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1 **Decoupling between upper crustal deformation of southern Tibet and underthrusting of**
2 **Indian lithosphere**

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5

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18 **Short title:** Upper crustal deformation of southern Tibet

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21 **Statement of significance**

22 In the India-Asia collision compressive context, surprising dominant east-west extension is
23 observed in southern Tibet, expressed as large north-south-trending rifts. Whether such upper
24 crustal extension is due to underthrusting of India (i.e., Indian lower crust + lithospheric mantle,
25 bending beneath the Himalayan range and flattening below southern Tibet) or in-plane forces
26 arising from the Indian indenter, is highly debated. Here, we use P-waves global tomography
27 images (at depths of ~200 km), that reveal the northern extent of the underthrust Indian plate
28 beneath Tibet, to show that there is no correlation with the location of the rifts that dissect southern
29 Tibet. On the contrary, as previously suggested, such strong east-west extension in southern Tibet is
30 correlated to the curved shape of the Himalayan arc, limited to the north by a major en-echelon
31 strike-slip fault zone joining the two extremities (syntaxes) of the arc. North of this zone however,
32 weaker extension is observed, driven by southeastward extrusion of eastern Tibet, bounded by
33 major east-trending strike-slip faults visible as strong discontinuities in the GPS velocity field.
34 Therefore, we argue that extension in Tibet appears correlated to upper crustal arc and fault
35 geometries, but decorrelated to underthrusting India underneath.

36 **Abstract**

37 More accurate normal fault mapping and more recently constrained extension rates in
38 southern and central Tibet allow to better discuss the mechanical processes responsible for the
39 distribution of extension in Tibet. First, we show that the location of the rifts in southern Tibet south
40 of the Karakorum-Jiali fault zone (KJFZ) does not exactly correspond to that of the rigid Indian
41 lower lithosphere flattening below southern Tibet (underthrusting) inferred by P-waves global
42 tomography, thus suggesting an absence of mechanical coupling between the two processes.
43 Instead, E-W extension south of the KJFZ appears primarily due to divergent, orthogonal thrusting
44 along the curved Himalayan arc, as proposed earlier. North of the KJFZ however, lower amplitude
45 extension, distributed on numerous scattered normal faults in the western Qiangtang terrane,
46 absorbs distributed eastward extrusion, while eastern Qiangtang is extruded more rigidly by the
47 Xianshuihe fault, following a slip-line resulting from in-plane forces due to the collision/indenter,
48 visible as a major discontinuity in the GPS velocity field.

49

50 **1. Introduction**

51 Whether and how upper crustal deformation in mountainous regions is linked to processes at
52 depth, in the lower crust and in the lithospheric mantle, has been debated for decades, leading to
53 irreconcilable models of crustal deformation. In particular, how exactly has underthrusting of the
54 Indian lower lithosphere (lower crust and upper mantle, flattening below Tibet) influenced Tibetan
55 tectonics remains debated due to the unknown exact location of its northern extent beneath Tibet.
56 Indeed, almost one century ago, it was first proposed that the Tibetan Plateau, with its uniformly
57 high elevation and vast extent, formed due to India underthrusting most of Tibet (Argand, 1924).
58 Since then, while S-waves tomography images, more accurate in the vertical direction, showed a
59 large cold anomaly interpreted as Indian lithospheric mantle beneath most of Tibet (Griot et al.,
60 1998; Priestley et al., 2006, 2008), P-waves tomography images, more accurate in the horizontal

61 direction, showed a smaller extent of the Indian lithosphere only beneath southern Tibet (e.g., Li et
62 al., 2008; Replumaz et al., 2004, 2010, 2014), thus refuting a correlation with the high elevation of
63 the plateau. Taking such more accurate extent, several numerical mechanical (e.g., Copley et al.,
64 2011) and geologic (e.g., DeCelles et al., 2002; Kapp and Guynn, 2004; Styron et al., 2015) models
65 have suggested that in southern Tibet, it is the underthrusting of India that drives the observed upper
66 crustal extension (Fig. 1D), while in the eastern plateau, extension would be due to gravitational
67 collapse of the high plateau, driven by buoyancy forces (e.g., Dewey, 1988; Clark and Royden,
68 2000; Copley, 2008) (Fig. 1E).

69 By contrast, upper crustal tectonic models are built on observation of upper crustal
70 deformation, considered to arise from in-plane forces resulting from the collision/indenter (e.g.,
71 Tapponnier and Molnar, 1976; Peltzer and Saucier, 1996), with minor depth variation of strain and
72 minor influence of the Indian lithospheric mantle beneath Tibet. These models focus on a
73 correlation between the location of the south Tibetan rifts south of the KJFZ and the arcuate shape
74 of the Himalaya, so that extension is driven by divergent, orthogonal thrusting along the curved
75 Himalayan arc (Fig. 1A), in contrast to the Qiangtang block north of the KJFZ, which behaves as a
76 rigid block that is extruded eastwards (e.g., Baranowski et al., 1984; Armijo et al., 1986, 1989).
77 Other models later pointed out that ~N-S trending rifts also exist north of the KJFZ in the
78 Qiangtang terrane, thus proposing that eastward motion of Qiangtang occurs through symmetrical,
79 conjugate strike-slip faults of different senses on each side of the KJFZ (Fig. 1C), leaving a
80 triangular basin at the trail end of the extruding wedge (Taylor et al., 2003). However, that rifts
81 north of the KJFZ are significantly less prominent than those to the south led Han et al. (2019) to
82 suggest that the Qiangtang terrane has undergone significant extension distributed on numerous
83 scattered small faults (Fig. 1B), so that it can no longer be treated as an integral block.

84 In this paper, we summarize, test and discuss these models for southern and eastern Tibet
85 deformation previously published by our group and others, by comparing the P-waves tomography

86 images of the extent of the underthrusting Indian lithosphere with the exact location of the south
87 Tibetan rifts. We eventually propose an improved model for upper crustal deformation in
88 southern and eastern Tibet.

89

90 **2. Upper crustal deformation in southern and eastern Tibet from tectonic, GPS and** 91 **earthquakes distribution**

92 The state of stress within the plateau is correlated to elevation: large-scale thrusting and
93 crustal thickening dominate the lower elevations surrounding the plateau, and a combination of
94 strike-slip and normal faulting dominates the high plateau interior, as shown by focal mechanisms
95 (e.g., Molnar and Lyon-Caen, 1989; Elliott et al., 2010). Chevalier et al. (2020) recently determined
96 E-W extension rates along the most prominent south Tibetan rift (Yadong-Gulu) that are relatively
97 uniform at 1.3 ± 0.3 mm/yr between the Yarlung Zangbo suture and the Gulu bend ($\sim 30.6^\circ\text{N}$). Rates
98 instead increase to 3-6 mm/yr at the northern termination of the rift close to the Beng Co right-
99 lateral strike-slip fault, part of the KJFZ, where seismicity increases (Fig. 2C). Summing their
100 average rate for each of the seven main south Tibetan rifts (Chevalier et al., 2012; Kali, 2010; Wu et
101 al., 2004, 2015; Ha et al., 2019; Wang et al., 2020), they further suggested a total extension rate of
102 9 ± 2 mm/yr between 81° and 92°E in southern Tibet (Chevalier et al., 2020). By contrast, extension
103 rates from single rifts located north of the KJFZ are much smaller, <0.3 mm/yr (Blisniuk and Sharp,
104 2003; Pan et al., 2018; Liu et al., 2021), in agreement with their different morphologies hence
105 kinematics (e.g., Chevalier et al., 2020). Note also that the directions of extension, perpendicular to
106 the rift trends, are slightly different on each side of the KJFZ: WNW-ESE to the south and NW-SE
107 to the north.

108 Taking the regional GPS velocity field in a Tibetan Plateau-fixed reference frame (e.g., Gan
109 et al., 2007) interestingly highlights the existence of different tectonic blocks with rather clear
110 boundaries, especially a southward motion near the Eastern Himalayan syntaxis (EHS), veering

111 to southeastward north of the Red River fault (Fig. 1B). In addition, a strong velocity gradient is
112 observed in eastern Tibet across both the Xianshuihe and Kunlun faults, suggesting a strong
113 localization of the deformation along those faults, consistent with fast (~10 mm/yr) left-lateral slip-
114 rates at all timescales (e.g., Van der Woerd et al., 2002; Chevalier et al., 2017; Bai et al., 2018). By
115 contrast, much less deformation is observed in the Songpan-Ganze terrane in between those
116 two faults, except in the far east near the Longmen Shan thrust belt (Fig. 1B). Note however that the
117 absence of GPS stations in western central Tibet also prevents a clear analysis of upper crustal
118 deformation in those remote regions.

119

120 **3. Lithospheric structure, from seismic profile and tomography data**

121 Nábělek et al. (2009) and Wittlinger et al. (2009), by using an 800 km-long, densely spaced
122 seismic array (Himalayan-tibetan Continental Lithosphere during Mountain Building, Hi-CLIMB
123 project, see location in Fig. 2A) from India to roughly the KJFZ, constrained the lithospheric
124 geometry beneath southern and central Tibet. They identified and interpreted a “double Moho” with
125 a 15-km-thick layer in the middle, beneath the southern Lhasa terrane, as the underthrust Indian
126 lower crust and lithospheric mantle, observed at least until 31°N beneath the Lhasa Moho. By
127 contrast, at the western extremity of the Himalayan arc, seismic refraction/wide-angle reflection
128 data (Tien shan—PAmir GEodynamic, TIPAGE project, see location in Fig. 2A) shows that Indian
129 lithosphere underthrusts beneath Kohistan and the central Pamir until 38°20'N, reaching the
130 southward Pamir subduction underlined by deep (>100 km) earthquakes (e.g., Mechie et al., 2012).
131 Similar southward subduction of the Tarim craton beneath Tibet has been interpreted along the
132 western end of the Altyn Tagh fault (Fig. 2C), underlined by shallower earthquakes between 50 and
133 100 km, with no interpretation of Indian lithosphere farther south (Wittlinger et al., 2004, Fig. 2A).

134 While such seismic profiles provide a 2D image of the crustal and lithospheric structures
135 along discrete lines, tomography images obtained from P-waves arrival time data are far better to

136 map in 3D the lithospheric structures beneath the collision zone (Fig. 2). In particular, the thick
137 positive (rapid, in blue) anomaly observed beneath India has been interpreted as the thick and cold
138 Indian craton (marked as CR in Fig. 2B), continuing northwards as underthrusting India beneath
139 Tibet (e.g., Li et al., 2008; Replumaz et al., 2010, 2014). Recent tomography images show that the
140 northern extent of underthrusting India beneath Tibet decreases from west to east (blue dashed line
141 in Fig. 2), with Indian lithosphere present till $\sim 36^{\circ}\text{N}$ beneath the entire (although narrow) Tibetan
142 Plateau to the west ($\sim 78^{\circ}\text{E}$), to $\sim 31^{\circ}\text{N}$ in the center ($\sim 86^{\circ}\text{E}$), while to the east ($\sim 92^{\circ}\text{E}$), it only
143 reaches the Yarlung Zangbo suture (YZS), in agreement with seismic profiles beneath the central
144 (Nábělek et al., 2009; Wittlinger et al., 2009) and western (Mechie et al., 2012) Himalayas, also
145 suggesting that Indian lithosphere may almost reach the Tarim slab (Wittlinger et al., 2004). While
146 global tomography, which images the lithospheric structures beneath the entire Tibetan Plateau, is
147 the most appropriate tool to test whether a correlation exists between underthrusting of India and
148 the location of the south Tibetan rifts, quantitative measurements of the Indian slab extent are not
149 yet possible due to the large uncertainties on the thermal and mineralogy structures of the Earth, so
150 that interpretation is always done in a qualitative manner (e.g., Li et al., 2008). Note that
151 interpretation will evolve with time as denser seismic data are obtained, so that the resulting
152 resolution of the tomography images will also increase with time. In any case, comparing the
153 position of the KJFZ, i.e., the northern extent of the south Tibetan rifts, with the northern extent of
154 underthrusting India beneath Tibet (e.g., Li et al., 2008; Replumaz et al., 2010, 2013, 2014), shows
155 an absence of correlation: to the west, as for the Thakkhola/Lopu Kangri rift (TKR/LKR) for
156 instance, the underthrusting of India reaches beyond the northern part of the rift (Fig. 3A), while to
157 the east as for the Yadong-Gulu rift (YGR) for example, the underthrusting of India does not reach
158 the northern part of the rift (Fig. 3B).

159

160

161 **4. Numerical mechanical model predictions of extension patterns in southern Tibet**

162 Copley et al. (2011) explored the mechanical coupling (i.e., when mantle material and crust
163 flow at the same velocity, Wang and Dixon, 2004) between the Tibetan upper crust and underthrust
164 Indian crust to explain the difference in tectonic regime between normal faulting south of the KJFZ
165 and strike-slip faulting with minor normal component north of it. Using a 3D numerical mechanical
166 model of the Tibetan crust, reconstructing both type of faulting and motion at the surface (directly
167 comparable to GPS data) by predicting the internal forces (stress field) within the crust, they
168 concluded that such difference in faulting style is best explained by a strong mechanical coupling
169 between India and the overlying Tibetan crust (Fig. 1D).

170 Other numerical models consider that the main driving forces are the buoyancy forces
171 resulting from the high elevation and large crustal thickness of the Tibetan Plateau, generating an
172 outward lower crustal viscous flow from the plateau center (“channel flow model”), hence a
173 southward (e.g., Beaumont et al., 2004) and eastward (e.g. Clark and Royden, 2000) collapse of the
174 plateau. In eastern Tibet, Copley (2008) built a 3D numerical mechanical model of the flow around
175 the Sichuan Basin, predicting that at the eastern edge of the plateau, normal faulting should be
176 perpendicular to the flow (parallel to the edge of the plateau) due to extension in the downslope
177 direction where the topographic gradient is the largest, as expected for a collapse of the plateau, that
178 eventually diverges south of the Sichuan Basin (Fig. 1E).

179

180 **5. Comparison between the extent of underthrusting India, normal faulting patterns, and** 181 **predictions of mechanical model**

182 The model of Copley et al. (2011) suggests that the location of the rifts in southern Tibet
183 coincides with a zone of mechanical coupling between the Tibetan upper crust and the
184 underthrusting strong Indian lower crust, assumed to reach the KJFZ (black and white lines in Fig.
185 1D). However, the global P-waves tomography positive anomaly at the very shallow depth of 200

186 km (Li et al., 2008; Replumaz et al., 2013) reveals no correlation: to the west, underthrusting India
187 reaches beyond the northern limit of the rifts while to the east, it does not reach the northern part of
188 the rifts (Fig. 3). This lack of correlation suggests that crustal deformation in southern Tibet is not
189 influenced by processes occurring at the lithospheric level.

190 Besides, while the direction of extension predicted by the model of Copley et al. (2011)
191 south of the KJFZ, roughly E-W, is rather consistent with the direction of extension perpendicular to
192 the trend of the rifts, WNW-ESE, the model predicts pure strike-slip faulting north of the KJFZ,
193 while NW-SE extension is observed (Fig. 1D). Similarly, the direction of extension predicted from
194 the outward crustal flow model in SE Tibet (Copley, 2008), parallel to the plateau's edge then
195 diverging along the margin (Fig. 1E), is inconsistent with the actual direction of extension in SE
196 Tibet observed along transtensive fault systems such as those of Litang (Chevalier et al., 2016) or
197 Lijiang, which are oblique to the plateau's edge (Zhang et al., 2015).

198

199 **6. Improvement for upper crustal models (tectonic models)**

200 The tectonic model of Armijo et al. (1986), built only on observation of upper crustal
201 deformation arising from in-plane forces due to the indenter, does not require a correlation with
202 underthrusting of India, in agreement with what tomography images suggest. It has been proposed
203 that only the upper crust thickens, not the mantle, so that such thickening must have been decoupled
204 from a more rigid lower lithosphere underneath (Tapponnier et al., 2001). For the upper crust, this
205 model proposed that the KJFZ corresponds to a large-scale, left-stepping en-echelon, right-lateral
206 strike-slip fault zone that decouples motion between the crusts of northern and southern Tibet,
207 allowing central Tibet's Qiangtang terrane to move eastward relative to India and southern Tibet
208 (Fig. 1A). Such right-lateral shearing indeed occurs far enough north of the Himalayan arc so that
209 eastward extrusion of central Tibet, between the KJFZ and the Altyn Tagh fault (Armijo et al.,
210 1989), considered as mostly rigid (Peltzer and Saucier, 1996), can bypass the EHS. By contrast,

211 southern Tibet deforms in a divergent manner due to the curved shape of the Himalayan arc,
212 generating extension through rifts confined within the arc curvature. That model requires that the
213 ~EW extension rate observed across southern Tibet south of the KJFZ be about half that of
214 divergent thrusting of rigid India beneath the Himalayan Range (Fig. 1A). Armijo et al. (1986) and
215 more recently, Chevalier et al. (2020), indeed suggested a total extension rate of 9 ± 2 mm/yr
216 between 81 and 92°E across southern Tibet, which corresponds to half of the Holocene (e.g., $21 \pm$
217 1.5 mm/yr, Lavé and Avouac, 2000) and geodetic (19 ± 2.5 mm/yr in eastern Nepal, Bettinelli et al.,
218 2006; or 15.5 ± 2 mm/yr, Lindsey et al., 2018) rates across the Himalaya.

219 However, shortcomings of Armijo et al. (1986, 1989)'s model are that considering central
220 Tibet as a rigid block does not explain the presence of rifts in the Qiangtang terrane north of the
221 KJFZ. However, given that rates of extension north of the KJFZ are only ~10-20% of those south of
222 the KJFZ (e.g., Chevalier et al., 2020 and references therein) rules out upper crustal tectonic models
223 suggesting that eastward motion occurs through symmetrical, conjugate strike-slip faults on each
224 side of the KJFZ (Taylor et al., 2003; Yin et al., 2011). Instead, it has recently been proposed that
225 eastward extrusion of the western and central parts of the Qiangtang terrane is absorbed by
226 significant internal extension distributed on numerous scattered normal faults, so that it can no
227 longer be treated as an integral block (Han et al., 2019). This internal deformation may be due to the
228 absence of major strike-slip faults north of central Qiangtang, thus limiting efficient eastward
229 extrusion (Fig. 4A). By contrast, rapid eastward motion of the eastern Qiangtang block is shown in
230 the GPS velocity field by a large gradient across the Xianshuihe fault to the north and the Jiali fault
231 to the SE, suggesting rigid block rotation around the EHS with strong localization of motion on
232 strike-slip faults (Bai et al., 2018). At the scale of the Tibetan Plateau, Tapponnier and Molnar
233 (1976) shown that such strike-slip faults follow slip-lines resulting from the Indian indenter
234 collision forces. We thus re-draw a complete deformation pattern of the collision zone in agreement
235 with the data synthesis we made in this study to suggest an improved model for upper crustal

236 deformation mechanisms of Tibet (Fig. 4). We conclude that upper crustal deformation in Tibet is
237 driven by indentation of India, with strong extension due to divergent orthogonal thrusting along the
238 curved Himalayan arc occurring south of the KJFZ, and eastward extrusion of the eastern and
239 central parts of the Qiangtang terrane occurring between the KJFZ (allowing extrusion to bypass the
240 EHS) and the Xianshuihe fault system, one of the major slip-line resulting from the indentation,
241 with smaller extension in western Qiangtang where the Xianshuihe fault is not observed, distributed
242 on numerous scattered normal faults (Fig. 4).

243

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249

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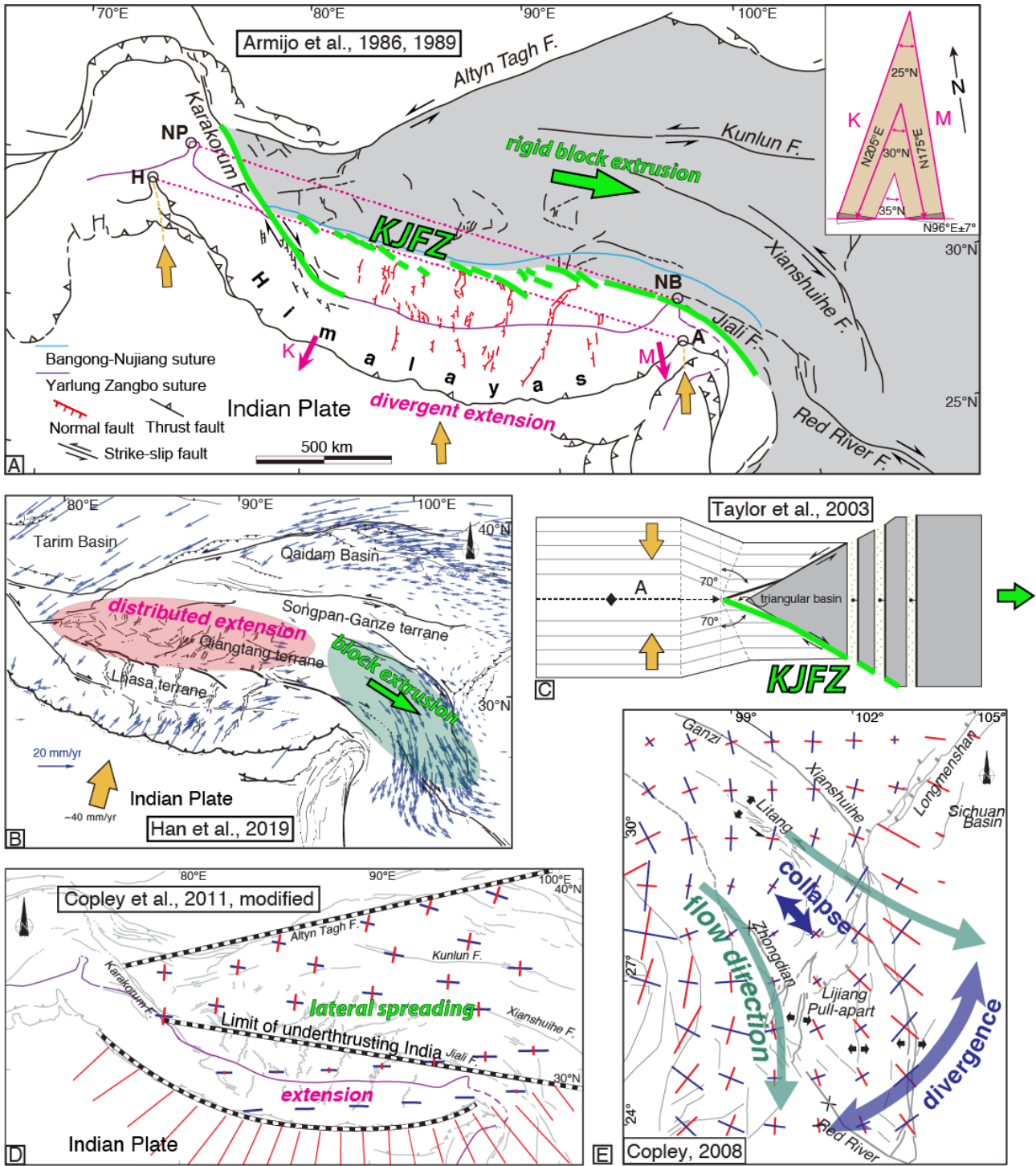
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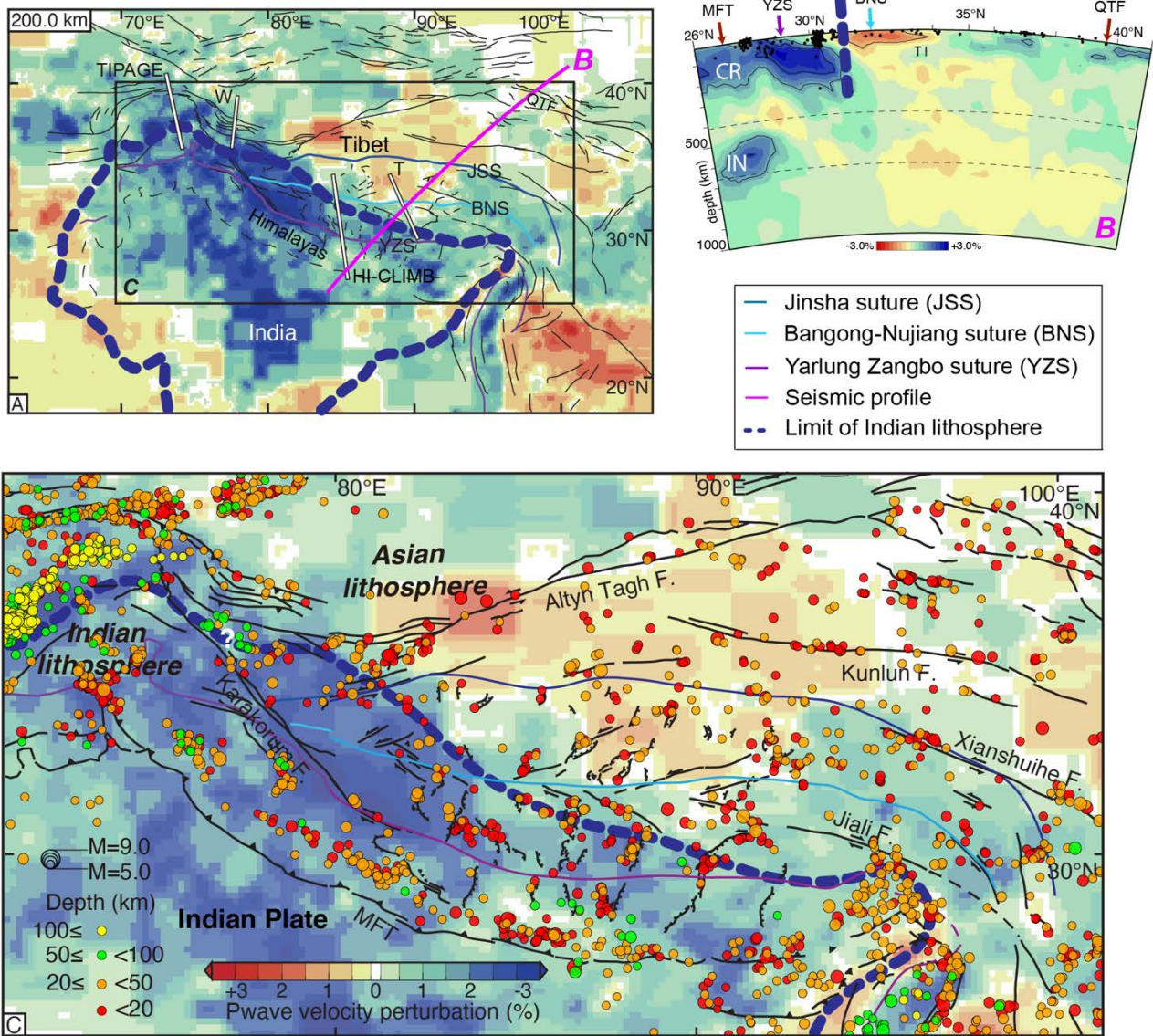
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 411 **Figure 1:** Upper crustal tectonic (A, B and C) and numerical mechanical (D and E) models for
 412 Tibet. (A) Armijo et al. (1986, 1989)'s model, with eastward extrusion of central Tibet (grey-shaded)
 413 north of Karakoram-Jiali fault zone (KJFZ, a series of discontinuous, en-echelon strike-slip fault
 414 segments), and divergent deformation of southern Tibet due to curved shape of Himalayan arc. Rifts
 415 (in red) are confined between two vectors perpendicular to the arc, 'K' and 'M'. KJFZ in between
 416 western (H = Hazara, NP = Nanga Parbat) and eastern (A = Assam, NB = Namche Barwa)

417 *Himalayan syntaxes (pink dashed lines). (B) Han et al. (2019)'s model, with rifts north of*
418 *KJFZ interpreted as extension distributed on numerous scattered small faults. GPS velocities*
419 *relative to Tibetan Plateau from Gan et al. (2007). (C) Taylor et al. (2003)'s model, with eastward*
420 *motion of Qiangtang occurring through symmetrical, conjugate strike-slip faults of different senses*
421 *on each side of KJFZ. (D) Copley et al. (2011)'s model with principal axes of upper crustal*
422 *horizontal strain-rate tensors (blue: extension; red: compression, both as crosses: strike-slip) due to*
423 *Indian rigid lower crust (south of central black and white line), modified to fit Altyn Tagh fault*
424 *(northern line) and Main Frontal thrust (southern line). (E) Copley (2008)'s model of upper crustal*
425 *horizontal strain-rate tensors for SE Tibet, predicting extension perpendicular to SE edge of plateau*
426 *due to gravitational collapse.*
427



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429 **Figure 2:** (A) P-waves global tomography images at 200 km depth from Replumaz et al. (2013),

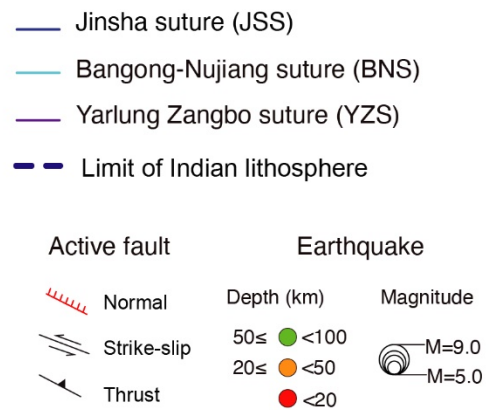
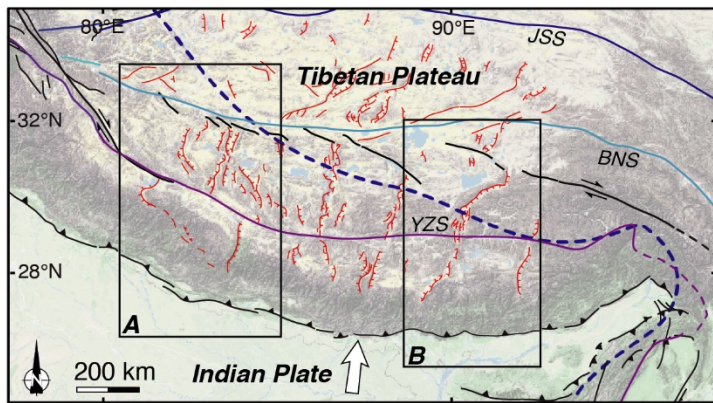
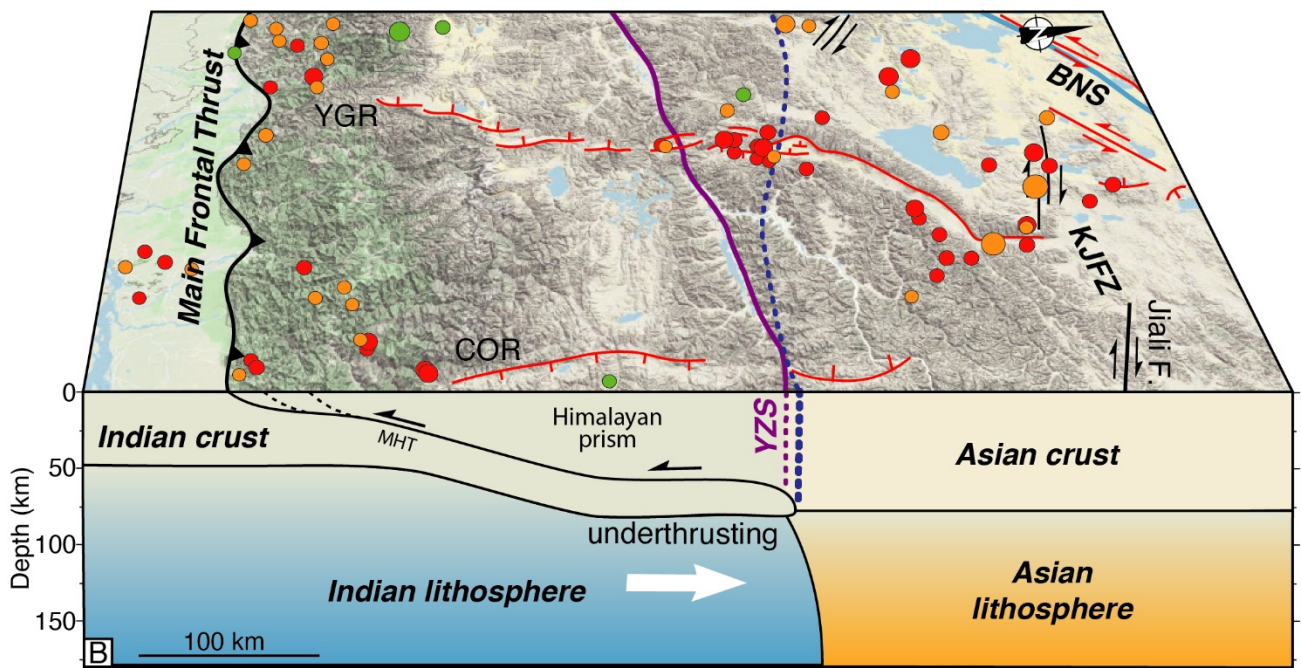
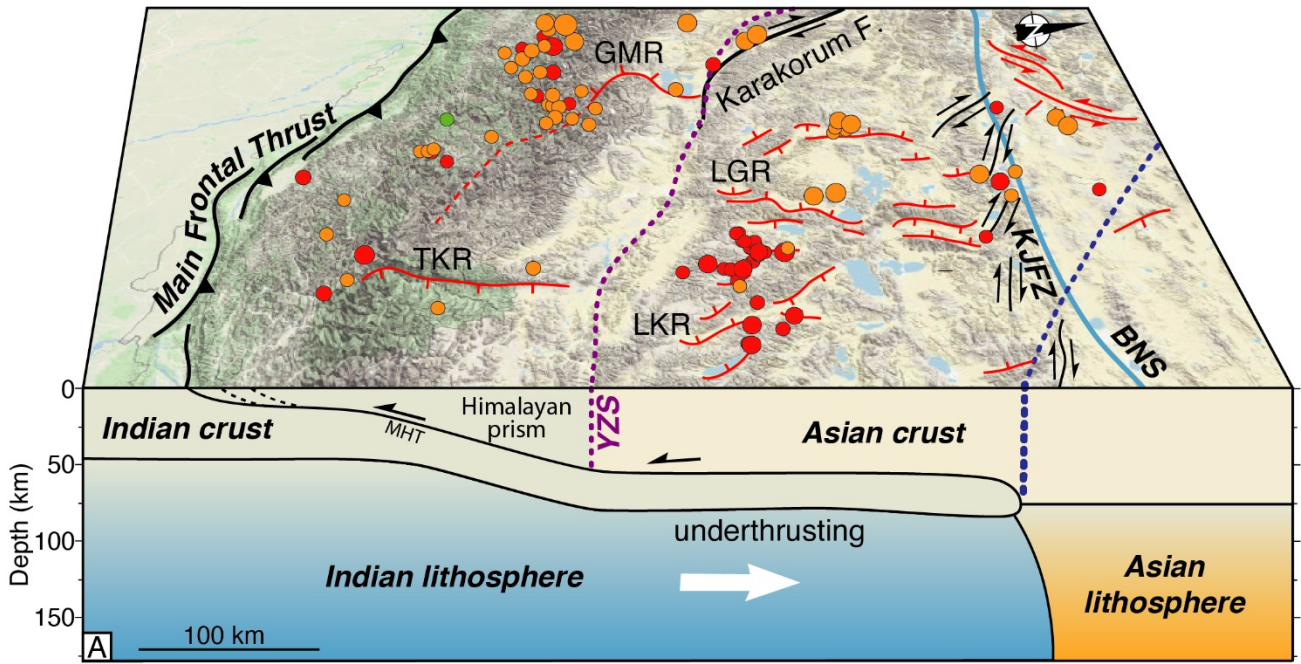
430 with location of seismic profiles (in white) TIPAGE (Mechie et al., 2012), W=Wittlinger et al.

431 (2004), HI-CLIMB (Nábělek et al., 2009) and T=Tilmann et al. (2003). QTF = Qilian Shan thrust

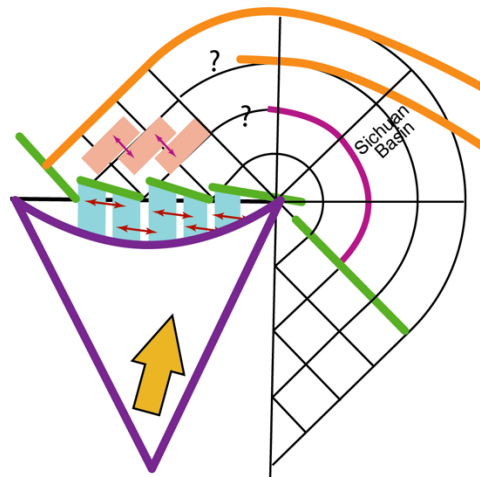
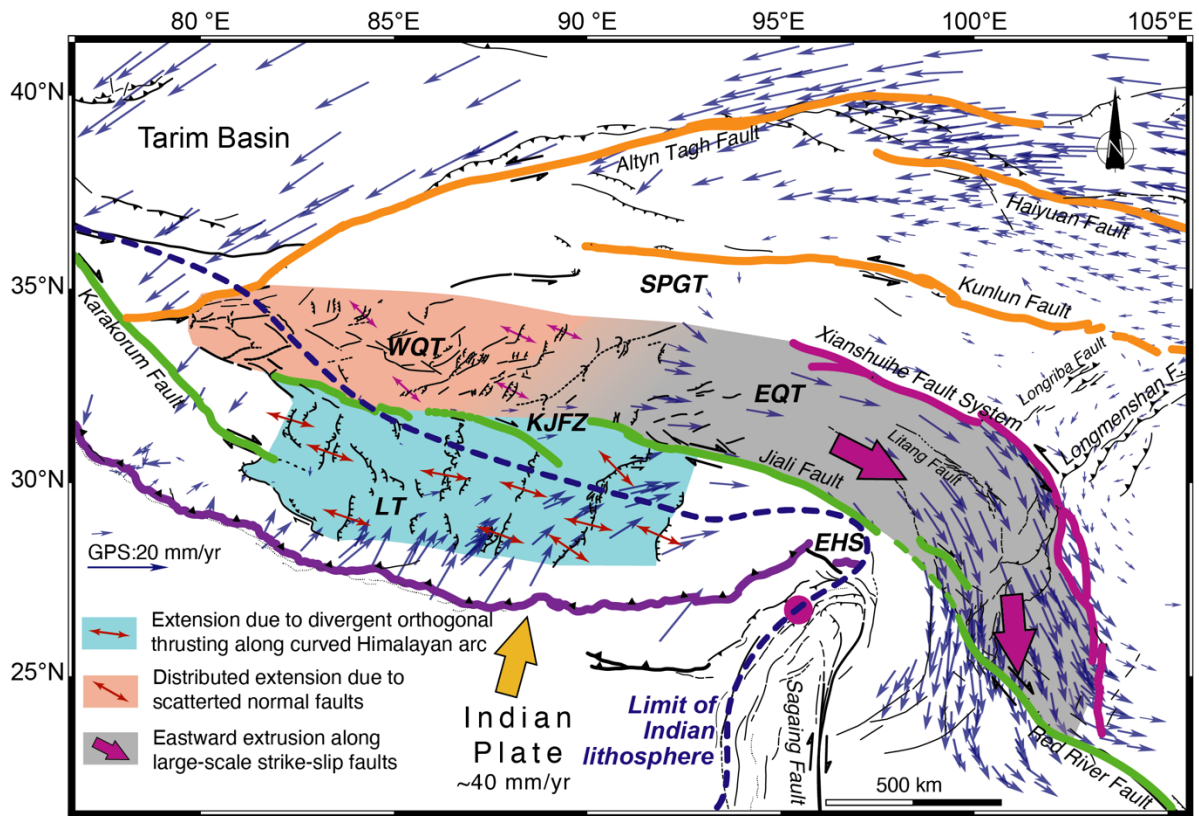
432 fault, MFT = Main Frontal thrust. (B) Tomography cross-section (location shown in A). CR =

433 Indian craton, IN = India, TI = Tibet. (C) Close-up with distribution of $M_w \geq 5.0$ earthquakes since

434 1900 (USGS), according to their depths.



436 **Figure 3:** 3D cartoon of western (A) and central (B) southern Tibet showing underthrusting of
437 India, as well as active fault traces and $M_w \geq 5.0$ earthquakes (as in Fig. 2C). Dashed blue line
438 represents northern extent of Indian lithosphere, deduced from P-waves global tomography as
439 shown in Figure 2. GMR = Gurla Mandhata rift, TKR = Thakkhola, LGR = Lunggar, LKR = Lopu
440 Kangri, YGR = Yadong-Gulu, COR = Cona-Oiga, MHT = Main Himalayan thrust, KJFZ =
441 Karakorum-Jiali fault zone.
442



443

444 **Figure 4:** Top: Kinematics of active tectonics in Tibet with GPS velocities relative to Tibetan
 445 Plateau (Gan et al., 2007). Red double-headed arrows show ESE-oriented extensional
 446 deformation in Lhasa terrane (LT) and purple ones show NW-SE extension in west-central
 447 Qiangtang terrane (WQT). Purple arrow to east indicates eastward extrusion
 448 along Xianshuihe fault and KJFZ of east-central Qiangtang terrane (EQT). Purple solid circle
 449 represents rotation pole of Eastern Himalayan Syntaxis (EHS). KJFZ = Karakorum-Jiali Fault
 450 Zone, SPGT = Songpan-Ganzi terrane. Bottom: Tapponnier and Molnar (1976) slip-lines model
 451 predicting geometry of strike-slip faults resulting from in-plane forces due to collision/indenter, re-
 452 drawn from faults mapping and GPS motion considering Tibet as fixed. Colors of strike-slip faults
 453 as in top panel.