

1 **Does pulsed Tibetan deformation correlate with Indian plate motion changes?**

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15

16 **Abstract** Models that aim to explain the causes of the significant Indian plate motion
17 acceleration around 70 Ma, and the subsequent deceleration around 52 Ma predict different
18 scenarios regarding crustal shortening of the Tibetan Plateau, which can be tested by precisely
19 determining the timing of regional shortening events in Tibet. Here we attempt to determine
20 this timing by presenting a high-resolution magnetostratigraphy of a ~3.5 km thick sedimentary
21 sequence in the syn-contractual Gonjo Basin, east-central Tibet. We successfully isolated the
22 primary remanence as confirmed by positive fold and reversal tests. Correlation to the
23 geomagnetic polarity time scale reveals a 69–41.5 Ma age for the Gonjo Basin sedimentary
24 succession. Average sedimentation rates indicate two episodes of enhanced sediment
25 accumulation rate at 69–64 Ma and 52–48 Ma, which coincide with periods of vertical axis
26 rotation recorded in the basin fill. This coincidence suggests a tectonic cause, which given
27 regional structures we interpret as shortening pulses. Our results are similar to those from
28 basins elsewhere in southern, central and northern Tibet, suggesting plateau-wide, synchronous
29 shortening pulses at ~69–64 Ma and ~52–48 Ma. These pulses are synchronous with major
30 acceleration and deceleration of India-Asia convergence rate, suggesting that both the
31 acceleration and deceleration of India-Asia convergence may be associated with enhanced
32 crustal deformation in Tibet, which we use to evaluate previous dynamic models explaining
33 the Indian plate motion changes and India-Asia collision processes.

34

35 **Keywords:** magnetostratigraphy, convergence rate, India-Asia collision, Tibetan Plateau,
36 paleomagnetism

37

38 1. Introduction

39 The Tibetan Plateau and the Himalayan mountains are the largest of modern orogens
40 caused mainly by the India-Asia collision. The collision was long thought to have started
41 around 52–50 Ma (e.g., Patriat and Achache, 1984), which corresponds to the significant
42 deceleration of India-Asia plate motion from >15 cm/yr to <8 cm/yr around 52–47 Ma (Patriat
43 and Achache, 1984; Copley et al., 2010; van Hinsbergen et al., 2011, Fig. 1a) and enhanced
44 crustal shortening and uplift of Tibet around this time (e.g., Searle et al., 1997), and therefore
45 suggest a straightforward link between the slow-down of India, initial India-Asia collision, and
46 deformation of Tibet (e.g., Patriat and Achache, 1984; Copley et al., 2010; Capitanio et al.,
47 2010).

48 However, recent stratigraphic analyses revealed that Asian-derived sediments were
49 already deposited on the Tethyan margin at 59 ± 1 Ma (Hu et al., 2015), and thereby constrained
50 the onset of continental collision in the central part of Tibet occurred ~ 6 Myr prior to the
51 deceleration of India-Asia convergence. This 6 Myr delay is significant: during this time
52 subduction rates were so high (>15 cm/kyr) that ~ 1000 km of Indian plate lithosphere
53 subducted between initial collision and slow-down. This suggests that not only is the dramatic
54 slow-down not directly related to collision, initial collision also did not trigger a dramatic slow-
55 down (e.g., van Hinsbergen et al., 2019). Within this context, it is now interesting to reassess
56 whether the Tibetan upper crustal shortening is contemporaneous with initial collision at 59 ± 1
57 Ma, or whether it coincides with, and may thus be linked to the Indian plate deceleration (and
58 in that case, also the rapid ~ 70 – 65 Ma acceleration from ~ 8 cm/yr to >16 cm/yr, Fig. 1a), or
59 neither.

60 The debate on the timing of collision, versus the timing of upper plate shortening, versus
61 the timing of India-Asia plate motion changes, is thus intriguing for the first-order geodynamic
62 questions regarding the driving mechanisms behind upper plate continental deformation as well

63 as major plate motion changes. Plate motion changes have been explained by changes in (ridge
64 or plume) push, (slab) pull, or (mantle) resistance against plate motion. Hypotheses for the
65 rapid acceleration of India at ~70 Ma (Fig. 1a) include: enhanced push, exerted on India by the
66 Deccan plume head (Cande and Stegman, 2011; van Hinsbergen et al., 2011); enhanced pull,
67 due to the development of a hypothesized second, intra-oceanic subduction system between
68 India and Asia since the Late Cretaceous (Jagoutz et al., 2015); or decreased resistance against
69 Indian plate motion due to the loss of India's deep roots melted by the Deccan plume (Kumar
70 et al., 2007), or plate interface lubrication by the arrival of Tethyan equatorial bulge sediments
71 at the subduction trench (Behr and Becker, 2018). Deceleration of India around 52 Ma may
72 relate to enhanced friction due to collision (e.g., Copley et al., 2010; Clark, 2012), or
73 alternatively to resistance against lower mantle penetration of the slab (van Hinsbergen et al.,
74 2019), slab break-off (Zhu et al., 2015) or the termination of one of the two subduction zones
75 (Jagoutz et al., 2015).

76 The hypothesis outlines contain explicit predictions for friction changes at the plate contact
77 which may be tested through dating crustal shortening across Tibet. Enhanced push will
78 increase friction and thus predicts enhanced shortening, whereas double subduction or plate
79 interface lubrication predicts a decrease in friction, thus predicting no deformation changes or
80 upper plate extension (Behr and Becker, 2018; Jagoutz et al., 2015). Therefore, determining
81 the timing of upper plate deformation relative to plate motion changes and collision during the
82 Late Cretaceous to Eocene may help evaluate geodynamic explanations for plate motion
83 changes, as well as the upper plate response to continental collision.

84 In this paper, we attempt to evaluate whether there were discrete events in the history of
85 Tibetan shortening during Late Cretaceous to Paleogene time. To this end, we focus on a series
86 of sedimentary basins (Hoh Xil, Nangqian-Yushu, and Gonjo basins, Fig. 1b) with several
87 kilometers of Late Cretaceous to Paleogene continental sediments, which are located on the

88 Qiangtang terrane of the central Tibetan Plateau and have been shown to be controlled by basin-
89 bounding, syn-sedimentary thrusts (Horton et al., 2002; Jin et al., 2018; Studnicki-Gizbert et
90 al., 2008). We provide a new, high-resolution magnetostratigraphy of the Gonjo Basin in the
91 eastern Qiangtang terrane, to determine sedimentation rates through time. We test whether
92 changes in sediment accumulation rates (SARs) may be an artifact of differences in compaction
93 and use vertical axis rotation changes constrained by the paleomagnetic data as an independent
94 proxy for tectonic activity. We then use our data to compare with records from other basins in
95 central Tibet to estimate the timing of periods of enhanced regional shortening of the Tibetan
96 Plateau, and evaluate the potential implications of our results for the causes of India-Asia plate
97 motion changes and India-Asia collision processes.

98

99 **2. Geological setting**

100 The Gonjo Basin is located in the eastern Qiangtang terrane of east-central Tibet, close to
101 the Eastern Himalayan Syntaxis (Fig. 1a). The basin structure is that of a basin-scale
102 asymmetric syncline verge to the east in the footwall of the Yangla fold-thrust system. This
103 thrust system thrusts Triassic rocks over the basin margin in the northeast and controlled the
104 subsidence and structure of the basin (Studnicki-Gizbert et al., 2008; Tang et al., 2017; Fig. 2).
105 Based on the presence of growth strata and the change of thickness of strata from west to east
106 in the basin (the thickness of strata in the western limb of the syncline is significantly thicker
107 than that in the eastern limb), Studnicki-Gizbert et al. (2008) interpreted that the Gonjo Basin
108 was a syn-contractional basin; thrust faults initiated concurrently with the deposition of the
109 Gonjo Basin sediments and continued after sedimentation, breaking through the original
110 bounding folds into the basin, and forming the asymmetric syncline that we observe today (Fig.
111 2). Within the basin sedimentary rocks, the succession is relatively continuous and undeformed;
112 small folds, thrust faults, and strike-slip faults which would suggest the presence of

113 hiatus/overlap of stratigraphy and secondary structures are only developed in the core of
114 syncline in the central part of the basin (see supplementary figure, Studnicki-Gizbert et al.,
115 2008).

116 The strata in the western limb of the Gonjo Basin syncline have a thickness of >3000 m,
117 and the strata are divided into the Gonjo Formation and the Ranmugou Formation (BGMR
118 Xizang, 1993). The latter is further divided into three parts: lower, middle and upper Ranmugou
119 Formation (Fig. 2). The Gonjo Formation and the lower and middle Ranmugou Formation are
120 dominated by red-colored mudstones, sandstones, and rare conglomerates (see supplementary
121 figure), reflecting alluvial fan, fan-delta, floodplain and lacustrine depositional environments
122 (Studnicki-Gizbert et al., 2008; Tang et al., 2017). In the northern part of the Gonjo Basin, a
123 large interval (~150 m) of volcanic rocks, which consist of andesites, dacites and pyroclastics,
124 are developed in the upper part of the middle Ranmugou Formation. The upper Ranmugou
125 Formation consists of alternating layers of green carbonaceous shales, carbonates, and red
126 mudstones (see supplementary figure), suggesting a lacustrine environment (Studnicki-Gizbert
127 et al., 2008).

128 The original age assignment for the Gonjo Basin was Paleocene-Eocene based on limited
129 palynological data from the upper part of the basin (BGMR Xizang, 1993). Recent isotopic
130 dating of the volcanic rocks in the upper part of the middle Ranmugou Formation yielded an
131 age of ~43 Ma (Studnicki-Gizbert et al., 2008; Tang et al., 2017). Detrital zircon U-Pb ages
132 suggested a maximum age of 52.5 Ma (Zhang et al., 2018), but averaged from three samples
133 at different depths of the strata; thus the true maximum age for the base of the sedimentary
134 succession in the Gonjo Basin remains undefined.

135

136 **3. Methods**

137 **3.1. Sampling**

138 Paleomagnetic samples were collected around Gonjo city, where the strata of the Gonjo
139 Basin are best exposed. The compiled section is a composite of three sub-sections with a
140 combined stratigraphic thickness of 3325 m (Fig. 2). We correlated sub-sections according to
141 strike; overlapped parts of the section share the same polarity suggesting our correlation
142 between sub-sections is robust. The bedding dip of the studied section increases toward the
143 core of the syncline from $\sim 15^\circ$ to $\sim 60^\circ$ (Fig. 2). A total of 1766 paleomagnetic samples were
144 collected in the field with an interval of ~ 2 m using a gasoline-powered drill. All samples were
145 oriented in the field with a magnetic compass. A sun-compass was also used on occasions to
146 identify the possible local declination anomaly, which is less than 2° ($1.59 \pm 0.69^\circ$, $n = 67$), by
147 comparing the orientation data from the two methods. All drilled cores were cut into 1–2
148 specimens (2.5 cm in diameter and 2.2 cm in height) in the laboratory, remaining parts were
149 used for rock magnetic analysis.

150

151 **3.2. Paleomagnetic analysis**

152 To identify the magnetic mineralogy in the Gonjo redbeds we measured hysteresis loops,
153 isothermal remanent magnetization (IRM) acquisition curves, and direct current field
154 demagnetization of the saturation IRM (SIRM) on 12 representative specimens using methods
155 as described in Li et al. (2017a). All specimens from the Gonjo Basin were subjected to
156 stepwise thermal demagnetization up to a maximum temperature of 690°C , with $25\text{--}50^\circ\text{C}$
157 intervals below 585°C and $10\text{--}15^\circ\text{C}$ intervals above 585°C , using a PGL-designed PGL-100
158 thermal demagnetizer with internal residual magnetic field less than 5 nT. The natural remanent
159 magnetization (NRM) was measured on a 2G Enterprises Model 760 cryogenic magnetometer
160 inside a magnetically shielded room (<300 nT). All the measurements were conducted in the
161 Paleomagnetism and Geochronology Laboratory (PGL) of the Institute of Geology and
162 Geophysics, Chinese Academy of Sciences.

163 The principal component analysis was computed either by least-squares fits (Kirschvink,
164 1980) or by the great circle path (McFadden and McElhinny, 1988). The online tool set
165 Paleomagnetism.org (Koymans et al., 2016) was employed to analyze the data.

166

167 **4. Results**

168 **4.1. Paleomagnetism**

169 The hysteresis loops are closed above a high field of 1 T, and the IRM acquisition curves
170 are still not saturated at the maximum applied field of 1 T (Fig. 3), suggesting the dominance
171 of high-coercivity minerals, e.g., hematite. However, the presence of goose-necked hysteresis
172 loops (e.g., Fig. 3g) and rapid increase of IRM at the low field suggest the coexistence of low-
173 (e.g., magnetite) and high-coercivity (e.g., hematite) phases (Roberts et al., 1995; Tauxe et al.,
174 1996), which is consistent with previous paleomagnetic studies (Tong et al., 2017; Zhang et
175 al., 2018).

176 As shown in Fig. 4, the demagnetization behavior of specimens from the Gonjo Basin is
177 grouped into four types. The first type has only a single univectorial component decaying
178 steadily toward a high temperature of 690°C (Fig. 4a). The demagnetization diagrams of the
179 second type show two magnetic components (Fig. 4b). A low-temperature magnetic
180 component (LTC) was removed with varied temperatures from 300–500°C. Above this
181 temperature, a high-temperature magnetic component (HTC) decays linearly toward the origin
182 and is regarded as the characteristic remanent magnetization (ChRM). The third type has three
183 magnetic components (Fig. 4c). A LTC was generally removed below 300°C, and an
184 intermediate temperature component was mostly removed between 300°C and 610°C, but for
185 some specimens as high as 650°C (e.g., G1240, Fig. 4c). After removal of this component, a
186 HTC was isolated until 690°C (Fig. 4c). The ChRMs of these three types were isolated between
187 temperatures of 610°C and 690°C with at least four continuous demagnetization points. A few

188 specimens (57) show the fourth type of demagnetization behavior: the demagnetization vectors
189 show a linear decay to the origin but move successively toward the reversed polarity on the
190 Zijderveld diagram (Fig. 4d). When plotted on an equal-area diagram, the remanence vectors
191 display well-defined great circle paths, suggesting that a reversed primary component is partly
192 overprinted by a secondary normal component caused by overlapping blocking temperature
193 spectra. In this case, a great circle approach was used to approximate the reversed direction
194 based on the method of McFadden and McElhinny (1988). Directions from this type were only
195 used for constructing the magnetic polarity (Fig. 5, pink diamonds).

196 In total, 1317 specimens yielded interpretable ChRM directions, including 42 specimens
197 analyzed by the great circle method. When calculating mean directions, we excluded the 42
198 specimens and those specimens with north (or south) but upward (or downward) inclinations
199 which may record the transitional behaviors of geomagnetic field. The remaining 1096
200 directions were grouped into 67 sites with a thickness of 50 m except the last site (see
201 supplement Table 1 for details). Most sites typically include more than ten specimens, while
202 site 23 was excluded because only 4 specimens are contained in this site. The plot of declination
203 relative to age was used to constrain vertical axis rotations during deposition, which suggests
204 a counter-clockwise rotation of $\sim 10^\circ$ from 69–67 Ma, no significant rotation between 67 and
205 52 Ma, $\sim 20^\circ$ clockwise rotation between 52 and 48 Ma, no rotation between 48 and 41 Ma, and
206 $\sim 30^\circ$ clockwise rotation sometime after 41 Ma.

207 To examine the reliability of the paleomagnetic results, we employed a fold test on all the
208 1096 directions and the reversal test on the non-rotated interval of 67–52 Ma and 48–41.5 Ma.
209 As shown in Fig. 6, the best grouping of the overall mean directions occurs at 98%–118% (Fig.
210 6d), showing a positive fold test (Tauxe and Watson, 1994). Moreover, the non-rotated
211 intervals of 67–52 Ma and 48–41.5 Ma pass a reversal test (Figs. 6e and 6f) (Tauxe, 2010).
212 These positive field tests support a primary origin of the remanence for the Gonjo Basin.

213

214 4.2. Magnetostratigraphy

215 The ChRM directions were converted to virtual geomagnetic pole (VGP) latitudes to
216 construct the magnetostratigraphy. As shown in Figure 5, 30 magnetozones were identified in
217 the studied section: 15 with normal polarity (N1–N15), and 15 with reversed polarity (R1–
218 R15). Each polarity zone was determined using at least four paleomagnetic sampling levels.

219 The biochronologic and geochronologic control of the sedimentary rocks in the Gonjo
220 Basin has been greatly improved recently. A Paleocene-Eocene age was first assigned based
221 on limited palynological data from the upper part of the basin, such as *Palibinia* sp., *Alstonia*
222 sp., *Carpinus* sp., *Ephedripites* and *Charites* sp. (BGMR Xizang, 1993). Studnicki-Gizbert et
223 al. (2008) reported $^{40}\text{Ar}/^{39}\text{Ar}$ dating of volcanic rocks at the top of the middle Ranmugou
224 Formation, which gave an average weighted age of 43.02 ± 0.23 Ma (Fig. 5). They also
225 identified several palynomorphs from the mudstones of the upper Ranmugou Formation, such
226 as *Momipites* sp., *Retitricolporites* sp., *Taxodiaceae* and/or *Cupressaceae* sp., *Inaperturites* sp.,
227 *Striatricolpites* sp., *Carya* sp., *Psilamonocolpites* sp., *Psilatricolpites* sp., *Tricolpites* sp. and
228 *Shizosporis* sp. of which *Momipites* is regarded as common throughout the Late Eocene and
229 Oligocene of North America (Studnicki-Gizbert et al., 2008). Later, Tang et al. (2017) carried
230 out U-Pb zircon dating of andesite from the volcanic rock unit, which yielded a similar age of
231 43.2 ± 0.2 Ma to Studnicki-Gizbert et al. (2008). Although these volcanic rocks were not
232 sampled from our section, the fold axes, strike of bedding and boundary faults, and the overall
233 orientation of the basin are of NW-striking and in generally parallel with each other (Fig. 2),
234 suggesting that the age of volcanic rocks in the northwestern part of the basin may be used as
235 an age indicator in the central part of the basin by stratigraphic correlation. Moreover, Zhang
236 et al. (2018) reported a youngest weighted mean age of 52.5 ± 1.5 Ma based on 16 zircon grains
237 from three samples, one from the top of the Gonjo Formation, and two from the middle

238 Ranmugou Formation (see Fig. 5 for the approximate stratigraphic locations), and concluded a
239 maximum deposition age of 52.5 Ma for the Gonjo Basin. These lines of evidence suggest a
240 ~43 Ma age for the top of the middle Ranmugou Formation and a Paleocene-Eocene age for
241 the main part of the Ranmugou Formation.

242 With this age framework in mind, the correlation of our magnetic polarity zones to the
243 global geomagnetic polarity time scale (GPTS) (Gradstein et al., 2012) is straightforward. We
244 correlated the top normal interval of our section N1 to Chron C20n, corresponding to a time
245 interval of 43.4–42.3 Ma. Our magnetic polarity zones are characterized by a dominance of
246 normal polarities at the lower (N11–N15) and upper (N1–N3) parts, and reversed polarities in
247 between (R4–R11) (Fig. 5c). This pattern of magnetozones is similar to the GPTS of the Late
248 Cretaceous-Middle Eocene, which shows a dominance of normal polarities in Late Cretaceous-
249 Early Paleocene and Middle Eocene, and a dominance of reversed polarities from Late
250 Paleocene to Early Eocene (Fig. 5d). Hence the reversed polarities of R4–R11 can be well
251 correlated to Chrons C22r–C27r, and the normal polarities of N1–N3 and N11–N15 can be
252 correlated to Chrons C20n–C22n and C27n–C31n, respectively (Figs. 5c and 5d). Although
253 our observed magnetozones can be straightforwardly correlated to the GPTS, we noted that the
254 correlation of three short reversed polarities R2, R3, and R10 to Chrons C20r, C21r, and C25r
255 is relatively discordant, which may be caused by punctuated erosion during the transition of
256 deposition from mudstones to sandstones (Fig. 5a). However, the erosion has only a minor
257 effect on our magnetostratigraphic correlation, and we thus conclude that the Gonjo redbeds
258 represent a relatively continuous depositional sequence from the Late Cretaceous (~69 Ma) to
259 Middle Eocene (~41.5 Ma). The boundary of the Gonjo/Ranmugou formations is ca. 65.2 Ma,
260 and the boundaries of the lower/middle and middle/upper Ranmugou formations are 55.5 Ma
261 and 43.4 Ma, respectively.

262 The basal age of the Gonjo redbeds (69 Ma) seems to be much older than the youngest
263 detrital U-Pb zircon age (52.5 ± 1.5 Ma) (Zhang et al., 2018), which normally represents the
264 maximum depositional age of host sediments. However, the youngest detrital zircon U-Pb age
265 in Zhang et al. (2018)'s study is an average of 16 zircon grains from three samples from
266 different depths in the stratigraphy (see the blue triangles in Fig. 5 for stratigraphic location).
267 The lowest sample at the top of the Gonjo Formation has two youngest zircon grains that are
268 younger than the ~65 Ma age as given by our magnetostratigraphic, which seems to
269 inconsistent with our results. However, as suggested by Dickinson and Gehrels (2009), at least
270 three robust youngest ages are required to reliably constrain the maximum depositional age of
271 the host rock, therefore the validity of these two zircon grains from that sample remains
272 uncertain. Ages of the other two samples from the middle Ranmugou Formation that yield the
273 youngest zircon grains of ~52 Ma are consistent with our magnetostratigraphic result.

274 A plot of magnetostratigraphic age versus thickness of the studied section (Fig. 7) reveals
275 four stages of deposition with different SARs for the Gonjo Basin: two stages of high SAR
276 (~20 cm/kyr for 69–64 Ma and 52–48 Ma) and two stages of low SAR (~8 cm/kyr for 64–52
277 Ma and 48–41.5 Ma).

278

279 **5. Discussion**

280 **5.1. Tectonic rotation of the eastern Tibet**

281 The Gonjo Basin is uniquely located in the transition zone where structural trends change
282 from east-west-oriented in the central plateau to north-south-oriented in the southeast margin
283 of the Tibetan Plateau (Fig. 1b), The rotation history of the Gonjo Basin during the Late
284 Cretaceous-Late Eocene therefore provides key information to address questions as to how and
285 when this change in orientation occurred. The stratigraphically grouped 66 sites of the ChRM
286 directions from the Gonjo Basin indicate five stages of rotation in eastern Tibet: a ~10° counter-

287 clockwise rotation from 69 to 67 Ma, no significant rotation between 67 and 52 Ma, $\sim 30^\circ$
288 clockwise rotation from 52 to ~ 48 Ma, no significant rotation between 48 and 41 Ma, and $\sim 30^\circ$
289 clockwise rotation sometime after 41 Ma (Fig. 8c).

290 Previously, Tong et al. (2017) averaged all their paleomagnetic sites from the Gonjo Basin
291 in one direction ($D = 35.5^\circ$, $I = 29.3^\circ$, $a95 = 3.2^\circ$). Because of the relative rotation during
292 deposition, this value represents a time-averaged declination, and therefore does not resolve
293 the variation in rotation history over the Late Cretaceous to Late Eocene interval. Zhang et al.
294 (2018) noticed varied declinations within their 61 paleomagnetic sites and identified a three-
295 stage rotation: a clockwise rotation followed by a counter-clockwise and then another
296 clockwise rotation, a pattern different to our result. The difference could be simply interpreted
297 to indicate that both Zhang et al. (2018) and our study record local rather than basin-scale
298 regional rotation, related to the thrust architecture of the basin. However, we note that Zhang
299 et al. (2018) did not show detailed stratigraphic and geochronologic information, or access to
300 a continuous section. Instead they correlated two sections 30 km apart and evenly distributed
301 their sites over a time interval of ~ 10 myr that they estimated for the Gonjo Basin, which now
302 we date to be of a duration of ~ 28 Myr (from 69 to 41 Ma). Therefore, the rotation pattern
303 identified by our data, based on a continuous section and precise age constraint, is better
304 constrained than that by Zhang et al. (2018).

305 The lack of rotation between 67 and 52 Ma suggests that eastern Tibet was probably
306 dominated by laterally coherent crustal shortening during this period. The $\sim 30^\circ$ clockwise
307 rotation between 52 and 48 Ma in the Gonjo Basin is consistent with previous paleomagnetic
308 results from northeast and southeast Tibet (Dupont-Nivet et al., 2004; Li et al., 2017b), which
309 also indicate that a clockwise rotation started in Eocene time (Fig. 9b). As discussed in section
310 5.2 below, 52 Ma marks the onset of a rapid increase in SAR of the Gonjo and Hoh Xil basins
311 and rapid deformation in other basins from southern, central and northern Tibet, which we

312 interpret as the onset of significant crustal shortening in the Tibetan Plateau. Therefore, the
313 initiation of the clockwise rotation from 52 Ma reflects regionally distributed right-lateral shear
314 between the rigid South China Block and shortening Tibetan Plateau (England and Molnar et
315 al., 1990, Fig. 9b), consistent with kinematic and paleomagnetic reconstructions of Tibetan
316 shortening and extrusion of Indochina (Li et al., 2018; van Hinsbergen et al., 2019). The
317 coincidence between crustal shortening in Tibet and initiation of clockwise rotation in northeast,
318 east, and southeast Tibet further suggests that upper plate deformation in Tibet at ~52 Ma was
319 large enough to affect northeastern and southeastern Tibet (Dupont-Nivet et al., 2004; Li et al.,
320 2017b), and to produce rapid and large-scale rotations of eastern Tibet.

321 Our previous paleomagnetic study from southeast Tibet suggested that the Qiangtang and
322 Indochina terranes were originally a linear structure with an orientation of N60°W (Li et al.,
323 2018, Fig. 9a). After a 30° clockwise rotation, the Gonjo Basin in eastern Tibet changed to
324 N30°W, which is consistent with the present-day strike of the Gonjo Basin (Fig. 9c). Further
325 to the south, the southeast borderland of the Tibetan Plateau underwent as large as 60°
326 clockwise rotation (see Li et al., 2017b and references therein), which resulted in the N-S strike
327 of geological features observed today (Fig. 9c). Therefore, the change of geological strike from
328 an east-west orientation in the central plateau to a north-south trend in the southeast margin of
329 the Tibetan Plateau is mainly a consequence of different clockwise rotations from the central
330 to southeast Tibet.

331

332 **5.2. Sediment accumulation rate changes**

333 Our new magnetostratigraphic study of the Gonjo Basin infill allows the calculation of
334 variations in SARs. Fig. 7 shows two periods of high SAR (~20 cm/kyr at 69–64 Ma and 52–
335 48 Ma) and two periods of low SAR (~8 cm/kyr at 64–52 Ma and 48–41.5 Ma) for the Gonjo
336 Basin. The increase of SAR at ~52 Ma is coincident with an increase of coarse-grained

337 sediments (Fig. 5a). Although our magnetostratigraphic study only represents a 1-D section of
338 the Gonjo Basin, the uniform structures and sediments from the northwest to the southeast of
339 the basin indicate that our 1-D velocity is likely a good approximation of 3-D volumetric SARs.
340 In a shortening-related sedimentary basin, such variation of SARs may simply reflect timing
341 of shortening pulses and related uplift and enhanced erosion. Alternatively, or additionally,
342 however, such variations may be an artifact of differences in compaction or reflect climatic
343 signals. Below, we discuss these potential contributions to the SAR changes.

344 We use two different methods to test whether the intervals of slow SAR are due to strong
345 compaction. We first decompacted sediment thicknesses of the Gonjo Basin according to the
346 observed lithologies following the methods and porosity values of Sclater and Christie (1980)
347 using the OSXBackstrip program version 4.7 (Cardozo, 2012). This method has been
348 successfully applied in the Xuanhua Basin of northeast Tibet (Lease et al., 2012) and in the
349 Tarim Basin of northern Tibet (Blayney et al., 2019). As shown in Fig. 7, the SAR of the Gonjo
350 Basin after decompaction displays a similar trend as that before decompaction: two periods of
351 high SARs (69–65.7 Ma and 53.8–49.6 Ma) alternate with two periods of relatively low SARs
352 (65.7–53.8 Ma and 49.6–41.5 Ma), although the time of change in SARs and relative values
353 are slightly different. This suggests that compaction plays a minor role in the SAR change.

354 An alternative way to evaluate the effect of compaction is through analysis of shallowing
355 of the paleomagnetic inclination using the E/I method of Tauxe and Kent (2004), which
356 assumes that there are strong variations in sediment compaction, whereby sediments deposited
357 during the phases of rotation compacted much less than during intervals without rotation. The
358 E/I method restores a measured distribution of virtual geomagnetic poles to a near-circular
359 distribution expected from paleosecular variation in their geomagnetic field model. Sediment
360 compaction leads to elongation of this distribution, and correcting the elongation provides an
361 estimate for the compaction factor and restores the inclination back to the original. A

362 prerequisite for this method is that the source of virtual geomagnetic pole scatter is
363 predominantly paleo-secular variation of the geomagnetic field: it is thus applicable to the parts
364 of the section that were not deposited during rotation, i.e. the intervals with low SAR of ~7–8
365 cm/yr, between ~1200 and 1800 m, and between ~2600 and 3400 m (Fig. 7), but not to the
366 intervals with high SAR of ~20 cm/yr that occurred during tectonic rotation. The E/I method
367 yielded flattening factors of 0.4–0.6 (see supplementary Table 2), which is the typical range
368 for redbeds (e.g., Tauxe and Kent, 2004). This would recover the low SAR from 7–8 cm/yr to
369 11–13 cm/yr, which is still lower than the high compacted SAR of ~20 cm/yr, suggesting that
370 the higher SARs of ~20 cm/yr in the intervals cannot only be explained by variations in
371 compaction. We use the compacted SARs when comparing the Gonjo Basin with the Hoh Xil
372 Basin to maintain consistency with them.

373 The SARs vary abruptly, differ by more than a factor 2, and the high SARs occur during
374 periods of significant vertical axis rotations in the basin (Fig. 8), demonstrating regional
375 deformation, which in this region is (oblique) shortening. It is of course possible that also
376 climatic changes coincided with these tectonic events and contributed to the changes in SARs.
377 Jin et al. (2018) used the global marine oxygen isotope ($\delta^{18}\text{O}$) curve (Zachos et al., 2008, Fig.
378 8b) as a paleoclimate reference to evaluate the potential role of climate change on the
379 sedimentation rate change of the Hoh Xil Basin (~400 km west of our study area, Fig. 1), and
380 suggested that climate change was not the dominant factor to the SAR change. However, the
381 validity of using the oxygen isotope curve in this manner is debatable. Without detailed
382 paleoclimate change background from Late Cretaceous-Eocene around the Tibetan Plateau, we
383 cannot fully preclude the climate effect on the deposition of the Gonjo Basin. However, the
384 strong temporal correlation between the increases in SAR and the timing of tectonic rotations
385 (Fig. 8) in the shortening-controlled Gonjo Basin (Studnicki-Gizbert et al., 2008) strongly
386 indicates that the SAR changes are dominantly tectonically-controlled. We thus interpret the

387 high SARs record in the Gonjo Basin to reflect pulses of crustal shortening in the eastern Tibet
388 between ~69–64 Ma, and ~52–48 Ma.

389

390 **5.3. Crustal Shortening of Tibet**

391 Basins to the west on the Qiangtang terrane have similar stratigraphic records as the Gonjo
392 Basin. The Hoh Xil Basin is the largest one in central Tibet and is controlled by the Tanggula
393 thrust system (Jin et al., 2018) (Fig. 1a). The basin strata were recently dated at 72–51 Ma by
394 magnetostratigraphy and geochronology of volcanic ash (Jin et al., 2018). The Hoh Xil Basin
395 not only has a similar structural architecture as the Gonjo Basin, but also a similar basal age
396 (~70 Ma) and SAR variation pattern: a high SAR from 72–63.5 Ma followed by a relative low
397 SAR between 63.5 and 54 Ma, and a significant increase of SAR since 54 Ma (Fig. 7). Similarly,
398 low-temperature thermochronology studies from the northern Qaidam Basin and central
399 Qiangtang also suggest that northern and central Tibet underwent two stages of rapid
400 exhumation between Late Cretaceous-Earliest Eocene and Eocene-Oligocene (Jian et al., 2018;
401 Staisch et al., 2014, Fig. 9). To the south, in the Lhasa terrane, folded Late Cretaceous redbeds
402 are overlain by weakly deformed Linzizong volcanics. The timing of deformation is dated
403 between 72 Ma (Sun et al., 2012) and 69 Ma (Kapp and DeCelles, 2019). The Eocene
404 deformation of Tibet around 52 Ma is also well documented, e.g., rapid exhumation of southern,
405 central and northern Tibet around ~55–48 Ma as suggested by low-temperature
406 thermochronology (Clark et al., 2010; Jian et al., 2018; and references in Li et al., 2015) and
407 initial/rapid deposition in the Qaidam, Xining, Lanzhou, Hoh Xil and Tarim basins (see reviews
408 in Ji et al., 2017 and Jin et al., 2018). Crustal shortening in the Lhasa terrane occurred at ~52
409 Ma has been evidenced by syn-contractional growth strata interbedded with 53 ± 2 Ma tuffs
410 along the northern Gangdese retroarc thrust belt (Kapp et al., 2007). Moreover, a series
411 thrust/strike-slip faults, e.g., the Tethyan Himalaya, Fenghuoshan and Nangqian thrust faults,

412 the left-lateral Altyn Tagh and western Qinlin faults initiated/reactivated around 50 Ma (e.g.,
413 Clark et al., 2010; Jin et al., 2018; Li et al., 2015; Spurlin et al., 2005, Fig. 9b). The
414 synchronicity of enhanced deformation in Tibet leads us to conclude that the Tibetan Plateau
415 underwent shortening pulses at ~69–64 Ma and ~52–48 Ma.

416

417 **5.4. Evaluating models explaining rapid India-Asia convergence rate changes**

418 The SAR and deformation (rotation) pulses at ~69–64 Ma and ~52–48 Ma are
419 synchronous with the periods of sharp acceleration and deceleration of India (Fig. 8d). If these
420 pulses reflect shortening pulses of the Tibetan upper crust as we interpret, then both the
421 acceleration and deceleration of India-Asia convergence appear to be associated with enhanced
422 friction at the India-Asia plate contact. This then allows us to briefly evaluate predictions made
423 by previous explanations for these plate convergence variations.

424 For the ~70 Ma plate acceleration and crustal deformation, enhanced friction is consistent
425 with the prediction of a northward push of the Deccan plume head on the Indian plate (van
426 Hinsbergen et al., 2011). Such a push would have caused acceleration of the Indian plate and
427 accelerated the rate of Neo-Tethyan subduction and trench advance, which then may well have
428 increased the friction between the subducting slab and overriding plate resulting in shortening
429 in Tibet (Kapp and DeCelles, 2019) (Fig. 10a). The scenario of a second, intra-oceanic
430 subduction zone explaining plate acceleration, as advocated by Jagoutz et al. (2015) assumed
431 that acceleration was gradual since ~90 Ma, and did not explicitly address the major 70–65 Ma
432 acceleration. Nevertheless, the numerical modeling of the double subduction scenario predicts
433 that the northern of the two subduction zones – below Tibet – would have the tendency to roll
434 back (Schellart, 2005), making an enhanced friction at ~70 Ma difficult to explain. Finally,
435 lubrication of the plate contact around 70 Ma, caused by the arrival of equatorial sediments in

436 the trench, as proposed by (Behr and Becker, 2018) would predict a decrease in friction at the
437 plate contact rather than an increase.

438 It is interesting to note that the central Tibet basins we studied and reviewed reveal no
439 clear pulse of enhanced sedimentation rate, rotation, and by inference, shortening at the time
440 of collision recorded in the Tethyan Himalaya at 59 ± 1 Ma (Hu et al., 2015), which is also
441 supported by the 69–44 Ma gently folded Linzizong volcanics in the Lhasa terrane (He et al.,
442 2007). This suggests that the initial collision at 59 ± 1 Ma may just represent a soft collision, or
443 the first phase of a two-stage collision, either an arc-India collision (Kapp and DeCelles, 2019)
444 or a minor collision between the Tethyan microplate and Asia (van Hinsbergen et al., 2012).

445 The subsequent slow-down of the Indian plate at ~ 52 Ma, some 6–8 Myr later than the
446 time of initial collision, is however correlated with a pulse of upper plate shortening. This slow-
447 down is classically explained by initial collision (e.g., Copley et al., 2010), but the offset
448 between collision and slow-down, during which time up to 1000 km of India-Asia convergence
449 occurred (e.g., Copley et al., 2010; van Hinsbergen et al., 2011), makes such an interpretation
450 not straightforward. Alternative explanations for the 52 Ma slow-down invoke a phase of slab
451 break-off (Zhu et al., 2015) (Fig. 10b), or slab overturning (van Hinsbergen et al., 2019) (Fig.
452 10c). Slab breakoff would have caused a decrease of the Indian plate's velocity due to the loss
453 of slab pull. The rebound of the subducted Indian continental lithosphere due to its lower
454 density relative to the mantle after slab break-off would have resulted in the hard collision of
455 India with Asia, which caused upper plate shortening as demonstrated in Gonjo and related
456 basins. The deceleration of India by the resistance of the lower mantle to the penetration of the
457 continental lithosphere of the Tethyan Himalaya that subducted at 58 Ma, upon its arrival at
458 the mantle transition zone. Obstruction of lower mantle penetration was proposed as an
459 explanation why the subducting slab overturned northward, as long shown from seismic

460 tomography (Replumaz et al., 2010). Both explanations, slab break-off or slab overturning,
461 predict enhanced friction, consistent with our new findings.

462 Regardless of the exact drivers of the ~70 Ma acceleration and ~52 Ma deceleration, our
463 study highlights the importance of, and a way towards obtaining independent constraints on
464 the timing of upper plate deformation in Tibet. These constraints are critical to evaluate the
465 geodynamic relationships (or absence thereof) between the continental collision, upper plate
466 deformation, and plate kinematics.

467

468 **6. Conclusions**

469 In this study, we present a high-resolution magnetostratigraphy from the syn-contractual
470 Gonjo Basin, eastern Tibet. Based on the magnetochronology, we calculate the SAR and its
471 temporal change in the Gonjo Basin and compare them with other basins in central Tibet and
472 the convergence rate between India and Asia. Paleomagnetic declinations were used to
473 constrain the rotations. With this information, we discuss the relationship between India-Asia
474 convergence rate and crustal shortening in the Tibetan Plateau during the India-Asia collision
475 process. Our main conclusions are summarized as follows:

476 (1) The positive fold and reversal tests suggest a primary origin of the remanence of the
477 Gonjo Basin.

478 (2) A continuous magnetostratigraphy for the Gonjo Basin reveals an age interval from 69
479 to 41.5 Ma.

480 (3) The Gonjo Basin records two periods of rapid SAR (~20 cm/yr) at 69–64 Ma and 52–48
481 Ma and two periods of low SAR (7–8 cm/yr) at 64–52 Ma and 48–41 Ma.

482 (4) Paleomagnetic declinations indicate that eastern Tibet experienced ~10° counter-
483 clockwise at 69–67 Ma and ~30° clockwise at 52–48 Ma, followed by another ~30°
484 clockwise rotation sometime after 41 Ma.

485 (5) The two periods of rapid sedimentation are coincident with periods of vertical axis
486 rotation, which we interpret as two pulses of crustal shortening. This result is similar to
487 those from basins in southern, central, and northern Tibet, suggesting that these pulses
488 occurred plateau-wide.

489 (6) The crustal shortening episodes of the Tibetan Plateau correlate with a rapid
490 acceleration and deceleration of India-Asia convergence, suggesting that both events
491 increased friction at the India-Asia plate contact. We hypothesize that plate motion
492 changes, rather than initial continental collision controlled the upper plate shortening
493 pulses of Tibet.

494

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506 **References**

507

- 508 Blayney, T., Dupont - Nivet, G., Najman, Y., Proust, J.N., Meijer, N., Roperch, P., Sobel, E.R.,
509 Millar, I. and Guo, Z., 2019. Tectonic evolution of the Pamir recorded in the western
510 Tarim Basin (China): sedimentologic and magnetostratigraphic analyses of the
511 Aertashi section. *Tectonics* 38(2), 492-515.
- 512 Behr, W.M., Becker, T.W., 2018. Sediment control on subduction plate speeds. *Earth Planet.*
513 *Sci. Lett.* 502, 166-173.
- 514 BGMR Xizang., 1993. Regional geology of Xizang (Tibet) Autonomous Region, Geological
515 Memoirs Series. Geological House, Beijing.
- 516 Cande, S.C., Stegman, D.R., 2011. Indian and African plate motions driven by the push force
517 of the Reunion plume head. *Nature* 475, 47-52.
- 518 Capitanio, F.A., Morra, G., Goes, S., Weinberg, R.F., Moresi, L., 2010. India–Asia convergence
519 driven by the subduction of the Greater Indian continent. *Nat. Geosci.* 3, 136-139.
- 520 Cardozo, N., 2012, OSX Backstrip v4.7: <http://www.ux.uis.no/~nestor/work/programs.html>.
- 521 Clark, M.K., 2012. Continental collision slowing due to viscous mantle lithosphere rather
522 than topography. *Nature* 483, 74-77.
- 523 Clark, M.K., Farley, K.A., Zheng, D., Wang, Z., Duvall, A.R., 2010. Early Cenozoic faulting of
524 the northern Tibetan Plateau margin from apatite (U–Th)/He ages. *Earth Planet. Sci.*
525 *Lett.* 296, 78-88.
- 526 Copley, A., Avouac, J.P., Royer, J.Y., 2010. India-Asia collision and the Cenozoic slowdown of
527 the Indian plate: Implications for the forces driving plate motions. *J. Geophys. Res.*
528 115, B03410, doi:10.1029/2009JB006634.
- 529 Dickinson, W.R., Gehrels, G.E., 2009. Use of U–Pb ages of detrital zircons to infer maximum
530 depositional ages of strata: A test against a Colorado Plateau Mesozoic database. *Earth*
531 *Planet. Sci. Lett.* 288, 115-125.
- 532 Dupont-Nivet, G., Horton, B.K., Butler, R.F., Wang, J., Zhou, J., Waanders, G.L., 2004.
533 Paleogene clockwise tectonic rotation of the Xining-Lanzhou region, northeastern
534 Tibetan Plateau. *J. Geophys. Res.* 109. B04401, doi:10.1029/2003JB002620
- 535 England, P., Molnar, P., 1990. Right-lateral shear and rotation as the explanation for strike-
536 slip faulting in eastern Tibet. *Nature* 344, 140-142.
- 537 Gradstein, F.M., Ogg, G., Schmitz, M., 2012. *The Geologic Time Scale 2012* Elsevier, Oxford,
538 UK.
- 539 He, S., Kapp, P., DeCelles, P.G., Heizler, G.E.G.M., 2007. Cretaceous–Tertiary geology of the
540 Gangdese Arc in the Linzhou area, southern Tibet. *Tectonophysics* 433, 15-37.
- 541 Horton, B.K., Yin, A., Spurlin, M.S., Zhou, J.Y., Wang, J.H., 2002. Paleocene-Eocene
542 syncontractional sedimentation in narrow, lacustrine-dominated basins of east-central
543 Tibet. *Geol. Soc. Am. Bull.* 114, 771-786.
- 544 Hu, X., Garzanti, E., Moore, T., Raffi, I., 2015. Direct stratigraphic dating of India-Asia
545 collision onset at the Selandian (middle Paleocene, 59 ± 1 Ma). *Geology* 43, 859-862.
- 546 Jagoutz, O., Royden, L., Holt, A.F., Becker, T.W., 2015. Anomalously fast convergence of
547 India and Eurasia caused by double subduction. *Nat. Geosci.* 8, 475-478.
- 548 Ji, J., Zhang, K., Clift, P.D., Zhuang, G., Song, B., Ke, X., Xu, Y., 2017. High-resolution
549 magnetostratigraphic study of the Paleogene-Neogene strata in the Northern Qaidam
550 Basin: Implications for the growth of the Northeastern Tibetan Plateau. *Gondwana Res.*
551 46, 141-155.

552 Jian, X., Guan, P., Zhang, W., Liang, H., Feng, F., Fu, L., 2018. Late Cretaceous to early Eocene
553 deformation in the northern Tibetan Plateau: Detrital apatite fission track evidence
554 from northern Qaidam basin. *Gond. Res.* 60, 94-104.

555 Jin, C., Liu, Q., Liang, W., Roberts, A.P., Sun, J., Hu, P., Zhao, X., Su, Y., Jiang, Z., Liu, Z., Duan,
556 Z., Yang, H., Yuan, S., 2018. Magnetostratigraphy of the Fenghuoshan Group in the
557 Hoh Xil Basin and its tectonic implications for India–Eurasia collision and Tibetan
558 Plateau deformation. *Earth Planet. Sci. Lett.* 486, 41-53.

559 Kapp, P., DeCelles, P.G., Leier, A.L., Fabijanic, J.M., He, S., Pullen, A., Gehrels, G.E., Ding, L.,
560 2007. The Gangdese retroarc thrust belt revealed. *GSA Today* 17 (7), doi:
561 10.1130/GSAT01707A.1.

562 Kapp, P., DeCelles, P., 2019. Mesozoic-Cenozoic geological evolution the Himalayan-Tibetan
563 orogen and working tectonic hypothesis *Am. J. Sci.* 319(3), 159-254.

564 Kirschvink, J., 1980. The least-squares line and plane and the analysis of palaeomagnetic
565 data. *Geophys. J. Int.* 62, 699-718.

566 Koymans, M.R., Langereis, C.G., Pastor-Galán, D., van Hinsbergen, D.J.J., 2016.
567 Paleomagnetism.org: An online multi-platform open source environment for
568 paleomagnetic data analysis. *Comp. & Geos.* 93, 127-137.

569 Kumar, P., Yuan, X., Kumar, M.R., Kind, R., Li, X., Chadha, R.K., 2007. The rapid drift of the
570 Indian tectonic plate. *Nature* 449, 894-897.

571 Lease, R.O., Burbank, D.W., Hough, B., Wang, Z., Yuan, D., 2012. Pulsed Miocene range
572 growth in northeastern Tibet: Insights from Xunhua Basin magnetostratigraphy and
573 provenance. *Geol. Soc. Am. Bull.* 124, 657-677.

574 Li, S.H., Yang, Z., Deng, C., He, H., Qin, H., Sun, L., Yuan, J., van Hinsbergen, D.J.J., Krijgsman,
575 W., Dekkers, M.J., Pan, Y., Zhu, R., 2017a. Clockwise rotations recorded in redbeds
576 from the Jinggu Basin of northwestern Indochina. *Geol. Soc. Am. Bull.* 129, 1100-1122.

577 Li, S.H., Advokaat, E.L., van Hinsbergen, D.J.J., Koymans, M., Deng, C., Zhu, R., 2017b.
578 Paleomagnetic constraints on the Mesozoic-Cenozoic paleolatitudinal and rotational
579 history of Indochina and South China: Review and updated kinematic reconstruction.
580 *Earth-Sci. Rev.* 171, 58-77.

581 Li, S.H., Hinsbergen, D.J.J.v., Deng, C., Zhu, E.L.A.R., 2018. Paleomagnetic Constraints From
582 the Baoshan Area on the Deformation of the Qiangtang-Sibumasu Terrane Around the
583 Eastern Himalayan Syntaxis. *J. Geophys. Res.* 123, 977-997.

584 Li, Y.L., Wang, C.S., Dai, J.G., Xu, G.Q., Hou, Y.L., Li, X.H., 2015. Propagation of the deformation
585 and growth of the Tibetan-Himalayan orogen: A review. *Earth-Sci. Rev.* 143, 36-61.

586 McFadden, P., McElhinny, M., 1988. The combined analysis of remagnetization circles and
587 direct observations in palaeomagnetism. *Earth Planet. Sci. Lett.* 87, 161-172.

588 Patriat, P., Achache, J., 1984. India–Eurasia collision chronology has implications for crustal
589 shortening and driving mechanism of plates. *Nature* 311(5987), 615-621.

590 Replumaz, A., Negredo, A.M., Guillot, S., Villaseñor, A., 2010. Multiple episodes of
591 continental subduction during India/Asia convergence: Insight from seismic
592 tomography and tectonic reconstruction. *Tectonophysics* 483, 125-134.

593 Roberts, A., Cui, Y.L., Verosub, K.L., 1995. Wasp-waisted hysteresis loops Mineral magnetic
594 characteristics and discrimination of components in mixed magnetic systems. *J.*
595 *Geophys. Res.* 100, 17909-17924.

596 Schellart, W.P., 2005. Influence of the subducting plate velocity on the geometry of the slab
597 and migration of the subduction hinge. *Earth Planet. Sci. Lett.* 231, 197-219.

598 Sclater, J.G., Christie, P.A.F., 1980. Continental stretching: An explanation of the Post-Mid-
599 Cretaceous subsidence of the central North Sea Basin. *J. Geophys. Res.* 85, 3711-3739.

600 Staisch, L.M., Niemi, N.A., Hong, C., Clark, M.K., Rowley, D.B., Currie, B., 2014. A
601 Cretaceous - Eocene depositional age for the Fenghuoshan Group, Hoh Xil Basin:
602 Implications for the tectonic evolution of the northern Tibet Plateau. *Tectonics* 33,
603 doi:10.1002/2013TC003367.

604 Studnicki-Gizbert, C., Burchfiel, B.C., Li, Z., Chen, Z., 2008. Early Tertiary Gonjo basin, eastern
605 Tibet: Sedimentary and structural record of the early history of India-Asia collision.
606 *Geos.* 4, 713-735.

607 Searle, M., Corfield, R. I., Stephenson, B. E. N., McCarron, J. O. E., 1997. Structure of the
608 North Indian continental margin in the Ladakh–Zaskar Himalayas: implications for the
609 timing of obduction of the Spontang ophiolite, India–Asia collision and deformation
610 events in the Himalaya. *Geol. Mag.* 134(3), 297-316.

611 Spurlin, M.S., Yin, A., Horton, B.K., Zhou, J., Wang, J., 2005. Structural evolution of the
612 Yushu-Nangqian region and its relationship to syncollisional igneous activity east-
613 central Tibet. *Geol. Soc. Am. Bull.* 117, 1293-1317.

614 Sun, Z., Pei, J.L., Li, H.B., Xu, W., Jiang, W., Zhu, Z.M., Wang, X.S., Yang, Z.Y., 2012.
615 Palaeomagnetism of late Cretaceous sediments from southern Tibet: Evidence for the
616 consistent palaeolatitudes of the southern margin of Eurasia prior to the collision with
617 India. *Gond. Res.* 21, 53-63.

618 Tang, M., Liu-Zeng, J., Hoke, G.D., Xu, Q., Wang, W., Li, Z., Zhang, J., Wang, W., 2017.
619 Paleoelevation reconstruction of the Paleocene-Eocene Gonjo basin, SE-central Tibet.
620 *Tectonophysics* 712-713, 170-181.

621 Tauxe, L., Watson, G.S., 1994. The fold test: an eigen analysis approach. *Earth Planet. Sci.*
622 *Lett.* 122, 331-341.

623 Tauxe, L., T. A. T. Mullender, and T. Pick (1996), Potbellies, wasp-waists, and
624 superparamagnetism in magnetic hysteresis. *J. Geophys. Res.*, 101, 571–583.

625 Tauxe, L., 2010. *Essentials of Paleomagnetism*. University of California Press, Berkeley, 512
626 pp.

627 Tauxe, L., Kent, D.V., 2004. A simplified statistical model for the geomagnetic field and the
628 detection of shallow bias in paleomagnetic inclinations: was the ancient magnetic field
629 dipolar?, in: Channell, J.E.T., Kent, D.V., Lowrie, W., Meert, J.G. (Eds.), *Timescales of*
630 *the Paleomagnetic Field*, *Geophys. Monogr. Ser.*, Vol, 145. American Geophysical
631 Union, Washington, D.C., pp. 101-115.

632 Tong, Y., Yang, Z., Mao, C., Pei, J., Pu, Z., Xu, Y., 2017. Paleomagnetism of Eocene red-beds in
633 the eastern part of the Qiangtang Terrane and its implications for uplift and
634 southward crustal extrusion in the southeastern edge of the Tibetan Plateau. *Earth*
635 *Planet. Sci. Lett.* 475, 1-14.

636 van Hinsbergen, D.J.J., Lippert, P.C., Dupont-Nivet, G., McQuarrie, N., Doubrovine, P.V.,
637 Spakman, W., Torsvik, T.H., 2012. Greater India Basin hypothesis and a two-stage
638 Cenozoic collision between India and Asia. *P Natl Acad Sci USA* 109, 7659-7664.

639 van Hinsbergen, D.J.J., Lippert, P.C., Li, S., Huang, W., Advokaat, E.L., Spakman, W., 2019.
640 Reconstructing Greater India: Paleogeographic, kinematic, and geodynamic
641 perspectives. *Tectonophysics* 760, 69-94.

642 van Hinsbergen, D.J.J., Steinberger, B., Doubrovine, P.V., Gassmüller, R., 2011. Acceleration
643 and deceleration of India-Asia convergence since the Cretaceous: Roles of mantle

644 plumes and continental collision. *J. Geophys. Res.* 116, B06101,
645 doi:10.1029/2010JB008051.

646 Zachos, J.C., Dickens, G.R., Zeebe, R.E., 2008. An early Cenozoic perspective on greenhouse
647 warming and carbon-cycle dynamics. *Nature* 451, 279-283.

648 Zhang, Y., Huang, W., Huang, B., van Hinsbergen, D.J.J., Yang, T., Dupont-Nivet, G., Guo, Z.,
649 2018. 53-43 Ma deformation of the Eastern Tibet revealed by three stages of tectonic
650 rotation in the Gongjue basin. *J. Geophys. Res.* 123, 3320-3338.

651 Zhu, D.C., Wang, Q., Zhao, Z.D., Chung, S.L., Cawood, P.A., Niu, Y., Liu, S.A., Wu, F.Y., Mo,
652 X.X., 2015. Magmatic record of India-Asia collision. *Sci. Rep.* 5, 14289.

653

654 **Figure Captions**

655

656 **Fig. 1.** (a) The India-Asia convergence rate (van Hinsbergen et al., 2011) along the two flow
657 lines of eastern (red) and western (black) Himalaya syntaxis. (b) Simplified tectonic map of
658 the Tibetan Plateau showing the distribution of main sedimentary basins and related strike-slip
659 and thrust faults, and the magmatism of the Gangdese arc. The blue polygon denotes the
660 location of the Gonjo Basin. Main abbreviations: HXB, Hoh Xil Basin; NYB, Nangqian-Yushu
661 Basin; GJB, Gonjo Basin; XNB, Xining Basin; LZB, Lanzhou Basin; YLF, Yangla thrust fault;
662 TGT, Tanggula thrust; EHS, Eastern Himalaya Syntaxis.

663

664 **Fig. 2.** Map of stratigraphy and structures of the Gonjo Basin around the Gonjo city (Modified
665 from BGMR Xizang (1993). The dashed yellow lines refer to the magnetostratigraphic
666 sampling sections. L/M/U RMG Fm, Lower/Middle/Upper Ranmugou Formation; C:
667 Carboniferous; Tr, Triassic; Q, Quaternary.

668

669 **Fig. 3.** (a-d, i-l) Hysteresis loops, and (e-h, m-p) IRM acquisition curves and direct current
670 field demagnetization of the saturation IRM from representative sample of the Gonjo Basin.

671

672 **Fig. 4.** Orthogonal vector projections of demagnetization for the Gonjo Basin in geographical
673 coordinates. Solid and open symbols refer to vector projected onto the horizontal and vertical
674 planes, respectively. NRM, natural remanent magnetization; LTC, low-temperature component;
675 ITC, intermediate temperature component; HTC, high-temperature component.

676

677 **Fig. 5.** Lithology (a), magnetostratigraphic (b–c) of the Gonjo Basin and their correlation with
678 the geomagnetic polarity timescale (GPTS) (d) (Gradstein et al., 2012). Blue triangles mark the
679 general stratigraphic position of detrital zircon U-Pb samples in Zhang et al. (2018), which
680 were used to constrain the maximum deposition age of the Gonjo Basin. Red line denotes the
681 stratigraphic position of the volcanic layer, which yields U-Pb (Tang et al., 2017) and $^{40}\text{Ar}/^{39}\text{Ar}$
682 (Studnicki-Gizbert et al., 2008) ages of ~43 Ma in the northwest Gonjo Basin. Orange line
683 represents the position of pedogenic carbonates, which indicate a minimum average elevation

684 of 2100–2500 m at ~60 Ma (Tang et al., 2017). The pink diamonds represent directions
685 computed by great circle.

686

687 **Fig. 6.** Equal-area projections of (a) all the paleomagnetic directions, the non-rotated intervals
688 of (b) 67–52 Ma and (c) 48–41.5 Ma from the Gonjo Basin. (d) Nonparametric fold tests
689 (Tauxe and Watson, 1994) of all the paleomagnetic results. The 95% bootstrapped statistics on
690 the first eigenvalues (τ_1) is [98, 118], indicating a positive fold test. Bootstrap reversal test
691 (Tauxe, 2010) on results from the non-rotated interval of (e) 67–52 Ma and (f) 48–41.5 Ma.
692 Reversed polarity directions have been inverted to their antipodes to test a common mean for
693 the normal (blue) and reversed (purple) magnetization directions. The overlap of 95%
694 confidence intervals for the X, Y, and Z components indicates a positive reversals test.

695

696 **Fig. 7.** Plot of magnetostratigraphic age versus stratigraphic thickness showing the variation of
697 sediment accumulation rates of the Gonjo Basin (compacted, red dots; decompacted, blue
698 triangle dots) and the Hoh Xil Basin (black dots, Jin et al., 2018). Note the synchronous change
699 of sediment accumulation rates between the Gonjo Basin and the Hoh Xil Basin.

700

701

702 **Fig. 8.** Comparisons of (a) the sediment accumulation rates of the Gonjo (blue, this study) and
703 Hoh Xil (red, Jin et al., 2018) basins, (b) stacked marine benthic oxygen-isotopic data (Zachos
704 et al., 2008), (c) vertical axis rotations, and (d) India-Asia convergence rates (van Hinsbergen
705 et al., 2011). Note the synchronous changes among sediment accumulation rates of the Gonjo
706 and Hoh Xil basins, vertical axis rotations, and India-Asia convergence rates at ~70 Ma and
707 ~52 Ma, respectively.

708

709 **Fig. 9.** Restored paleogeography map of Tibet at (a) 70 Ma, (b) 52 Ma and (c) present. (a) The
710 rapid subduction of Neo-Tethyan at ~70 Ma resulted in the activation of thrust faults in central
711 and northeast Tibet and initial deposition of a series sedimentary basins. (b) The synchronous
712 between pulsed crustal shortening of Tibet and clockwise rotation of northeast Tibet (Dupont-

713 Nivet et al., 2004), east Tibet (this study), and southeast Tibet (Li et al., 2017b) at ~52 Ma. (c)
714 The change of geological trends and basin distribution after differential clockwise rotation. See
715 text for the detailed discussion. The white dots and numbers denote tectonic deformation ages
716 documented by previous studies. AS, Andaman Sea; IBR, Indo-Burman ranges; KL, Kohistan-
717 Ladakh arc; HXL, Hoh Xil Basin; NQ, Nangqian-Yushu Basin; GJ, Gongjo Basin; LP, Lanping
718 Basin; LZ, Lanzhou Basin; TH, Tethyan Himalaya thrust belt; FHST, Fenghuoshan thrust;
719 NQT, Nangqian thrust; WQL: western Qinling fault. A, B, C, and D represent the four sub-
720 terranes defined in Li et al. (2017b), including Southeast Indochina, Southern Simao, Northern
721 Simao, and Lanping.

722

723 **Fig. 10.** Schematic models illustrating (a) the acceleration of India and increased deformation
724 in Tibet by the push of the Deccan plume head at ~70 Ma, and the deceleration of India and
725 pulse of upper plate shortening by (b) slab break-off or (c) slab overturning at ~52 Ma
726 (Modified after Kapp et al. (2019), Zhu et al. (2015), and van Hinsbergen et al. (2019)).