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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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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 ± 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 ~ 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 ± 0.7 km asl. during deposition of the Jiuziyan Fm.
218 (E_2jz) to between 0.9 km asl and 2.9 ± 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 $0.57-0.80$ mm yr^{-1}
221 between ~ 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_{2b}*; Figs.
255 2 and 4). To the east of the fault, the Baoxiangsi Fm. (*E_{2b}*) 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 ± 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 ± 4.6 Ma and 234.5 ± 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_{1-2p}). Several ages are pre-Cenozoic, but the lower intercept defined by the linear
397 regression of 10 ages clusters at two group ages at ~ 270 Ma and ~ 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 ± 8.5 Ma,
399 overlapping with published zircon U-Pb ages spanning from ~ 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 ~ 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 ± 1.3 Ma,
406 34.3 ± 1.6 Ma and 35.3 ± 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 ± 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 ~ 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 ~ 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 μm (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⁻¹ (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⁻¹. The cooling rate of the Ludian pluton between ~50-39 Ma translates to an apparent exhumation rate of ~0.3-0.6 mm a⁻¹. 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⁻¹ (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_{2b}) (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_{2b}) 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 ~ 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 ± 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 homogeneously 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).

625

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**

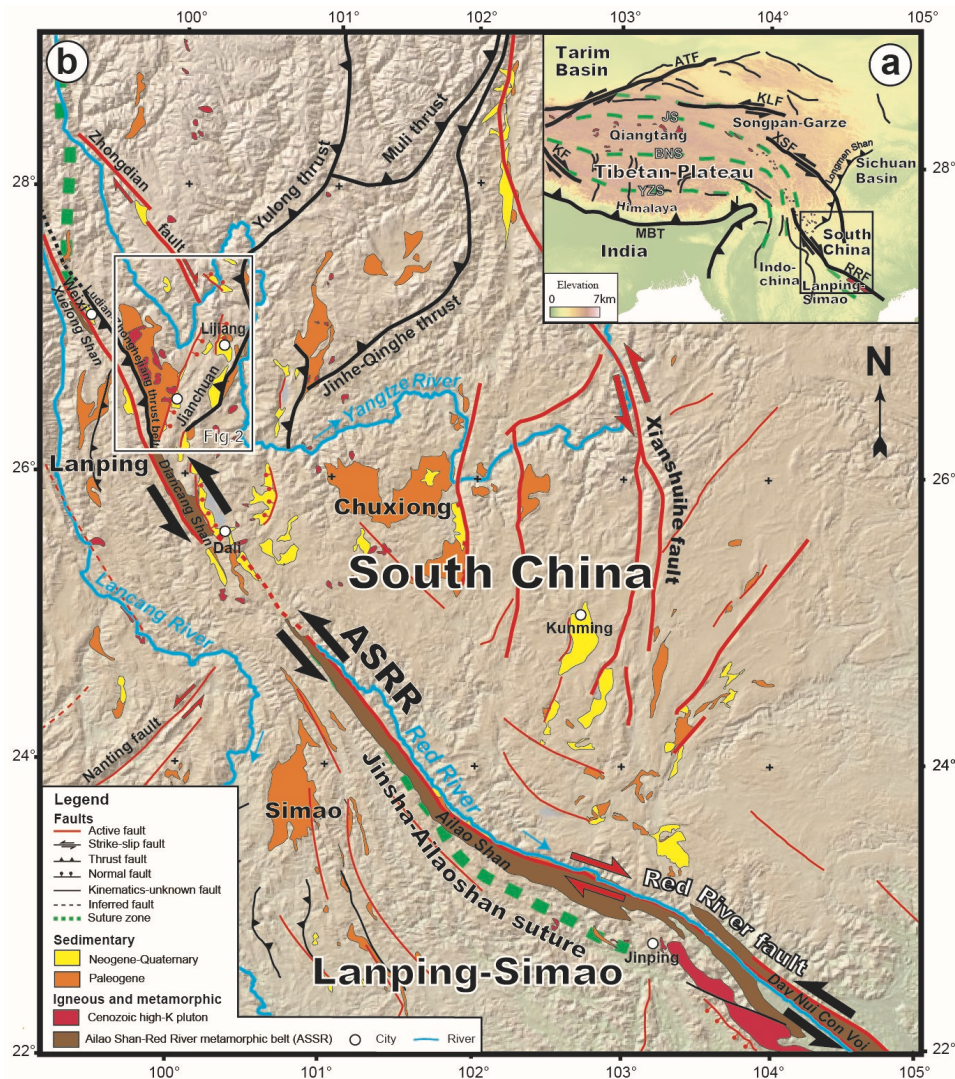
659 We thank Peter Decelles and Jay Chapman for enlightening discussion. LA-ICP-MS apatite fission-
 660 track dating was accomplished by Paul O'Sullivan and Raymond Donelick at Apatite to Zircon, Inc.,
 661 Viola, Idaho, USA. We are grateful to Peter Reiners and Uttam Chowdhury for help in the (U-Th)/He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

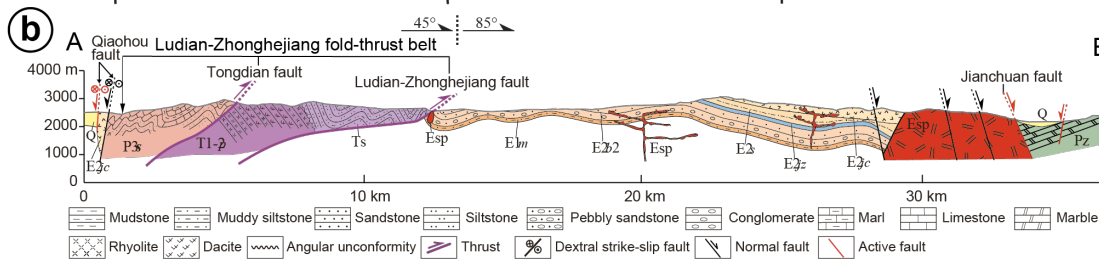
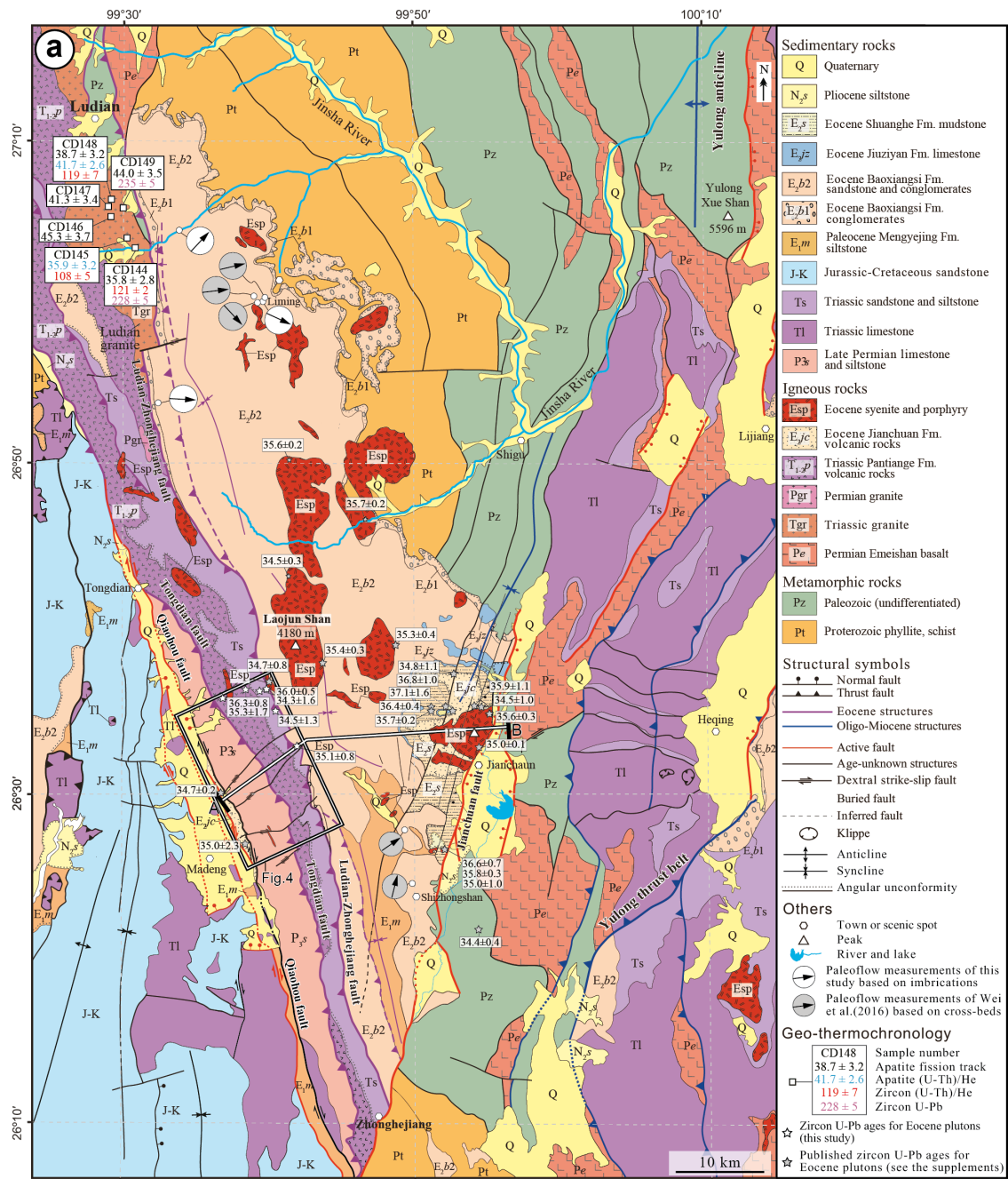
672 Table 1. Summary of geochronological and thermochronological results within the LZTB, SE Tibet.

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.

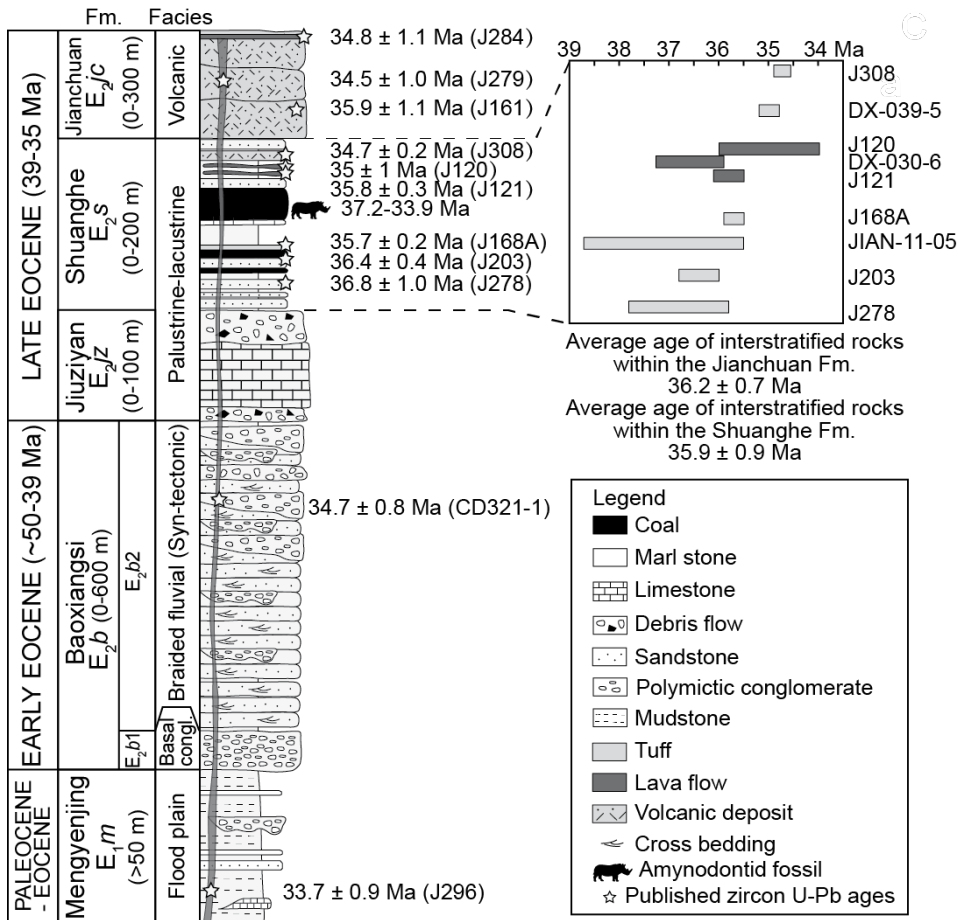


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 676 **Fig.1** (a) Simplified geological map of the southeast Tibet, showing major Cenozoic structures and
 677 basins, modified from Gourbet et al. (2017). Black arrows indicate Oligo-Miocene motion of the ASRR
 678 while red arrows indicate Plio-Quaternary 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.



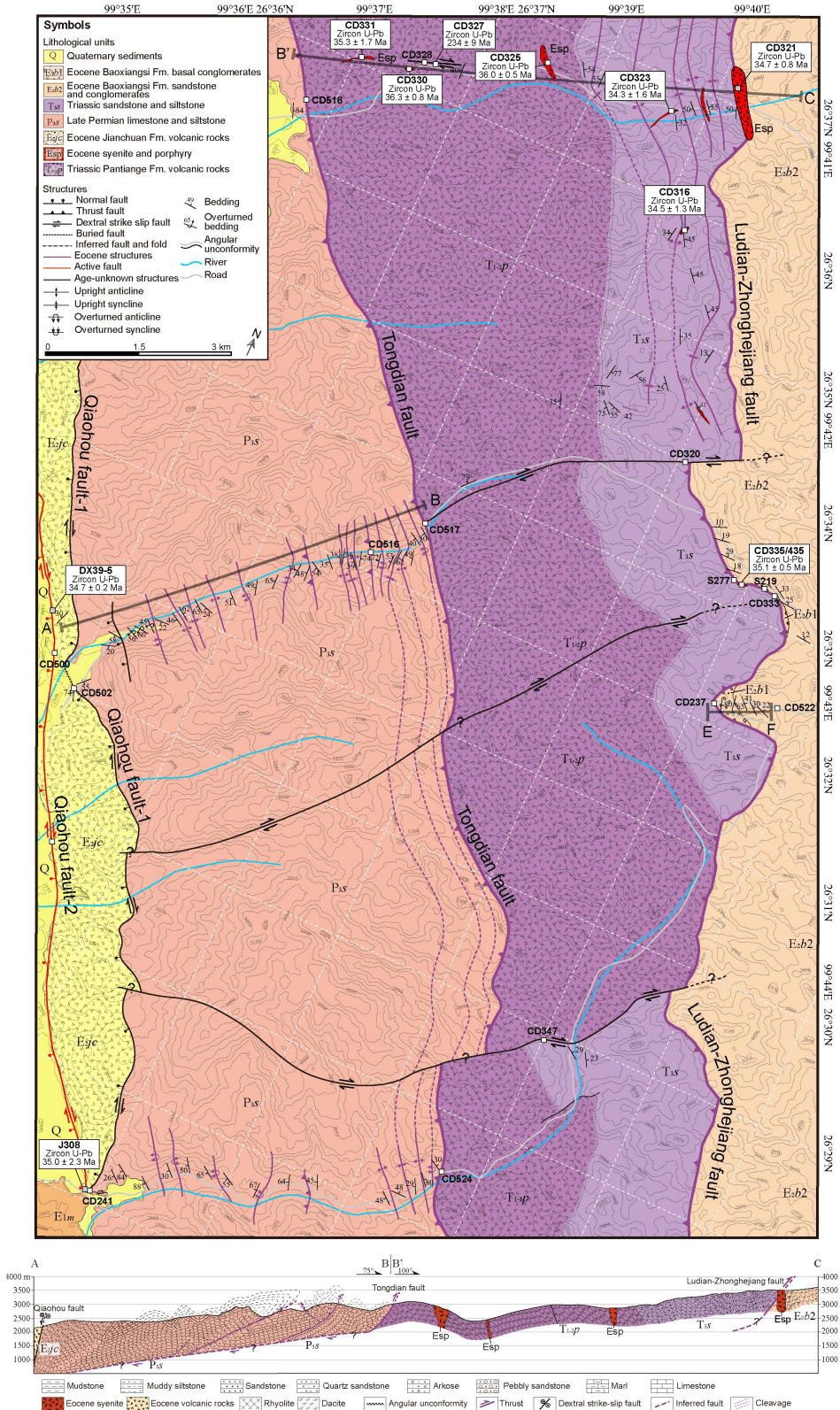
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Fig.2 (a) Geological map of the Jianchuan area, southeast Tibet, based on BGMRY (1990), Gourbet et al. (2017), Cao et al. (2019) and new mapping results. See location on Fig. 1a. Geochronology and thermochronology ages are indicated from this study and previous studies in the Tables 1 and S2-S6, as well as paleocurrent directions in the Baoxiangsi Fm. (E₂b) from this study and Wei et al. (2016). The frame corresponds to Fig. 4. (b) Sketch geological cross section across the LZTB and the Jianchuan basin, showing relationships between major structures and lithological units. Sections are located on Fig. 2a.



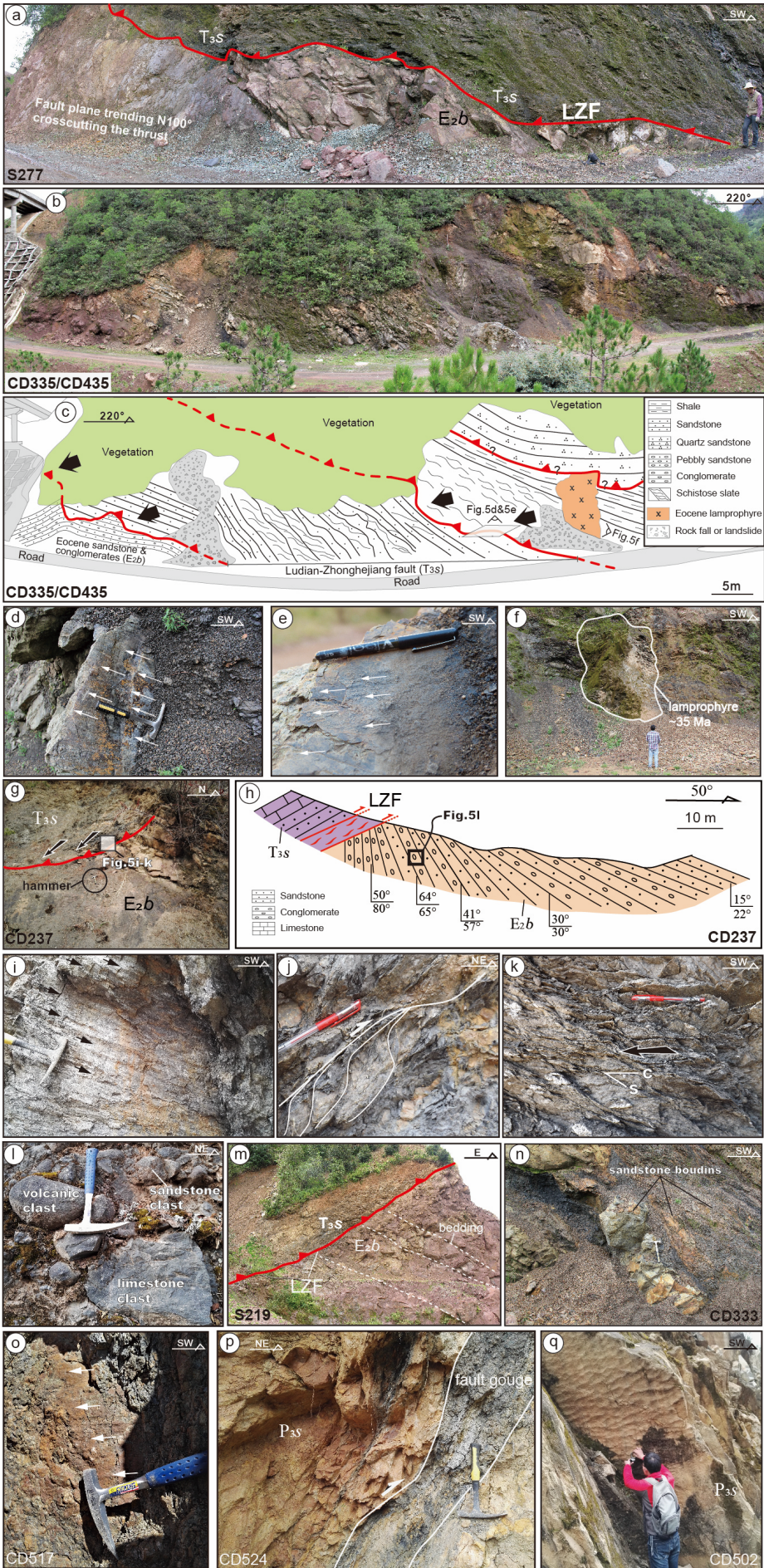
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Fig.3 Stratigraphy of the Jianchuan basin with age constraints on the upper part of the sediment sequences, modified from Gourbet et al. (2017) and Sorrel et al. (2017). Age constraints on the sediment sequences are based on Gourbet et al. (2017),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

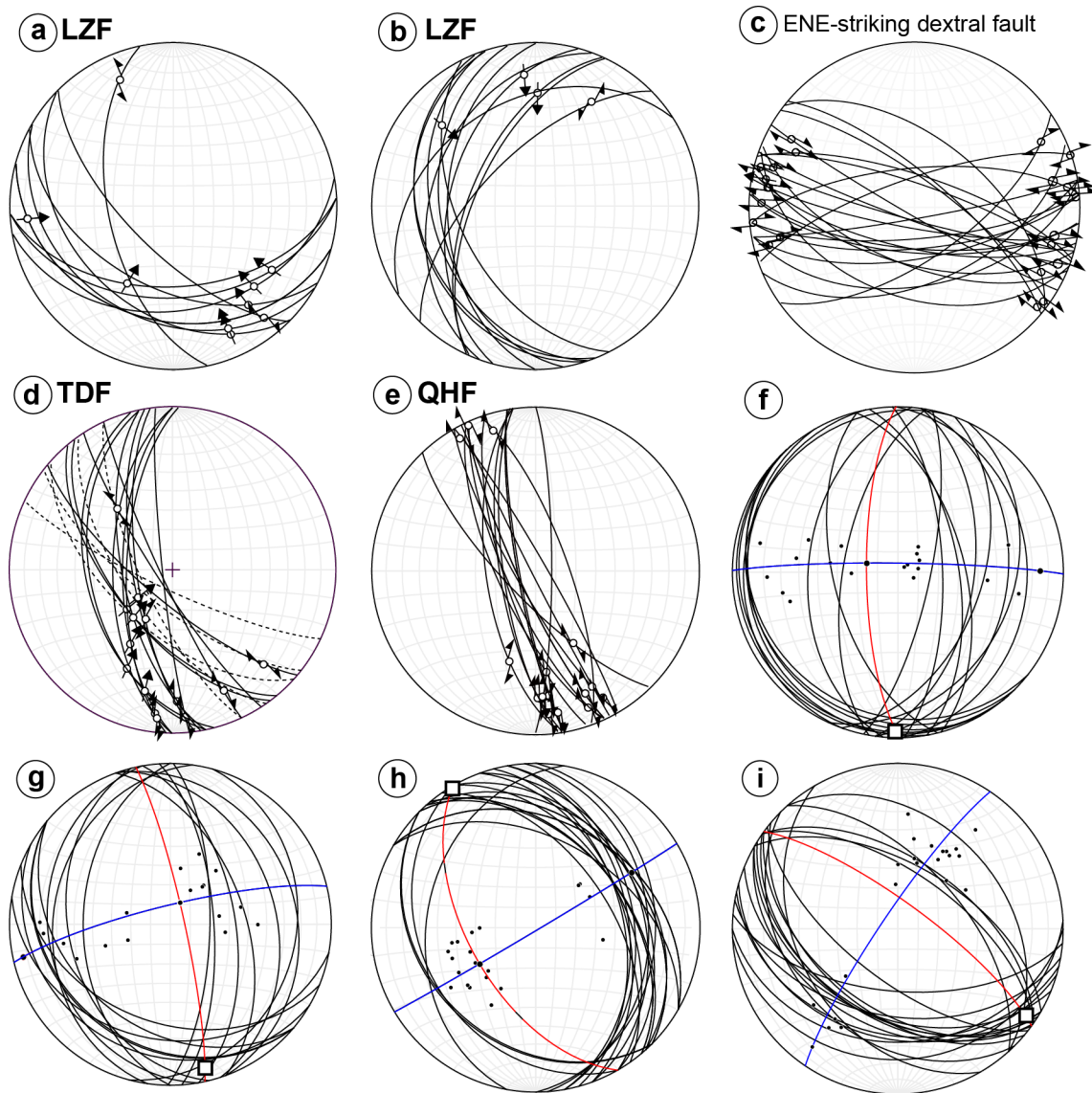


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699 **Fig.4** Geological map in the central segment of the LZTB, focusing on the major structures and
 700 lithological units to the west of the Jianchuan basin. Mapping based on BGMRY (1990) and this study.
 701 The structural measurements for southern 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.

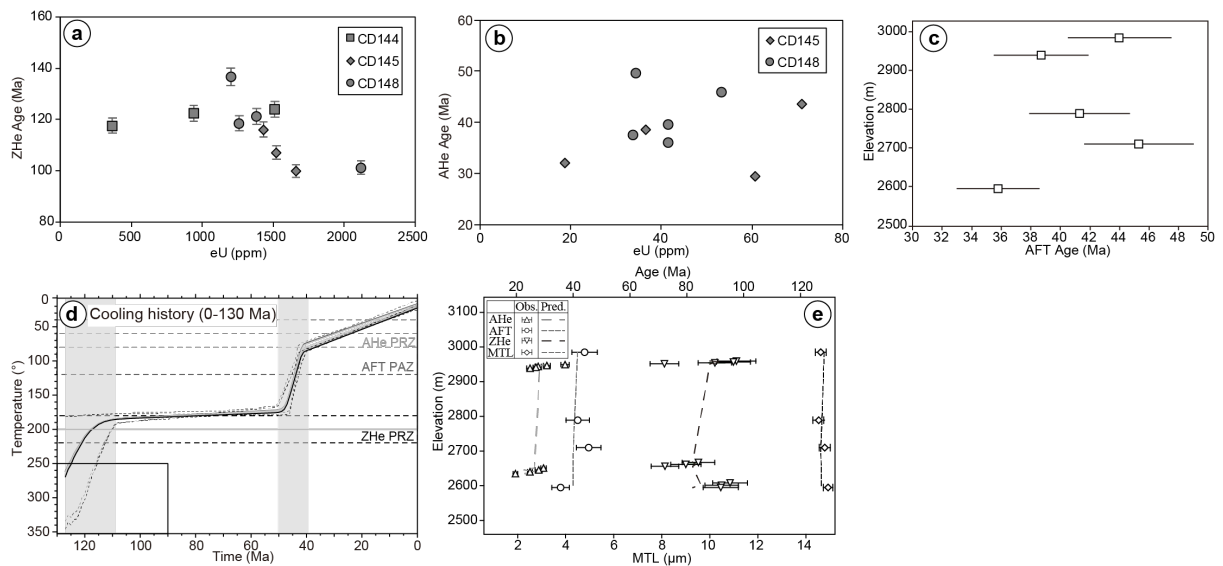


706 **Fig.5** Photos showing the main structures of the LZTB. (a) Triassic slate thrustured above Eocene
707 sediments at site S277. (b-f) field observations at site CD335/CD435: (b) field photo and (c)
708 corresponding sketch interpretation, showing schistosed Triassic meta-sandstone and coal-bearing 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}) thrustured 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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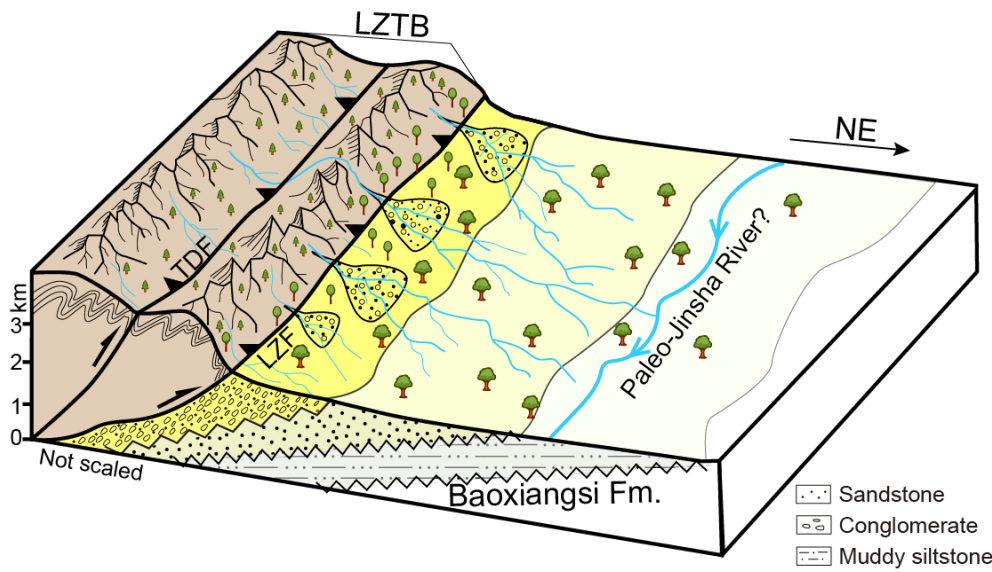
726 **Fig.6** Geometry of faults and folds in the LZTB and western Jianchuan basin. Stereographic projection,
 727 lower hemisphere atop the equal area net. (a-b) fault splays within the LZF at outcrops (a)
 728 CD335/CD435 and (b) CD237, (c) ENE-striking dextral strike-slip faults at outcrops CD241, 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 ± 50 °C and 110 ± 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 Baoliangsi Fm. (E_2b) in the Jiachuan 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).

776 **References**

- 777 Allégre, C. J., Courtillot, V., Tapponnier, P., Hirn, A., Mattauer, M., Coulon, C., Jaeger, J. J., Achache, J.,
778 Schäfer, U., Marcoux, J., Burg, J. P., Girardeau, J., Armijo, R., Gariépy, C., Göpel, C., Tindong, L.,
779 Xuchang, X., Chenfa, C., Guangqin, L., Baoyu, L., Jiwen, T., Naiwen, W., Guoming, C., Tonglin, H.,
780 Xibin, W., Wanming, D., Huaibin, S., Yougong, C., Ji, Z., Hongrong, Q., Peisheng, B., Songchan, W.,
781 Bixiang, W., Yaoxiu, Z., and Xu, R., 1984, Structure and evolution of the Himalaya–Tibet orogenic belt:
782 *Nature*, v. 307, no. 5946, p. 17-22.
- 783 Allen, C. R., Gillespie, A. R., Han, Y., Sieh, K. E., Zhang, B., and Zhu, C., 1984, Red River and associated
784 faults, Yunnan Province, China: Quaternary geology, slip rates, and seismic hazard: *Geological Society*
785 *of America Bulletin*, v. 95, no. 6, p. 686-700.
- 786 Bird, P., 1991, Lateral extrusion of lower crust from under high topography in the isostatic limit: *Journal of*
787 *Geophysical Research*, v. 96, no. B6, p. 10275-10286.
- 788 Burchfiel, B. C., and Chen, Z., 2012, Tectonics of the southeastern Tibetan Plateau and its adjacent foreland:
789 *Geological Society of America Memoirs*, v. 210, p. 1-164.
- 790 Bureau of Geology and Mineral Resources of Yunnan Province (BGMRY) (1990), *Regional Geology of*
791 *Yunnan Province*, 178 pp., Bureau of Geology and Mineral Resources of Yunnan Province, Beijing.
- 792 Cao, K., Wang, G., Leloup, P. H., Mahéo, G., Xu, Y., van der Beek, P. A., Replumaz, A., and Zhang, K.,
793 2019, Oligocene-Early Miocene topographic relief generation of southeastern Tibet triggered by
794 thrusting: *Tectonics*, v. 38, no. 1, p. 374-391.
- 795 Cao, K., Wang, G., van der Beek, P., Bernet, M., and Zhang, K., 2013, Cenozoic thermo-tectonic evolution
796 of the northeastern Pamir revealed by zircon and apatite fission-track thermochronology: *Tectonophysics*,
797 v. 589, p. 17-32.
- 798 Cao, K., Wang, G., Bernet, M., van der Beek, P., and Zhang, K., 2015, Exhumation history of the West
799 Kunlun Mountains, northwestern Tibet: Evidence for a long-lived, rejuvenated orogen: *Earth and*
800 *Planetary Science Letters*, v. 432, p. 391-403.
- 801 Cao, S., Liu, J., Leiss, B., Vollbrecht, A., Genser, J., Neubauer, F., and Zhao, C., 2011, Initiation of left-
802 lateral deformation along the Ailao Shan–Red River shear zone: new microstructural, textural, and
803 geochronological constraints from the Diancang Shan metamorphic massif, SW Yunnan, China:
804 *International Geology Review*, v. 54, no. 3, p. 348-367.
- 805 Cherniak, D. J., Watson, E. B., Grove, M., and Harrison, T. M., 2004, Pb diffusion in monazite: a combined
806 RBS/SIMS study: *Geochimica et Cosmochimica Acta*, v. 68, no. 4, p. 829-840.
- 807 Chung, S., Lee, T., Lo, C., Wang, P., Chen, C., Yem, N. T., Hoa, T. T., and Genyao, W., 1997, Intraplate
808 extension prior to continental extrusion along the Ailao Shan–Red River shear zone: *Geology*, v. 25, no.
809 4, p. 311-314.
- 810 Clark, M. K., Farley, K. A., Zheng, D., Wang, Z., and Duvall, A. R., 2010, Early Cenozoic faulting of the
811 northern Tibetan Plateau margin from apatite (U-Th)/He ages: *Earth and Planetary Science Letters*, v.
812 296, no. 1-2, p. 78-88.
- 813 Clark, M. K., House, M. A., Royden, L. H., Whipple, K. X., Burchfiel, B. C., Zhang, X., and Tang, W., 2005,
814 Late Cenozoic uplift of southeastern Tibet: *Geology*, v. 33, no. 6, p. 525-528.
- 815 Clark, M. K., and Royden, L. H., 2000, Topographic ooze: Building the eastern margin of Tibet by lower
816 crustal flow: *Geology*, v. 28, no. 8, p. 703-706.
- 817 DeCelles, P. G., Robinson, D. M., and Zandt, G., 2002, Implications of shortening in the Himalayan fold-
818 thrust belt for uplift of the Tibetan Plateau: *Tectonics*, v. 21, no. 6, p. 1062.
- 819 Decelles, P. G., Kapp, P., Gehrels, G. E., & Ding, L. (2014). Paleocene–Eocene foreland basin evolution in
820 the Himalaya of southern Tibet and Nepal: Implications for the age of initial India–Asia collision.
821 *Tectonics*, vol. 33, no. 5, p. 824-849.
- 822 Deng, J., Wang, Q., Li, G., Li, C., and Wang, C., 2014a, Tethys tectonic evolution and its bearing on the
823 distribution of important mineral deposits in the Sanjiang region, SW China: *Gondwana Research*, v. 26,
824 no. 2, p. 419-437.
- 825 Deng, J., Wang, Q., Li, G., and Santosh, M., 2014b, Cenozoic tectono-magmatic and metallogenic processes
826 in the Sanjiang region, southwestern China: *Earth-Science Reviews*, v. 138, p. 268-299.
- 827 Dewey, J. F., and Burke, K. C. A., 1973, Tibetan, Variscan, and Precambrian basement reactivation: products
828 of continental collision: *The Journal of Geology*, v. 8, no. 6, p. 683-692.
- 829 Duvall, A. R., Clark, M. K., van der Pluijm, B. A., and Li, C., 2011, Direct dating of Eocene reverse faulting
830 in northeastern Tibet using Ar-dating of fault clays and low-temperature thermochronometry: *Earth and*
831 *Planetary Science Letters*, v. 304, no. 3-4, p. 520-526.

832 Ding, L., Qasim, M., Jadoon, I. A. K., Khan, M. A., Xu, Q., Cai, F., Wang, H., Baral, U., and Yue, Y., 2016,
833 The India-Asia collision in north Pakistan: Insight from the U-Pb detrital zircon provenance of Cenozoic
834 foreland basin: *Earth and Planetary Science Letters*, v. 455, p. 49-61.

835 England, P. C., and Houseman, G. A., 1986, Finite strain calculations of continental deformation 2.
836 Comparison with the India-Asia collision zone: *Journal of Geophysical Research*, v. 91, p. 3664-3676.

837 Faure, M., Lepvrier, C., Nguyen, V. V., Vu, T. V., Lin, W., and Chen, Z., 2014, The South China block-
838 Indochina collision: Where, when, and how? *Journal of Asian Earth Sciences*, v. 79, p. 260-274.

839 Galbraith, R. F., and Green, P. F., 1990, Estimating the component ages in a finite mixture: *International
840 Journal of Radiation Applications and Instrumentation. Part D. Nuclear Tracks and Radiation
841 Measurements*, v. 17, no. 3, p. 197-206.

842 Gallagher, K., 2012, Transdimensional inverse thermal history modeling for quantitative thermochronology:
843 *Journal of Geophysical Research*, v. 117, p. B02408.

844 Gautheron, C., Tassan-Got, L., Barbarand, J., and Pagel, M., 2009, Effect of alpha-damage annealing on
845 apatite (U-Th)/He thermochronology: *Chemical Geology*, v. 266, no. 3, p. 157-170.

846 Gourbet, L., Leloup, P. H., Paquette, J., Sorrel, P., Maheo, G., Wang, G., Yadong, X., Cao, K., Antoine, P.,
847 Eymard, I., Liu, W., Lu, H., Replumaz, A., Chevalier, M., Kexin, Z., Jing, W., and Shen, T., 2017,
848 Reappraisal of the Jianchuan Cenozoic basin stratigraphy and its implications on the SE Tibetan plateau
849 evolution: *Tectonophysics*, v. 700-701, p. 162-179.

850 Guenther, W. R., Reiners, P. W., Ketcham, R. A., Nasdala, L., and Giester, G., 2013, Helium diffusion in
851 natural zircon: Radiation damage, anisotropy, and the interpretation of zircon (U-Th)/He
852 thermochronology: *American Journal of Science*, v. 313, no. 3, p. 145-198.

853 Guillot, S., Garzanti, E., Baratoux, D., Marquer, D., Mahéo, G., & De Sigoyer, J. (2003). Reconstructing the
854 total shortening history of the NW Himalaya. *Geochemistry, Geophysics, Geosystems*, vol. 4(7).

855 Hoke, G. D., Liu-Zeng, J., Hren, M. T., Wissink, G. K., and Garzzone, C. N., 2014, Stable isotopes reveal
856 high southeast Tibetan Plateau margin since the Paleogene: *Earth and Planetary Science Letters*, v. 394,
857 p. 270-278.

858 Horton, B. K., Yin, A., Spurlin, M. S., Zhou, J., and Wang, J., 2002, Paleocene–Eocene syncontractional
859 sedimentation in narrow, lacustrine-dominated basins of east-central Tibet: *Geological Society of
860 America Bulletin*, v. 114, no. 7, p. 771 -786.

861 Hu, X., Garzanti, E., Wang, J., Huang, W., An, W., and Webb, A., 2016, The timing of India-Asia collision
862 onset – Facts, theories, controversies: *Earth-Science Reviews*, v. 160, p. 264-299.

863 Jian, P., Liu, D., Kröner, A., Zhang, Q., Wang, Y., Sun, X., and Zhang, W., 2009a, Devonian to Permian
864 plate tectonic cycle of the Paleo-Tethys Orogen in southwest China (I): Geochemistry of ophiolites,
865 arc/back-arc assemblages and within-plate igneous rocks: *Lithos*, v. 113, no. 3–4, p. 748-766.

866 Jian, P., Liu, D., Kröner, A., Zhang, Q., Wang, Y., Sun, X., and Zhang, W., 2009b, Devonian to Permian
867 plate tectonic cycle of the Paleo-Tethys Orogen in southwest China (II): Insights from zircon ages of
868 ophiolites, arc/back-arc assemblages and within-plate igneous rocks and generation of the Emeishan CFB
869 province: *Lithos*, v. 113, no. 3–4, p. 767-784.

870 Kapp, P., and DeCelles, P. G., 2019, Mesozoic–Cenozoic geological evolution of the Himalayan-Tibetan
871 orogen and working tectonic hypotheses: *American Journal of Science*, v. 319, no. 3, p. 159 -254.

872 Kapp, P., DeCelles, P. G., Gehrels, G. E., Heizler, M., and Ding, L., 2007, Geological records of the Lhasa-
873 Qiangtang and Indo-Asian collisions in the Nima area of central Tibet: *Geological Society of America
874 Bulletin*, v. 119, no. 7-8, p. 917 -933.

875 Kapp, P., Yin, A., Harrison, T. M., and Ding, L., 2005, Cretaceous-Tertiary shortening, basin development,
876 and volcanism in central Tibet: *Geological Society of America Bulletin*, v. 117, no. 7-8, p. 865-878.

877 Ketcham, R. A., Carter, A., Donelick, R. A., Barbarand, J., and Hurford, A. J., 2007, Improved modeling of
878 fission-track annealing in apatite: *American Mineralogist*, v. 92, no. 5-6, p. 799-810.

879 Leloup, P. H., Arnaud, N., Lacassin, R., Kienast, J. R., Harrison, T. M., Trong, T. T. P., Replumaz, A., and
880 Tapponnier, P., 2001, New constraints on the structure, thermochronology, and timing of the Ailao Shan-
881 Red River shear zone, SE Asia: *Journal of Geophysical Research*, v. 106, p. 6683-6732.

882 Leloup, P. H., Harrison, T. M., Ryerson, F. J., Wenji, C., Qi, L., Tapponnier, P., and Lacassin, R., 1993,
883 Structural, petrological and thermal evolution of a Tertiary ductile strike-slip shear zone, Diancang Shan,
884 Yunnan: *Journal of Geophysical Research*, v. 98, no. B4, p. 6715-6743.

885 Leloup, P. H., Lacassin, R., Tapponnier, P., Schärer, U., Zhong, D., Liu, X., Zhang, L., Ji, S., and Trinh, P.
886 T., 1995, The Ailao Shan-Red River shear zone (Yunnan, China), Tertiary transform boundary of
887 Indochina: *Tectonophysics*, v. 251, no. 1–4, p. 3-84.

888 Leloup, P. H., R. Lacassin, P. Tapponnier; Discussion on the role of the Red River shear zone, Yunnan and
889 Vietnam, in the continental extrusion of SE Asia; *Journal of the geological society, London*, vol. 164, p.
890 1253-1260, 2007. DOI: 10.1144/0016-76492007-065

891 Leloup P. H., Arnaud, N.O., Mahéo, G., Paquette, J.L., Guillot, S., Valli, F., Li H., Xu Z., Lacassin, R., and
892 Tapponnier, P., 2012. Successive deformation episodes along the Lungmu Co zone west-central Tibet;
893 *Gondwana research*, vol. 21, 1, p. 37-52.

894 Li, S., Currie, B. S., Rowley, D. B., and Ingalls, M., 2015, Cenozoic paleoaltimetry of the SE margin of the
895 Tibetan Plateau: Constraints on the tectonic evolution of the region: *Earth and Planetary Science Letters*,
896 v. 432, p. 415-424.

897 Lin, T., Lo, C., Chung, S., Hsu, F., Yeh, M., Lee, T., Ji, J., Wang, Y., and Liu, D., 2009, $^{40}\text{Ar}/^{39}\text{Ar}$ dating of
898 the Jiali and Gaoligong shear zones: Implications for crustal deformation around the Eastern Himalayan
899 Syntaxis: *Journal of Asian Earth Sciences*, v. 34, no. 5, p. 674-685.

900 Liu-Zeng, J., Zhang, J., McPhillips, D., Reiners, P., Wang, W., Pik, R., Zeng, L., Hoke, G., Xie, K., Xiao,
901 P., Zheng, D., and Ge, Y., 2018, Multiple episodes of fast exhumation since Cretaceous in southeast Tibet,
902 revealed by low-temperature thermochronology: *Earth and Planetary Science Letters*, v. 490, p. 62-76.

903 Metcalfe, I., 2006, Palaeozoic and Mesozoic tectonic evolution and palaeogeography of East Asian crustal
904 fragments: The Korean Peninsula in context: *Gondwana Research*, v. 9, no. 1, p. 24-46.

905 Meyer, B., Tapponnier, T., Bourjot, L., Métivier, F., Gaudemer, Y., Peltzer, G., Guo, S., and Chen, Z., 1998,
906 Crustal thickening in Gansu-Qinghai, lithospheric mantle subduction, and oblique, strike-slip controlled
907 growth of the Tibet Plateau: *Geophysical Journal International*, v. 135, no. 1, p. 1-47.

908 Najman, Y., Appel, E., Boudagher-Fadel, M., Bown, P., Carter, A., Garzanti, E., Godin, L., Han, J., Liebke,
909 U., Oliver, G., Parrish, R., and Vezzoli, G., 2010, Timing of India-Asia collision: Geological,
910 biostratigraphic, and palaeomagnetic constraints: *Journal of Geophysical Research*, v. 115, no. B12, p.
911 B12416.

912 Ouimet, W., Whipple, K., Royden, L., Reiners, P., Hodges, K., and Pringle, M., 2010, Regional incision of
913 the eastern margin of the Tibetan Plateau: *Lithosphere*, v. 2, no. 1, p. 50-63.

914 Palin, R. M., Searle, M. P., Waters, D. J., Parrish, R. R., Roberts, N. M. W., Horstwood, M. S. A., Yeh, M.
915 W., Chung, S. L., and Anh, T. T., 2013, A geochronological and petrological study of anatectic paragneiss
916 and associated granite dykes from the Day Nui Con Voi metamorphic core complex, North Vietnam:
917 constraints on the timing of metamorphism within the Red River shear zone: *Journal of Metamorphic
918 Geology*, v. 31, no. 4, p. 359-387.

919 Reiners, P. W., and Brandon, M. T., 2006, Using thermochronology to understand orogenic erosion: *Annual
920 Review of Earth and Planetary Sciences*, v. 34, p. 419-466.

921 Replumaz, A., Lacassin, R., Tapponnier, P., and Leloup, P. H., 2001, Large river offsets and Plio-Quaternary
922 dextral slip rate on the Red River Fault (Yunnan, China): *Journal of Geophysical Research*, v. 106, no.
923 B1, p. 819-836.

924 Rowley, D. B., 1996, Age of initiation of collision between India and Asia: A review of stratigraphic data:
925 *Earth and Planetary Science Letters*, v. 145, no. 1-4, p. 1-13.

926 Royden, L. H., Burchfiel, B. C., King, R. W., Wang, E., Chen, Z., Feng, S., and Liu, Y., 1997, Surface
927 deformation and lower crustal flow in eastern Tibet: *Science*, v. 276, no. 5313, p. 788-790.

928 Royden, L. H., Burchfiel, B. C., and van der Hilst, R. D., 2008, The Geological Evolution of the Tibetan
929 Plateau: *Science*, v. 321, no. 5892, p. 1054-1058.

930 Schoenbohm, L. M., Burchfiel, B. C., and Liangzhong, C., 2006, Propagation of surface uplift, lower crustal
931 flow, and Cenozoic tectonics of the southeast margin of the Tibetan Plateau: *Geology*, v. 34, no. 10, p.
932 813 -816.

933 Searle, M.P., 2006, Role of the Red River Shear zone, Yunnan and Vietnam, in the continental extrusion of
934 SE Asia: *Journal of the Geological Society*, v. 163, p. 1025-1036, doi: 10.1144/0016-76492005-144.

935 Searle, M. P., Yeh, M., Lin, T., and Chung, S., 2010, Structural constraints on the timing of left-lateral shear
936 along the Red River shear zone in the Ailao Shan and Diancang Shan Ranges, Yunnan, SW China:
937 *Geosphere*, v. 6, no. 4, p. 316 -338.

938 Sorrel, P., Eymard, I., Leloup, P., Maheo, G., Olivier, N., Sterb, M., Gourbet, L., Wang, G., Jing, W., Lu,
939 H., Li, H., Yadong, X., Zhang, K., Cao, K., Chevalier, M., and Replumaz, A., 2017, Wet tropical climate
940 in SE Tibet during the Late Eocene: *Scientific Reports*, v. 7, no. 1, p. 7809.

941 Spurlin, M. S., Yin, A., Horton, B. K., Zhou, J., and Wang, J., 2005, Structural evolution of the Yushu-
942 Nangqian region and its relationship to syncollisional igneous activity, east-central Tibet: *Geological
943 Society of America Bulletin*, v. 117, no. 9-10, p. 1293 -1317.

- 944 Staisch, L. M., Niemi, N. A., Clark, M. K., and Chang, H., 2016, Eocene to late Oligocene history of crustal
945 shortening within the Hoh Xil Basin and implications for the uplift history of the northern Tibetan Plateau:
946 *Tectonics*, v. 35, no. 4, p. 862-895.
- 947 Studnicki-Gizbert, C. T., 2006, Deformation, erosion and sedimentation in collisional orogens: case studies
948 from eastern Tibet and southwestern China, Massachusetts Institute of Technology, Dept. of Earth,
949 Atmospheric, and Planetary Sciences, p. 296.
- 950 Studnicki-Gizbert, C., Burchfiel, B. C., Li, Z., and Chen, Z., 2008, Early Tertiary Gonjo basin, eastern Tibet:
951 Sedimentary and structural record of the early history of India-Asia collision: *Geosphere*, v. 4, no. 4, p.
952 713 -735.
- 953 Tang, L., Xue, C., Yang, T., Liang, M., Xiang, K., Liao, C., Jiang, L., and Xin, D., 2016, Late Permian to
954 Early Triassic tectonostratigraphy of Madeng area, northwestern Yunnan, S.W. China: Volcanics zircon
955 U-Pb dating: *Acta Petrologica Sinica*, no. 8, p. 2535-2554.
- 956 Tang, M., Liu-Zeng, J., Hoke, G. D., Xu, Q., Wang, W., Li, Z., Zhang, J., and Wang, W., 2017,
957 Paleoelevation reconstruction of the Paleocene-Eocene Gonjo basin, SE-central Tibet: *Tectonophysics*,
958 v. 712-713, p. 170-181.
- 959 Tapponnier, P., and Molnar, P., 1976, Slip-line field theory and large-scale continental tectonics: *Nature*, v.
960 264, no. 5584, p. 319-324.
- 961 Tapponnier, P., Peltzer, G., Le Dain, A. Y., Armijo, R., and Cobbold, P., 1982, Propagating extrusion
962 tectonics in Asia: New insights from simple experiments with plasticine: *Geology*, v. 10, no. 12, p. 611.
- 963 Tapponnier, P., Lacassin, R., Leloup, P. H., Schaerer, U., Zhong, D., Wu, H., Liu, X., Ji, S., Zhang, L., and
964 Zhong, J., 1990, The Ailao Shan/Red River metamorphic belt; Tertiary left-lateral shear between
965 Indochina and South China: *Nature*, v. 343, no. 6257, p. 431-437.
- 966 Tapponnier, P., Xu, Z., Roger, F., Meyer, B., Arnaud, N., Wittlinger, G., and Yang, J., 2001, Oblique
967 stepwise rise and growth of the Tibet Plateau: *Science*, v. 294, no. 5547, p. 1671-1677.
- 968 Tong, Y., Yang, Z., Jing, X., Zhao, Y., Li, C., Huang, D., and Zhang, X., 2016, New insights into the
969 Cenozoic lateral extrusion of crustal blocks on the southeastern edge of Tibetan Plateau: Evidence from
970 paleomagnetic results from Paleogene sedimentary strata of the Baoshan Terrane: *Tectonics*, v. 35, no.
971 11, p. 2494-2514.
- 972 Tong, Y., Yang, Z., Mao, C., Pei, J., Pu, Z., and Xu, Y., 2017, Paleomagnetism of Eocene red-beds in the
973 eastern part of the Qiangtang Terrane and its implications for uplift and southward crustal extrusion in
974 the southeastern edge of the Tibetan Plateau: *Earth and Planetary Science Letters*, v. 475, p. 1-14.
- 975 Turab, S. A., Stüwe, K., Stuart, F. M., Chew, D. M., and Cogné, N., 2017, Tectonics drives rapid exhumation
976 of the western Himalayan syntaxis: Evidence from low- temperature thermochronometry of the Neelum
977 valley region, Pakistan: *Lithosphere*, v. 9, no. 6, p. 874-888.
- 978 van Hinsbergen, D. J. J., Kapp, P., Dupont-Nivet, G., Lippert, P. C., DeCelles, P. G., and Torsvik, T. H.,
979 2011, Restoration of Cenozoic deformation in Asia and the size of Greater India: *Tectonics*, v. 30, no. 5,
980 p. TC5003.
- 981 Wang, C., Zhao, X., Liu, Z., Lippert, P. C., Graham, S. A., Coe, R. S., Yi, H., Zhu, L., Liu, S., and Li, Y.,
982 2008, Constraints on the early uplift history of the Tibetan Plateau: *Proceedings of the National Academy*
983 *of Sciences*, v. 105, no. 13, p. 4987-4992.
- 984 Wang, E., Burchfiel, B. C., Royden, L. H., Chen, L., Chen, J., Li, W., and Chen, Z., 1998, Late Cenozoic
985 Xianshuihe-Xiaojiang, Red River, and Dali Fault Systems of Southwestern Sichuan and Central Yunnan,
986 China: *Geological Society of America Special Papers*, v. 327, p. 1 -108.
- 987 Wang, J., Yin, A., Harrison, T. M., Grove, M., Zhang, Y., and Xie, G., 2001, A tectonic model for Cenozoic
988 igneous activities in the eastern Indo-Asian collision zone: *Earth and Planetary Science Letters*, v. 188,
989 no. 1-2, p. 123-133.
- 990 Wang, Y., Zhang, B., Schoenbohm, L. M., Zhang, J., Zhou, R., Hou, J., and Ai, S., 2016, Late Cenozoic
991 tectonic evolution of the Ailao Shan-Red River fault (SE Tibet): Implications for kinematic change during
992 plateau growth: *Tectonics*, v. 35, no. 8, p. 1969-1988.
- 993 Wei, H., Wang, E., Wu, G., and Meng, K., 2016, No sedimentary records indicating southerly flow of the
994 paleo-Upper Yangtze River from the First Bend in southeastern Tibet: *Gondwana Research*, v. 32, p. 93-
995 104.
- 996 Wissink, G. K., Hoke, G. D., Garzzone, C. N., and Liu-Zeng, J., 2016, Temporal and spatial patterns of
997 sediment routing across the southeast margin of the Tibetan Plateau: Insights from detrital zircon:
998 *Tectonics*, v. 35, no. 11, p. 2538-2563.

- 999 Wu, J., Zhang, K., Xu, Y., Wang, G., Garzzone, C. N., Eiler, J., Leloup, P. H., Sorrel, P., and Mahéo, G.,
1000 2018, Paleoelevations in the Jianchuan Basin of the southeastern Tibetan Plateau based on stable isotope
1001 and pollen grain analyses: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 510, p. 93-108.
- 1002 Yang, T. N., Liang, M. J., Fan, J. W., Shi, P. L., Zhang, H. R., and Hou, Z. H., 2014, Paleogene sedimentation,
1003 volcanism, and deformation in eastern Tibet: Evidence from structures, geochemistry, and zircon U–Pb
1004 dating in the Jianchuan Basin, SW China: *Gondwana Research*, v. 26, no. 2, p. 521-535.
- 1005 Yin, A., 2010, Cenozoic tectonic evolution of Asia: A preliminary synthesis: *Tectonophysics*, v. 488, no. 1,
1006 p. 293-325.
- 1007 Yin, A., Dang, Y., Wang, L., Jiang, W., Zhou, S., Chen, X., Gehrels, G. E., and McRivette, M. W., 2008,
1008 Cenozoic tectonic evolution of Qaidam basin and its surrounding regions (Part 1): The southern Qilian
1009 Shan-Nan Shan thrust belt and northern Qaidam basin: *Geological Society of America Bulletin*, v. 120,
1010 no. 7-8, p. 813-846.
- 1011 Yin, A., Rumelhart, P. E., Butler, R., Cowgill, E., Harrison, T. M., Foster, D. A., Ingersoll, R. V., Qing, Z.,
1012 Xian-Qiang, Z., Xiao-Feng, W., Hanson, A., and Raza, A., 2002, Tectonic history of the Altyn Tagh fault
1013 system in northern Tibet inferred from Cenozoic sedimentation: *Geological Society of America Bulletin*,
1014 v. 114, no. 10, p. 1257-1295.
- 1015 Yin, A., and Harrison, T. M., 2000, Geologic Evolution of the Himalayan-Tibetan Orogen: *Annual Review*
1016 *of Earth and Planetary Sciences*, v. 28, no. 1, p. 211-280.
- 1017 Zhang, B., Zhang, J., Liu, J., Wang, Y., Yin, C., Guo, L., Zhong, D., Lai, Q., and Yue, Y., 2014, The
1018 Xuelongshan high strain zone: Cenozoic structural evolution and implications for fault linkages and
1019 deformation along the Ailao Shan–Red River shear zone: *Journal of Structural Geology*, v. 69, p. 209-
1020 233.
- 1021 Zhang, B., Zhang, J., Zhong, D., Wang, X., Qu, J., and Guo, L., 2011, Structural feature and its significance
1022 of the northernmost segment of the Tertiary Biluoxueshan–Chongshan shear zone, east of the Eastern
1023 Himalayan Syntaxis: *Science China Earth Sciences*, v. 54, no. 7, p. 959-974.
- 1024 Zhang, B., Zhang, J., and Zhong, D., 2010, Structure, kinematics and ages of transpression during strain-
1025 partitioning in the Chongshan shear zone, western Yunnan, China: *Journal of Structural Geology*, v. 32,
1026 no. 4, p. 445-463.
- 1027 Zhang, Y., Huang, W., Huang, B., van Hinsbergen, D. J. J., Yang, T., Dupont-Nivet, G., and Guo, Z., 2018,
1028 53-43 Ma deformation of eastern Tibet revealed by three stages of tectonic rotation in the Gongjue Basin:
1029 *Journal of Geophysical Research: Solid Earth*, v. 123, no. 5, p. 3320-3338.
- 1030 Zhang, Y., Replumaz, A., Leloup, P. H., Wang, G., Bernet, M., van der Beek, P., Paquette, J. L., and
1031 Chevalier, M., 2017, Cooling history of the Gongga batholith: Implications for the Xianshuihe Fault and
1032 Miocene kinematics of SE Tibet: *Earth and Planetary Science Letters*, v. 465, p. 1-15.
- 1033 Zhang, Y., Replumaz, A., Wang, G., Leloup, P. H., Gautheron, C., Bernet, M., Beek, P., Paquette, J. L.,
1034 Wang, A., Zhang, K., Chevalier, M., and Li, H., 2015, Timing and rate of exhumation along the Litang
1035 fault system, implication for fault reorganization in Southeast Tibet: *Tectonics*, v. 34, no. 6, p. 1219-1243.
- 1036 Zi, J., Cawood, P. A., Fan, W., Tohver, E., Wang, Y., McCuaig, T. C., and Peng, T., 2013, Late Permian-
1037 Triassic magmatic evolution in the Jinshajiang orogenic belt, SW China and implications for orogenic
1038 processes following closure of the Paleo-Tethys: *American Journal of Science*, v. 313, no. 2, p. 81 -112.
- 1039 Zi, J., Cawood, P. A., Fan, W., Tohver, E., Wang, Y., and McCuaig, T. C., 2012, Generation of Early
1040 Indosinian enriched mantle-derived granitoid pluton in the Sanjiang Orogen (SW China) in response to
1041 closure of the Paleo-Tethys: *Lithos*, v. 140-141, p. 166-182.
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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 μm . 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 ≤ 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).

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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 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 μm spot and a 5 Hz repetition rate
1064 with the laser set in constant energy mode. Analyses were corrected by ^{43}Ca as an internal standard for
1065 variations in ablation volume. For detailed procedures of sample analysis refer to Donelick et al. (2005)

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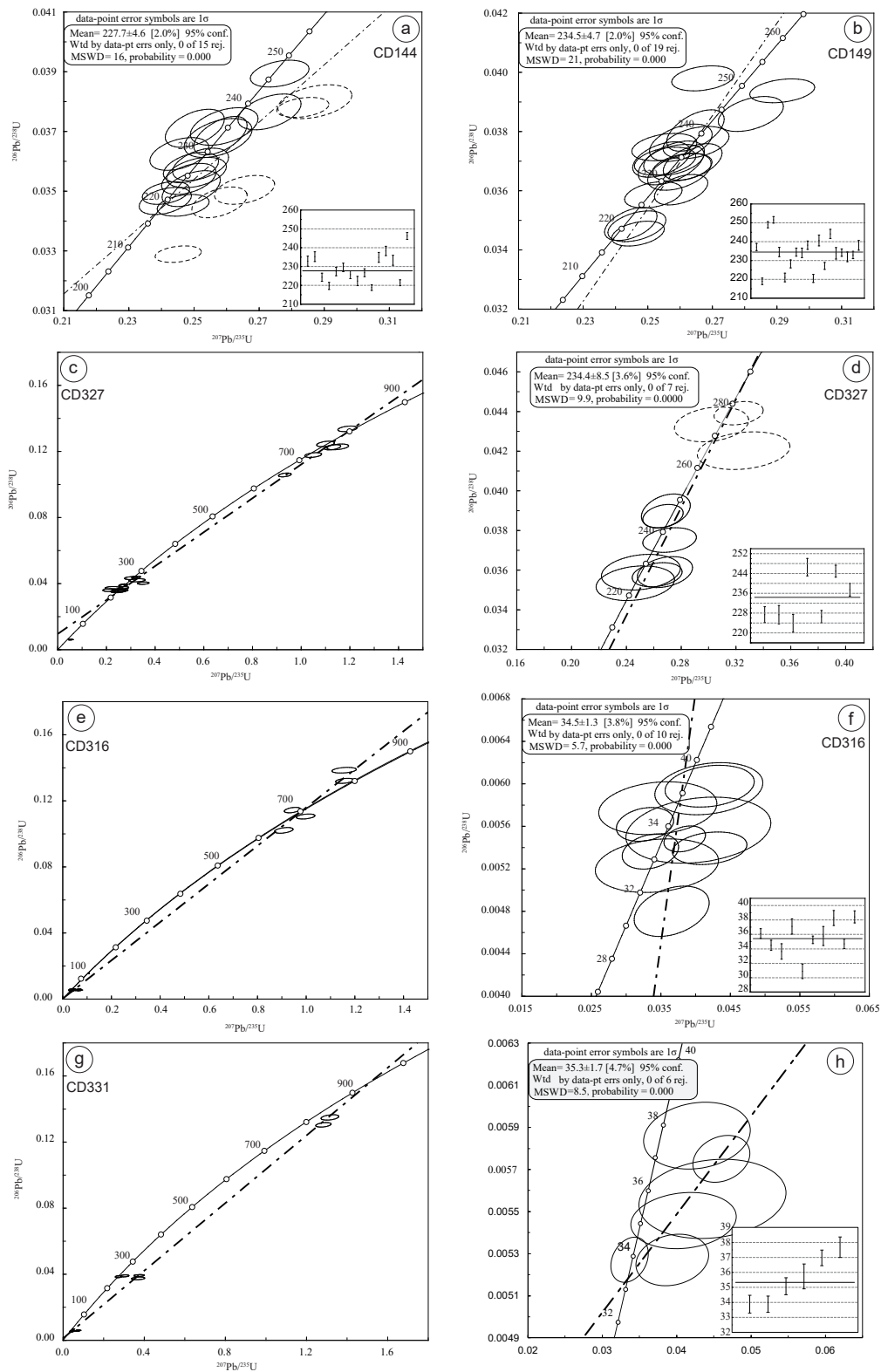
1067 Zircon and Apatite (U-Th)/He dating was accomplished at the University of Arizona, USA. Normally,
1068 3-5 euhedral zircon and apatite crystals without visible inclusions, fracture and stainless surface were
1069 chosen using a stereo-zoom polarized microscope. The geometry of each grain was measured and
1070 photographed. The grains larger than 60 μm but smaller than 500 μm 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 ^3He 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 α -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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1080 **References**

- 1081 Donelick, R. A., O'Sullivan, P. B., and Ketcham, R. A., 2005, Apatite Fission-Track Analysis: Reviews in
1082 Mineralogy and Geochemistry, v. 58, no. 1, p. 49-94.
1083 Farley, K. A., 2002, (U-Th)/He Dating: Techniques, Calibrations, and Applications: Reviews in Mineralogy
1084 and Geochemistry, v. 47, no. 1, p. 819-844.
1085 Liu, Y., Hu, Z., Gao, S., Günther, D., Xu, J., Gao, C., and Chen, H., 2008, In situ analysis of major and trace
1086 elements of anhydrous minerals by LA-ICP-MS without applying an internal standard: Chemical
1087 Geology, v. 257, no. 1-2, p. 34-43.
1088 Ludwig, K. R., 2012, User's Manual for Isoplot 3.75: A geochronological toolkit for microsoft excel:
1089 Berkeley, California, Berkeley Geochronology Center Special Publication No. 5, 1-75 p.

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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)												
	U (ppm)	Th (ppm)	U/Th	207Pb* ± 235U (%)	206Pb* ± 238U (%)	error corr.	206Pb* ± 238U (Ma)	207Pb* ± 235U (Ma)	206Pb* ± 238U (Ma)	207Pb* ± 235U (Ma)	Best age (Ma)	± (Ma)	Discordance				
CD144																	
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%
CD149																	
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%
CD316																	
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%
CD323																	
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%
CD325																	
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%
CD327																	
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%
CD330																	
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%
CD331																	
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%
CD335-1/CD435-1																	
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 _{1-2p})	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 _{1-2p})	Zircon U-Pb	244.9	3.3	Yang et al., 2014
Jianchuan	QD-5	99.5082	26.7703	dacite	Pantiange Fm.(T _{1-2p})	Zircon U-Pb	236.9	2.8	Yang et al., 2014
Jianchuan	DX038-2	99.6860	26.5533	volcanoclastic	Pantiange Fm.(T _{1-2p})	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 _{1-2p})	Zircon U-Pb	247.0	4.3	Tang et al.,2016
Maliqing	D3052-1	99.6835	26.4501	rhyolite	Pantiange Fm.(T _{1-2p})	Zircon U-Pb	250.0	4.3	Tang et al.,2016
Maliqing	D3053-1	99.7000	26.4501	rhyolite	Pantiange Fm.(T _{1-2p})	Zircon U-Pb	246.7	4.3	Tang et al.,2016
Maliqing	D3055-5A	99.7001	26.4667	rhyolitic lava	Pantiange Fm.(T _{1-2p})	Zircon U-Pb	244.0	5.2	Tang et al.,2016

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 1106 References

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 1108 Yang, T. N., Liang, M. J., Fan, J. W., Shi, P. L., Zhang, H. R., and Hou, Z. H., 2014, Paleogene
 1109 sedimentation, volcanism, and deformation in eastern Tibet: Evidence from structures, geochemistry,
 1110 and zircon U-Pb dating in the Jianchuan Basin, SW China: Gondwana Research, v. 26, no. 2, p. 521-
 1111 535.
 1112 Tang, L., Xue, C., Yang, T., Liang, M., Xiang, K., Liao, C., Jiang, L., and Xin, D., 2016, Late Permian
 1113 to Early Triassic tectonostratigraphy of Madeng area, northwestern Yunnan, S.W. China: Volcanics
 1114 zircon U-Pb dating: Acta Petrologica Sinica, no. 8, p. 2535-2554.

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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
Within the Ludian-Zhonghejiang fold-thrust belt									
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
Jianchuan basin interstratified (Jianchuan Fm.(E_{1c}))									
Jianchuan basin	J161	99.8919	26.5913	Volcanoclastics	Jianchuan Fm.(E _{1c})	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 _{1c})	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 _{1c})	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 _{1c})	Zircon U-Pb weighed mean age of the youngest concordant zircons (4 ages)	34.7	0.2	Yang et al., 2014
Jianchuan basin interstratified (Shuanghe Fm.(E_{1s}))									
Jianchuan basin	J121	99.8672	26.4477	Trachy-andesitic lava flow	Shuanghe Fm.(E _{1s})	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 _{1s})	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 _{1s})	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 _{1s})	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 _{1s})	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 _{1s})	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 _{1s})	Zircon U-Pb weighed mean age of the youngest concordant zircons (5 ages)	37.1	1.6	Hoke et al., 2014
Plutonic rocks around the Jianchuan county									
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
Plutonic rocks away from the Jianchuan county									
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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- 1118 References
1119 Gourbet, L., Leloup, P. H., Paquette, J., Sorrel, P., Maheo, G., Wang, G., Yadong, X., Cao, K., Antoine, P., Eymard,
1120 I., Liu, W., Lu, H., Replumaz, A., Chevalier, M., Kexin, Z., Jing, W., and Shen, T., 2017, Reappraisal of the
1121 Jianchuan Cenozoic basin stratigraphy and its implications on the SE Tibetan plateau evolution: Tectonophysics,
1122 v. 700-701, no. Supplement C, p. 162-179.
1123 Hoke, G. D., Liu-Zeng, J., Hren, M. T., Wissink, G. K., and Garziona, C. N., 2014, Stable isotopes reveal high
1124 southeast Tibetan Plateau margin since the Paleogene: Earth and Planetary Science Letters, v. 394, no. 0, p. 270-
1125 278.
1126 Liang, H. Y., Campbell, I. H., Allen, C. M., Sun, W. D., Yu, H. X., Xie, Y. W., and Zhang, Y. Q., 2007, The Age
1127 of the Potassic Alkaline Igneous Rocks along the Ailao Shan – Red River Shear Zone: Implications for the Onset
1128 Age of Left - Lateral Shearing: The Journal of Geology, v. 115, no. 2, p. 231-242.
1129 Liu, Y., Hu, Z., Gao, S., Günther, D., Xu, J., Gao, C., and Chen, H., 2008, In situ analysis of major and trace
1130 elements of anhydrous minerals by LA-ICP-MS without applying an internal standard: Chemical Geology, v. 257,
1131 no. 1–2, p. 34-43.
1132 Lu, Y., Kerrich, R., Cawood, P. A., McCuaig, T. C., Hart, C. J. R., Li, Z., Hou, Z., and Bagas, L., 2012, Zircon
1133 SHRIMP U–Pb geochronology of potassic felsic intrusions in western Yunnan, SW China: Constraints on the
1134 relationship of magmatism to the Jinsha suture: Gondwana Research, v. 22, no. 2, p. 737-747.
1135 Schärer, U., Zhang, L., and Tapponnier, P., 1994, Duration of strike-slip movements in large shear zones: The Red
1136 River belt, China: Earth and Planetary Science Letters, v. 126, no. 4, p. 379-397.
1137 Yang, T. N., Liang, M. J., Fan, J. W., Shi, P. L., Zhang, H. R., and Hou, Z. H., 2014, Paleogene sedimentation,
1138 volcanism, and deformation in eastern Tibet: Evidence from structures, geochemistry, and zircon U-Pb dating in
1139 the Jianchuan Basin, SW China: Gondwana Research, v. 26, no. 2, p. 521-535.
1140 Zhang, L., and Schärer, U., 1999, Age and origin of magmatism along the Cenozoic Red River shear belt, China:
1141 Contributions to Mineralogy and Petrology, v. 134, no. 1, p. 67-85.
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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_{i2} 38)	Ejection corr. (F_{i2} 35)	Ejection corr. (F_{i2} 32)	Rs (μm)	[U] (ppm)	[Th] (ppm)	[eU] (ppm)	Uncorr. He age (Ma)	F _i -Corr. He age (Ma)	1 σ (Ma)	Weighted mean age (Ma)	1 σ (Ma)
		vol. (nc)	1 σ (%)	mass (ng)	1 σ (%)	mass (ng)	1 σ (%)														
Zircon																					
CD 144	z1	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
	z2	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		
	z3	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	z1	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
	z2	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		
	z3	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	z1	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
	z2	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		
	z3	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		
	z4	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	*a1	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
	a2	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		
	a3	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		
	a4	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		
	a6	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	a1	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
	*a2	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		
	a3	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		
	a4	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		
	a5	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		
	a6	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), 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 ^d	$\pm 1\sigma$	N_t^e	D_{par}	D_{per}
			(10^3 cm^{-2})	(ppm)	(%)	(%)	(Ma)	(Ma)	(μm)	(μm)		(μm)	(μm)
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 ν degrees of freedom ($\nu=N-1$).

1153 d Track length measured after ^{252}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 ± 0.1407 .

