevation in the Late Eocene  
214 (Li et al., 2015). However, the Shuanghe Fm. ( $E_2s$ ) was recently revised to be Late Eocene in age, and  
215 basin elevation was also re-evaluated to indicate a lower elevation of  $\sim 1.2 \pm 1.2$  km asl. (Gourbet et al.,  
216 2017). Recent stable isotope and fossil pollen coexistence data suggest the Jianchuan basin experienced  
217 a gradual uplift from between 0.5 km asl. and  $2.5 \pm 0.7$  km asl. during deposition of the Jiuziyan Fm.  
218 ( $E_2jz$ ) to between 0.9 km asl and  $2.9 \pm 0.6$  km asl. during deposition of the Shuanghe Fm. ( $E_2s$ ) (Wu et  
219 al., 2018). Low temperature thermochronology data interpreted in the light of thermal modelling suggest  
220 that the Jianchuan basin experienced 2.3-3.2 km of rapid exhumation at a rate of  $0.57\text{-}0.80$  mm  $\text{yr}^{-1}$   
221 between  $\sim 28$  and 20 Ma (Cao et al., 2019). These results allowed us to link pronounced relief generation

222 of southeast Tibet during the Oligocene-Early Miocene to thrusting in the context of regional NW-SE  
223 crustal shortening (Cao et al., 2019).

224

### 225 **3. Geological mapping**

226 The geometry, kinematics and timing of Cenozoic deformation of the Jianchuan basin and adjacent area  
227 have remained debated (Burchfiel and Chen, 2012; Deng et al., 2014b; Gourbet et al., 2017; Leloup et  
228 al., 1993; Tang et al., 2016; Wang et al., 1998; Yang et al., 2014). New mapping results on the western  
229 flank of the Jianchuan basin (Figs. 2 and 4) indicate that this area is predominantly affected by NNW-  
230 striking, WSW-dipping brittle thrusts separating narrow panels of Permo-Triassic and Paleocene strata.  
231 These panels are deformed by upright and tight folds with axes subparallel to the trend of the main  
232 faults. These structures define a fold-thrust belt that lacks detailed descriptions and quantitative  
233 constraints in Yang et al. (2014) and tentatively named “Qiaohou thrust belt” in Gourbet et al. (2017).  
234 In order to avoid confusion with the dextral strike-slip Qiaohou fault that is considered as a part of the  
235 active Red River fault system (Allen et al., 1984; Leloup et al., 1995), we use the new term Ludian-  
236 Zhonghejiang fold-thrust belt (LZTB) instead of “Qiaohou thrust belt”. The fold-thrust belt consists of  
237 two main thrusts: the Tongdian and Ludian-Zhonghejiang faults and several parallel folds (Figs. 2 and  
238 4). The following sections present the mapping results that focus on geology of the central and southern  
239 portions of the Ludian-Zhonghejiang fold-thrust belt, NE-trending faults and Qiaohou fault, as well as  
240 folded lithologic units along three main transects A-B, B'-C and E-F (Fig. 4).

241

#### 242 **3.1 Ludian-Zhonghejiang fold-thrust belt (LZTB)**

243 The LZTB stretches over 120 km between the Xuelong Shan and Diancang Shan metamorphic gneiss  
244 belts (Fig. 1) along a zone used to be called “Madeng gap”, where no high-grade metamorphic rocks  
245 are related to the ASRR (Leloup et al., 2001). The 7-12 km wide deformation zone involves Permo-  
246 Triassic sedimentary and volcanic rocks in the hanging wall, as well as Paleogene terrestrial sediments  
247 of the Jianchuan basin in the footwall (Fig. 4). The northern part of the fold-thrust belt is poorly defined  
248 due to heavy vegetation, but the principal fault still can be identified based on field observations of  
249 prominent topographic relief and intensively folded Eocene sediments proximal to the fault trace. In  
250 contrast, the central segment of the fold-thrust belt outcrops well and is thus the target of our detailed  
251 mapping.

252

##### 253 **3.1.1 Ludian-Zhonghejiang fault and Paleogene strata**

254 The Ludian-Zhonghejiang fault brings Triassic strata on top of the Eocene Baoxiangsi Fm. (*E<sub>2b</sub>*; Figs.  
255 2 and 4). To the east of the fault, the Baoxiangsi Fm. (*E<sub>2b</sub>*) is dominated by thick-bedded red medium-  
256 grained lithic sandstone interbedded with lenticular layers of conglomerates that are poorly-sorted,  
257 grain-supported, sub-rounded, and display scour-and-fill and cross bedding structures. This unit is  
258 interpreted as an alluvial fan fed by a braided river proximal to a local topographic gradient (Gourbet  
259 et al., 2017).

260

261 The Ludian-Zhonghejiang fault (LZF) is a NNW-SSE-striking and west-dipping thrust fault (Fig. 2).  
262 Folding is more intense on either side of the fault zone than it is further away, indicative of localized  
263 deformation along the contact between the Triassic and Paleogene strata. The fault has locally a  
264 complex trace (Fig. 4). At sites S277 and S219, a fault striking N92E brings the Triassic rocks on top  
265 of the Eocene red beds (Figs. 5a and 5m). At site CD335/CD435, faults with various orientations bring  
266 the Triassic rocks atop the Eocene sediments (Figs. 5b, 5c and 6a). The main fault contact in general  
267 trends NW-SE and dips to the SW, but is locally close to horizontal, gently dipping to the south, or even  
268 to the SE (Fig. 6a). This results in a complex shape of contact between the Triassic and Paleogene units.  
269 The primary fault appears as a low angle thrust nappe affected by latter deformation. The fault contact  
270 bears striations (Figs. 5d and 5e) but with various orientations, which prevents to define a clear common  
271 direction of motion for the thrusting (Fig. 6a). The intrusive relationship of a late Eocene lamprophyre  
272 with the main thrust fault is ambiguous (Figs. 5b and 5c). However, the intrusion clearly cut across the  
273 schistosity parallel to the thrust affecting the Triassic rocks (Fig. 5f), suggesting that the intrusion  
274 postdated the thrusting. This observation is also supported by the intrusion of a late Eocene syenite  
275 within the LZF at site CD321 (Fig. 4). The Eocene and Triassic sediments are folded and affected by  
276 later faults (Figs. 6a-c). Some of these faults are parallel to the main contact, but others are ~N80° to

277 N120° trending dextral faults (Fig. 6c). As this later set of faults cartographically crosscuts the contact  
278 between the Eocene and Triassic sediments (Fig. 4), we interpret them as resulting from a SE-NW  
279 compression after the thrust motion. At site CD237, Triassic coal-bearing slates above the nearly N-S-  
280 striking thrust are schistosed with S-C fabrics (Figs. 5g, 5h and 6b), suggesting top to the NE ductile-  
281 brittle thrusting (Figs. 5i-k). In contrast, sandstone beds of stronger competence at site CD333 show  
282 less ductile-brittle fabrics but are deformed, forming meter-scale asymmetric necked boudins (Fig. 5n).  
283

284 Along transect E-F between the observation sites CD237 and CD522 (Fig. 5h), the Eocene strata dip  
285 almost vertically at the vicinity of the fault, but dip gradually more gently away from the fault. The  
286 vertical clastic layers proximal to the thrust fault are dominated by a mixture of very poorly-sorted, sub-  
287 angular to sub-rounded pebbles and boulders of limestone, sandstone and volcanic origin (Fig. 5l),  
288 indicative of debris flow and hyper-concentrated flood flow deposits. In general, the Eocene strata east  
289 of the fault are deformed by a set of open synclines with steep axial planes striking N-S to NW-SE (Figs.  
290 2b, 6f and 6g). A section across the Paleogene sediments (mostly  $E_{1m}$  and  $E_{2b}$ ) of the Jianchuan basin  
291 is typified by long-wavelength folds with one syncline showing a steep western limb adjacent to the  
292 thrust front (Fig. 2b). The axial traces of the folds within the  $E_{2b2}$  are sub-parallel to the strike of the  
293 LZF (Figs. 6f and 6g). The Triassic clastic sediments ( $T_{3s}$ ) are also strongly folded with fold hinge  
294 striking NNW (Fig. 6h), parallel to the fault trace of the LZF.  
295

### 296 3.1.2 Tongdian fault and flanking units

297 West of the LZF, the Tongdian fault places folded late Permian clastic deposits over Triassic volcanic  
298 sequences (Fig. 4). To the west of the Tongdian fault, the rocks comprise a thick sequence of limestone  
299 interlayered with siltstone and mudstone of late Permian ages (Tang et al., 2016) that was originally  
300 considered to be Triassic in age (BGMRY, 1990). Limestone and marl are most common in the lower  
301 part of the unit that shows an overturned anticline at site CD524. In the upper part the strata contain  
302 more fine-grained clastic deposits of siltstone and mudstone. East of the Tongdian fault, the early to  
303 middle Triassic volcanic rocks ( $T_{1-2p}$ ) consist of massive rhyolitic lava, dacitic lava, rhyolitic or dacitic  
304 breccias and tuff. In the northern end of the mapped area, these rocks are intruded by small bodies of  
305 Eocene syenite with irregular intrusive margins (Fig. 4). In general, this volcanic sequence is strongly  
306 fractured by discretely-spaced small scale secondary faults and abundant cleavages that trends S115-  
307 155° and dips SW60-86°(Fig. 6d). Locally, NE-dipping tuff layers are still distinguished in the lower  
308 part of the unit (Tang et al., 2016). The suite of Triassic volcanic rocks shows a nonconformable contact  
309 with the overlying Triassic clastic deposits ( $T_{3s}$ ) to the east.  
310

311 The Tongdian fault is a steeply dipping fault zone that locally strikes S130-160° and dips SW46-80° at  
312 sites CD517, CD518 and CD524 (Figs. 4, 5o and 5p). Striated surfaces within the fault zone show both  
313 top to the NE reverse slip and right slip (Fig. 6d) indicative of transpressional deformation. The late  
314 Permian strata are deformed by a set of open to tight, upright-plunging folds that trend NW nearly  
315 parallel to the bounding Tongdian fault (Fig. 6i), locally showing overturned limb compatible with a  
316 NE vergence (Fig. 4). At distances of <1 km from the Tongdian fault, the fold are recumbent and  
317 chevron folds less spaced than further away from the fault (Fig. 4), suggesting that the folds are  
318 genetically related to thrusting along the fault. Proximal to the Tongdian fault, the Triassic volcanic unit  
319 has well-developed cleavages (Fig. 5d) that strikes parallel to the principal fault planes, indicating  
320 localized deformation associated with the transpression.  
321

322 At site CD516 ~500 m to the southwest of the Tongdian fault, a steeply dipping brittle fault strikes  
323 S140-180° and dips SW60-80° (Fig. 6d). Striations and chatter marks on the fault surfaces indicate both  
324 reverse slip and right slip (Fig. 6d). These suggest this fault to be a transpressional structure, which led  
325 to folding of the late Permian strata in its hanging wall (Figs. 4 and 6i). The similarity of geometry and  
326 kinematics of this fault to the Tongdian fault suggest that this fault is likely a branch fault of the  
327 Tongdian fault.  
328

### 329 3.2 ENE-trending dextral strike-slip faults

330 Apart from thrust faults, we observed a set of ENE-trending, steeply dipping, brittle faults at several  
331 localities (e.g., CD241, CD320, CD327, CD328 and CD347; Figs. 4 and 6c). On the fault planes, nearly



332 horizontal calcite growth striae together with the asymmetric calcite crystallization marks indicate a  
333 dextral sense of shear. Besides, meters-scale of right lateral separation of Eocene conglomerate beds  
334 near site CD320 attests to dextral strike slip offset on the fault. Although the relationship between these  
335 ENE-striking right lateral faults with the fold-thrust belt cannot be easily examined in the field, we infer  
336 that these faults could postdate the thrust structures based on the observations that the ENE-striking  
337 dextral strike slip faults apparently cut all the rocks involved in the LZTB and especially the Eocene  
338 Baoxiangsi Fm. (e.g., at site CD320; Fig. 4). More convincing evidences for this relationship would  
339 require more work.

340

### 341 **3.3 Qiaohou fault**

342 The Qiaohou fault was regarded as a part of the Red River fault system (Allen et al., 1984; Leloup et  
343 al., 1995). In the mapped area, this fault zone consists of two splays, named Qiaohou fault-1 and  
344 Qiaohou fault-2 respectively (Fig. 4). The Qiaohou fault-1 separates Eocene volcanic rocks in the west  
345 from late Permian siltstone and limestone to the east, between which a prominent topographic step  
346 occurs. Field measurements show that it is a NNE-striking, steeply dipping, brittle fault at site CD502  
347 (Figs. 4 and 6e). Nearly horizontal striae and chatter marks on the fault planes indicate a sense of dextral  
348 strike slip with a minor normal component (Fig. 6e). Likewise, the Qiaohou fault-2 shares a similar  
349 geometry and kinematics with the Qiaohou fault-1. This fault splay bounds the eastern margin of the  
350 Quaternary Madeng basin and is presumably an active fault. These dextral faults are thus young  
351 structures that probably initiated in the Late Miocene or later (Allen et al., 1984; Leloup et al., 1995).

352

353 To sum up, field observations provide relative timing for the Cenozoic deformation in the study area  
354 based on cutoffs between the structures and Cenozoic sediments and Eocene magmas. Accordingly, we  
355 identified four Cenozoic deformation generations. The LZTB dominated the first deformation phase  
356 with top to the NE-directed thrusting that took place prior to the Late Eocene. The exact magnitude of  
357 crustal shortening across the LZTB is difficult to restore due to the paucity of constraints on the deep  
358 structure of the thrust belt. Subsequently, the Qiaohou fault being a part of the Red River system likely  
359 commenced in the Late Miocene or later (Allen et al., 1984; Leloup et al., 1995). The ENE-trending  
360 dextral strike-slip faults offset the fold-thrust belt, indicating that this set of faults postdated the thrusting,  
361 but their exact activity timing remains unknown. The latest deformation generation is typified by the  
362 Qiaohou fault-2, which could be an active fault controlling the Quaternary Madeng basin. Meanwhile,  
363 we do not exclude the existence of Pre-Cenozoic structures in this area, but it seems that they have been  
364 modified by Cenozoic deformation. In this paper, we thus concentrate on the geometry, kinematics,  
365 timing and implications of the first deformation generation expressed by the LZTB.

366

### 367 **4. Sampling and analytical methods**

368 In order to address the timing of deformation within the LZTB, we employed radiometric dating within  
369 the deformation zones (Fig. 2; Tables 1 and S1). On one hand, we collected 8 samples from syenitic  
370 plutons and lamprophyres intruding the fold-thrust belt for zircon U-Pb dating. These results will firmly  
371 place minimum age for the activity of the thrust belt. We also took 6 samples along a vertical profile in  
372 the Ludian pluton in the hanging wall of the LZFB for multiple dating techniques, including zircon U-  
373 Pb, zircon (U-Th)/He (ZHe), apatite fission track (AFT) and apatite (U-Th)/He (AHe). The zircon U-  
374 Pb geochronology with closure temperature of  $750\pm 50$  °C (Cherniak et al., 2004) resolves the  
375 crystallization age of the igneous rocks. By contrast, the combination of lower-temperature  
376 thermochronological systems of ZHe, AFT and AHe with closure temperatures ranging from ~220 to  
377 40 °C record the cooling path in the upper several kilometers of the crust (Reiners and Brandon, 2006).  
378 Together, these data analyzed with inverse thermal modeling, are able to constrain a complete thermal  
379 history of the rocks in the hanging wall of the LZFB and further provide information on the onset, duration  
380 and rate of rock exhumation, which can be related to thrusting (Reiners and Brandon, 2006; Turab et  
381 al., 2017). Apatite and zircon aliquots were extracted from samples using standard crushing, magnetic  
382 and heavy-liquid separation techniques. Detailed analytical procedures for zircon U-Pb geochronology,  
383 apatite fission track and zircon and apatite (U-Th)/He are described in the supplementary material S1.

384

### 385 **5. Results and interpretation**

386 The analytical datasets are presented in Fig. 2 and Table 1, as well as supplementary material S1 and

387 Tables S1-S6.

### 388 **5.1 Zircon U-Pb geochronology**

389 The majority of dated zircon grains from Mesozoic igneous rocks with oscillatory zoning have low  
390 U/Th ratios of <10 (Table S2), indicative of igneous origin. Two samples CD144 and CD149 were  
391 collected from the Ludian granite in the hanging wall of the northern segment of the Ludian-  
392 Zhonghejiang fault (Fig. 2a). Most zircon grains yield concordant ages clustering at 208-252 Ma (Tables  
393 1 and S2; Fig. S1a). Fifteen and nineteen age points from samples CD144 and CD149 give weighted  
394 mean U-Pb ages of  $227.7 \pm 4.6$  Ma and  $234.5 \pm 4.7$  Ma respectively (Figs. S1a and S1b). These two ages  
395 thus represent the crystallization age of the Ludian granite. The sample CD327 is a dacite collected in  
396 the Pangtiange Fm. (T<sub>1-2p</sub>). Several ages are pre-Cenozoic, but the lower intercept defined by the linear  
397 regression of 10 ages clusters at two group ages at  $\sim 270$  Ma and  $\sim 235$  Ma (Tables 1 and S2; Figs. S1c  
398 and S1d). Seven out of ten zircon grains yield a younger weighted mean U-Pb age of  $234.4 \pm 8.5$  Ma,  
399 overlapping with published zircon U-Pb ages spanning from  $\sim 237$  to 250 Ma in the same volcanic unit  
400 (Yang et al., 2014; Table S3).

401

402 Six samples CD316, CD323, CD325, CD330, CD331, CD335/CD435 were collected from some small  
403 porphyry dykes intruding in the LZTB in the northern end of the mapped area (Figs. 2 and 4). Of them,  
404 samples CD316, CD323 and CD331 have a few Cenozoic ages that are sub-concordant at  $\sim 34$ -36 Ma  
405 (Tables 1 and S4; Figs. S1e-j). Ten, five and six ages yield weighted mean U-Pb ages of  $34.5 \pm 1.3$  Ma,  
406  $34.3 \pm 1.6$  Ma and  $35.3 \pm 1.7$  Ma for samples CD316, CD323 and CD331 respectively (Fig. S1; Tables 1  
407 and S2). Samples CD335 and CD435 were taken from the same lamprophyre at site CD335, so we  
408 combined their zircon U-Pb data sets together. Most zircons from these two samples present large range  
409 of pre-Cenozoic ages spanning from 251 Ma to 2273 Ma. Six zircon grains yield a weighted mean U-  
410 Pb age of  $35.1 \pm 0.5$  Ma (Figs. S1k and S1l). The other two samples CD325 and CD330 yield much more  
411 inherited pre-Cenozoic ages (Figs. S1m-p). Only one grain per sample yield Eocene ages that may  
412 represent the intrusion age, but the points fall off the concordant curves and thus do not provide a robust  
413 age constraint. Overall, the late Eocene ages recorded by these samples generally overlap with previous  
414 zircon U-Pb data for the porphyry, granite and syenite plutons and dykes as well as volcanic clasts in  
415 and around the Jianchuan basin (Fig. 3 and Table S4), indicating a major flare-up event occurred from  
416  $\sim 35.7$  to 34.5 Ma (Gourbet et al., 2017).

417

### 418 **5.2 Low-temperature thermochronology**

419 Single-grain ZHe ages obtained from the samples CD144, CD145 and CD148 consistently cluster  
420 within  $\sim 100$ -140 Ma (Tables 1 and S5; Fig. 7a), significantly younger than the Triassic emplacement  
421 age of the Ludian granite. These ages thus reflect later cooling or exhumation event. Single-grain ZHe  
422 ages of samples CD145 and CD148 show reverse relationships with the effective uranium  
423 concentrations ( $[eU]=[U]+0.235*[Th]$ ; Guenther et al., 2013; Fig. 7a), indicating that radiation damage  
424 affected the zircon grains (Guenther et al., 2013).

425

426 Four single-grain AHe ages from the low-elevation sample CD145 range from 29.4 Ma to 43.6 Ma (Fig.  
427 7b). Five single-grain ages from the high-elevation sample CD148 span from 36.0 Ma to 49.6 Ma. In  
428 general, neither positive nor negative relationships between the AHe ages and eU appear in Fig. 7b.  
429 The single-grain AHe ages of the sample CD148 overlaps with the AFT ages of CD148 and CD149  
430 within errors at comparable elevations, but much younger than the corresponding ZHe ages, indicating  
431 self-consistency of the multiple thermochronology data. Two replicates from samples CD145 and  
432 CD148 yield very young ZHe ages probably because of grain loss during the preparation process. These  
433 two data were not used for inverse modeling and interpretation. The Eocene cooling ages broadly  
434 overlap with AHe ages from the northern part of the Ludian pluton (Liu-Zeng et al., 2018).

435

436 Five samples CD144, CD146, CD147, CD148 and CD149 from an elevation profile along the Ludian  
437 granite with sufficiently countable grains and kinetic parameters yield a cluster of Eocene AFT ages  
438 ranging from 35.8 Ma to 45.3 Ma (Tables 1 and S6). All ages passed the  $P(\chi^2)$  test with very low  
439 dispersion values, indicative of single age populations (Galbraith and Green, 1990). The mean track  
440 lengths span from 13.35 to 14.01  $\mu\text{m}$  (Table S6). AFT age plot against elevation show a general positive  
441 correlation (Fig. 7c).

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### 5.3 Thermal modeling

The cooling histories of the Ludian granite were further derived by using the Bayesian transdimensional Markov chain Monte Carlo protocol (Gallagher, 2012). The inverse scheme of this program is preferably designed to reconstruct thermal history from a thermochronological age-elevation profile. The model was set up taking into account all AFT ages, track length distribution and kinetic parameters, as well as acceptable single ZHe and AHe ages, apatite and zircon crystal dimensions and U, Th and Sm concentrations from samples CD144, CD145 and CD148. Fission track annealing and He diffusion algorithms used for ZHe, AFT and AHe modelling refer to Guenther et al. (2013), Ketcham et al. (2007) and Gautheron et al., (2009), respectively.

In order to make the modeling informative and convincing, two independent geological boundary conditions were given: 1) samples collected from the Ludian granite are at the surface, and thus between 0 and 10 °C at present day; 2) a loosely constrained condition of a temperature of 300±50 °C at 110±20 Ma was given as a start. This constraint box forces the model to pass through the ZHe partial retention zone during the late Cretaceous based on reported Late Cretaceous rapid cooling event of the same batholith near Weixi ~100 km northwest of our samples (Liu-Zeng et al., 2018). We used the default values of 30 °C/km for the paleo and present geothermal gradients and allow the temperature offset to vary over time. Each 1,000,000 iterations were performed as burn-in and post-burn-in iterations. The optimized temperature-time curves present a four-episode cooling history (Fig. 7d). The first cooling stage at ~125-110 Ma reflects a rapid exhumation process for the pluton passing through the ZHe partial retention zone (PRZ). The following cooling episode between 110-50 Ma shows the rock resided on the upper boundary of the ZHe PRZ for ~60 Ma. Notably, the subsequent accelerated cooling between ~50 and 39 Ma at a rate of ~9 °C Ma<sup>-1</sup> (Fig. 7d) is interpreted as exhumation related to thrusting along the LZTB. Based on the modelled cooling histories, the temperature difference of the highest and lowest samples ranges from ~6 to ~12 °C (Fig. 7d). An elevation difference of ~400 m between these two samples thus infers geothermal gradients between ~15-30 °C km<sup>-1</sup>. The cooling rate of the Ludian pluton between ~50-39 Ma translates to an apparent exhumation rate of ~0.3-0.6 mm a<sup>-1</sup>. The relatively rapid exhumation ended at ~39 Ma and was followed by a protracted period of extremely slow cooling at a rate of <1.75 °C Ma<sup>-1</sup> (Fig. 7d) indicative of the cessation of the deformation in the LZTB.

## 6. Discussion

### 6.1 Temporal and spatial constraints on the Ludian-Zhonghejiang fold-thrust belt

Geological crosscutting relationships provide relative chronology for the activity of the LZTB. For example, the intrusion of porphyry dykes of 35-36 Ma within the LZTB (Figs. 4, 5b and 5c) indicates that the LZTB was active prior to ~36 Ma. Likewise, the occurrence of syn-tectonic sediments of Baoxiangsi Fm. (E<sub>2b</sub>) (see below) older than the Shuanghe Fm. dated at ~35.9±0.9 Ma (Gourbet et al., 2017) suggest that the deformation within the fold-thrust belt occurred no later than 36 Ma. Independently, rapid cooling of the Ludian pluton in the hanging wall of the LZFB derived from thermochronology and inverse models are compatible with thrusting activity of the LZTB during 50-39 Ma. The existence of syn-tectonic sediments of the Baoxiangsi Fm. (E<sub>2b</sub>) in the footwall of the thrust belt rules out regional uplift at that time span (See the detailed discussion in the next section), and thus implies NE-oriented crustal shortening initiated at 50 Ma and continued until 39 Ma on the western margin of the South China block. This robust temporal constraint is consistent with geological crosscutting observations. Since 39 Ma, the quiescence of the LZTB is supported by the deposition of sediments in low-lying and flat alluvial to palustrine and fluvial systems of the Jiuziyan and Shuanghe Fms. (Figs. 2 and 3; Gourbet et al., 2017; Sorrel et al., 2017) in the eastern part of the Jianchuan basin. In space, this fold-thrust system may extend to the northwest near Weixi county, where the onset of rapid exhumation during 60-40 Ma was interpreted as relating to the reactivation of local structures (Liu-Zeng et al., 2018). Further investigations on the fault extent and correlation are still needed.

### 6.2 Syn-tectonic deposition in the Jianchuan basin

The Jianchuan basin, filled by kilometers-thick Paleogene terrestrial sediments, has attracted much attention in order to understand the tectonic, paleoenvironmental and topographic evolution of southeast

496 Tibet. Despite its importance, how the basin did form remains unclear. Two sets of models have been  
497 proposed to explain the basin formation and evolution. In the first set of models, the alluvial-fan and  
498 braided-stream clasts of the Baoxiangsi Fm. were interpreted as deposits coeval with the ultrapotassic  
499 magmatism from 40 to 27 Ma in a rift setting (Wei et al., 2016), which was induced by intraplate  
500 extension related to the delamination of a thickened lithosphere (Chung et al., 1997). However, field  
501 evidences show that the deposition of the Shuanghe and Jianchuan Fms. ( $E_{2s}$  and  $E_{2jc}$ ), rather than the  
502 Baoxiangsi Fm. ( $E_{2b}$ ), was coeval with the magmatic episode that was restricted to a very short time  
503 between 35 and 36 Ma (Table S4; Gourbet et al., 2017; this study). Therefore, the argument for the  
504 deposition of the Baoxiangsi Fm. in a rift basin is not supported by the new stratigraphy of the Jianchuan  
505 basin. Furthermore, no normal fault of that age has been described up to now, neither within nor close  
506 to the Jianchuan basin. In the second model, Paleogene sedimentation in the Jianchuan basin was  
507 proposed to be simultaneous with basement uplift and thrusting in a regional NE-SW compression based  
508 on the existence of possible syn-depositional structures (e.g., mudstone dykes in the major thrust fault  
509 plane and diapirs in the fracture of hanging wall) in the thrust (Yang et al., 2014). This hypothesis seems  
510 partly consistent with local structural observations but lends no support from our observations on the  
511 architecture of the LZTB and the syn-depositional structures of the Jianchuan basin.

512  
513 Our results suggest that deposition of the Baoxiangsi Fm. ( $E_{2b}$ ) in the Jianchuan basin is syn-tectonic  
514 and closely related to the development of the LZTB during crustal shortening (Fig. 8) based on several  
515 lines of evidence. Field observations show that the sediments in the Baoxiangsi Fm. ( $E_{2b}$ ) were  
516 predominately sourced from the hanging wall of the LZF. At the bottom of the Baoxiangsi Fm. ( $E_{2b1}$ ),  
517 an abrupt appearance of massive basal conglomerates and up-section sandstones bearing cross bedding  
518 marks a significant change of sedimentary facies from flood plain (i.e., the Mengyejing Fm. ( $E_{1m}$ )) to  
519 alluvial fan and braided river (Fig. 3). This indicates prominent topographic relief generation triggered  
520 by the contractional deformation within the LZTB, which supplied large amounts of terrestrial clasts to  
521 the adjacent Jianchuan basin (Fig. 8). This inference is also corroborated by predominantly eastward  
522 and northeastward paleocurrents restored by measurements of pebble imbrications and cross beddings  
523 in the Baoxiangsi Fm. (Wei et al., 2016; Wissink et al., 2016; this study; Fig. 2). Apart from these, a  
524 combination of poorly-sorted, sub-angular to sub-rounded pebbles and boulders in the basal  
525 conglomerates are composed of limestone, sandstone and volcanic rocks (Fig. 5l), which were  
526 apparently derived from proximal Permo-Triassic lithologic units in the hanging wall of the LZF. We  
527 thus propose that sedimentation of the Baoxiangsi Fm. ( $E_{2b}$ ) commenced since ~50 Ma and lasted until  
528 ~39 Ma, coevally with the duration of the crustal shortening in the LZTB. This timing is broadly in  
529 agreement with estimated Eocene age from fossil assemblages for the Baoxiangsi Fm. (BGMRY, 1990),  
530 overlain by deposition of the Jiuziyan Fm. ( $E_{2jz}$ ), Shuanghe Fm. ( $E_{2s}$ ) and Jianchuan Fm. ( $E_{2jc}$ ) during  
531 the Late Eocene (Gourbet et al., 2017; Sorrel et al., 2017; Wu et al., 2018). Sedimentation during the  
532 Jiuziyan and Shuanghe Fms. ( $E_{2jz}$  and  $E_{2s}$ ) likely took place in distal alluvial fan-deltas and sub-  
533 lacustrine (alluvial-lake) environments characteristics of low-lying depositional systems (Sorrel et al.,  
534 2017), which is congruent with the cessation of the fold-thrust belt and final infill of the Late Eocene  
535 intermontane Jianchuan basin.

### 536 537 **6.3 Cretaceous-Early Cenozoic crustal deformation and uplift of the southeast Tibet and** 538 **implications for the lithospheric rheology of the Tibet**

539 Rapid Cretaceous cooling events have been revealed by thermochronometres in the east and southeast  
540 Tibet (Tian et al., 2014; Liu-Zeng et al., 2018). They most likely corresponded to crustal thickening as  
541 a result of the collision between the Lhasa and Qiangtang terranes implied from the geological records  
542 of central Tibet (Kapp et al., 2005, 2007). We follow this hypothesis to interpret rapid Cretaceous  
543 exhumation in the Jianchuan area recorded by our thermochronological data. However, the detailed  
544 geological processes in southeast Tibet during Lhasa-Qiangtang collisional orogenesis would need  
545 much more work. We focus here on Early Cenozoic deformation as discussed below.

546  
547 A growing number of structural and paleomagnetic investigations suggest that southeast Tibet has been  
548 dominated by extrusion tectonics since the Late Eocene, which was predominantly accommodated by  
549 major strike slip faults along the block boundaries (Tapponnier et al., 1982; 1990; Cao et al., 2011;  
550 Leloup et al., 1993, 2001; Lin et al., 2009; Tong et al., 2016; Zhang et al., 2011, 2014), though some



551 others argued for a geodynamic model of lower crustal flow for Late Cenozoic surface uplift (Clark et  
552 al., 2005; Ouimet et al., 2010; Royden et al., 1997, 2008; Schoenbohm et al., 2006; Wang et al., 2016).  
553 Nevertheless, how regional crustal deformation in the Early Cenozoic was partitioned remains poorly  
554 understood. Our results indicate that the western margin of the South China block was affected by NE-  
555 directed compression since ~50 Ma nearly synchronous with the onset of the India-Asian collision,  
556 which is expressed by compressive deformation in the LZTB and simultaneous sediment deposition in  
557 the adjacent Jianchuan basin. The Permo-Triassic rocks were intensely deformed within the LZTB in a  
558 pattern of tight and recumbent fold assemblages in a short wavelength and high amplitude between  
559 major thrust faults (Fig. 2b). In contrast, the Eocene sediments in the Jianchuan basin show typical  
560 broad, long-wavelength folds in the footwall of the LZF (Fig. 2b). The discrepancy of deformation  
561 intensity between the basin and fold-thrust belt raise two questions of 1) whether southeast Tibet  
562 attained its present-day height due to crustal shortening in the Eocene, and 2) how the strain propagated  
563 to accommodate the India-Asian convergence.

564  
565 The Eocene paleoaltimetry of southeast Tibet, taking the Jianchuan basin in northwest Yunnan as an  
566 example, remains controversial. Previous studies argued that the Jianchuan basin has uplifted to an  
567 elevation of  $\sim 3.3 \pm 0.5$  km asl. (Hoke et al., 2014) or  $\sim 2.6$  km asl. (Li et al., 2015) in the Eocene close  
568 to a modern surface height, which was interpreted as resulting from crustal shortening in response to  
569 the India-Asian collision (Li et al., 2015). However, recent work based on stable isotopes and fossil  
570 pollen coexistence instead argue for a lower elevation for the Eocene basin ranging from  $\sim 1.2 \pm 1.2$  km  
571 asl. (Gourbet et al., 2017) to  $0.9\text{-}2.9 \pm 0.6$  km asl. (Wu et al., 2018). Our structural data suggest limited  
572 uplift of the Jianchuan basin in the Eocene as follows. The long wavelength of the folds affecting the  
573 Paleogene sediments (i.e.,  $E_{1m}$  and  $E_{2b}$ ) imply a small crustal shortening (less than 5 km estimated from  
574 cross section in Fig. 2b) in the Jianchuan basin during the activity of the LZTB between ~50 Ma and  
575 39 Ma. In addition, Late Eocene rocks (i.e.,  $E_{2jz}$ ,  $E_{2s}$  and  $E_{2jc}$ ) restricted in the southeastern corner of  
576 the Jianchuan basin, are generally flat-lying and partly involved in a broad fold with a NE-trending axis  
577 parallel to the striking of the Yulong thrust belt (Fig. 1), which was likely related to the NW-directed  
578 compression in a later stage during the basin exhumation at ~28-20 Ma (Cao et al., 2019). Therefore,  
579 our results indicate a prominent topographic gradient in the hanging wall of the LZF that supplied clasts  
580 to the nearby lowland-Jianchuan basin, and thus support a relatively lower surface elevation for the  
581 Jianchuan basin in the Late Eocene. Independently, an altitude of  $0.5\text{-}2.9 \pm 0.6$  km asl. is suggested for  
582 the basin by new stable isotope results integrated with fossil pollen coexistence (Wu et al., 2018). The  
583 topographic relief generated by intense crustal shortening within the LZTB created a local vertical  
584 vegetation variation (Fig. 8), consistent with the wide range of pollen assemblage and major flood  
585 events documented in the Late Eocene sediments of the basin (Sorrel et al., 2017; Wu et al., 2018).

586  
587 The collision between Indian and Asian plates since ~60-50 Ma (Allègre et al., 1984; Ding et al., 2016;  
588 Hu et al., 2016; Najman et al., 2010; Rowley, 1996) has induced widespread deformation across the  
589 Tibetan Plateau, but the details of strain propagation remains debated. Apart from the Himalayan fold-  
590 thrust belt bounding the collision belt (Guillot et al., 2003; DeCelles et al., 2014), a growing body of  
591 studies documented extensive upper crustal shortening and development of syn-contractual basins  
592 within the Qiangtang terrane coevally with or shortly after the onset of the India-Asian collision (Fig.  
593 9). For example, geological mapping integrated with balanced cross section and radiometric dating  
594 revealed upper crustal shortening of  $34 \pm 12$  km and ~61 km in the Hoh Xil basin and Yushu-Nangqian  
595 basin since ~48-52 Ma and ~51 Ma (Horton et al., 2002; Spurlin et al., 2005; Wang et al., 2008; Staisch  
596 et al., 2016), respectively. This is also the case for the crustal shortening deformation in the Gonjo basin  
597 and LZTB in east and southeast Tibet (Studnicki-Gizbert et al., 2008; Tong et al., 2017; Yin and  
598 Harrison, 2000; Gourbet et al., 2017; this study; Fig. 9). In contrast, limited post-50 Ma shortening have  
599 been documented in the interiors of the Lhasa, Songpan-Garze and Kunlun terranes (Kapp et al., 2005,  
600 2007; van Hinsbergen et al., 2011). Such an intervening deformation pattern implies that the whole  
601 Plateau has not been homogenously shortened and thickened in the early stage of the collision as often  
602 assumed (Dewey and Burke, 1973; England and Houseman, 1986).

603  
604 The deformation pattern approximately fit with the proposition of an Eocene Tibet corresponding to the  
605 Qiangtang terrane (Tapponnier et al., 2001). However, other compressional structures, including the

606 Main Pamir thrust-West Kunlun thrust belt (Cao et al., 2013, 2015; Yin et al., 2002), the Lungmuco  
607 fault (Leloup et al., 2012), Altyn Tagh fault and Qaidam thrust (Yin et al., 2002), Northern Qaidam  
608 thrust belt (Yin et al., 2008) and West Qinling thrust (Clark et al., 2010; Duvall et al., 2011), located far  
609 away (> 400 to 1400 km) from the plate boundary appear active soon after the collision (Fig. 9). This  
610 implies that the compressive stresses as a result of the India-Asian collision have been transmitted  
611 efficiently across the whole plateau indicating a rigid-plastic rheology, such that an early Cenozoic stage  
612 of deformation along the northern boundary of the plateau preceded the migration to the north of the  
613 main deformation events in a stepwise manner (Tapponnier et al., 2001). We thus suggest that the  
614 deformation pattern is more complex than simple propagation from central to northern Tibet through  
615 time as proposed by Tapponnier et al. (2001). Accordingly, a synthesis of middle Eocene tectonic  
616 scenario throughout the India-Asian collision zone illustrates that contraction concentrated in the  
617 Qiangtang terrane, which intervened the less deformed Lhasa, Songpan-Garze and Kunlun terranes (Fig.  
618 9). The Eocene contractional structures that localized in the Qiangtang terrane were probably inherited  
619 from preexisting structures formed during mid-Cretaceous crustal shortening related to the Lhasa-  
620 Qiangtang collision (Kapp et al., 2005, 2007), while deformation in the Songpan-Garze and Kunlun  
621 terranes was older. The spaced deformation pattern of crustal shortening may be explained by the  
622 difference of deeper crustal strength as the deep crust of the Qiangtang terrane is composed of large  
623 volume of mélangé and flysch that are relatively weaker than the Lhasa, Songpan-Garze and Kunlun  
624 terranes (Kapp et al., 2005).

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## 626 **7. Conclusions**

627 An integration of geological mapping and geochronological and thermochronological dating illustrate  
628 Early Cenozoic configuration of tectonic deformation, rock exhumation and basin development on the  
629 western margin of the South China block (western Yunnan) during the early stage of the India-Asian  
630 collision. The Early Cenozoic deformation is expressed by the LZTB, which is a contractional structure  
631 which presently outcrop for ~120 km between the Diancang Shan and Xuelong Shan metamorphic belt  
632 in western Yunnan. This deformation belt mainly consists of two major SW-dipping brittle thrust faults,  
633 named the Ludian-Zhonghejiang fault (LZF) and the Tongdian fault from east to west. Between them,  
634 Permo-Triassic strata are involved in a set of short-wavelength, nearly vertical and southwest-vergent  
635 tight folds with axes that trend subparallel to the traces of the principal faults. The Paleocene sediments  
636 in the Jianchuan basin were deformed by a long-wavelength, vertical broad syncline. Inverse modeling  
637 with multiple low temperature thermochronological data, including ZHe, AHe and AFT, from a Triassic  
638 pluton in the hanging wall of the LZF reveals two episodes of accelerated cooling during 125-110 Ma  
639 and 50-39 Ma. The Cretaceous cooling event was probably ascribed to crustal thickening during the  
640 Lhasa and Qiangtang collision. The Eocene rapid exhumation is interpreted to date the activity of the  
641 Ludian-Zhonghejiang fold-thrust system. This timing is corroborated by the intrusive relationship  
642 between Eocene magmas of ~35-36 Ma and the fold-thrust belt. The Eocene contraction seemingly  
643 controlled deposition of alluvial-fan and braided-river sediments of the Baoxiangsi Fm. in the Jianchuan  
644 basin, which is supported by paleoflows and provenance analysis. The contractional deformation likely  
645 ended at ~39 Ma reflected by significantly decreasing cooling rates in the thermal history and the  
646 occurrence of low-lying palustrine and alluvial-lake depositional systems in the basin since then.

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648 At the plateau scale, our results along with geological records of contraction in central, northern and  
649 eastern Tibet document Eocene upper crustal shortening localized in the Himalaya, Qiangtang terrane  
650 and northern plateau margins (intervened by Lhasa, Songpan-Garze and Kunlun terranes) together with  
651 contractional basin development coevally with, or shortly after, the onset of the India-Asian collision,  
652 which is inconsistent with a homogenous crustal thickening (Dewey and Burke, 1973; England and  
653 Houseman). Moderate crustal shortening affected a large part of Tibet in a spaced way soon after the  
654 collision, prior to the main crustal thickening propagated progressively from south to north (Tapponnier  
655 et al., 2001). This spaced deformation pattern of crustal shortening illustrates the strain of the India-  
656 Asian collision and convergence propagated from the plate boundary within the Asian continent during  
657 the Early Cenozoic in a more complex way than what were assumed in the existing geodynamic models.

658 **Acknowledgements**

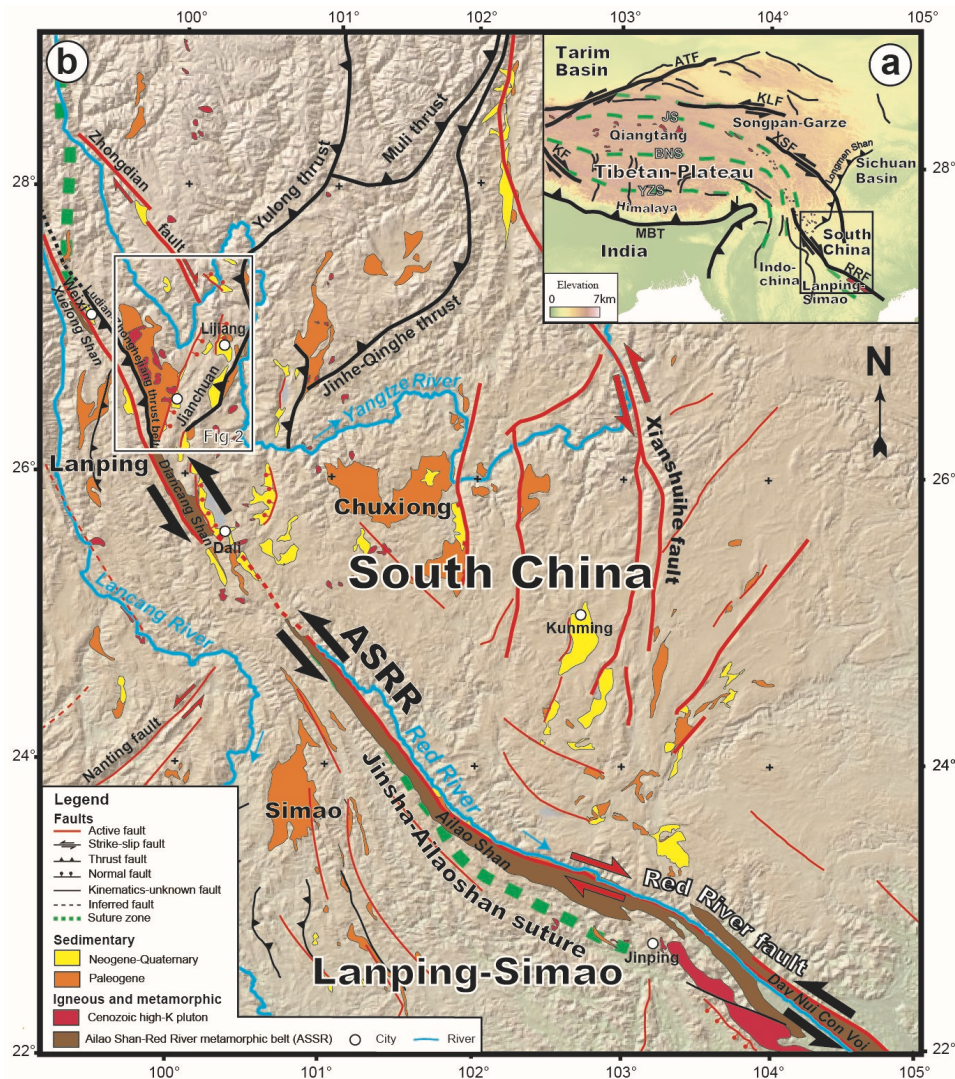
659 We thank Peter Decelles and Jay Chapman for enlightening discussion. LA-ICP-MS apatite fission-  
 660 track dating was accomplished by Paul O'Sullivan and Raymond Donelick at Apatite to Zircon, Inc.,  
 661 Viola, Idaho, USA. We are grateful to Peter Reiners and Uttam Chowdhury for help in the (U-Th)/He  
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671 **Tables**

672 Table 1. Summary of geochronological and thermochronological results within the LZTB, SE Tibet.

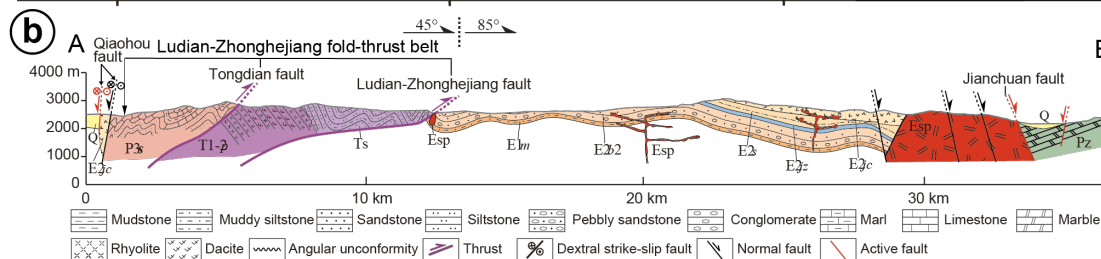
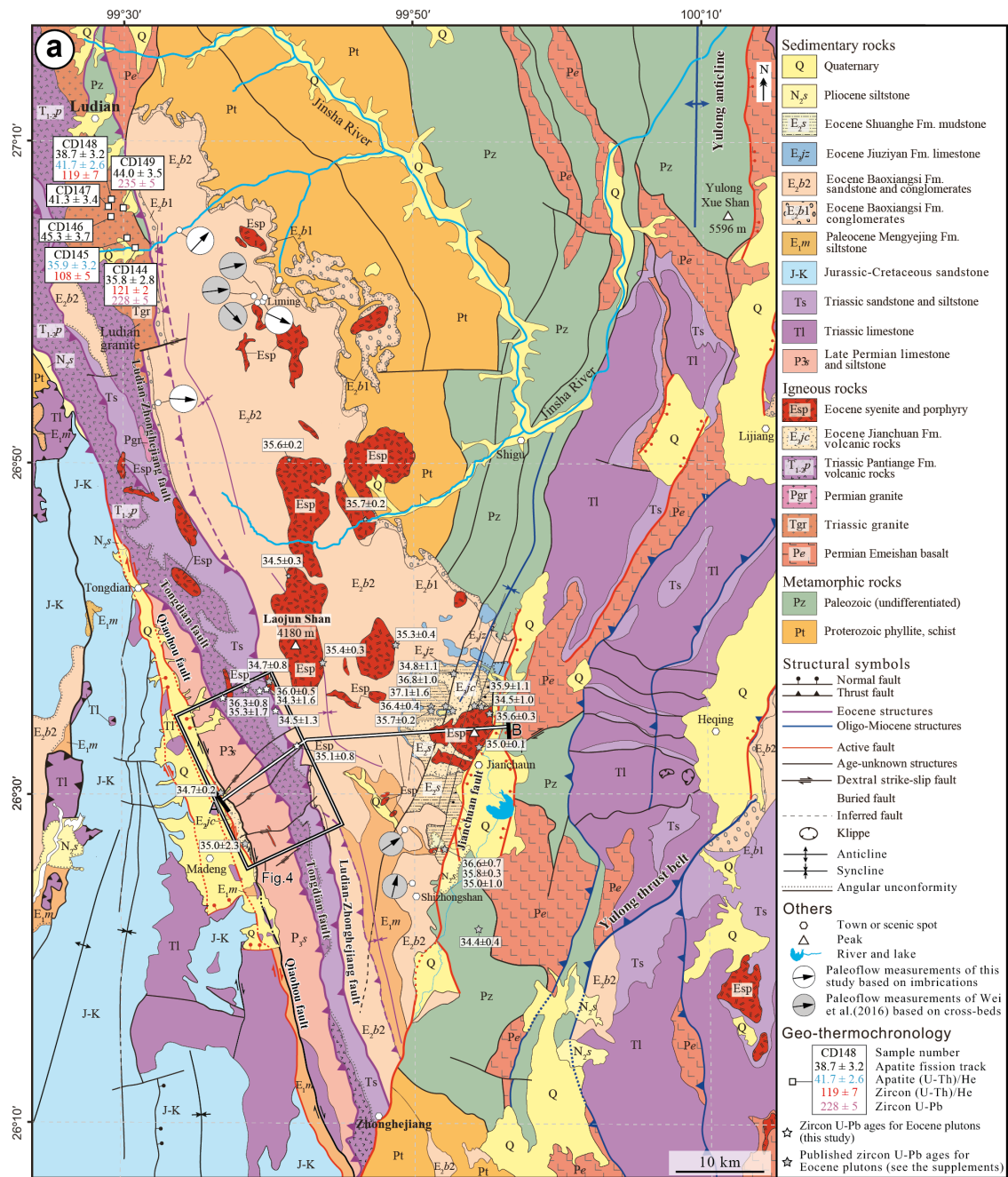
Sample ID	Longitude (°E)	Latitude (°N)	Elevation (m)	Zircon U-Pb age (Ma)	Mean ZHe age (Ma)	Pooled AFT age (Ma)	Mean AHe age (Ma)
CD144	99.5151	27.0599	2595	228 ± 5	121 ± 2	35.8 ± 2.8	-
CD145	99.5034	27.0696	2635	-	108 ± 5	-	35.9 ± 3.2
CD146	99.4895	27.0908	2710	-	-	45.3 ± 3.7	-
CD147	99.4851	27.1013	2789	-	-	41.3 ± 3.4	-
CD148	99.4927	27.1031	2939	-	119 ± 7	38.7 ± 3.2	41.7 ± 2.6
CD149	99.4999	27.0996	2985	235 ± 5	-	44.0 ± 3.5	-
CD316	99.6712	26.5934	3143	34.5 ± 1.3*	-	-	-
CD323	99.6616	26.6113	3060	34.3 ± 1.6*	-	-	-
CD325	99.6420	26.6105	2818	36.0 ± 0.5*	-	-	-
CD327	99.6304	26.6027	2806	234 ± 9*	-	-	-
CD330	99.6248	26.6014	2842	36.3 ± 0.8*	-	-	-
CD331	99.6171	26.6010	2876	35.3 ± 1.7*	-	-	-
CD335/ CD435	99.6991	26.5534	2592	35.1 ± 0.5*	-	-	-

673 Note: \* denotes youngest peak ages of plutons in ≤ 10% discordance.



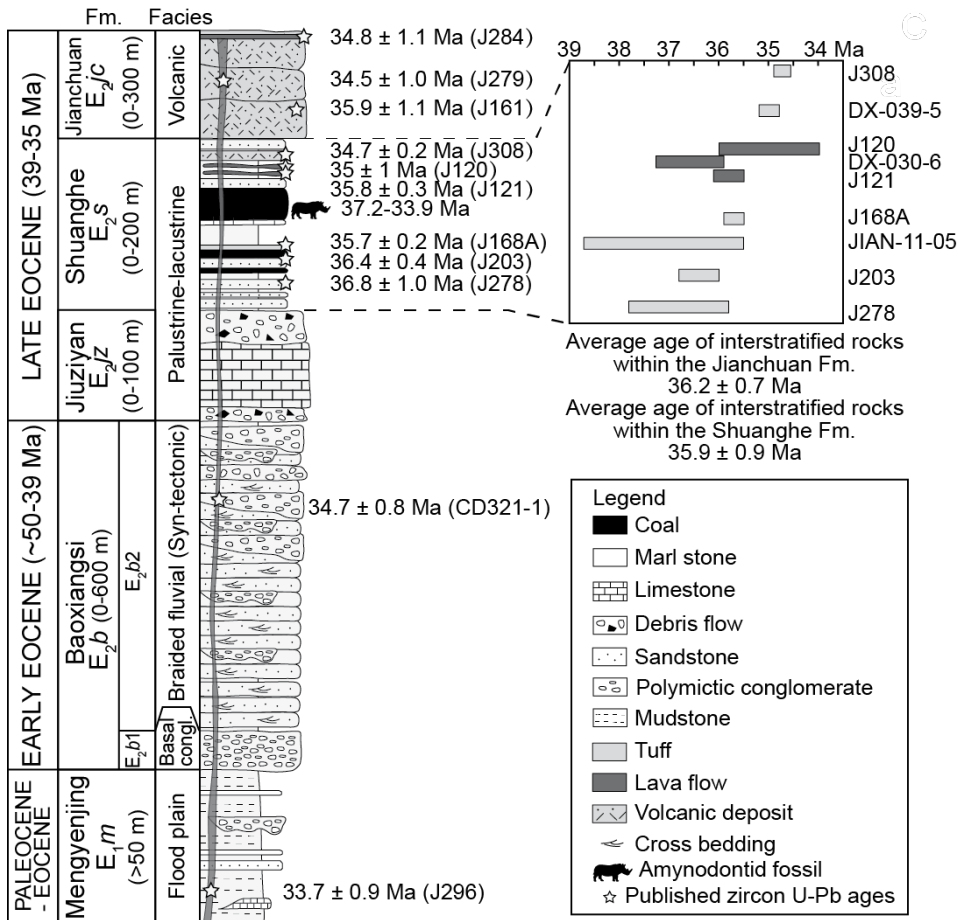
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 676 **Fig.1** (a) Simplified geological map of the southeast Tibet, showing major Cenozoic structures and  
 677 basins, modified from Gourbet et al. (2017). Black arrows indicate Oligo-Miocene motion of the ASRR  
 678 while red arrows indicate Plio-Quaternary motion of the Red River fault. (b) The inset shows location  
 679 within Tibet. Abbreviations: ATF–Altyn Tagh fault, ASRR–Ailao Shan-Red River shear zone, BNS–  
 680 Bangong-Nujiang suture, MBT–Main boundary thrust, JS–Jinsha suture, KLF–Kunlun fault, KF–  
 681 Karakorum fault, RRF–Red River fault, XSF–Xianshuihe fault, IYS–Indus-Yarlung suture.





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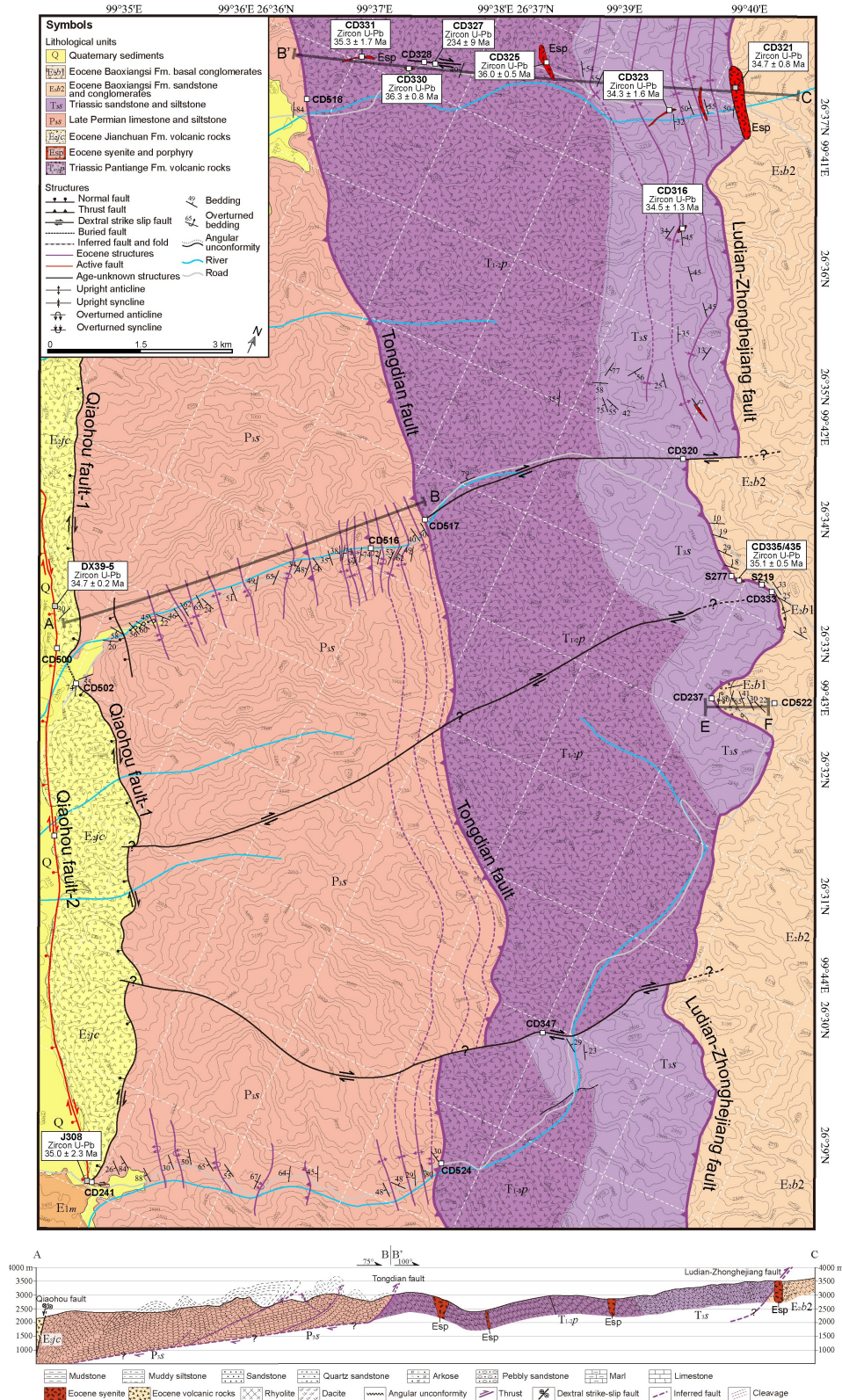
684 **Fig.2** (a) Geological map of the Jianchuan area, southeast Tibet, based on BGMRY (1990), Gourbet et  
 685 al. (2017), Cao et al. (2019) and new mapping results. See location on Fig. 1a. Geochronology and  
 686 thermochronology ages are indicated from this study and previous studies in the Tables 1 and S2-S6, as  
 687 well as paleocurrent directions in the Baoxiangsi Fm. (E<sub>2</sub>b) from this study and Wei et al. (2016). The  
 688 frame corresponds to Fig. 4. (b) Sketch geological cross section across the LZTB and the Jianchuan  
 689 basin, showing relationships between major structures and lithological units. Sections are located on  
 690 Fig. 2a.



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**Fig.3** Stratigraphy of the Jianchuan basin with age constraints on the upper part of the sediment sequences, modified from Gourbet et al. (2017) and Sorrel et al. (2017). Age constraints on the sediment sequences are based on Gourbet et al. (2017), Sorrel et al. (2017), Wu et al. (2018) and this study.

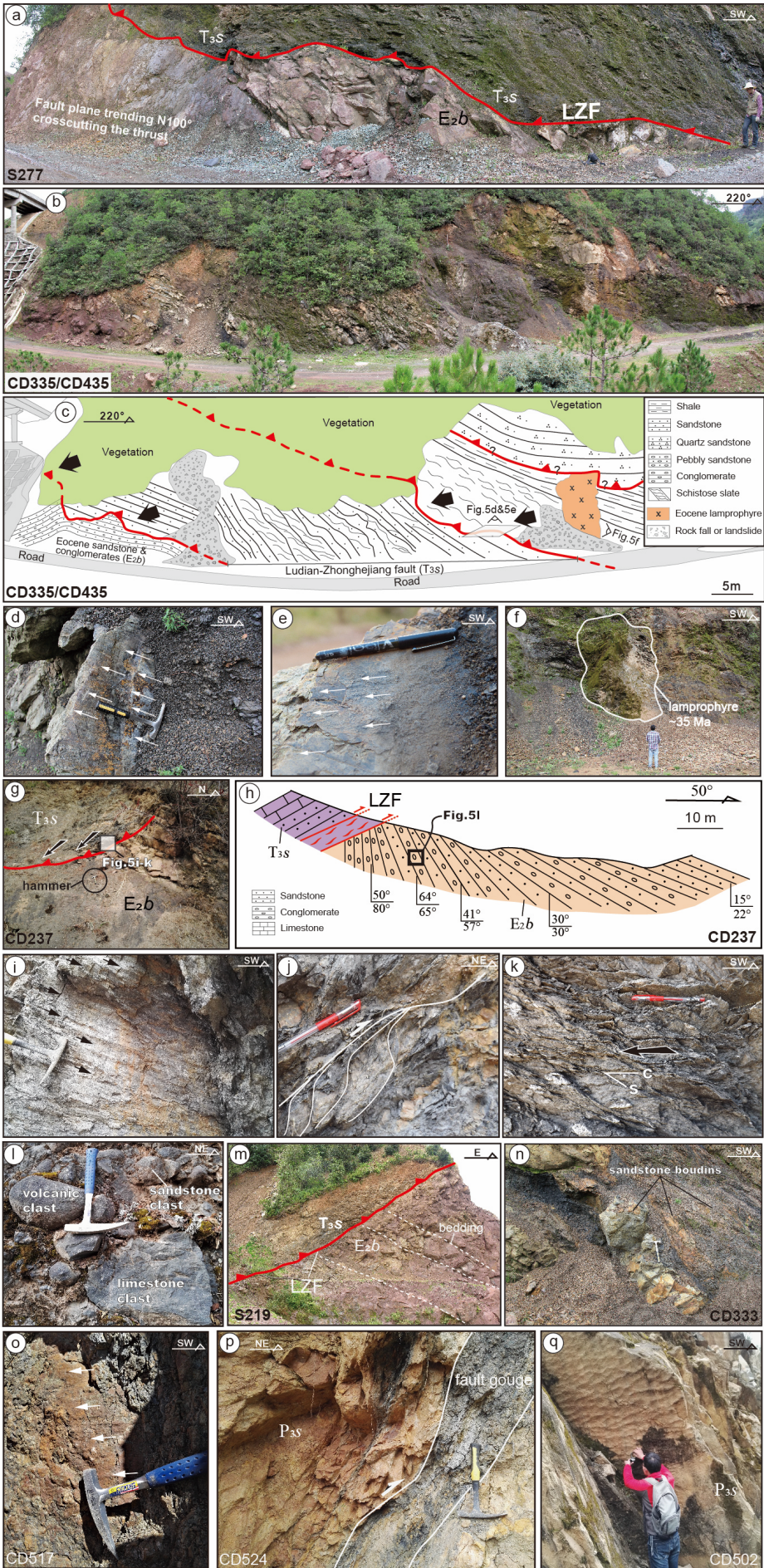




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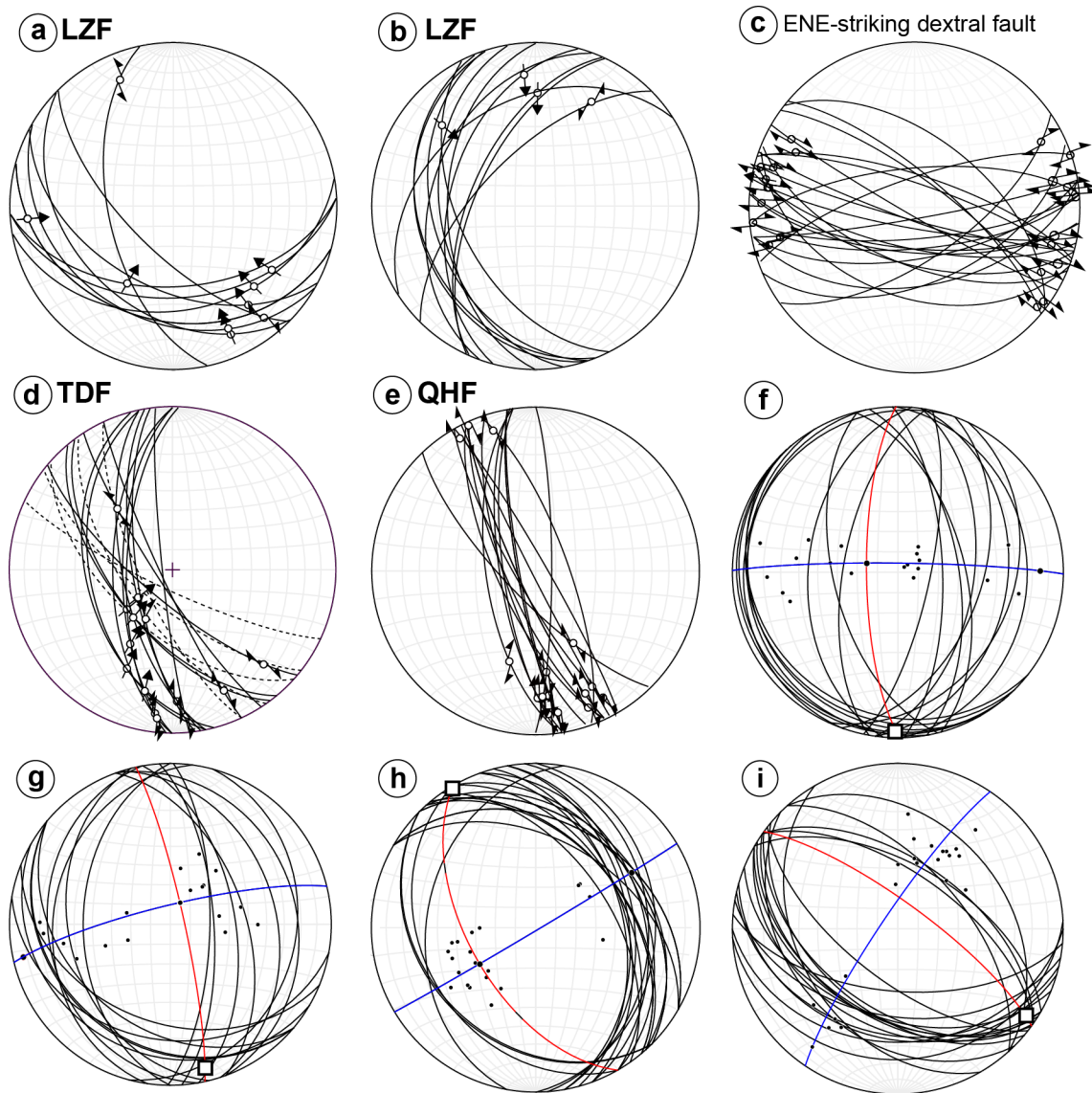
699 **Fig.4** Geological map in the central segment of the LZTB, focusing on the major structures and  
 700 lithological units to the west of the Jianchuan basin. Mapping based on BGMRY (1990) and this study.  
 701 The structural measurements for southern section of the mapping area are partly from Tang et al. (2016).  
 702 Observation sites are shown with corresponding structural observation and samples ages (Table S1).  
 703 See location on Fig 2a. The lower panel is a composite cross section across the LZTB, composed of A-  
 704 B, B'-C and E-F segments located on the above panel.





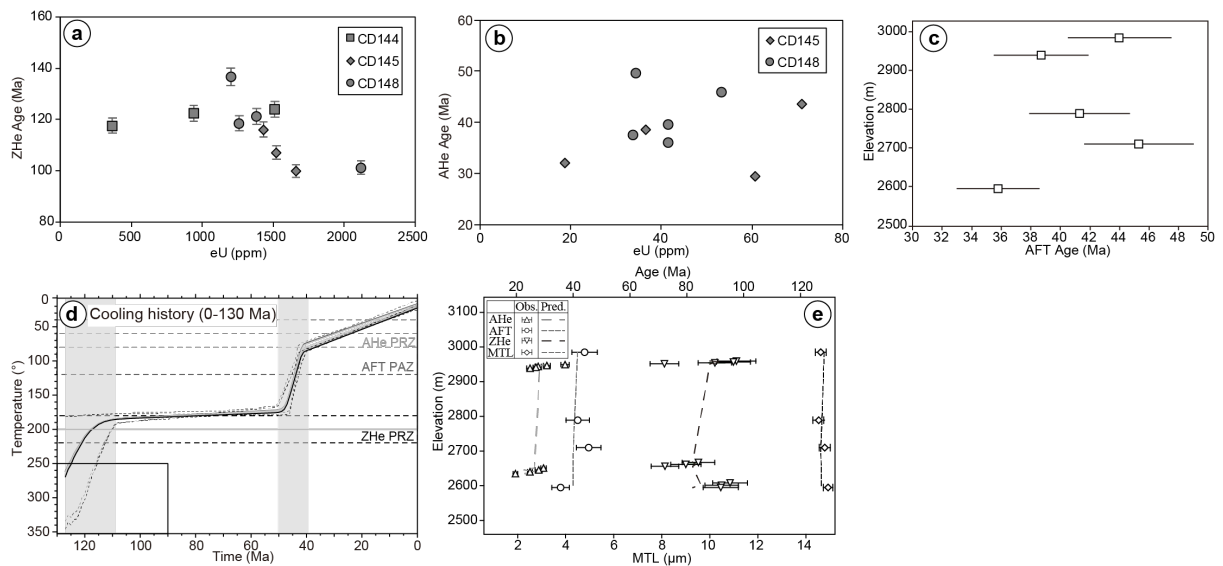


706 **Fig.5** Photos showing the main structures of the LZTB. (a) Triassic slate thrust above Eocene  
707 sediments at site S277. (b-f) field observations at site CD335/CD435: (b) field photo and (c)  
708 corresponding sketch interpretation, showing schistosed Triassic meta-sandstone and coal-bearing slate  
709 ( $T_{3s}$ ) resting above folded Eocene sandstones and conglomerates ( $E_2b1/E_2b2$ ). Black arrows indicate  
710 the direction of motion given by the striae (d-e) gently dipping fault within the Triassic metasandstone  
711 and slate ( $T_{3s}$ ) with striae indicative of thrust motion towards the northwest to northeast (see Fig. 6b).  
712 (f) a ~35 Ma lamprophyre dyke crosscutting schistosed Triassic slate ( $T_{3s}$ ) suggestive of initial thrusting  
713 prior to ~35 Ma. (g-l) field observations at sites CD237 and CD522 (cross section E-F on Fig. 4). (g)  
714 LZF placing Triassic coal-bearing slates ( $T_{3s}$ ) on top of Eocene sandstone ( $E_2b1$ ) at site CD237. (h) a  
715 cross section E-F between CD237 and CD522 showing the LZF placing Triassic strata ( $T_{3s}$ ) over the  
716 Baoxiangsi Fm. ( $E_2b$ ). (i) gently dipping striae and slickensides and (j-k) sigmoid breccia lenses and S-  
717 C fabrics in highly schistosed Triassic slate ( $T_{3s}$ ) indicating top to the NE low-angle thrusting. (l) syn-  
718 tectonic conglomerates in the footwall of the LZF near site CD237 with abundant cobbles and boulders  
719 of volcanic, sandstone and limestone sourced from the hanging wall of the LZF. (m) Triassic clastic  
720 sediments ( $T_{3s}$ ) thrust above Eocene sediments ( $E_2b2$ ) at site S219. (n) sandstone boudins within the  
721 LZF at site CD333. (o) striae and slickensides and (p) fault gouge in the Tongdian fault suggesting  
722 thrusting at sites CD517 and CD524. (q) asymmetrical ripples in the Late Permian sandstone near site  
723 CD506 indicative of overturned bedding dipping to the SW. All sites are shown in Fig. 4 and Table S1b.  
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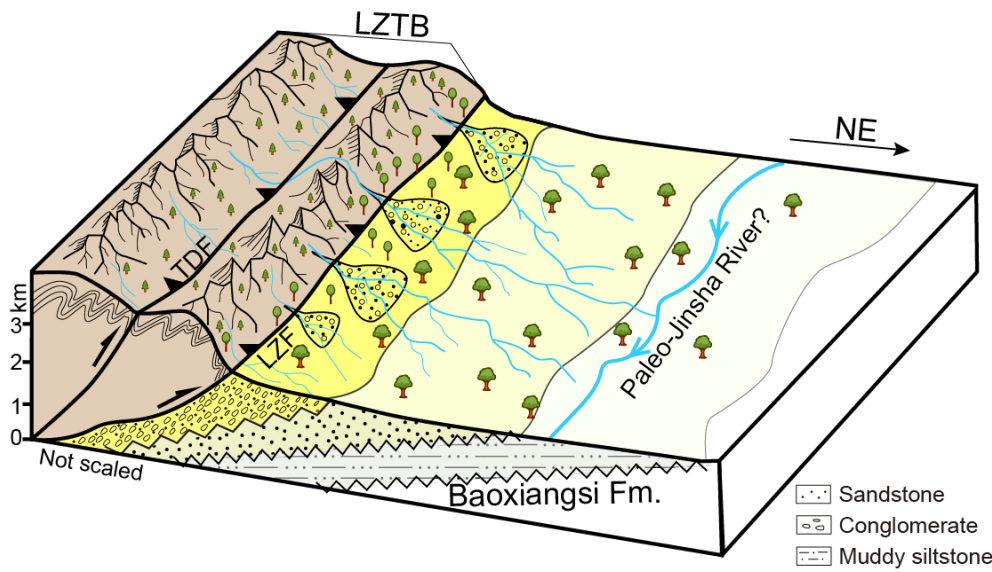
726 **Fig.6** Geometry of faults and folds in the LZTB and western Jianchuan basin. Stereographic projection,  
 727 lower hemisphere atop the equal area net. (a-b) fault splays within the LZF at outcrops (a)  
 728 CD335/CD435 and (b) CD237, (c) ENE-striking dextral strike-slip faults at outcrops CD241, CD320,  
 729 CD327, CD328 and CD347, (d) fault splays (solid curves) within the Tongdian fault (TDF) at outcrops  
 730 CD516, CD517, CD518 and CD524 and cleavages (dash curves) in the Triassic volcanic rocks close to  
 731 the TDF at site CD517, (e) fault splays within the Qiaohou fault (QHF) at outcrops CD500 and CD502.  
 732 Arrows indicate fault kinematics (motion of the upper block). (f-i) stratification (great circles) and poles  
 733 to stratification (dots). (f) and (g) Eocene sediments ( $E_2b$ ) in the syncline proximal to the LZF, to the  
 734 NW and to the SE respectively. (h) and (i) within the fold-thrust belt west of the LZF: Triassic meta-  
 735 sediments ( $T_3s$ ) and Late Permian sediments ( $P_3s$ ) respectively. The axis and hinge orientations of the  
 736 folds are calculated based on representative strike-and-dip measurements of the limbs of the folded  
 737 bedding surface. The blue lines are the planes passing by the stratification poles. The red lines are the  
 738 axial planes with fold axis plotted as squares.



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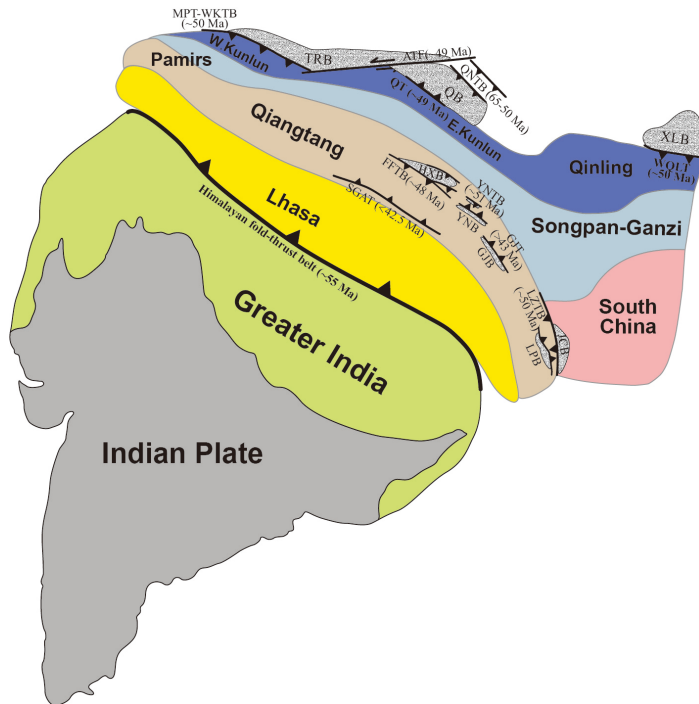
Fig.7 Cooling ages and results of thermal history modelling of the Triassic Ludian granite in the hanging wall of the LZF. (a-b) corrected single-grain ZHe and AHe ages versus effective uranium content (eU). (c) apatite fission-track age and elevation relationship. (d) cooling history of the Ludian granite derived from QTQt inverse modelling with an age-temperature box of  $300 \pm 50$  °C and  $110 \pm 20$  Ma as an initial simulation constraint. The thermal history of the uppermost sample is shown in blue, with the 95% confidence interval in cyan, while the thermal history of the lowermost sample is shown in red, with the 95% confidence interval in magenta. Thermal histories for samples at intermediate elevations are in grey. These reflect the combined uncertainty in the inferred thermal history and the offset parameters. (e) the fits of the predicted and observed data.

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Fig.8 Cartoon showing middle Eocene source-to-sink relationship between the LZTB and syn-tectonic sediments of Baoxiangsi Fm. ( $E_2b$ ) in the Jianchuan basin. Topographic relief was produced by the activity of the LZTB during ~50-39 Ma, resulting in a high vegetation diversity from the mountains to relatively low-elevation basin recorded by pollen grains (Wu et al., 2018).



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**Fig.9** Middle Eocene tectonic scenario across the Tibetan plateau with emphasis on initial activity of the contractional structures and syn-contractional basins immediately after the onset of the India-Asian collision. The size of the Greater India with respect to the Tibet is approximated from van Hinsbergen et al. (2011). Names of the major crustal blocks and sutures are shown. Abbreviations: ATF–Altyn Tagh fault, BNS–Bangong-Nujiang suture, FFB–Fenghuoshan fold-thrust belt, GJB–Gonjo basin, GJT–Gonjo thrust, HXB–Hoh Xil basin, JCB–Jianchuan basin, JS–Jinsha suture, LMC–Lungmuco fault, LPB–Lanping basin, LZTB–Ludian-Zhonghejiang thrust belt, MPT-WKTB–Main Pamir thrust-West Kunlun thrust belt, QNTB–North Qaidam thrust, YNTB–Yushu-Nangqian thrust belt, YNB–Yushu-Nangqian basin, QB–Qaidam basin, QT–Qaidam thrust, SGAT–Shiquanhe-Gaize-Amdo thrust, TRB–Tarim basin, WQLT–West Qinling thrust, XNB–Xining basin. Initial timing for major faults are labeled: FFB at ~52-48 Ma (Wang et al., 2008; Staisch et al., 2016); GJT at ~54 Ma (Zhang et al., 2018); Himalayan fold-thrust belt at ~50-45 Ma (Guillot et al., 2003; Decelles et al., 2014); LMC at 60-55 Ma (Leloup et al., 2011); LZTB at 50-39 Ma (this study); MPT-WKTB at ~50 Ma (Cao et al., 2013, 2015; Yin et al., 2002); QNTB at 65-50 Ma (Yin et al., 2008); QT and ATF at ~49 Ma (Yin et al., 2002); SGAT at <42.5 Ma (Yin and Harrison, 2000); WQLT at ~50 Ma (Clark et al., 2010; Duvall et al., 2011), YNTB at ~51 Ma (Horton et al., 2002; Spurlin et al., 2005).

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1043 **Appendix**  
1044 **Supplementary material S1 Analytical procedures for geochronology and**  
1045 **thermochronology**

1046 **Zircon U-Pb geochronology**

1047 Zircon U-Pb geochronological analyses were conducted at China University of Geosciences, Wuhan,  
1048 China. U-Pb dating was performed using an Agilent 7500a ICP-MS, which is equipped with a GeoLas  
1049 2005 excimer laser ablation system at a spot diameter of 32  $\mu\text{m}$ . Zircon 91500 was used as an external  
1050 standard and analyzed twice every 5 unknowns. To keep age reproducibility and instrument stability,  
1051 four GJ-1 zircon standards were inserted at the beginning and end of each run. Typical operating  
1052 conditions and detailed analytical procedures are described in (Liu et al., 2008). Selection and  
1053 integration of analytic signals, time-drift correction, and quantitative calibration for U-Pb dating were  
1054 performed by ICP-MS DataCal. Ages were accepted with up to 10% and 20% discordance for plutonic  
1055 and volcanic samples, respectively. The results reported here are  $^{206}\text{Pb}/^{238}\text{U}$  ages for zircon ages  $\leq 1.0$   
1056 Ga and  $^{207}\text{Pb}/^{206}\text{Pb}$  ages for grains with ages  $> 1.0$  Ga. Age-distribution plots and age-concordia  
1057 diagrams were generated using Isoplot/Ex. ver. 3.75 (Ludwig, 2012).

1058

1059 **Low-temperature thermochronology**

1060 Apatite fission track analysis was performed at Apatite to Zircon, Inc., Viola, Idaho, USA. Apatite aliquots  
1061 were mounted in epoxy and polished, and then etched in a 5.5 M  $\text{HNO}_3$  solution at 21°C for 20 s. Apatite  
1062 fission track data were acquired using a New Wave Neodymium-YAG 213 nm laser ablation system  
1063 coupled to a Finigan Element II Magnetic Sector ICP-MS at a 12  $\mu\text{m}$  spot and a 5 Hz repetition rate  
1064 with the laser set in constant energy mode. Analyses were corrected by  $^{43}\text{Ca}$  as an internal standard for  
1065 variations in ablation volume. For detailed procedures of sample analysis refer to Donelick et al. (2005)

1066

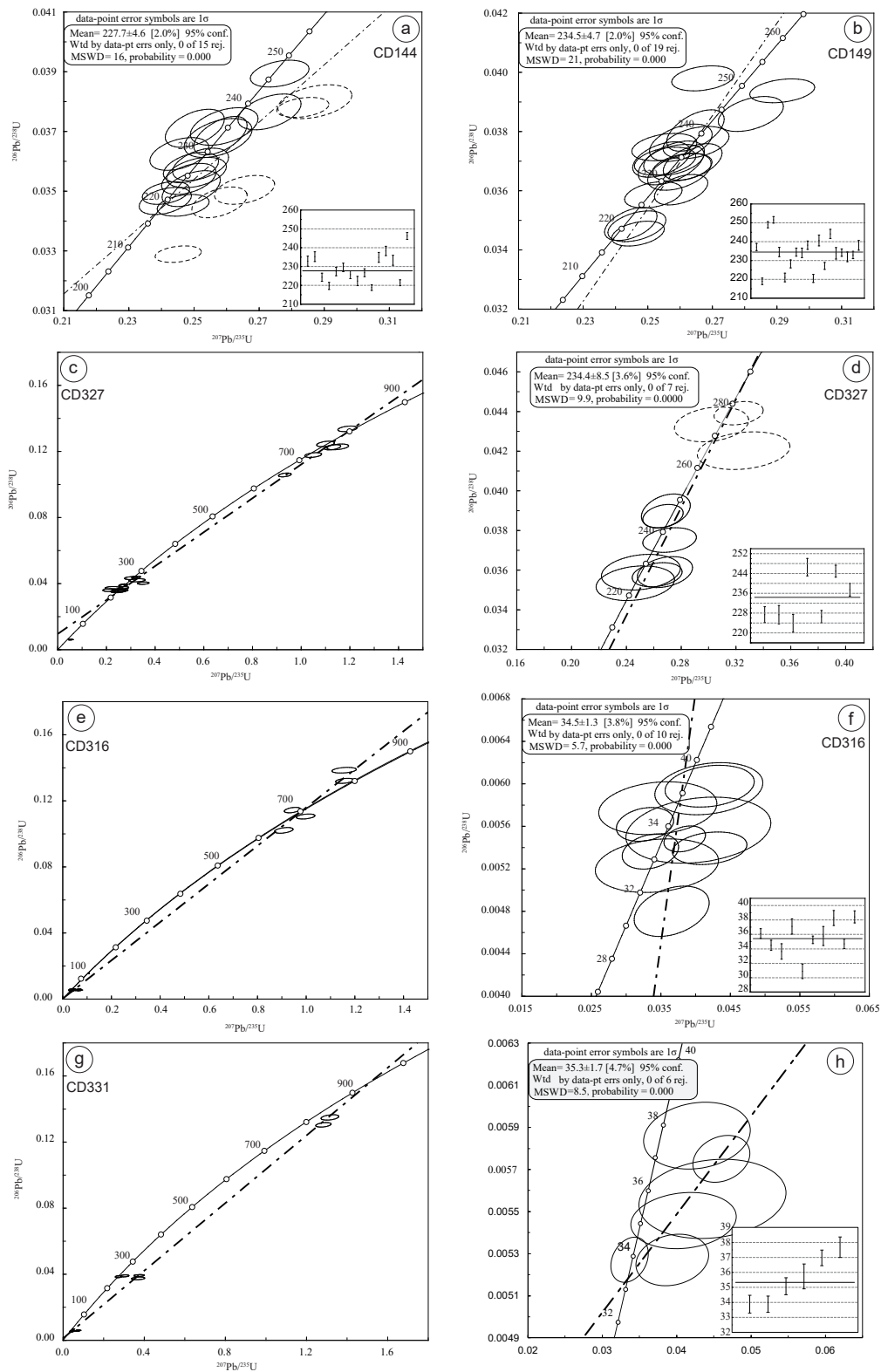
1067 Zircon and Apatite (U-Th)/He dating was accomplished at the University of Arizona, USA. Normally,  
1068 3-5 euhedral zircon and apatite crystals without visible inclusions, fracture and stainless surface were  
1069 chosen using a stereo-zoom polarized microscope. The geometry of each grain was measured and  
1070 photographed. The grains larger than 60  $\mu\text{m}$  but smaller than 500  $\mu\text{m}$  in both length and width were  
1071 accepted to processed for (U-Th)/He analysis. The zircon and apatite grains were wrapped into Nb foil  
1072 tubes and degassed by laser heating, and then analyzed for He using  $^3\text{He}$  isotope dilution, cryogenic  
1073 purification and quadrupole mass spectrometry. The U, Th and Sm concentrations of each dissolved  
1074 aliquots was measured on a sector inductively coupled plasma-mass spectrometer. Corrected (U-Th)/He  
1075 ages were processed by applying the  $\alpha$ -ejection correction factor (Farley, 2002). Standard Fish Canyon  
1076 Tuff zircon and Durango apatite fragments were identically analyzed together with unknowns to  
1077 validate age determination, age reproducibility and measurement accuracy. Mean ages of each sample  
1078 were calculated based on all grain ages and relevant errors.

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Fig. S1 Concordia diagrams and weighted mean ages of zircon U-Pb samples. The ages that were not used for final age calculation were marked by dashed ellipses on concordia diagram.

**Table S1a** Sample location and description.

Location	Sample ID	Lithology	Era	Longitude (°E)	Latitude (°N)	Elevation (m)
Weixi	CD144	Granite	Triassic	99.5151	27.0599	2595
Weixi	CD145	Granite	Triassic	99.5034	27.0696	2635
Weixi	CD146	Granite	Triassic	99.4895	27.0908	2710
Weixi	CD147	Granite	Triassic	99.4851	27.1013	2789
Weixi	CD148	Granite	Triassic	99.4927	27.1031	2939
Weixi	CD149	Granite	Triassic	99.4999	27.0996	2985
Laojun Shan	CD316	Porphyry	Eocene	99.6712	26.5934	3143
Laojun Shan	CD323	Granitic porphyry	Eocene	99.6616	26.6113	3060
Laojun Shan	CD325	Granite	Eocene	99.6420	26.6105	2818
Laojun Shan	CD327	Dacite	Triassic	99.6304	26.6027	2806
Laojun Shan	CD330	Granitic porphyry	Eocene	99.6248	26.6014	2842
Laojun Shan	CD331	Granitic porphyry	Eocene	99.6171	26.6010	2876
Laojun Shan	CD335	Lamprophyre	Eocene	99.6991	26.5534	2592
Laojun Shan	CD435	Lamprophyre	Eocene	99.6991	26.5534	2592

**Table S1b** Sites for structural and sedimentary observations.

Sites	Longitude (°E)	Latitude (°N)	Target
CD237	99.7031	26.5370	Ludian-Zhonghejiang fault
S219	99.7030	26.5534	Ludian-Zhonghejiang fault
S277	99.6942	26.5545	Ludian-Zhonghejiang fault
CD333	99.7057	26.5532	Ludian-Zhonghejiang fault
CD335/CD435	99.6991	26.5534	Ludian-Zhonghejiang fault
CD320	99.6851	26.5668	ENE-trending dextral fault
CD327	99.6304	26.6027	ENE-trending dextral fault
CD328	99.6267	26.6023	ENE-trending dextral fault
CD347	99.7060	26.4792	ENE-trending dextral fault
CD241	99.6479	26.4346	Qiaohou fault and ENE-trending dextral fault
CD502	99.6168	26.5003	Qiaohou fault
CD517	99.6556	26.5408	Tongdian fault
CD518	99.6136	26.5903	Tongdian fault
CD524	99.6943	26.4586	Tongdian fault
CD522	99.7081	26.5396	Baoxiangsi Formation

Table S2 Zircon U-Pb geochronologic data analyzed by Laser-Ablation ICP Mass Spectrometry.

Sample #	Isotopic ratios						Apparent ages (Ma)						Best age (Ma)	Discordance			
	U (ppm)	Th (ppm)	U/Th	207Pb* (235U)	± (%)	206Pb* (238U)	± (%)	error corr.	206Pb* (238U)	± (Ma)	207Pb* (235U)	± (Ma)			207Pb* (206Pb*)	± (Ma)	
<b>CD144</b>																	
CD144-1-1	7136	2201	3.2	0.2578	0.0056	0.0346	0.0003	0.4525	219.4	2.1	232.9	4.5	372.3	50.0	219.4	2.1	6%
CD144-1-2	5259	1320	4.0	0.2574	0.0069	0.0368	0.0004	0.4389	232.8	2.7	232.6	5.5	227.8	57.4	232.8	2.7	0%
CD144-1-3	4757	1230	3.9	0.2593	0.0068	0.0372	0.0004	0.4218	235.2	2.6	234.1	5.5	213.0	55.5	235.2	2.6	0%
CD144-1-4	6075	1640	3.7	0.2484	0.0055	0.0354	0.0003	0.4362	224.3	2.1	225.3	4.5	227.8	43.5	224.3	2.1	0%
CD144-1-5	6939	1356	5.1	0.2412	0.0053	0.0347	0.0003	0.3948	219.7	1.9	219.4	4.3	213.0	50.0	219.7	1.9	0%
CD144-1-6	5746	1814	3.2	0.2520	0.0057	0.0359	0.0004	0.4433	227.4	2.2	228.2	4.6	235.3	50.0	227.4	2.2	0%
CD144-1-7	5197	1154	4.5	0.2455	0.0060	0.0362	0.0004	0.4112	229.5	2.3	222.9	4.9	142.7	47.2	229.5	2.3	3%
CD144-1-8	5135	1528	3.4	0.2508	0.0060	0.0356	0.0003	0.3900	225.7	2.1	227.2	4.9	231.6	47.2	225.7	2.1	1%
CD144-1-9	5066	967	5.2	0.2491	0.0059	0.0351	0.0004	0.4766	222.3	2.5	225.9	4.8	261.2	56.5	222.3	2.5	2%
CD144-1-10	7971	1840	4.3	0.2452	0.0047	0.0329	0.0002	0.2864	208.6	1.1	222.6	3.8	361.2	73.1	208.6	1.1	6%
CD144-1-11	5171	1664	3.1	0.2871	0.0075	0.0380	0.0004	0.3801	240.4	2.3	256.3	5.9	390.8	49.1	240.4	2.3	6%
CD144-1-12	5909	1839	3.2	0.2491	0.0056	0.0358	0.0003	0.4163	226.7	2.1	225.8	4.5	213.0	50.0	226.7	2.1	0%
CD144-1-13	6337	1324	4.8	0.2467	0.0053	0.0345	0.0002	0.3264	218.8	1.5	223.9	4.3	272.3	43.5	218.8	1.5	2%
CD144-1-14	5490	1908	2.9	0.2835	0.0053	0.0378	0.0002	0.3118	239.2	1.4	253.4	4.2	383.4	47.2	239.2	1.4	6%
CD144-1-15	5032	796	6.3	0.2502	0.0060	0.0371	0.0004	0.4743	234.9	2.6	226.8	4.9	146.4	49.1	234.9	2.6	4%
CD144-1-16	5235	1506	3.5	0.2732	0.0064	0.0377	0.0004	0.4482	238.3	2.5	245.2	5.1	305.6	50.0	238.3	2.5	3%
CD144-1-17	5291	1234	4.3	0.2581	0.0054	0.0369	0.0004	0.5534	233.3	2.7	233.2	4.4	235.3	48.1	233.3	2.7	0%
CD144-1-18	7296	2040	3.6	0.2414	0.0048	0.0349	0.0003	0.3612	221.4	1.6	219.5	3.9	194.5	46.3	221.4	1.6	1%
CD144-1-19	5257	1132	4.6	0.2763	0.0059	0.0389	0.0003	0.3539	246.2	1.8	247.7	4.7	253.8	46.3	246.2	1.8	1%
CD144-1-20	6596	1513	4.4	0.2655	0.0061	0.0350	0.0003	0.3964	222.0	2.0	239.1	4.9	466.7	48.1	222.0	2.0	7%
<b>CD149</b>																	
CD149-2-1	5020	1382	3.6	0.2551	0.0066	0.0375	0.0003	0.3126	237.2	1.9	230.7	5.4	161.2	57.4	237.2	1.9	3%
CD149-2-2	6844	1788	3.8	0.2470	0.0054	0.0346	0.0003	0.3682	219.0	1.7	224.1	4.4	276.0	43.5	219.0	1.7	2%
CD149-2-3	4000	1186	3.4	0.2916	0.0066	0.0394	0.0003	0.2970	249.0	1.6	259.8	5.2	366.7	51.8	249.0	1.6	4%
CD149-2-4	3269	805	4.1	0.2671	0.0064	0.0398	0.0003	0.2932	251.6	1.7	240.4	5.1	200.1	57.4	251.6	1.7	5%
CD149-2-5	5276	1058	5.0	0.2542	0.0059	0.0371	0.0004	0.4614	234.5	2.5	230.0	4.7	189.0	50.0	234.5	2.5	2%
CD149-2-6	5795	1075	5.4	0.2447	0.0054	0.0349	0.0004	0.4824	221.0	2.3	222.3	4.4	231.6	46.3	221.0	2.3	1%
CD149-2-7	5110	1023	5.0	0.2603	0.0055	0.0360	0.0003	0.4494	228.2	2.1	234.9	4.4	301.9	48.1	228.2	2.1	3%
CD149-2-8	4607	1195	3.9	0.2581	0.0062	0.0370	0.0003	0.3892	234.5	2.1	233.1	5.0	213.0	51.8	234.5	2.1	1%
CD149-2-9	4747	1412	3.4	0.2639	0.0060	0.0370	0.0004	0.4836	234.1	2.5	237.8	4.8	333.4	48.1	234.1	2.5	2%
CD149-2-10	4069	1256	3.2	0.2649	0.0067	0.0376	0.0004	0.3739	238.1	2.2	238.6	5.4	239.0	55.5	238.1	2.2	0%
CD149-2-11	4731	1399	3.4	0.2466	0.0059	0.0348	0.0003	0.4084	220.5	2.1	223.8	4.8	261.2	55.5	220.5	2.1	1%
CD149-2-12	6056	1851	3.3	0.2648	0.0059	0.0380	0.0005	0.5466	240.6	2.9	238.5	4.7	213.0	44.4	240.6	2.9	1%
CD149-2-13	5837	1262	4.6	0.2517	0.0059	0.0359	0.0003	0.3509	227.1	1.8	228.0	4.8	231.6	47.2	227.1	1.8	0%
CD149-2-14	4177	1186	3.5	0.2819	0.0067	0.0386	0.0004	0.4279	244.1	2.4	252.2	5.3	324.1	50.0	244.1	2.4	3%
CD149-2-15	4738	833	5.7	0.2573	0.0068	0.0369	0.0005	0.5037	233.8	3.0	232.5	5.5	216.7	55.5	233.8	3.0	1%
CD149-2-16	3731	977	3.8	0.2554	0.0063	0.0370	0.0003	0.3441	234.2	1.9	230.9	5.1	211.2	57.4	234.2	1.9	1%
CD149-2-17	5222	1694	3.1	0.2598	0.0065	0.0366	0.0004	0.4481	231.9	2.5	234.5	5.2	253.8	45.4	231.9	2.5	1%
CD149-2-18	6445	1527	4.2	0.2607	0.0061	0.0368	0.0003	0.3607	232.9	1.9	235.2	4.9	253.8	47.2	232.9	1.9	1%
CD149-2-19	4645	1416	3.3	0.2602	0.0064	0.0376	0.0004	0.4502	238.1	2.6	234.8	5.2	211.2	55.5	238.1	2.6	1%
CD149-2-20	5398	1064	5.1	0.3621	0.0115	0.0400	0.0003	0.2637	252.8	2.1	313.7	8.6	772.2	52.8	252.8	2.1	19%
<b>CD316</b>																	
CD316-1-1	558	387	1.4	0.0624	0.0059	0.0056	0.0002	0.3625	35.8	1.2	61.5	5.6	1636.7	244.4	35.8	1.2	42%
CD316-1-2	871	893	1.0	0.0460	0.0044	0.0057	0.0001	0.2569	36.8	0.9	45.7	4.3	738.9	222.2	36.8	0.9	19%
CD316-1-3	577	394	1.5	0.0366	0.0036	0.0048	0.0002	0.3339	30.9	1.0	36.5	3.5	683.3	245.2	30.9	1.0	15%

CD316-1-4	2191	136	16.1	1.1579	0.0244	0.1321	0.0010	0.3603	799.8	5.7	781.0	11.5	722.2	43.7	799.8	5.7	2%
CD316-1-5	442	232	1.9	0.0404	0.0069	0.0056	0.0002	0.2166	35.8	1.3	40.2	6.7	990.7	415.6	35.8	1.3	11%
CD316-1-6	858	325	2.6	0.9079	0.0251	0.1021	0.0011	0.4054	626.8	6.7	655.9	13.4	750.0	61.1	626.8	6.7	4%
CD316-1-7	1548	224	6.9	0.9978	0.0250	0.1105	0.0010	0.3567	675.7	5.7	702.7	12.7	775.9	54.5	675.7	5.7	4%
CD316-1-8	3402	7003	0.5	0.0384	0.0020	0.0055	0.0001	0.2861	35.2	0.5	38.3	1.9	279.7	131.5	35.2	0.5	8%
CD316-1-9	1903	331	5.7	0.9431	0.0216	0.1144	0.0011	0.4151	698.2	6.3	674.5	11.3	583.4	50.0	698.2	6.3	4%
CD316-1-10	472	303	1.6	0.0590	0.0082	0.0054	0.0002	0.2254	34.7	1.1	58.2	7.8	1418.2	289.4	34.7	1.1	40%
CD316-1-11	535	362	1.5	0.0344	0.0059	0.0052	0.0002	0.1872	33.6	1.1	34.4	5.7	305.6	322.2	33.6	1.1	2%
CD316-1-12	1382	1523	0.9	0.0335	0.0027	0.0054	0.0001	0.2550	34.5	0.7	33.4	2.6	100.1	179.6	34.5	0.7	3%
CD316-1-13	559	388	1.4	0.0653	0.0064	0.0058	0.0002	0.3606	37.1	1.3	64.2	6.1	1457.4	201.9	37.1	1.3	42%
CD316-1-14	556	436	1.3	0.0695	0.0061	0.0053	0.0002	0.3520	34.3	1.1	68.2	5.8	1820.7	197.4	34.3	1.1	50%
CD316-1-15	1369	344	4.0	1.1559	0.0330	0.1385	0.0011	0.2848	836.4	6.4	780.0	15.6	633.4	61.1	836.4	6.4	7%
CD316-1-16	1127	821	1.4	0.0420	0.0042	0.0060	0.0001	0.2156	38.4	0.8	41.8	4.1	527.8	244.4	38.4	0.8	8%
CD316-1-17	1773	1584	1.1	0.0327	0.0027	0.0056	0.0001	0.2247	36.1	0.7	32.7	2.7		36.1	0.7	10%	
CD316-1-18	711	429	1.7	0.0346	0.0056	0.0058	0.0002	0.1751	37.1	1.1	34.5	5.5		37.1	1.1	8%	
CD316-1-19	1609	2026	0.8	0.0420	0.0035	0.0054	0.0001	0.2225	34.7	0.6	41.8	3.5	553.7	197.2	34.7	0.6	17%
CD316-1-20	780	710	1.1	0.0419	0.0051	0.0060	0.0002	0.2221	38.3	1.0	41.7	5.0	527.8	276.7	38.3	1.0	8%
<b>CD323</b>																	
CD323-1-1	484	142	3.4	0.3028	0.0150	0.0425	0.0005	0.2389	268.1	3.1	268.5	11.7	283.4	118.5	268.1	3.1	0%
CD323-1-2	1026	125	8.2	1.3077	0.0306	0.1398	0.0013	0.4051	843.5	7.5	849.1	13.5	857.4	50.0	843.5	7.5	1%
CD323-1-3	5841	374	15.6	0.6305	0.0113	0.0745	0.0004	0.3307	463.0	2.7	496.4	7.1	635.2	37.0	463.0	2.7	7%
CD323-1-4	2615	2145	1.2	0.0429	0.0033	0.0055	0.0001	0.1854	35.6	0.5	42.7	3.2	524.1	174.8	35.6	0.5	17%
CD323-1-5	1102	156	7.1	1.2674	0.0260	0.1380	0.0009	0.3313	833.4	5.3	831.2	11.6	820.4	44.4	833.4	5.3	0%
CD323-1-6	845	644	1.3	1.1804	0.0254	0.1281	0.0010	0.3499	777.0	5.5	791.5	11.9	827.8	45.5	777.0	5.5	2%
CD323-1-7	128	79	1.6	0.2684	0.0420	0.0202	0.0006	0.2025	129.2	4.1	241.4	33.6	1620.7	294.0	129.2	4.1	46%
CD323-1-8	533	397	1.3	0.9399	0.0321	0.0992	0.0009	0.2722	609.6	5.4	672.8	16.8	887.0	68.5	609.6	5.4	9%
CD323-1-9	3993	77	51.6	0.7509	0.0153	0.0874	0.0011	0.5931	540.2	6.3	568.7	8.9	679.6	37.0	540.2	6.3	5%
CD323-1-10	1612	1715	0.9	0.0315	0.0029	0.0052	0.0001	0.1998	33.7	0.6	31.5	2.8		33.7	0.6	7%	
CD323-1-11	1561	963	1.6	1.0661	0.0226	0.1194	0.0013	0.5098	727.1	7.4	736.8	11.1	761.1	39.7	727.1	7.4	1%
CD323-1-12	2036	177	11.5	1.2449	0.0225	0.1355	0.0009	0.3682	819.1	5.1	821.1	10.2	833.3	37.0	819.1	5.1	0%
CD323-1-13	1927	511	3.8	0.8840	0.0189	0.1003	0.0008	0.3520	615.9	4.4	643.2	10.2	738.9	44.4	615.9	4.4	4%
CD323-1-14	2270	1326	1.7	0.0350	0.0027	0.0053	0.0001	0.1897	33.8	0.5	34.9	2.6	189.0	177.8	33.8	0.5	3%
CD323-1-15	1655	1054	1.6	0.1878	0.0077	0.0234	0.0004	0.4586	149.2	2.8	174.7	6.6	531.5	76.8	149.2	2.8	15%
CD323-1-16	612	728	0.8	0.6277	0.0237	0.0780	0.0012	0.3987	484.2	7.0	494.6	14.8	553.7	76.8	484.2	7.0	2%
CD323-1-18	4982	2712	1.8	0.0361	0.0018	0.0055	0.0001	0.2203	35.4	0.4	36.0	1.7	105.6	114.8	35.4	0.4	2%
CD323-1-19	904	678	1.3	0.8523	0.0208	0.1015	0.0008	0.3287	622.9	4.8	625.9	11.4	635.2	49.1	622.9	4.8	0%
CD323-1-20	4678	12	####	0.0301	0.0017	0.0051	0.0001	0.2214	32.7	0.4	30.1	1.7		32.7	0.4	9%	
<b>CD325</b>																	
CD325-1-1	2028	4147	0.5	0.6883	0.0167	0.0842	0.0006	0.3110	521.0	3.8	531.8	10.0	572.3	58.3	521.0	3.8	2%
CD325-1-2	1788	772	2.3	1.2091	0.0335	0.1219	0.0012	0.3631	741.8	7.1	804.8	15.4	966.4	47.2	741.8	7.1	8%
CD325-1-3	5851	329	17.8	1.0207	0.0188	0.1145	0.0009	0.4171	698.8	5.1	714.2	9.5	750.0	38.1	698.8	5.1	2%
CD325-1-4	1073	1449	0.7	4.4102	0.0835	0.3031	0.0021	0.3601	1706.7	10.3	1714.2	15.7	1710.8	35.2	1706.7	10.3	0%
CD325-1-5	307	392	0.8	0.2959	0.0273	0.0389	0.0007	0.1965	245.9	4.4	263.2	21.4	501.9	207.4	245.9	4.4	7%
CD325-1-6	6189	5120	1.2	0.1922	0.0087	0.0159	0.0002	0.2476	101.8	1.1	178.5	7.4	1358.3	80.3	101.8	1.1	43%
CD325-1-7	817	700	1.2	1.4828	0.0416	0.1470	0.0013	0.3066	884.1	7.1	923.4	17.0	1005.6	57.4	884.1	7.1	4%
CD325-1-8	955	1342	0.7	1.1198	0.0288	0.1180	0.0012	0.4030	719.3	7.1	762.9	13.8	900.0	57.4	719.3	7.1	6%
CD325-1-9	345	533	0.6	1.4278	0.0937	0.0438	0.0010	0.3316	276.5	5.9	900.6	39.2	3047.8	95.2	276.5	5.9	69%
CD325-1-10	6070	935	6.5	2.1298	0.0467	0.1834	0.0017	0.4311	1085.4	9.5	1158.5	15.2	1264.8	35.7	1085.4	9.5	6%
CD325-1-11	3021	6603	0.5	0.0437	0.0035	0.0056	0.0001	0.1917	36.0	0.5	43.4	3.4	505.6	177.6	36.0	0.5	17%
CD325-1-12	1917	2803	0.7	0.0555	0.0045	0.0058	0.0001	0.1995	37.5	0.6	54.8	4.4	925.0	166.7	37.5	0.6	32%
CD325-1-13	7102	4390	1.6	0.7384	0.0203	0.0781	0.0005	0.2438	485.0	3.1	561.5	11.9	855.2	56.3	485.0	3.1	14%
CD325-1-14	313	504	0.6	0.2714	0.0197	0.0378	0.0006	0.2013	239.1	3.4	243.8	15.8	342.7	169.4	239.1	3.4	2%



CD325-1-15	1614	3570	0.5	0.8492	0.0214	0.0978	0.0008	0.3071	601.3	4.5	624.2	11.8	687.1	53.7	601.3	4.5	4%
CD325-1-16	477	912	0.5	0.2829	0.0151	0.0378	0.0006	0.3012	239.4	3.8	253.0	11.9	420.4	127.8	239.4	3.8	5%
CD325-1-17	2654	3075	0.9	0.3044	0.0082	0.0430	0.0004	0.3075	271.2	2.2	269.9	6.3	253.8	67.6	271.2	2.2	0%
CD325-1-18	228	277	0.8	0.3973	0.0186	0.0386	0.0006	0.3082	244.3	3.5	339.7	13.6	1094.4	100.0	244.3	3.5	28%
CD325-1-19	804	678	1.2	1.4524	0.0367	0.1502	0.0012	0.3173	902.3	6.8	910.9	15.2	920.4	47.2	902.3	6.8	1%
CD325-1-20	1163	431	2.7	1.2839	0.0304	0.1438	0.0012	0.3658	866.3	7.0	838.6	13.5	762.7	51.1	866.3	7.0	3%
<b>CD327</b>																	
CD327-1-1	551	300	1.8	0.2682	0.0133	0.0359	0.0005	0.2898	227.4	3.2	241.2	10.6	376.0	114.8	227.4	3.2	6%
CD327-1-2	309	221	1.4	0.2506	0.0190	0.0359	0.0006	0.2177	227.3	3.7	227.0	15.4	276.0	177.8	227.3	3.7	0%
CD327-1-3	2052	296	6.9	1.1287	0.0222	0.1225	0.0011	0.4380	745.1	6.1	767.1	10.6	816.7	38.9	745.1	6.1	3%
CD327-1-4	732	391	1.9	1.1503	0.0292	0.1228	0.0012	0.3694	746.4	6.6	777.4	13.8	861.1	54.8	746.4	6.6	4%
CD327-1-5	559	493	1.1	0.3512	0.0156	0.0403	0.0005	0.2590	254.5	2.9	305.6	11.7	744.5	98.9	254.5	2.9	17%
CD327-1-6	1634	219	7.5	1.1003	0.0240	0.1246	0.0011	0.4014	756.8	6.3	753.5	11.6	727.8	46.3	756.8	6.3	0%
CD327-1-7	324	182	1.8	0.2465	0.0189	0.0353	0.0006	0.2129	223.9	3.6	223.7	15.4	320.4	185.2	223.9	3.6	0%
CD327-1-8	782	289	2.7	0.2688	0.0118	0.0390	0.0006	0.3318	246.5	3.5	241.7	9.4	198.2	97.2	246.5	3.5	2%
CD327-1-9	293	143	2.0	0.3256	0.0224	0.0420	0.0006	0.2175	265.4	3.9	286.2	17.1	472.3	155.5	265.4	3.9	7%
CD327-1-10	304	223	1.4	0.2152	0.0197	0.0361	0.0006	0.1723	228.6	3.5	197.9	16.4			228.6	3.5	15%
CD327-1-11	2725	380	7.2	0.9329	0.0172	0.1058	0.0008	0.3910	648.2	4.4	669.2	9.0	727.8	39.7	648.2	4.4	3%
CD327-1-12	1046	864	1.2	0.0521	0.0056	0.0061	0.0001	0.1931	39.0	0.8	51.6	5.4	731.5	231.5	39.0	0.8	24%
CD327-1-13	348	249	1.4	0.2241	0.0196	0.0374	0.0005	0.1673	236.7	3.4	205.3	16.3			236.7	3.4	15%
CD327-1-14	447	255	1.8	0.3021	0.0180	0.0434	0.0006	0.2239	273.6	3.6	268.0	14.0	242.7	137.0	273.6	3.6	2%
CD327-1-15	796	625	1.3	0.2625	0.0120	0.0358	0.0004	0.2445	226.5	2.5	236.7	9.7	353.8	105.5	226.5	2.5	4%
CD327-1-16	1284	606	2.1	0.2667	0.0097	0.0387	0.0004	0.2759	244.9	2.4	240.1	7.8	187.1	115.7	244.9	2.4	2%
CD327-1-17	1210	752	1.6	1.1901	0.0259	0.1337	0.0011	0.3755	809.0	6.2	796.0	12.0	766.7	245.4	809.0	6.2	2%
CD327-1-18	1043	198	5.3	1.0494	0.0228	0.1178	0.0010	0.3734	718.1	5.5	728.6	11.3	753.7	44.4	718.1	5.5	1%
CD327-1-19	1223	569	2.1	0.3219	0.0119	0.0439	0.0004	0.2404	277.1	2.4	283.3	9.1	338.9	83.3	277.1	2.4	2%
CD327-1-20	733	368	2.0	0.2715	0.0129	0.0375	0.0004	0.2297	237.4	2.6	243.9	10.3	338.9	111.1	237.4	2.6	3%
<b>CD330</b>																	
CD330-1-1	1776	558	3.2	1.4761	0.0285	0.1481	0.0010	0.3446	890.2	5.5	920.6	11.7	988.6	38.9	890.2	5.5	3%
CD330-1-2	905	393	2.3	0.1823	0.0088	0.0223	0.0004	0.4148	142.4	2.8	170.1	7.6	694.5	128.5	142.4	2.8	16%
CD330-1-3	3233	2733	1.2	8.4031	0.1312	0.4114	0.0022	0.3502	2221.5	10.3	2275.5	14.3	2315.7	20.8	2221.5	10.3	2%
CD330-1-4	7040	455	15.5	4.9598	0.0803	0.2995	0.0018	0.3636	1688.7	8.8	1812.5	13.7	1950.0	28.4	1688.7	8.8	7%
CD330-1-5	6261	409	15.3	4.8644	0.0889	0.2941	0.0022	0.4080	1662.0	11.0	1796.1	15.4	1946.3	29.8	1662.0	11.0	7%
CD330-1-6	1101	397	2.8	1.1849	0.0289	0.1262	0.0010	0.3238	766.1	5.7	793.6	13.4	864.8	51.9	766.1	5.7	3%
CD330-1-7	566	493	1.1	0.4897	0.0225	0.0640	0.0007	0.2246	400.2	4.0	404.7	15.4	442.6	99.1	400.2	4.0	1%
CD330-1-8	4155	3006	1.4	8.0144	0.1854	0.3930	0.0034	0.3737	2136.8	15.8	2232.6	20.9	2322.2	37.7	2136.8	15.8	4%
CD330-1-9	7219	476	15.2	4.9904	0.0993	0.2998	0.0019	0.3113	1690.2	9.3	1817.7	16.9	1958.3	34.1	1690.2	9.3	7%
CD330-1-10	2696	1410	1.9	0.5	0.0112	0.0644	0.0005	0.3347	402.3	2.9	410.4	7.6	450.0	17.6	402.3	2.9	2%
CD330-1-11	5867	3937	1.5	8.3841	0.1460	0.4079	0.0032	0.4461	2205.1	14.6	2273.5	15.9	2329.3	32.6	2205.1	14.6	3%
CD330-1-12	5935	481	12.3	5.2788	0.0842	0.3103	0.0019	0.3773	1741.9	9.2	1865.4	13.7	2002.2	26.7	1741.9	9.2	7%
CD330-1-13	6758	8410	0.8	0.2640	0.0060	0.0340	0.0003	0.3352	215.3	1.6	237.9	4.8	477.8	50.0	215.3	1.6	9%
CD330-1-14	3305	1530	2.2	9.1913	0.1693	0.4141	0.0029	0.3839	2233.5	13.4	2357.3	16.9	2464.8	28.5	2233.5	13.4	5%
CD330-1-15	318	204	1.6	0.2503	0.0201	0.0342	0.0006	0.2186	216.8	3.8	226.8	16.4	394.5	187.0	216.8	3.8	4%
CD330-1-16	899	798	1.1	0.0453	0.0049	0.0056	0.0001	0.2075	36.3	0.8	44.9	4.7	633.0	242.6	36.3	0.8	19%
CD330-1-17	400	231	1.7	0.3441	0.0195	0.0414	0.0006	0.2441	261.3	3.5	300.3	14.7	650.0	124.1	261.3	3.5	13%
CD330-1-18	9753	701	13.9	4.9415	0.0740	0.3009	0.0018	0.4022	1696.0	9.0	1809.4	12.7	1935.5	25.6	1696.0	9.0	6%
CD330-1-19	2733	981	2.8	0.0767	0.0037	0.0094	0.0001	0.2280	60.4	0.7	75.0	3.5	561.1	105.5	60.4	0.7	20%
CD330-1-20	602	253	2.4	0.2913	0.0142	0.0369	0.0004	0.2467	233.8	2.8	259.6	11.2	524.1	111.1	233.8	2.8	10%
<b>CD331</b>																	
CD331-2-1	1000	345	2.9	0.2735	0.0106	0.0386	0.0004	0.2741	243.8	2.5	245.5	8.4	276.0	88.0	243.8	2.5	1%
CD331-2-2	4329	3071	1.4	0.0573	0.0025	0.0057	0.0001	0.2611	36.8	0.4	56.6	2.4	1020.4	91.5	36.8	0.4	35%

CD331-2-3	2178	2073	1.1	0.0726	0.0044	0.0060	0.0001	0.2186	38.3	0.5	71.2	4.1	1402.8	118.1	38.3	0.5	46%
CD331-2-4	3542	3166	1.1	0.0459	0.0025	0.0058	0.0001	0.2329	37.0	0.5	45.6	2.4	553.7	122.2	37.0	0.5	19%
CD331-2-5	1153	216	5.3	1.3154	0.0289	0.1349	0.0011	0.3622	815.9	6.1	852.5	12.7	942.6	44.1	815.9	6.1	4%
CD331-2-6	884	608	1.5	0.0448	0.0065	0.0056	0.0001	0.1532	35.7	0.8	44.5	6.3	635.2	346.1	35.7	0.8	20%
CD331-2-7	597	406	1.5	0.3698	0.0213	0.0375	0.0006	0.2562	237.1	3.4	319.5	15.8	950.0	114.8	237.1	3.4	26%
CD331-2-8	862	208	4.1	0.3024	0.0143	0.0390	0.0004	0.2136	246.7	2.5	268.3	11.2	461.2	103.7	246.7	2.5	8%
CD331-2-9	796	471	1.7	0.0738	0.0076	0.0059	0.0002	0.2596	38.0	1.0	72.3	7.2	1701.9	223.9	38.0	1.0	47%
CD331-2-10	1985	2071	1.0	0.0560	0.0044	0.0058	0.0001	0.2135	37.0	0.6	55.3	4.3	1044.1	162.8	37.0	0.6	33%
CD331-2-11	4955	2547	1.9	0.0472	0.0021	0.0054	0.0001	0.2848	34.9	0.4	46.8	2.0	750.0	102.8	34.9	0.4	26%
CD331-2-12	802	487	1.6	0.0599	0.0078	0.0056	0.0001	0.1987	35.9	0.9	59.1	7.5	1395.4	265.7	35.9	0.9	39%
CD331-2-13	2532	1582	1.6	0.0394	0.0032	0.0053	0.0001	0.1862	33.9	0.5	39.2	3.1	387.1	185.2	33.9	0.5	14%
CD331-2-14	5450	4762	1.1	0.0336	0.0017	0.0053	0.0001	0.2741	33.9	0.5	33.6	1.6	42.7	118.5	33.9	0.5	1%
CD331-2-15	5423	968	5.6	0.0490	0.0023	0.0068	0.0001	0.2255	43.9	0.5	48.6	2.2	300.1	104.6	43.9	0.5	10%
CD331-2-16	2850	1691	1.7	0.0656	0.0052	0.0056	0.0001	0.1846	36.2	0.5	64.5	5.0	1258.9	154.6	36.2	0.5	44%
CD331-2-17	2009	151	13.3	1.2834	0.0249	0.1304	0.0009	0.3543	790.3	5.1	838.4	11.1	961.1	39.7	790.3	5.1	6%
CD331-2-18	1209	691	1.8	0.0409	0.0047	0.0055	0.0001	0.1409	35.1	0.6	40.7	4.6	450.0	247.2	35.1	0.6	14%
CD331-2-19	1417	366	3.9	0.3743	0.0169	0.0392	0.0004	0.2070	248.1	2.3	322.8	12.5	875.9	87.0	248.1	2.3	23%
CD331-2-20	1339	1181	1.1	0.0427	0.0047	0.0059	0.0001	0.1620	37.7	0.7	42.4	4.6	483.4	254.6	37.7	0.7	11%
<b>CD335-1/CD435-1</b>																	
CD335-1-1	1194	384	3.1	1.7252	0.0310	0.1649	0.0011	0.3731	984.1	6.1	1018.0	11.6	1083.3	30.6	1018.0	11.6	3%
CD335-1-3	1469	265	5.5	1.1206	0.0228	0.1338	0.0009	0.3385	809.6	5.3	763.3	11.0	620.4	42.6	809.6	5.3	6%
CD335-1-4	897	322	2.8	4.7725	0.0849	0.3283	0.0026	0.4379	1830.3	12.4	1780.1	15.0	1714.5	29.9	1780.1	15.0	3%
CD335-1-6	2311	314	7.4	1.0505	0.0221	0.1272	0.0009	0.3397	771.7	5.2	729.1	11.0	598.2	42.6	771.7	5.2	6%
CD335-1-7	942	294	3.2	1.0315	0.0264	0.1293	0.0010	0.3135	783.6	5.9	719.7	13.2	527.8	55.5	783.6	5.9	9%
CD335-1-8	1520	311	4.9	1.0120	0.0237	0.1262	0.0010	0.3225	766.1	5.5	709.9	12.0	538.9	48.1	766.1	5.5	8%
CD335-1-9	1259	181	6.9	0.9721	0.0227	0.1156	0.0012	0.4622	705.0	7.2	689.5	11.7	642.6	46.3	705.0	7.2	2%
CD335-1-10	1624	477	3.4	1.0365	0.0209	0.1245	0.0009	0.3438	756.6	5.0	722.2	10.5	616.7	42.6	756.6	5.0	5%
CD335-1-11	3420	304	11.2	0.4277	0.0095	0.0613	0.0006	0.4103	383.7	3.4	361.6	6.7	216.7	48.1	383.7	3.4	6%
CD335-1-12	2222	349	6.4	1.1468	0.0209	0.1332	0.0008	0.3412	806.0	4.7	775.7	9.9	683.3	38.1	806.0	4.7	4%
CD335-1-13	3332	102	32.5	0.3487	0.0085	0.0470	0.0005	0.4773	296.0	3.4	303.7	6.4	350.1	48.1	296.0	3.4	3%
CD335-1-14	548	663	0.8	1.0572	0.0300	0.1219	0.0010	0.2972	741.5	5.9	732.5	14.8	698.2	63.9	741.5	5.9	1%
CD335-1-15	1301	454	2.9	1.1695	0.0254	0.1292	0.0012	0.4128	783.1	6.6	786.4	11.9	790.7	46.3	783.1	6.6	0%
CD335-1-16	495	209	2.4	0.6517	0.0204	0.0846	0.0008	0.3123	523.8	4.9	509.5	12.5	455.6	75.0	523.8	4.9	3%
CD335-1-17	1774	8	###	0.4903	0.0119	0.0641	0.0005	0.3196	400.2	3.0	405.1	8.1	420.4	53.7	400.2	3.0	1%
CD335-1-18	1044	255	4.1	1.2445	0.0261	0.1346	0.0009	0.3214	813.9	5.2	820.9	11.8	825.6	44.4	813.9	5.2	1%
CD335-1-19	1014	667	1.5	1.1755	0.0270	0.1294	0.0010	0.3284	784.7	5.6	789.2	12.6	787.0	48.9	784.7	5.6	1%
CD335-1-20	1413	424	3.3	1.2181	0.0279	0.1268	0.0009	0.3131	769.8	5.2	808.9	12.8	901.9	48.9	769.8	5.2	5%
CD435-1-1	419	228	1.8	0.0423	0.0026	0.0058	0.0001	0.3774	37.3	0.9	42.1	2.6	427.8	121.3	37.3	0.9	11%
CD435-1-2	281	125	2.2	1.1364	0.0482	0.1378	0.0016	0.2739	832.2	9.1	770.8	22.9	590.8	91.7	832.2	9.1	8%
CD435-1-3	340	77	4.4	1.0862	0.0529	0.1363	0.0015	0.2279	823.6	8.6	746.6	25.7	531.5	114.8	823.6	8.6	10%
CD435-1-14	907	75	12.1	1.0314	0.0397	0.1255	0.0016	0.3330	762.4	9.2	719.6	19.9	583.4	83.3	762.4	9.2	6%
CD435-1-15	395	70	5.6	1.1774	0.0384	0.1408	0.0021	0.4568	849.1	11.9	790.1	17.9	635.2	69.3	849.1	11.9	7%
CD435-1-16	327	47	7.0	1.1457	0.0338	0.1330	0.0017	0.4454	805.0	10.0	775.2	16.0	699.7	63.0	805.0	10.0	4%
CD435-1-17	443	54	8.3	1.2145	0.0322	0.1356	0.0022	0.6102	819.5	12.4	807.3	14.8	783.3	53.7	819.5	12.4	2%
CD435-1-18	318	84	3.8	1.1136	0.0279	0.1250	0.0014	0.4465	759.1	8.0	759.9	13.4	761.1	52.9	759.1	8.0	0%
CD435-1-19	300	53	5.7	1.3047	0.0315	0.1392	0.0018	0.5494	840.4	10.4	847.8	13.9	873.8	45.4	840.4	10.4	1%
CD435-1-21	345	60	5.7	1.2496	0.0306	0.1326	0.0021	0.6321	802.8	11.7	823.2	13.8	887.0	80.6	802.8	11.7	2%
CD435-1-22	565	111	5.1	0.9750	0.0224	0.1068	0.0014	0.5632	654.1	8.0	691.1	11.5	803.4	47.2	654.1	8.0	5%
CD435-1-24	862	152	5.7	1.1934	0.0281	0.1256	0.0015	0.5113	762.8	8.7	797.5	13.0	900.0	47.1	762.8	8.7	4%
CD435-1-26	515	103	5.0	1.1952	0.0264	0.1282	0.0015	0.5363	777.4	8.7	798.4	12.2	857.4	45.5	777.4	8.7	3%
CD435-1-28	433	79	5.5	1.2929	0.0287	0.1330	0.0018	0.6154	805.2	10.3	842.6	12.7	946.3	43.1	805.2	10.3	4%
CD435-1-29	204	73	2.8	1.2868	0.0357	0.1385	0.0021	0.5391	836.2	11.7	839.9	15.9	870.1	59.3	836.2	11.7	0%

CD435-1-30	447	79	5.7	1.2303	0.0273	0.1286	0.0014	0.4787	780.1	7.8	814.5	12.4	905.6	44.4	780.1	7.8	4%
CD435-1-31	385	255	1.5	0.3062	0.0114	0.0397	0.0005	0.3597	251.2	3.3	271.2	8.9	438.9	83.3	251.2	3.3	7%
CD435-1-32	332	73	4.6	1.5409	0.0383	0.1506	0.0017	0.4562	904.1	9.6	946.9	15.3	1042.6	48.6	904.1	9.6	5%
CD435-1-33	208	83	2.5	8.3802	0.1888	0.4153	0.0054	0.5718	2239.3	24.4	2273.0	20.5	2299.7	36.4	2273.0	20.5	1%
CD435-1-36	541	82	6.6	1.3323	0.0272	0.1414	0.0017	0.5974	852.5	9.8	859.9	11.9	883.3	44.4	852.5	9.8	1%
CD435-1-37	425	88	4.8	1.3843	0.0298	0.1462	0.0017	0.5363	879.9	9.5	882.3	12.7	900.0	77.9	879.9	9.5	0%
CD435-1-39	396	69	5.8	1.3293	0.0314	0.1413	0.0017	0.5197	852.0	9.8	858.6	13.7	872.2	44.0	852.0	9.8	1%
CD435-1-40	567	93	6.1	1.2748	0.0297	0.1369	0.0017	0.5455	827.1	9.9	834.5	13.3	847.8	152.8	827.1	9.9	1%
CD435-1-41	167	135	1.2	2.6526	0.0732	0.2297	0.0034	0.5407	1332.7	18.0	1315.4	20.4	1300.0	53.4	1315.4	20.4	1%
CD435-1-44	403	70	5.7	1.2468	0.0331	0.1326	0.0024	0.6868	802.6	13.8	821.9	15.0	887.0	53.7	802.6	13.8	2%
CD435-1-45	233	93	2.5	1.2766	0.0380	0.1329	0.0019	0.4898	804.2	11.0	835.3	17.0	920.4	65.7	804.2	11.0	4%
CD435-1-46	366	87	4.2	1.2720	0.0313	0.1332	0.0018	0.5550	806.1	10.4	833.3	14.0	905.6	56.5	806.1	10.4	3%
CD435-1-47	354	70	5.1	1.2307	0.0342	0.1327	0.0021	0.5758	803.2	12.1	814.7	15.6	861.1	61.1	803.2	12.1	1%
CD435(2)-1-2	59	47	1.3	0.2816	0.0166	0.0419	0.0006	0.0141	264.3	3.8	251.9	13.1	198.2	137.0	264.3	3.8	5%
CD435(2)-1-4	161	94	1.7	0.0304	0.0042	0.0056	0.0001	0.0021	36.3	0.9	30.4	4.1		36.3	0.9	20%	
CD435(2)-1-6	306	72	4.3	1.1843	0.0190	0.1313	0.0012	0.0413	795.0	6.9	793.3	8.9	794.4	34.3	795.0	6.9	0%
CD435(2)-1-7	98	58	1.7	0.0438	0.0052	0.0055	0.0001	0.0017	35.1	0.9	43.5	5.1	683.3	266.6	35.1	0.9	19%
CD435(2)-1-8	749	853	0.9	0.0335	0.0014	0.0055	0.0001	0.0018	35.1	0.4	33.4	1.3		35.1	0.4	5%	
CD435(2)-1-9	531	533	1.0	0.0383	0.0018	0.0054	0.0001	0.0017	34.5	0.6	38.2	1.8	366.7	104.6	34.5	0.6	10%
CD435(2)-1-10	170	117	1.5	0.0377	0.0037	0.0055	0.0001	0.0019	35.5	0.7	37.6	3.7	205.6	225.9	35.5	0.7	5%
CD435(2)-1-12	178	118	1.5	0.0345	0.0034	0.0054	0.0001	0.0017	34.9	0.7	34.4	3.4	77.9	220.3	34.9	0.7	1%
CD435(2)-1-13	160	97	1.6	0.0437	0.0041	0.0059	0.0001	0.0020	37.8	0.7	43.4	4.0	435.2	213.9	37.8	0.7	13%

Note: Ages were accepted with up to 10% and 20% discordance for plutonic and volcanic samples, respectively. All errors are at the 1-sigma level.

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1103 Table S3 Zircon U-Pb geochronologic ages for Mesozoic magmatic rocks exposed within the LZTB,  
 1104 SE Tibet.

Location	Sample ID	Longitude (E)	Latitude (N)	Lithology	Formation	Age type	Age (Ma)	± (Ma)	Reference
Weixi	CD144	99.5151	27.0599	granite	Tgr	Zircon U-Pb	227.7	4.6	This study
Weixi	CD149	99.4999	27.0996	granite	Tgr	Zircon U-Pb	234.5	4.7	This study
Jianchuan	CD327	99.6304	26.6027	dacite	Pantiange Fm.(T <sub>1-2p</sub> )	Zircon U-Pb Weighed mean age of youngest concordant zircons (7 ages)	234.4	8.5	This study
Jianchuan	CX036-8	99.6646	26.5578	granite	Tgr	Zircon U-Pb	244.9	2.2	Yang et al., 2014
Jianchuan	CX037-10	99.6765	26.5671	granite	Tgr	Zircon U-Pb	244.9	2.2	Yang et al., 2014
Jianchuan	QD-2	99.5082	26.7703	dacite	Pantiange Fm.(T <sub>1-2p</sub> )	Zircon U-Pb	244.9	3.3	Yang et al., 2014
Jianchuan	QD-5	99.5082	26.7703	dacite	Pantiange Fm.(T <sub>1-2p</sub> )	Zircon U-Pb	236.9	2.8	Yang et al., 2014
Jianchuan	DX038-2	99.6860	26.5533	volcanoclastic	Pantiange Fm.(T <sub>1-2p</sub> )	U/Pb Weighed mean age of youngest concordant zircons (14 ages)	246.5	6.3	Yang et al., 2014
Maliqing	D2047-3	99.6834	26.4501	dacite	Pantiange Fm.(T <sub>1-2p</sub> )	Zircon U-Pb	247.0	4.3	Tang et al.,2016
Maliqing	D3052-1	99.6835	26.4501	rhyolite	Pantiange Fm.(T <sub>1-2p</sub> )	Zircon U-Pb	250.0	4.3	Tang et al.,2016
Maliqing	D3053-1	99.7000	26.4501	rhyolite	Pantiange Fm.(T <sub>1-2p</sub> )	Zircon U-Pb	246.7	4.3	Tang et al.,2016
Maliqing	D3055-5A	99.7001	26.4667	rhyolitic lava	Pantiange Fm.(T <sub>1-2p</sub> )	Zircon U-Pb	244.0	5.2	Tang et al.,2016

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Table S4 Geochronologic ages for Eocene volcanic clasts and plutonic rocks in and around the Jianchuan basin and LZTB, SE Tibet.

Location	Sample ID	Longitude (E)	Latitude (N)	Lithology	Formation	Age type	Age (Ma)	± (Ma)	Reference
<b>Within the Ludian-Zhonghejiang fold-thrust belt</b>									
Laojun Shan	CD316	99.6712	26.5934	Porphyry		Zircon U-Pb weighed mean age of the youngest concordant zircons (10 ages)	34.5	1.3	This study
Laojun Shan	CD323	99.6616	26.6113	Granitic porphyry		Zircon U-Pb weighed mean age of the youngest concordant zircons (5 ages)	34.3	1.6	This study
Laojun Shan	CD325	99.6420	26.6105	Granite		Zircon U-Pb age of the only youngest age (1 age)	36.0	0.5	This study
Laojun Shan	CD330	99.6248	26.6014	Granitic porphyry		Zircon U-Pb age of the only youngest age (1 age)	36.3	0.8	This study
Laojun Shan	CD335/CD435	99.6991	26.5534	Lamprophyre		Zircon U-Pb weighed mean age of the youngest concordant zircons (6 ages)	35.1	0.5	This study
Laojun Shan	CD331	99.6171	26.6010	Granitic porphyry		Zircon U-Pb weighed mean age of the youngest concordant zircons (6 ages)	35.3	1.7	This study
Laojun Shan	CD321-1	99.6713	26.6175	Granitic porphyry		Zircon U-Pb weighed mean age of the youngest concordant zircons (12 ages)	34.7	0.8	Gourbet et al., 2017
<b>Jianchuan basin interstratified (Jianchuan Fm.(E<sub>1c</sub>))</b>									
Jianchuan basin	J161	99.8919	26.5913	Volcanoclastics	Jianchuan Fm.(E <sub>1c</sub> )	Zircon U-Pb lower intercept of the youngest population (3 ages)	35.9	1.1	Gourbet et al., 2017
Jianchuan basin	J284	99.8509	26.6324	Rhyolitic tuff	Jianchuan Fm.(E <sub>1c</sub> )	Zircon U-Pb lower intercept of the youngest population (3 ages)	34.8	1.1	Gourbet et al., 2017
Laojun Shan	J308	99.6484	26.4346	Volcanoclastics	Jianchuan Fm.(E <sub>1c</sub> )	Zircon U-Pb weighed mean age of the youngest concordant zircons (4 ages)	35.0	2.3	Gourbet et al., 2017
Laojun Shan	DX-39-5	99.6113	26.5082	Volcanoclastics	Jianchuan Fm.(E <sub>1c</sub> )	Zircon U-Pb weighed mean age of the youngest concordant zircons (4 ages)	34.7	0.2	Yang et al., 2014
<b>Jianchuan basin interstratified (Shuanghe Fm.(E<sub>1s</sub>))</b>									
Jianchuan basin	J121	99.8672	26.4477	Trachy-andesitic lava flow	Shuanghe Fm.(E <sub>1s</sub> )	Zircon U-Pb lower intercept of the main population (22 ages)	35.8	0.3	Gourbet et al., 2017
Jianchuan basin	J120	99.8672	26.4477	Trachy-andesitic lava flow	Shuanghe Fm.(E <sub>1s</sub> )	Zircon U-Pb lower intercept of the youngest grain (2 ages)	35.0	1.0	Gourbet et al., 2017
Jianchuan basin	J168A	99.8529	26.5970	Volcanoclastic	Shuanghe Fm.(E <sub>1s</sub> )	Zircon U-Pb lower intercept of the main population (34 ages)	35.7	0.2	Gourbet et al., 2017
Jianchuan basin	J278	99.8770	26.5918	Volcanoclastic	Shuanghe Fm.(E <sub>1s</sub> )	Zircon U-Pb age of the only youngest age (1 age)	36.8	1.0	Gourbet et al., 2017
Jianchuan basin	J203	99.8531	26.5904	Volcanic tuff	Shuanghe Fm.(E <sub>1s</sub> )	Zircon U-Pb lower intercept of the youngest zircons (18 ages)	36.4	0.4	Gourbet et al., 2017
Jianchuan basin	DX-030-6	99.8672	26.4477	Trachydaicite volcanic level	Shuanghe Fm.(E <sub>1s</sub> )	Zircon U-Pb weighed mean age of the youngest concordant zircons (18 ages)	36.6	0.7	Yang et al., 2014
Jianchuan basin	JIAN-11-06	99.8531	26.5904	Tuffaceous sandstone	Shuanghe Fm.(E <sub>1s</sub> )	Zircon U-Pb weighed mean age of the youngest concordant zircons (5 ages)	37.1	1.6	Hoke et al., 2014
<b>Plutonic rocks around the Jianchuan county</b>									
Jianchuan (S808)	J279	99.9030	26.5923	Lamprophyre (dyke)		Ar/Ar inverse isochron	34.5	1.0	Gourbet et al., 2017
Jianchuan (Shamao Shan)	JC-9	99.9197	26.5842	Amphibole syenite		Zircon U-Pb	35.6	0.3	Lu et al., 2012
Jianchuan (~8 km east of the Laojun Shan)	JC-7	99.8121	26.6567	Biotite monzogranite porphyry		Zircon U-Pb	35.3	0.4	Lu et al., 2012
Jianchuan (Laojun Shan)	JC-1	99.7253	26.6323	Amphibole syenite		Zircon U-Pb	35.4	0.2	Lu et al., 2012
Jianchuan (~8 km northeast of the Laojun Shan)	SG-12	99.7764	26.7819	Monzogranite porphyry		Zircon U-Pb	35.7	0.2	Lu et al., 2012
Jianchuan (Laojun Shan)	Y81-791	99.6873	26.7243	Quartz monzonite		Zircon U-Pb	34.5	0.3	Liang et al., 2007
Jianchuan (~10 km north of the Laojun Shan)	Y81-909	99.6944	26.8417	Syenite, monzonite		Zircon U-Pb	35.6	0.2	Liang et al., 2007
~5 km to the east of Jianchuan	Y81-862	99.9000	26.3667	Trachyte		Zircon U-Pb	34.4	0.4	Liang et al., 2007
Jianchuan (Shamao Shan)	YU70			Monzonitic-syenitic		Zircon U-Pb	35.0	0.1	Schärer et al., 1994
<b>Plutonic rocks away from the Jianchuan county</b>									
Midu Gap	Y83-803	100.2889	25.2236	Quartz monzonite porphyry		Zircon U-Pb	34.8	0.3	Liang et al., 2007
Yongping-Weishan	WS-4	100.2870	25.1545	Quartz monzonite porphyry		Zircon U-Pb	35.4	0.6	Lu et al., 2012
Machangqing	BXC-8	100.4258	25.5278	Biotite amphibole monzogranite		Zircon U-Pb	35.6	0.3	Lu et al., 2012
Machangqing	BXC-2	100.4519	25.5341	Amphibole monzogranite porphyry		Zircon U-Pb	35.0	0.2	Lu et al., 2012
Machangqing	BXC-9	100.4258	25.5278	Granite aplite		Zircon U-Pb	34.4	0.2	Lu et al., 2012
Binchuan	BC-4	100.6568	25.7736	Biotite quartz monzonite porphyry		Zircon U-Pb	35.4	0.4	Lu et al., 2012
Binchuan	BC-5	100.4763	25.7926	Amphibole monzonite quartz porphyry		Zircon U-Pb	36.6	0.6	Lu et al., 2012
Beiya	72ZK11-207			Monzogranite porphyry		Zircon U-Pb	36.9	0.3	Lu et al., 2012
Beiya	BY-9	100.1804	26.1462	Alkali feldspar granite porphyry		Zircon U-Pb	36.2	0.3	Lu et al., 2012
Beiya	56ZK14-4			Alkali feldspar syenite porphyry		Zircon U-Pb	34.6	0.5	Lu et al., 2012
Beiya	BY-YKD	100.1845	26.1628	Biotite monzogranite porphyry		Zircon U-Pb	36.8	0.7	Lu et al., 2012
Beiya	TKT	100.2042	26.1640	Monzonite porphyry		Zircon U-Pb	36.9	0.7	Lu et al., 2012
Beiya	LH-1	100.3294	26.4522	Biotite-amphibole-augite syenite porphyry		Zircon U-Pb	36.9	0.3	Lu et al., 2012
Beiya	PTS	100.1864	26.2873	Quartz monzonite porphyry		Zircon U-Pb	36.5	0.8	Lu et al., 2012
Beiya	BL-2	100.2257	26.1478	Monzogranite porphyry		Zircon U-Pb	35.7	0.8	Lu et al., 2012
Yao'an	YA-2	101.2891	25.3853	Biotite quartz monzonite porphyry		Zircon U-Pb	33.4	0.3	Lu et al., 2012
Yongsheng-Ninglang	DHS-1	100.9860	26.8467	Biotite quartz monzodiorite porphyry		Zircon U-Pb	33.1	0.4	Lu et al., 2012
Yongsheng-Ninglang	DHS-4	100.9742	26.8595	Biotite granite porphyry		Zircon U-Pb	34.1	0.3	Lu et al., 2012
Yongsheng-Ninglang	BNC-3	100.9307	27.3614	Granite porphyry		Zircon U-Pb	32.5	0.3	Lu et al., 2012
~100 km east of Midu	Y81-974	101.2528	25.3833	Trachydaicite		Zircon U-Pb	34.0	0.5	Liang et al., 2007
~25 km east of Xiaguan	Y83-634	100.4292	25.5250	Syenite, quartz monzonite		Zircon U-Pb	35.5	0.4	Liang et al., 2007
~25 km east of Xiaguan	Y83-620	100.4319	25.5194	Quartz monzonite porphyry		Zircon U-Pb	34.8	0.2	Liang et al., 2007
~25 km south of CD100	Y83-745	100.2028	26.1125	Quartz monzonite porphyry		Zircon U-Pb	35.6	0.5	Liang et al., 2007
~25 km south of CD101	Y83-740	100.2333	26.1631	Quartz monzonite porphyry		Zircon U-Pb	35.7	0.6	Liang et al., 2007
~25 km south of CD102	Y83-760	100.1722	26.3000	Quartz monzonite porphyry		Zircon U-Pb	36.2	0.6	Liang et al., 2007
Phan Si Pan	YS50	103.7744	22.3646	Syenite, quartz monzonite		Zircon U-Pb	35.0	0.3	Zhang and Schärer, 1999
Phan Si Pan	Sh-126	103.1292	22.7500	Syenite, quartz monzonite		Zircon U-Pb	35.4	0.4	Liang et al., 2007
Phan Si Pan	Y81-78	103.0583	22.7917	Granite porphyry, quartz monzonite porphyry		Zircon U-Pb	35.1	0.3	Liang et al., 2007

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Table S5 Zircon and apatite (U-Th)/He data.

Sample	Aliq.	He		U		Th		Th/U	grain mass (μg)	Ejection corr. (F <sub>1</sub> 2 38)	Ejection corr. (F <sub>1</sub> 2 35)	Ejection corr. (F <sub>1</sub> 2 32)	Rs (μm)	[U] (ppm)	[Th] (ppm)	[eU] (ppm)	Uncorr. He age (Ma)	F <sub>1</sub> -Corr. He age (Ma)	1σ (Ma)	Weighted mean age (Ma)	1σ (Ma)
		vol. (nc)	1σ (%)	mass (ng)	1σ (%)	mass (ng)	1σ (%)														
Zircon																					
CD 144	z 1	2.532	0.053	4.772	0.068	1.278	0.018	0.275	2.39	0.742	0.706	0.706	46.47	1422.94	381.13	1512.51	91.88	124.02	3.10	121.37	1.93
	z 2	2.717	0.057	5.000	0.071	1.082	0.015	0.222	4.17	0.778	0.746	0.746	54.55	895.89	193.94	941.47	95.15	122.46	3.06		
	z 3	1.349	0.029	2.530	0.036	0.693	0.010	0.281	5.04	0.785	0.754	0.754	56.46	345.25	94.55	367.47	92.17	117.63	2.94		
CD 145	z 1	1.686	0.035	3.982	0.057	1.372	0.020	0.354	1.83	0.726	0.687	0.687	43.45	1537.76	529.91	1662.29	72.24	99.87	2.48	107.68	4.68
	z 2	2.343	0.049	5.078	0.072	1.479	0.021	0.299	2.49	0.745	0.708	0.708	46.95	1425.89	415.50	1523.50	79.58	107.14	2.67		
	z 3	1.842	0.039	3.703	0.052	1.428	0.020	0.396	1.83	0.726	0.688	0.688	43.56	1312.19	505.96	1431.09	84.00	116.04	2.87		
CD 148	z 1	2.757	0.058	5.254	0.075	1.696	0.024	0.331	0.0	0.760	0.725	0.725	50.18	1172.58	378.46	1261.52	89.81	118.46	2.94	119.42	7.27
	z 2	2.312	0.049	5.558	0.079	1.532	0.022	0.283	0.0	0.714	0.673	0.673	41.41	1989.97	548.64	2118.90	72.04	101.26	2.52		
	z 3	1.709	0.033	3.023	0.043	0.874	0.012	0.297	0.0	0.714	0.673	0.673	41.41	1124.88	325.28	1201.33	97.39	136.77	3.42		
	z 4	5.956	0.125	10.255	0.146	4.762	0.068	0.476	0.0	0.798	0.767	0.767	60.14	1248.12	579.57	1384.32	96.33	121.18	2.99		
Apatite																					
CD 145	* a 1	0.000	0.000	0.135	0.002	0.173	0.002	1.307	2.41	0.726	0.689	0.689	51.92	43.57	55.52	56.62	0.06	0.09	0.01	35.85	3.2
	a 2	0.012	0.000	0.089	0.001	0.110	0.002	1.263	1.41	0.675	0.632	0.632	42.96	47.07	57.93	60.68	19.57	29.40	0.41		
	a 3	0.017	0.000	0.087	0.001	0.104	0.001	1.223	1.37	0.647	0.601	0.601	39.17	55.45	66.09	70.98	27.78	43.58	0.64		
	a 4	0.019	0.000	0.056	0.001	0.343	0.005	6.320	5.08	0.796	0.768	0.768	71.37	7.61	46.87	18.62	24.96	31.97	0.44		
	a 6	0.034	0.000	0.150	0.002	0.253	0.004	1.725	4.84	0.775	0.743	0.743	64.06	26.26	44.16	36.64	29.47	38.43	0.48		
CD 148	a 1	0.035	0.000	0.120	0.002	0.222	0.003	1.889	4.25	0.756	0.723	0.723	58.95	24.01	44.20	34.40	37.06	49.59	0.73	41.67	2.58
	* a 2	0.002	0.000	0.127	0.002	0.246	0.004	1.991	4.37	0.762	0.730	0.730	60.54	24.30	47.16	35.38	1.81	2.40	0.06		
	a 3	0.019	0.000	0.089	0.001	0.172	0.002	1.991	2.51	0.710	0.671	0.671	48.72	28.57	55.44	41.60	27.59	39.48	0.57		
	a 4	0.014	0.000	0.074	0.001	0.134	0.002	1.865	2.27	0.697	0.656	0.656	46.37	29.07	52.86	41.49	24.73	36.07	0.59		
	a 5	0.021	0.000	0.098	0.001	0.198	0.003	2.079	3.30	0.726	0.689	0.689	51.93	22.89	46.39	33.79	26.79	37.45	0.50		
	a 6	0.021	0.000	0.085	0.001	0.166	0.002	2.007	2.11	0.682	0.640	0.640	44.00	36.42	71.26	53.17	30.65	45.78	0.61		

\* Ages were deemed outliers based on Dixon's q-test ([https://en.wikipedia.org/wiki/Dixon%27s\\_Q\\_test](https://en.wikipedia.org/wiki/Dixon%27s_Q_test)), and not used for weight mean age calculation and inverse modeling.

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1148 Table S6 Apatite fission-track data.

Sample ID	$N_g^a$	Track number	Density	$U^b$	$P(\chi^2)^c$	Dispersion	Pooled age	$\pm 1\sigma$	Length <sup>d</sup>	$\pm 1\sigma$	$N_t^e$	$D_{par}$	$D_{per}$
			( $10^3 \text{ cm}^{-2}$ )	(ppm)	(%)	(%)	(Ma)	(Ma)	( $\mu\text{m}$ )	( $\mu\text{m}$ )		( $\mu\text{m}$ )	( $\mu\text{m}$ )
CD144	40	946	21.99	16.46	43	0.31	35.8	2.8	13.93	1.29	169	2.15	0.36
CD146	39	872	15.87	13.35	56	0.03	45.3	3.7	13.74	1.56	171	2.15	0.36
CD147	40	852	17.00	13.38	55	0.47	41.3	3.4	13.35	1.72	161	2.00	0.35
CD148	40	841	17.91	12.08	66	0.00	38.7	3.2	14.01	1.41	162	2.03	0.35
CD149	40	930	17.42	13.29	65	0.01	44.0	3.5	13.50	1.48	161	1.99	0.37

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1150 a Number of grains analyzed.

1151 b Average uranium content of all crystals measured using LA-ICP-MS.

1152 c Chi-square value for  $\nu$  degrees of freedom ( $\nu=N-1$ ).

1153 d Track length measured after  $^{252}\text{Cf}$  irradiation, and projected in respect to c axis (Ketchum et al., 2007).

1154 e Number of track length measured.

1155 Note: Zeta value is  $8.27266 \pm 0.1407$ .

