

1 **Reworked Precambrian metamorphic basement of the Lhasa**
2 **terrane, southern Tibet: Zircon/Titanite U–Pb geochronology,**
3 **Hf isotope and Geochemistry**

4
5 Dong Xin^{1,2}, Zhang Zeming¹, Niu Yaoling², Tian Zuolin¹, Zhang Liangliang³

- 6
7 1. Key Laboratory of Deep-Earth Dynamics of Ministry of Land and Resources, Institute of
8 Geology, Chinese Academy of Geological Sciences, Beijing, 100037, China
9 2. Department of Earth Sciences, Durham University, Durham, DH1 3LE, UK
10 3. State Key Laboratory of Geological Processes and Mineral Resources, and Institute of Earth
11 Sciences, China University of Geosciences, Beijing, 100083, China

12 **ABSTRACT**

13 Due to the paucity of exposure, the formation and evolution of the Precambrian
14 basement of the Lhasa terrane remain poorly known. Here we report zircon and
15 titanite *in situ* U–Pb ages, bulk-rock geochemical and zircon Hf isotopic data on the
16 orthogneisses from the Dongjiu area of the southern Lhasa subterrane (SLT), southern
17 Tibet. Geochemical data suggest that the protoliths of the biotite-amphibole gneiss
18 and biotite gneiss are granodiorite and granite, respectively. Inherited magmatic
19 zircon cores from these orthogneisses give protolith crystalline ages of 1520–1506
20 Ma, whereas the overgrown zircon rims give metamorphic ages of 605–590 Ma. The

21 Mesoproterozoic granitic rocks have bulk-rock $\epsilon_{\text{Nd}}(t)$ values of -3.6 to +0.1 and zircon
22 core $\epsilon_{\text{Hf}}(t)$ values of -4.5 to +2.6, which give similar T_{DM2} ages of 2.35–2.05 Ga and
23 2.54–2.10 Ga respectively, suggesting their derivation from partial melting of
24 Paleoproterozoic crustal material. The granitic rocks are also local provenance for the
25 Mesoproterozoic detrital zircons in the Paleozoic strata in the Lhasa terrane. Titanite
26 *in situ* U–Pb ages further indicate that the Dongjiu orthogneiss experienced more
27 recent metamorphism at ~ 26 Ma. The mineral assemblage and thermobarometry
28 calculations indicate that the Oligocene metamorphism occurred under medium-
29 pressure (MP) amphibolite-facies conditions (5.4–7.2 kbar, 691–765 °C). We propose
30 that the Dongjiu gneisses represent the Precambrian metamorphic basement of the
31 Lhasa terrane, ~~the oldest basement rocks so far recognized~~, but have been intensively
32 reworked by metamorphism in the SLT in response to the continued India-Asia
33 convergence since the collision.

34

35 **Keywords:**

36 Zircon and Titanite *in situ* U–Pb dating; Mesoproterozoic; Precambrian metamorphic
37 basement; Reworking; Lhasa terrane

38

39 **1. Introduction**

40 Like much of the central and southeastern Asian geology, the Tibetan Plateau
41 formed via amalgamation of terranes during the Phanerozoic (Chang and Zheng,

42 1973; Allégre et al., 1984; Chang et al., 1986; Sengör and Natal'in, 1996; Yin and
43 Nie, 1996). However, our knowledge on the histories of these terranes prior to their
44 amalgamation remains limited. The early history of these terranes that make up the
45 Tibetan Plateau is obscured by the paucity of basement exposure, by the strong
46 reworking of basement rocks during the later thermal events, and by the
47 predominance of younger supracrustal rocks ~~with strong reworking of later thermal~~
48 ~~events~~.

49 As the main tectonic component of the Tibetan Plateau, the Lhasa terrane has
50 been considered to be composed dominantly of Paleozoic to Mesozoic strata,
51 Mesozoic and Cenozoic igneous rocks and Precambrian basement (e.g., Yin and
52 Harrison, 2000; Pan et al., 2004, 2006). The nature and spatial distribution of the
53 Precambrian basement beneath the entire terrane ~~have~~ been speculative. The
54 limited works on the basement to date suggest that the Lhasa terrane crust is relatively
55 young (< ~~2.045~~ Ga). U–Pb dating of zircons in gneissic rocks shows the presence of
56 the Neoproterozoic crystalline crust in the Amdo block (~ 850 ~~and 500~~ Ma, Guynn et
57 al., 2006, 2012; Zhang et al., 2012a) and in the Xainza area in the central Lhasa
58 subterrane (CLT) (~ 925–760 Ma, Hu et al., 2005; Zhang et al., 2012b; Hu et al.,
59 ~~Proterozoic~~ ~~Mesoproterozoic~~ 2018a, b; Zeng et al., 2018). There is also ~~Proterozoic~~ ~~Mesoproterozoic~~ crystalline
60 basement in the Bomi area in the eastern CLT (ca. 1866 Ma, ~~(~ 1343–and 1250 Ma~~
61 and 824 Ma, Xu et al., 2013a; Chen et al., 2019) (Fig. 1a). These ages represent the
62 only known Precambrian crystalline basement from the Lhasa terrane. Nd–Hf isotopic
63 model ages have been used to suggest that the crust of the Lhasa terrane may be older,

64 perhaps even Archean. Bulk-rock Nd isotope data on the Amdo Cambrian orthogneiss
65 give Mesoproterozoic model ages (Harris et al., 1988a), while bulk-rock Nd and
66 zircon Hf isotopic data on the Cretaceous granitoids of the Lhasa terrane yield
67 Proterozoic and Archean model ages (Chiu et al., 2009; Zhu et al., 2009a). Zhu et al.
68 (2011) suggest that the CLT was once a microcontinent with Proterozoic and Archean
69 basement rocks, whereas the southern and northern parts of the Lhasa terrane are
70 dominated by younger juvenile ~~granitoid~~ crust. However, zircon Hf isotopic mapping
71 for the Mesozoic-Cenozoic magmatic rocks shows that the eastern segment of the
72 northern Lhasa subterrane (NLT) is an ancient block; the southern Lhasa subterrane
73 (SLT) is not entirely a juvenile block with inhomogeneity of crustal compositions
74 (Hou et al., 2015). However, no Archean rocks have been identified so far. It is
75 possible that the enriched radiogenic isotopic compositions could have resulted from
76 the assimilation of melted sedimentary rocks that were themselves sourced from older
77 continents (e.g., Indian craton), rather than from pre-Neoproterozoic basement of the
78 Lhasa terrane itself (Ding et al., 2003). Therefore, the true and complete constituent of
79 the Precambrian basement beneath the Lhasa terrane remains to be revealed.

80 In this paper, we report the results of ~~our~~ petrological, geochronological and
81 geochemical studies on reworked Precambrian metamorphic basement rocks from the
82 Dongjiu area of the SLT (Fig. 1). The ~~Dongjiu~~ metamorphic rocks not only provide
83 information on their protolith, but also record two episodes of subsequent
84 metamorphism and Phanerozoic reworking of the Precambrian basement of the Lhasa
85 terrane.

87 2. Geological setting and sample description

88 2.1. Geological setting

89 The Lhasa terrane on the southern segmentmargin of the Tibetan Plateau is
90 located between the Qiangtang terrane and Himalayan belt, bounded by the Bangong-
91 Nuijiang suture zone to the north and the Indus-Yarlung Zangbo suture zone to the
92 south (Fig. 1a). From north to south, the Lhasa terrane has been divided into the
93 northern (NLT), central (CLT) and southern (SLT) subterrane, separated by the
94 Shiquan River-Nam Tso mélange zone to the north and the Luobadui-Milashan fault
95 to the south (Fig. 1a; Zhu et al., 2009a).

96 The NLT is characterized by the presence of juvenile crust and absence of a
97 Precambrian basement (cf. Pan et al., 2004; Zhu et al., 2011). The sedimentary cover
98 in the NLT is mainly Jurassic–Cretaceous with minor Triassic in age (e.g., Pan et al.,
99 2004, 2006; Nimaciren et al., 2005). Voluminous Mesozoic volcanic rocks are
100 exposed in this subterrane, and Mesozoic plutonic rocks are mainly confined to its
101 western and eastern segments generally as huge batholiths (e.g., Zhu et al., 2011).

102 The CLT is covered with the widespread Permo-Carboniferous metasedimentary
103 rocks, plus minor Ordovician, Silurian, and Triassic strata (cf. Pan et al., 2004). The
104 volcanic rocks in this subterrane are mostly early Cretaceous in age with minor being
105 Permian. The Mesozoic plutonic rocks occur as batholiths of varying age (~ 215–88
106 Ma; cf. Zhu et al., 2011 and references therein). Cambrian volcanic rocks are

107 scattered in the west and middle of the CLT (Fig. 1a, Zhu et al., 2012; Hu et al., 2013;
108 Ding et al., 2015). The late Permian high-pressure eclogite and late Triassic–early
109 Jurassic metamorphic rocks are exposed in the middle and eastern parts of the CLT
110 (e.g., Yang et al., 2009; Zeng et al., 2009; Dong et al., 2011a; Lin et al., 2013a; Cheng
111 et al., 2015; Weller et al., 2015; Chen et al., 2017). The Nyainqêntanglha Group in the
112 middle part of the CLT has been interpreted as its Precambrian basement (Li, 1955;
113 Allégre et al., 1984; Harris et al., 1988b; Pan et al., 2004). On the basis of zircon U–
114 Pb dating, the protoliths of the Nyainqêntanglha Group near Xainza area were
115 emplaced in the Neoproterozoic (Fig. 1a, Hu et al., 2005; Zhang et al., 2012b; Hu et
116 al., 2018a, b; Zeng et al., 2018). Recent petrological studies with zircon U–Pb age
117 data reveal that the rocks from the Xainza area are the relics of the Neoproterozoic (~
118 900 Ma) ocean crust metamorphosed subsequently at ~ 690–650 Ma (Dong et al.,
119 2011b; Zhang et al., 2012b). Moreover, Xu and co-workers (Xu et al., 2013a; Chen
120 et al., 2019) reported the presence of ~~Proterozoic~~~~Mesoproterozoic~~ basement with a
121 crystallization ~~ages~~ of ~~ca. 1866–1300 Ma, 1343–1250 Ma and 824 Ma from the~~
122 ~~Bomi complex~~ in the southeastern ~~part of the~~ CLT. ~~Chen et al. (2019) suggested that~~
123 ~~these Proterozoic gneisses revealed two metamorphic events at ca. 625–600 Ma and~~
124 ~~80 Ma~~. These new data confirm the presence of a Precambrian metamorphic basement
125 in the CLT.

126 The SLT is mainly composed of the Paleogene volcanic rocks, Cretaceous–
127 Tertiary intrusions, Triassic–Cretaceous volcano-sedimentary rocks and minor
128 medium- to high-grade metamorphic rocks (e.g., Pan et al., 2004; Zhu et al., 2008,

129 2013; Zhang et al., 2014a). The sedimentary cover in the SLT is largely restricted to
130 its eastern segment (cf. Pan et al., 2004). The Nyingchi complex in the eastern SLT
131 has been interpreted as the Precambrian basement (Pan et al., 2004; Yin et al., 2003;
132 Xie et al., 2007). However, more recent studies indicated that ~~most~~the protoliths of
133 the Nyingchi complex included both sedimentary and magmatic rocks of Cambrian (~
134 496 Ma), Devonian (~ 360 Ma), Cretaceous (~ 90 Ma) and Eocene (~ 55 Ma),
135 metamorphosed in the Mesozoic to Cenozoic (Dong et al., 2010, 2012, 2014; Guo et
136 al., 2011, 2012; Palin et al., 2014; Xu et al., 2013b; Zhang et al., 2010, 2013, 2014a,
137 b, 2015). Based on zircon U–Pb dating, Lin et al. (2013b) reported a metamorphic age
138 of ~ 600 Ma from the Nyingchi complex in the eastern SLT, with a protolith age of ~
139 1780 Ma. However, their samples are close to the northeast of the Eastern Himalayan
140 Syntaxis, and are widely intruded by the Mesozoic–Cenozoic granitoids or occur as
141 xenoliths within these granitoids (Lin et al., 2013b).~~gneisses in the eastern SLT.~~
142 Therefore, a Precambrian crystalline basement may indeed be present at least locally
143 in the SLT.

144 ~~The present~~Our study area is located northwest of the Dongjiu area at the eastern
145 edge of the SLT, where metamorphic rocks and Cenozoic intrusive rocks are exposed
146 (Fig. 1b). The metamorphic rocks are offset by an east-west fault. The rocks north of
147 the fault include schists and gneisses that experienced ~~amphibolite-facies~~peak
148 kyanite-grade metamorphism at ~ 190 Ma (Chen et al., 2017). The studied samples
149 ~~are~~rocks in the south comprise gneisses collected south of the fault. These
150 metamorphic rocks are all intruded by the Cenozoic granites (~ 40–25 Ma; Booth et

151 al., 2004). ~~The studied samples are gneisses collected south of the fault (Figs. 1b and~~
152 ~~2).~~

153 2.2. Sample description

154 Sample details are given in Table 1, including protolith type, location, mineral
155 assemblage, protolith ~~and age~~, metamorphic ~~ages~~ and metamorphic P - T
156 conditions.

157 The biotite-amphibole (Bt-amp) gneisses consist of plagioclase (~30 vol%), K-
158 feldspar (~15 vol%), quartz (~35 vol%), amphibole (~10 vol%), biotite (~5 vol%),
159 titanite (~3 vol%), allanite (~1 vol%), and accessory phases including epidote,
160 ilmenite, apatite, rutile and zircon (Fig. 2a3a-d). The ~~biotite~~ Biotite (Bt) gneisses are
161 comprised of plagioclase (~20 vol%), K-feldspar (~35 vol%), quartz (~40 vol%),
162 biotite (~4 vol%), and accessory minerals of allanite, epidote, apatite and zircon (Fig.
163 2e3e, f). The foliation is defined by aligned biotite flakes and quartz-feldspar bands.
164 Thereinto, allanite occurs in two ways: those ~~with replaced by~~ epidote ~~at rims~~ and
165 zircon inclusions (Fig. 2c3e-e), ~~including zircon grains (Fig. 3e, d)~~, and those as
166 inclusions within titanite (Fig. 7f8f, g, m, o, p). Most titanite grains ~~rim are rimmed by~~
167 ilmenite, and some have inclusions of biotite, allanite, apatite, plagioclase, quartz or
168 ~~minor~~ rutile. The ~~gneisses have a petrography shows the~~ mineral assemblage of
169 plagioclase + K-feldspar + biotite + quartz + epidote \pm amphibole \pm titanite.

170 The studied gneisses underwent partial melting as revealed by the following
171 evidence: presence of prior melt along grain boundaries is evident on thin section

172 ~~seals, such as~~ (1) feldspar grains with cusped extensions along quartz-quartz
173 contacts (Fig. ~~2b3b~~), (2) narrow trains of K-feldspar blebs along quartz-plagioclase
174 contacts (Fig. ~~2a3a~~, f), (3) adjacent grains of quartz, feldspar and biotite ~~grains~~ are
175 corroded (Fig. ~~2a3a~~, b, e, f). These microstructures are interpreted as crystallization
176 products/pseudomorphs of the former ~~presence of~~ melt (e.g., Sawyer, 2001; Brown,
177 2002; Timmermann et al., 2002).

178

179 **3. Analytical methods and results**

180 Analytical method details are given in **Supplementary Text 1**, including
181 Cathodoluminescence (CL) images, back scattered electron (BSE) images and
182 analytical data on mineral major elements, bulk-rock major and trace elements, Sr–Nd
183 isotopes, zircon U–Pb dating, trace elements and Hf isotopes, and titanite *in situ* U–Pb
184 dating.

185 **3.1. Mineral major element data**

186 Major element compositions of plagioclase and amphibole in the (Bt-amp gneiss
187 (samples 169-1 and 39-1) are given in **Supplementary Table 1** and **2**, respectively.

188 Plagioclase grains in both samples are oligoclase, with An contents of 0.28–0.30.
189 Amphibole grains have 10.98–11.68 wt% CaO and 1.19–1.42 wt% Na₂O classified as
190 calcic amphibole (Leake et al., 1997).

191 3.2. Bulk-rock major and trace element and Sr–Nd isotope data

192 Bulk-rock major element, trace element and Sr–Nd isotopic compositions on the
193 studied samples are given in [Table 2](#).

194 The Bt-amp gneiss samples (169-1, 169-2 and 39-1) have 64.2–68.4 wt% SiO₂,
195 15.0–15.7 wt% Al₂O₃, 3.33–3.80 wt% CaO, 3.40–4.10 wt% Na₂O and 2.40–3.72 wt%
196 K₂O. The Bt gneiss samples (168-1 and 169-4) are characterized by higher SiO₂
197 (70.3–71.9 wt%) and K₂O (4.33–5.34 wt%), but lower Al₂O₃ (13.9–14.7 wt%), CaO
198 (1.85–2.06 wt%) and Na₂O (3.21–3.38 wt%). Using the Ab-An-Or classification for
199 silicic rocks ([Barker, 1979](#)), the Bt-amp gneisses are granodiorite whereas the Bt
200 gneisses are granite ([Fig. 3a4a](#)). These granitoid gneisses are metaluminous ([Fig.](#)
201 [3b4b](#)), with the aluminum saturation indices (A/CNK = molecular Al₂O₃ / (CaO +
202 Na₂O + K₂O)) of 0.95–1.02.

203 These orthogneisses are enriched in light rare earth elements (REE) and
204 relatively depleted in heavy REEs with highly fractionated REE patterns ($((La/Yb)_N =$
205 [15.3–143.5](#)) and a weak negative Eu anomaly ($(Eu/Eu^* = 0.62–0.87)$ ($((La/Yb)_N =$
206 [15.3–143.5](#); [Fig. 4a5a, Table 2](#)). Furthermore, most samples display characteristic arc-
207 like signature of negative Nb, Ta and Ti anomalies (except for sample 169-2 without
208 Ti anomaly due to low REE contents, [Fig. 4b5b](#)).

209 For [the analyzed](#) four samples, their initial ⁸⁷Sr/⁸⁶Sr isotopic ratios and ε_{Nd}(t)
210 values calculated at $t = 1520$ Ma (see 3.3 below). The Bt-amp gneiss samples (169-1,
211 169-2 and 39-1) have ~~relatively high~~ initial ⁸⁷Sr/⁸⁶Sr ratios of 0.7008–0.7036 and
212 ε_{Nd}(t) values of -3.6 to +0.1, with model ages $T_{DM2} = 2.35–2.05$ Ga. The Bt gneiss

213 sample (168-1) gives $\epsilon_{\text{Nd}}(t) = -2.2$ and $T_{\text{DM2}} = 2.24$ Ga, with an abnormally low
214 $^{87}\text{Sr}/^{86}\text{Sr}_{\text{initial}} = 0.6866$. This unusual (~~Note that this initial Sr~~ isotopic ratio has no
215 petrogenetic significance because of the mobility of Rb, which led to the excessive
216 subtraction of $^{87}\text{Rb}/^{86}\text{Sr}$ ratio. Sr).

217 3.3. Zircon U–Pb age and Hf isotope

218 LA-ICP-MS zircon U–Pb dating and trace element analysis of five samples and
219 zircon Hf isotope compositions of four samples are given in **Supplementary Tables 3**
220 and **4**, respectively.

221 Zircon grains from the five gneisses are ~~mostly~~ colorless, subhedral–euhedral
222 oblong or prismatic with varying size of ~ 100 – 200 μm . CL images show that zircon
223 grains have a core–rim structure consisting of inherited cores with oscillatory zoning
224 and dark rims with weak or no zoning (**Figs. 56** and **6**). ~~The7~~. All the analyzed spots
225 on zircon cores from two Bt-amp gneiss samples (169-1 and 169-2) and two Bt gneiss
226 samples (168-1 and 169-4) yield weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ ages of 1519 ± 36 Ma ($n =$
227 $=5$, $\text{MSWD} = 0.016$), 1520 ± 18 Ma ($n = 12$, $\text{MSWD} = 0.85$), 1516 ± 15 Ma ($n =$
228 $=20$, $\text{MSWD} = 0.046$) and 1506 ± 6 Ma ($n = 16$, $\text{MSWD} = 0.45$), with upper
229 intercept ages of 1544 ± 47 Ma, 1551 ± 23 Ma, 1544 ± 26 Ma and 1498 ± 6 Ma,
230 respectively (**Figs. 5a6a, c** and **6a7a, c**). All analyzed spots on core domains have
231 relatively high Th contents (57.7–927 ppm), Th/U ratios (0.10–1.52) and REE
232 contents (170–1576 ppm) with remarkable negative Eu anomalies ($\text{Eu}/\text{Eu}^* = 0.07$ –
233 0.55) (~~;~~ **Figs. 5b6b, d** and **6b, d**, **Supplementary Tables 37b, d**). Analyzed spots on

234 zircon rims from three Bt-amp gneiss samples (169-1, 169-2 and 39-1) and one Bt
235 gneiss sample (168-1) yield weighted mean $^{206}\text{Pb}/^{238}\text{U}$ ages of 605 ± 27 Ma ($n = 15$,
236 $\text{MSWD} = 0.96$), 591 ± 3 Ma ($n = 14$, $\text{MSWD} = 0.54$) and 595 ± 2 Ma ($n = 21$,
237 $\text{MSWD} = 0.40$), with lower intercept ages of 585 ± 11 Ma, 592 ± 18 Ma, 588 ± 6 Ma
238 and 563 ± 10 Ma, respectively (Figs. 5a6a, c, e and 6a7a). Only one zircon rim spot
239 from sample 169-2 is obtained with $^{206}\text{Pb}/^{238}\text{U}$ age of 590 ± 2 Ma (Figs. 5c6e).
240 Compared with zircon cores, analyzed spots on rim domains have relatively low Th
241 contents (22.0–82.2 ppm), Th/U ratios (0.03–0.10) and REE contents (50.3–473
242 ppm), with weak or no negative Eu anomalies ($\text{Eu}/\text{Eu}^* = 0.21$ –1.86) (Figs. 5b6b,
243 d, f and 6a, Supplementary Tables 37a).

244 Therefore, the zircon LA–ICP–MS U–Pb analyses yield two age groups: 1520–
245 1506 Ma of weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age for zircon cores and 605–590 Ma of
246 weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age for zircon rims.

247 Fifty-three Hf isotopic analyses on zircon cores from two Bt-amp gneiss samples
248 (169-1 and 169-2) and two Bt gneiss samples (168-1 and 169-4) give initial
249 $^{176}\text{Hf}/^{177}\text{Hf}$ isotopic ratios of 0.281697–0.281891 and $\varepsilon_{\text{Hf}}(t)$ values ranging from -4.5
250 to +2.6, with two-stage model ages T_{DM2} of 2.54–2.10 Ga (Supplementary Tables 4).

251 3.4. Titanite *in situ* U–Pb age

252 Two titanite-rich gneiss samples (169-1 and 39-1) were selected for LA-ICP-MS
253 titanite *in situ* U–Pb dating. BSE images and photomicrographs of representative
254 titanite are shown in Fig. 78 and the titanite U–Pb dating and trace element data are

255 given in [Supplementary Table 5](#).

256 Most titanite crystals are brown and subhedral–anhedral in shape with inclusions
257 of ilmenite, biotite, allanite, apatite, plagioclase, quartz and ~~minor~~ rutile ([Fig.](#)
258 [78](#)). BSE images show that the titanite crystals mostly have patchy zoning. The
259 analyzed spots of titanite yield lower intercept ages are 25.1 ± 0.6 Ma for sample 169-1
260 ([Fig. 8a9a](#)) and 24.7 ± 0.5 Ma for sample 39-1 ([Fig. 8b9b](#)). After correction using
261 ^{207}Pb , the weighted mean $^{206}\text{Pb}/^{238}\text{U}$ ages are 26.2 ± 0.4 Ma ($n=40$, $\text{MSWD}=2.5$) and
262 26.0 ± 0.6 Ma ($n=29$, $\text{MSWD}=3.1$) ([Fig. 89](#)).

263

264 **4. Metamorphic P – T conditions**

265 **4.1. Hbl-Pl-Q thermobarometry**

266 Amphibole–plagioclase thermometry ([Holland and Blundy, 1994](#)) and
267 amphibole–plagioclase–quartz barometry ([Bhadra and Bhattacharya, 2007](#)) are used
268 to calculate the ~~peak~~ metamorphic P – T condition of the Bt-amp gneisses. The
269 ~~amphibole–plagioclase–quartz~~Hbl-Pl-Q thermobarometry yields metamorphic P – T
270 conditions of 6.2–7.2 kbar and 691–736 °C for sample 169-1, and 5.4–6.5 kbar and
271 716–765 °C for sample 39-1.

272 **4.2. Zr-in-titanite thermometry**

273 ~~Titanite~~For comparison, titanite formation temperatures ~~are~~were estimated using
274 the Zr-in-titanite thermometry (T (°C) = $[7708 + 960P] / [10.52 - \log(\alpha_{\text{TiO}_2}) -$

275 $\log(\alpha_{\text{SiO}_2}) - \log(\text{ppm Zr, titanite})] - 273$; Hayden et al., 2008). The activity of TiO_2 is
276 assumed to be 0.5 (plausible lower limits in typical crustal rocks), with SiO_2 activity
277 assumed as 1.0 (Hayden and Watson 2007; Ferry and Watson 2007). Based on
278 ~~amphibole-plagioclase-quartz~~~~Hbl-Pl-Q~~ barometer, the metamorphic pressure
279 conditions of the Bt-amp gneisses are ~ 6 kbar. Zr concentrations range from 158 to
280 591 ppm in sample 169-1, and from 276 ppm to 620 ppm in sample 39-1. The
281 calculations of Zr-in-titanite thermometry are 688–756 °C for sample 169-1 and 716–
282 759 °C for sample 39-1 (Supplementary Table 5). The temperature data display a
283 cluster at 700–750 °C (64/69, Fig. 910), which is consistent with the ~~peak~~ temperature
284 conditions obtained by the ~~amphibole~~~~Amphibole~~-plagioclase thermometry.

285

286 5. Discussion

287 5.1. Age interpretation

288 Zircon LA-ICP-MS U–Pb dating shows two age groups of 1520–1506 Ma and
289 605–590 Ma. Most zircons of the studied Dongjiu gneisses show euhedral-prismatic
290 forms and display rounded terminations, which in some cases generate an ovoid
291 morphology. CL images show that all zircon grains have a core–rim structure, i.e.,
292 oscillatory-zoned core and rim with ~~no or~~ weak or no zoning (Figs. 56 and 67). The
293 inherited zircon cores yield concordant ages of 1520–1506 Ma without detrital age
294 distribution (analyses with concordance $> 95\%$, Supplementary Tables 3). These
295 zircon cores have relatively high Th contents (usually > 50 ppm) with high Th/U

296 ratios (≥ 0.1 , up to 1) (Fig. 1044) and REE patterns with remarkable negative Eu
297 anomalies (Figs. 5b6b, d and 6b7b, d). These properties are consistent with the
298 zircons ~~being~~ of magmatic origin (e.g., Hoskin and Schaltegger, 2003). Thus, the
299 Mesoproterozoic ~~ageages~~ of ~ 1500 Ma given by the zircon cores ~~represents~~represent
300 the protolith crystallization age of the gneisses. By comparison, CL images show that
301 zircon rims have ~~no or~~ weak or no zoning. Most zircon rims occur as lobes with
302 smooth or rough edges, and may overprint pre-existing structures (Fig. 5b6b, f). All
303 these characteristics suggest that ~~most~~ zircon rims have developed during
304 metamorphic recrystallization near the solidus (Hoskin and Black, 2000; Rubatto,
305 2017). The zircon rims have lower Th contents (usually < 50 ppm) and Th/U ratios ($<$
306 0.1) (Fig. 1044) without remarkable negative Eu anomalies (Figs. 5b6b, d, f and
307 6b7b), which are ~~indeed~~ consistent with ~~being of~~ metamorphic zirconorigin (e.g.,
308 Rubatto et al., 2009; Rubatto, 2017). Based on the zircon internal structure, Th/U
309 ratios and REE patterns, we suggest that the zircon rims provide the metamorphic
310 ages of 605–590 Ma for the orthogneisses in the Dongjiu area ~~in the SLT~~.

311 Titanite crystals from two Bt-amp gneiss samples are ~~all~~ subhedral–anhedral in
312 shape with metamorphic mineral inclusions of ilmenite, biotite, allanite, plagioclase,
313 quartz or minorrutile (Fig. 78). BSE images show that titanite crystals have
314 patchy zonation, characteristic of metamorphic titanite (Rubatto, 2017). Therefore,
315 LA–ICP–MS titanite *in situ* U–Pb dating indicates that these gneisses experienced
316 Oligocenemetamorphism at ~ 26 Ma.

317 In summaryconclusion, the protolithprotolith of the gneisses from the Dongjiu

318 area ~~of the SLT~~ crystallized in the Mesoproterozoic (1520–1506 Ma), and followed
319 by subsequent metamorphism in the Neoproterozoic (605–590 Ma) and more recently
320 in the Oligocene (~ 26 Ma).

321 **5.2. Mesoproterozoic magmatism**

322 The Lhasa terrane, as the southernmost part of the Asian continent, experienced
323 intense deformation, magmatism and metamorphism related to the northward Neo-
324 Tethyan seafloor subduction in the Mesozoic and the India-Asia continental collision
325 in the Cenozoic (e.g., [Zhu et al., 2011](#); [Zhang et al., 2014a](#)). Due to [these](#) strong
326 reworking [processes](#), the Precambrian thermotectonic records are rarely reported (e.g.,
327 [Dong et al., 2010, 2011b](#); [Guynn et al., 2012](#); [Zhang et al., 2012b](#); [Xu et al., 2013a](#);
328 [Hu et al., 2018b](#); [Chen et al., 2019](#)).

329 Based on the zircon U–Pb geochronology, the inherited magmatic zircon cores of
330 the Dongjiu gneisses yield crystallization ages of 1520–1506 Ma (lack detrital
331 components; see above), indicate that the protoliths of Dongjiu gneisses are
332 Mesoproterozoic magmatic rocks. The bulk-rock chemical compositions of the
333 Dongjiu gneisses suggest that their protoliths are metaluminous granodiorite and
334 granite ([Fig. 34](#)), characteristic of arc-like signature with negative Nb, Ta and Ti
335 anomalies ([Fig. 4b5b](#)). The Mesoproterozoic granitic rocks have bulk-rock $\epsilon_{Nd}(t)$
336 values of -3.6 to +0.1 and zircon $\epsilon_{Hf}(t)$ values of -4.5 to +2.6, with similar T_{DM2} ages
337 of 2.35–2.05 Ga and 2.54–2.10 Ga, respectively, suggesting that the magmatic rocks
338 are derived from partial melting of Paleoproterozoic crustal material.

339 The coeval ~ 1500 Ma magmatic rocks are widespread in several continental
340 fragments ~~in different tectonic settings~~, including West Africa, South America, North
341 America, Australia, Baltica (Northern Europe), Siberia and India. The rock types are
342 mainly mafic dikes and sills (e.g., [Ernst et al., 2013, 2016](#); [Silveira et al., 2013](#)), and
343 massif-type anorthosites (e.g., [Emslie, 1978](#); [Weis, 1986](#); [Sadowski and Bettencourt,](#)
344 [1996](#); [Mukherjee and Das, 2002](#)). The Mesoproterozoic Era, dominated by the break-
345 up of the Columbia supercontinent and the formation of the Rodinia supercontinent,
346 was an important crust-forming period in many continents in Earth's history. The
347 global Mesoproterozoic magmatism has commonly been attributed to the rifting and
348 fragmentation of the Columbia supercontinent (e.g., [Rogers and Santosh, 2002](#); [Zhao](#)
349 [et al., 2003](#)). However, ~ 1.6–1.5 Ga metamorphic and magmatic rocks of the Central
350 Indian Tectonic Zone are the products of south-north Indian subcontinental collision
351 (e.g., [Acharyya, 2003](#); [Kröner et al., 2012](#)). For the studied Mesoproterozoic granitic
352 rocks in the SLT, it is too ~~early and~~ difficult to discuss the tectonic setting in a global
353 context owing to their limited distribution and subsequent reworking.

354 The Mesoproterozoic inherited zircons in the Gangdese batholith (e.g., [Zhu et al.,](#)
355 [2011](#); [Ji et al., 2017](#)), and detrital zircons from the sedimentary rocks of the
356 Carboniferous–Triassic strata ([Leier et al., 2007](#); [Pullen et al., 2008](#); [Dong et al.,](#)
357 [2010](#); [Zhu et al., 2013](#); [Li et al., 2014](#); [Guo et al., 2017](#)) indicate that the
358 Mesoproterozoic magmatic rocks are probably more widely distributed than exposed
359 in the Lhasa terrane. Moreover, the metasedimentary rocks from the Nyingchi
360 complex in the SLT contain abundant ~1500 Ma detrital zircons ([Guo et al., 2017](#)).

361 The 1550–1450 Ma detrital zircons from the CLT Permian–Triassic strata define a
362 broad band of $\varepsilon_{\text{Hf}}(t)$ values (-16.7 to +9.6; Fig. 1142). By comparison, the coeval
363 detrital zircons from the SLT metasedimentary rocks have lower $\varepsilon_{\text{Hf}}(t)$ values (-11.3
364 to +3.2; Fig. 1142). The studied Mesoproterozoic granitic rocks, with the coeval
365 gneisses of the southern Nyingchi complex (our unpublished data) have the similar
366 zircon $\varepsilon_{\text{Hf}}(t)$ values as the above, suggesting that they might be local sources for the
367 Mesoproterozoic detrital zircons of the Paleozoic strata (Fig. 1142).

368 **5.3. Neoproterozoic and Oligocene metamorphism**

369 Based on zircon and titanite U–Pb geochronology, the Dongjiu orthogneisses
370 experienced two metamorphic events at 605–590 Ma recorded by zircon and 26 Ma
371 by titanite, respectively.

372 **5.3.1. Neoproterozoic metamorphism**

373 Due to the Oligocene metamorphism, the Neoproterozoic metamorphic minerals
374 are usually overprinted. The petrography shows that ilmenite is all surrounded by
375 titanite; rare rutile only occurs as inclusions within titanite; and allanite is rimmed by
376 epidote including zircon grains (Figs. 2c3e, d and 78). Along with titanite formed in
377 the later metamorphism, we speculate that the mineral assemblage of the
378 Neoproterozoic metamorphism is represented as ilmenite and allanite. Lacking index
379 metamorphic minerals, it is difficult to calculate the detailed P – T conditions of the
380 Neoproterozoic metamorphism for the studied gneisses. However, the characteristics

381 of zircon internal structure and chemistry show that zircon rims of the Dongjiu
382 gneisses likely form under conditions near solidus. Rubatto et al. (2009) show that the
383 metamorphic zircon rims of metatonalite with the similar mineral assemblage to this
384 study formed under amphibolite-facies condition ($T = 620\text{--}700\text{ }^{\circ}\text{C}$). For diorite bulk
385 composition, recent phase equilibrium modeling indicated that the H_2O -saturated
386 (wet) solidus occurs between $\sim 650\text{--}700\text{ }^{\circ}\text{C}$ and garnet becomes stable above ~ 8.5
387 kbar (e.g., Palin et al., 2016). On the formation condition of zircon rim, bulk
388 composition and lack of garnet, we reasonspeakulate that the Dongjiu granitic gneisses
389 underwent MPmedium-pressure amphibolite-facies metamorphism at 605–590 Ma.

390 According to the Gondwana-derived affinity, the ~ 600 Ma metamorphic event
391 of the Lhasa terrane is likely related to the assembly of Gondwana supercontinent
392 (e.g., Meert, 2003; Veevers, 2004; Collins and Pisarevsky, 2005). Early
393 palaeogeographic models based on limited data interpreted the presence of a single
394 super-continent throughout the Proterozoic (Piper, 1976). McWilliams (1981)
395 suggested that two Neoproterozoic continental masses, East Gondwana (India, East
396 Australia, Antarctica, Madagascar and Sri Lanka) and West Gondwana (Africa and
397 South America) collided along the Mozambique Belt to form Gondwana. Form the
398 Rodinia fragments to the final amalgamation Gondwana, there have been many
399 accretionary terranes and collisional events (Collins and Pisarevsky, 2005). Although
400 more work is needed on details of such amalgamation. Meert and co-workers (Meert,
401 et al., 1995; Meert and Van der Voo, 1997; Meert, 2001, 2003) suggested a
402 multiphase assembly of two main periods of orogenesis, including an earlier East

403 African Orogeny (EAO) (~ 750–620 Ma) and a later Kuunga Orogeny (~ 570–530
404 Ma). The later orogeny marks the collision of Australia and Antarctica with the rest of
405 Gondwana and was subsequently correlated with a broad belt of orogenesis from the
406 Damara Orogen in the west to the Pinjarra Orogen in the east (Meert, 2003). They
407 proposed a Neoproterozoic continent consisting of Sri Lanka, Madagascar and India
408 colliding with a combined Congo/Kalahari (African) continent at ~ 750–620 Ma,
409 followed by Australia/East Antarctica colliding with the bulk of Gondwana at ~ 570–
410 530 Ma (Meert, 2003; Meert and Torsvik, 2003). However, Boger and Miller (2004)
411 proposed that the EAO evolved as an accretionary orogeny and was partially
412 superimposed by a ~ 590–560 Ma orogen created by the collision of combined India,
413 Madagascar and part of Antarctica land masses with eastern Africa along the
414 Mozambique suture. In their model, Australia–Antarctica collided with India along
415 the Kuunga suture at ~ 535–520 Ma. Until now, the Precambrian metamorphic events
416 of the Lhasa terrane are only reported in the Nyainqêntanglha Group in the central
417 CLT (~ 690–650 Ma, Dong et al., 2011b; Zhang et al., 2012b), the Bomi complex in
418 the eastern CLT (~ 625–600 Ma, Chen et al., 2019), and the Nyingchi complex in the
419 eastern SLT (~ 600 Ma, Lin et al., 2013b and this study). The Nyainqêntanglha Group
420 experienced an early granulite-facies peak-metamorphism at ~ 690–650 Ma, and late
421 amphibolite-facies retrogression at ~ 480 Ma (Dong et al., 2011b; Zhang et al.,
422 2012b). Zhang et al. (2012b, 2014a) suggested that the Neoproterozoic metamorphism
423 occurred during the assembly of East and West Gondwana within the EAO. For all
424 other Precambrian metamorphic events, only the Nyingchi complex is speculated to

425 experience MP amphibolite-facies metamorphism without knowing exact P - T
426 conditions due to the Cenozoic metamorphic reworking. Therefore, this study
427 suggests that the ~ 600 Ma metamorphism events recorded in the Nyingchi complex
428 in the eastern SLT and the Bomi complex in the eastern CLT are likely response to
429 the assembly of Gondwana supercontinent.

430 **5.3.2. Oligocene metamorphism and melting**

431 In this study, titanite formed at ca. ~ 26 Ma is observed either mostly rimming
432 ilmenite or as separate grains. Titanite can be in contact with a variety of minerals,
433 e.g., amphibole, biotite, plagioclase and epidote, and contains inclusions of biotite,
434 allanite, plagioclase and quartz (Fig. 78). The formation of titanite rims on the
435 ilmenite could be explained in terms of reactions such as: ilmenite + allanite + K-
436 feldspar + quartz = titanite + anorthite + annite + H₂O (Harlov et al., 2006; Angiboust
437 and Harlov, 2017). Titanite rimming ilmenite is commonly present in the amphibolite-
438 facies rocks (e.g., Nijland and Maijer, 1993; Nijland and Visser, 1995; Hansen et al.,
439 2002; Harlov and Hansen, 2005). The mineral assemblage (plagioclase + K-feldspar +
440 biotite + quartz + epidote \pm amphibole \pm titanite) also indicates that the later
441 Oligocene metamorphism occurred at amphibolite-facies condition. Hbl-Pl-Q
442 thermobarometry shows that the Dongjiu gneisses experienced peak P - T conditions
443 of 5.4–7.2 kbar and 691–765 °C. Zr-in-titanite thermometry yields the similar T
444 conditions of 688–759 °C at ~ 6 kbar. Moreover, the microstructure proves that these
445 studied gneisses record the presence of melt, ~~along grain boundaries~~. Therefore, we

446 suggest that the prior ~~presence of~~ melt ~~represents~~represent the product of the
447 Oligocene metamorphism, and the Dongjiu ~~granitic~~gneisses underwent ~~MP~~medium-
448 ~~pressure~~ amphibolite-facies metamorphism and melting at ca.~ 26 Ma. In the southern
449 part of the studied area, the coeval metamorphic rocks of the Nyingchi complex have
450 also been reported to take place under amphibolite-facies conditions (e.g., Zhang et
451 al., 2010; Dong et al., 2012; Palin et al., 2014; Kang et al., 2019).

452 **5.4. The nature of the Precambrian basement of the Lhasa terrane**

453 The spatial distribution and nature of the Precambrian basement beneath the
454 entire Lhasa terrane ~~have~~has been speculative. Duo to medium- to high-grade
455 metamorphism, the Nyainqêntanglha Group in the CLT and the Nyingchi complex in
456 the SLT have been regarded as the Precambrian metamorphic basement (Xu et al.
457 1985; Dewey et al. 1988; Harris 1988b; Hu et al. 2005). However, adequate age
458 constraints are lacking. Based on zircon Hf isotope data, Zhu et al (2011) suggested
459 that the CLT has ancient basement rocks of Proterozoic and Archean ages with NLT
460 and SLT being younger and juvenile crust (Phanerozoic) accreted towards the CLT.

461 The Amdo basement, consisting of orthogneisses and mafic granulites, is
462 reported to represent the Precambrian basement of the Lhasa terrane (Xu et al., 1985;
463 Coward et al., 1988; Kidd et al., 1988; Pan et al., 2004). The gneisses have
464 crystallization ages of Neoproterozoic (~820 Ma; Zhang et al., 2012a) and Cambro-
465 Ordovician (540–460 Ma; Xu et al., 1985; Xie et al., 2010; Guynn et al., 2012; Zhang
466 et al., 2012a). The mafic granulites ~~have undergone~~underwent peak granulite-facies

467 metamorphism at ~ 190 Ma and retrogressed under amphibolite-facies conditions at ~
468 180 Ma (e.g., Xu et al., 1985; Guynn et al., 2006; Zhang et al., 2012a; Zhang XR et
469 al., 2014). Therefore, the Amdo gneiss represents a Neoproterozoic crystallization
470 basement, which ~~undergoes~~~~underwent~~ metamorphism in the early Jurassic.

471 The existence of a Precambrian basement in the CLT has been previously
472 inferred using older inherited zircon ages of the gneiss (Allégre et al., 1984) and the
473 bulk-rock Nd isotope composition from sedimentary rocks (Zhang KJ et al., 2007).
474 Recently reported old rocks are the ~~ca.~~~ 925–748 Ma granitoids and gabbros of the
475 Nyainqêntanglha Group in the Xianza area west of Nam Tso Lake (Hu et al., 2005;
476 Zhang et al., 2012b; Hu et al., 2018 a, b; Zeng et al., 2018). These rocks have
477 experienced ~~amphibolite-to~~ granulite-facies ~~peak~~-metamorphism at ~~ca. 690~680~~–650
478 Ma ~~and 480 Ma~~ (Dong et al., 2011b; Zhang et al., 2012b). Some studies suggest that
479 the Neoproterozoic magmatic rocks are crust of the Mozambique Ocean (Zhang et al.,
480 2012b; Zeng et al., 2018), but others propose that these rocks formed in a back-arc
481 setting (Hu et al., 2018 a, b). In addition, the Bomi complex consists of the
482 Proterozoic magmatic rocks formed at ca. 1866 Ma, 1343–1250 Ma and 824 Ma, and
483 undergoes metamorphism at ca. 625–600 Ma and 80 Ma (Xu et al., 2013a; Chen et al.,
484 2019). Thereinto, the Paleoproterozoic and Neoproterozoic granitoid gneisses show
485 geochemical affinity of volcanic arc granites (Chen et al., 2019); the Mesoproterozoic
486 granite gneisses have an aluminous A-type granite affinity (Xu et al., 2013a).
487 However, there is no constraint on the metamorphic condition. Therefore, the CLT
488 indeed has~~In addition, Xu et al. (2013a) reported ~1343 and 1250 Ma A-type granites~~

489 ~~in the eastern CLT. These Mesoproterozoic granitoids have zircon T_{DM2} ages of 2.1–~~
490 ~~1.4 Ga, suggesting that CLT may have~~ Proterozoic basement.

491 In the SLT, the Nyingchi complex has been interpreted to represent slivers of a
492 Precambrian basement of the Lhasa terrane (e.g., Pan et al., 2004; Xie et al., 2007;
493 Yin et al., 2003). However, more recent studies suggested that ~~most~~some high-grade
494 metamorphic rocks in the eastern SLT underwent Mesozoic to Cenozoic
495 metamorphism and their protoliths included both sedimentary and magmatic rocks
496 with various protolith ages (Dong et al., 2010, 2012, 2014; Guo et al., 2011, 2012,
497 2017; Palin et al., 2014; Xu et al., 2013b; Zhang et al., 2010, 2013, 2014a, 2014b,
498 2015). Here, the Dongjiu gneisses, as a part of ~~the~~ Nyingchi complex, have ~~a~~ protolith
499 crystalline age of 1520–1506 Ma, and experienced amphibolite-facies metamorphism
500 at 605–590 Ma, representing a Precambrian metamorphic basement of the SLT.

501 Moreover, the studied Mesoproterozoic granitic rocks have T_{DM2} of ~~2.545–2.10 Ga,~~
502 ~~along with Meso- to Paleoproterozoic zircon Hf model ages of Cambrian and~~
503 ~~Devonian–Carboniferous granitoids (Ji et al., 2012; Dong et al., 2014, 2015), 1–Ga,~~
504 implying the presence of an older early Paleoproterozoic crust ~~yet unidentified~~ in the
505 SLT.

506 ~~Excluding~~Until now, the ~~ca. 1780 Ma xenoliths reported by Lin et al. (2013b),~~
507 ~~the~~ ~ 1500 Ma granitic gneisses from the Dongjiu area ~~we report~~ here are the oldest
508 rocks reported of the ~~SLT Lhasa terrane~~. The zircon Hf and bulk-rock Nd isotopes
509 give similar T_{DM2} ages up to 2.5 Ga, suggesting that the Mesoproterozoic granitic
510 rocks are derived from melting of the Paleoproterozoic crustal material. ~~By contrast,~~

511 ~~the ~1300 Ma granitoids from the CLT have younger zircon Hf T_{DM2} age of 2.0–1.4~~
512 ~~Ga. Moreover, the ~ 1500 Ma gneisses from the southern Nyingchi complex give~~
513 ~~Paleoproterozoic zircon Hf model ages (Fig. 11, our (unpublished data). By~~
514 ~~comparison, the Proterozoic granitoids from the Bomi complex in the CLT have~~
515 ~~similar zircon Hf T_{DM2} ages ranging from 2.5 to 1.) give zircon Hf T_{DM2} age of 2.3 Ga~~
516 ~~(Xu et al., 2013a; Chen et al., 2019). Furthermore, the magmatic rocks (before 360~~
517 ~~Ma) from both the SLT and CLT have the same ranges of zircon $\epsilon_{Hf}(t)$ values and~~
518 ~~model ages (Fig. 11).–1.7 Ga. Therefore, we suggest thateither the SLT is~~
519 ~~heterogeneous with older Precambrian basement than the CLT or the SLT and CLT~~
520 ~~share a common Precambrian basement, but older rocks have not yet been identified~~
521 ~~in the CLT. We prefer the latter to be more likely because before 360 Ma, the~~
522 ~~magmatic rocks from both the SLT and CLT share the same $\epsilon_{Hf}(t)$ range and the same~~
523 ~~range of model ages (Fig. 12).~~

524 **5.5. Reworking of the Precambrian basement of the Lhasa terrane**

525 Although both SLT and CLT share a common Precambrian basement, the strong
526 thermal events (including metamorphism and mainly mantle-derived magmatism) as a
527 consequence of the northward subduction of the Neo-Tethyan seafloor beneath the
528 Lhasa terrane and the subsequent India-Asia continental collision have intensively
529 reworked the Precambrian basement.

530 Since the early Mesozoic, important mantle contributions have caused the
531 drastically elevated zircon $\epsilon_{Hf}(t)$ of the magmatic rocks from the SLT (Fig 11~~12~~).

532 However, their zircon $\epsilon_{\text{Hf}}(t)$ values vary significantly (up to 20 units from ~ -5 to $+15$;
533 Fig. 1142), indicating the presence of old basement. The input of mantle material not
534 only contributed to juvenile continental crust growth (e.g., Mo et al., 2007; Zhu et al.,
535 2011), but also reworked the Precambrian basement of the SLT. In contrast, the
536 granitoids from the CLT exhibit negative zircon $\epsilon_{\text{Hf}}(t)$ and old T_{DM2} ages, suggesting
537 that they ~~are~~ were mainly derived from partial melting of ancient continental crust.
538 Therefore, the basement of the CLT underwent weaker reworking, preserving more
539 rocks with Nd-Hf isotopes characteristic of ancient continental crust than the SLT.

540 This study shows that the Precambrian metamorphic basement of the Lhasa
541 terrane has also undergone more recent metamorphism at ~ 26 Ma. Due to similar
542 metamorphic conditions, it is difficult to distinguish mineral assemblages as the result
543 of recent metamorphism from those of the Neoproterozoic metamorphism, except for
544 the preserved inclusions of ilmenite and allanite. The main mineral assemblage of
545 plagioclase + K-feldspar + biotite + quartz + epidote \pm amphibole \pm titanite is the
546 product of the Oligocene metamorphism. The coeval metamorphic rocks have been
547 widely reported in the south part of the Nyingchi complex (e.g., Zhang et al., 2010,
548 2014a; Guo et al., 2011; Dong et al., 2012; Palin et al., 2014; Kang et al., 2019).
549 Zhang et al. (2015) suggested that the crustal shortening and thickening resulting from
550 the continental collision and continued convergence is the very ~~tectonic~~ physical
551 mechanism for the Oligocene reworking of the Lhasa terrane crust.

552

553 6. Conclusion

554 (1) The protoliths of the Dongjiu ~~orthogneisses~~gneisses in the SLT are granodiorite
555 and granite emplaced at 1520–1506 Ma, which provide source materials for the
556 Paleozoic metasedimentary rocks in the Lhasa terrane. ~~The~~On the basis of crustal
557 ~~model ages using bulk rock Nd and zircon Hf isotopes, we conclude that the~~
558 Mesoproterozoic granitoids ~~must~~ have derived from partial melting of earlier
559 Paleoproterozoic crustal material.

560 (2) The Mesoproterozoic ~~orthogneisses~~granitic gneisses from the Dongjiu area have
561 experienced the Neoproterozoic (605–590 Ma ~~on zircon U-Pb dating~~)
562 metamorphism, and therefore represent the Precambrian metamorphic basement
563 of the SLT.

564 (3) The Dongjiu gneisses also underwent the Oligocene (26 Ma ~~on titanite in situ U-~~
565 ~~Pb dating~~) metamorphism under MP~~medium-pressure~~ amphibolite-facies
566 conditions as the result of crustal shortening and thickening in response to the
567 continued India-Asia continental convergence.

568 (4) The CLT and SLT share a common Precambrian metamorphic basement, but the
569 SLT basement has been strongly reworked by mantle-derived magmatism and
570 metamorphism since the Mesozoic.

571

572 Acknowledgments

573 We want to thank two anonymous journal referees and Editor Guochun Zhao for

574 their constructive comments, which have helped improve the quality of this paper.

575 This study was supported by the National Natural Science Foundation of China

576 (grants 41872070 and 91855210) and the ~~Geological Survey Project of the~~ China

577 Geological Survey (grants DD20160122~~DD20160022~~ and

578 DD20190057~~DD20160201~~). Xin Dong acknowledges the China Scholarship Council

579 for funding a 12-month research at Durham University, UK (CSC NO.

580 201809110024). We thank Dr. Zhenyu He, Hua Xiang and Fenghua Liang for their

581 support of this work; ~~Dr. Ph.D. students~~ Zhengbin Gou and Huixia Ding for taking

582 part in field work, and Ph.D. students Yanhong Chen and Fangyu Shen for helpful

583 discussion.

584

585 **References**

586 Acharyya, S.K., 2003. The Nature of Mesoproterozoic Central Indian Tectonic Zone

587 with Exhumed and Reworked Older Granulites. *Gondwana Res.* 6 (2), 197–214.

588 Allégre, C.J., et al., 1984. Structure and evolution of the Himalaya–Tibet orogenic

589 belt. *Nature* 307, 17–22.

590 Angiboust, S., Harlov, D., 2017. Ilmenite breakdown and rutile-titanite stability in

591 metagranitoids: Natural observations and experimental results. *Am. Mineral.* 102

592 (8), 1696–1708.

593 Barker, F., 1979. Trondhjemite: definition environment and hypothesis of origin. In:

594 Barker F (Ed) *Trondhjemites dacites and related rocks*. Elsevier, Amsterdam, pp.

595 1–12.

596 Bhadra, S., Bhattacharya, A., 2007. The barometer tremolite + tschermakite + 2 albite
597 = 2 pargasite + 8 quartz: constraints from experimental data at unit silica activity,
598 with application to garnet-free natural assemblages. *Am. Mineral.* 92 (4), 491–
599 502.

600 Boger, S.D., Miller, J.M., 2004. Terminal suturing of Gondwana and the onset of the
601 Ross–Delamerian Orogeny: The cause and effect of an Early Cambrian
602 reconfiguration of plate motions. *Earth Planet. Sci. Lett.* 219, 35–48.

603 Booth, A.L., Zeitler, P.K., Kidd, W.S.F., Wooden, J., Liu, Y.P., Idleman, B., Hren,
604 M., Chamberlain, C.P., 2004. U–Pb zircon constraints on the tectonic evolution
605 of southeastern Tibet, Namche Barwa area. *Am. J. Sci.* 304 (10), 889–929.

606 Brown, M., 2002. Retrograde processes in migmatites and granulites revisited. *J.*
607 *Metamorph. Geol.* 20 (1), 25–40.

608 Chang, C.F., et al., 1986. Preliminary conclusions of the Royal Society and
609 Academia-Sinica 1985 Geotraverse of Tibet. *Nature* 323, 501–507.

610 Chang, C.F., Zheng, S.L., 1973. Tectonic features of the Mount Jolmo Lungma region
611 in southern Tibet, China. *Chin. J. Geol.* 1 (1), 1–12.

612 Chen, L.R., Xu, W.C., Zhang, H.F., Zhao, P.L., Guo, J.L., Luo, B.J., Guo, L., Pan,
613 F.B., 2019. Origin and early evolution of the Lhasa Terrane, South Tibet:
614 Constraints from the Bomi Gneiss Complex. *Precambrian Res.* 331, 105360.

615 Chen, Z.J., Tian, Z.L., Zhang, Z.M., Dong, X., 2017. Early Jurassic metamorphism of
616 the eastern segment of the Lhasa terrane in south Tibet and its tectonic

617 significance. *Int. Geol. Rev.* 59 (14), 1–17.

618 Cheng, H., Liu, Y., Vervoort, J.D., Lu, H., 2015. Combined U–Pb, Lu–Hf, Sm–Nd
619 and Ar–Ar multichronometric dating on the Bailang eclogite constrains the
620 closure timing of the Paleo-Tethys Ocean in the Lhasa terrane, Tibet. *Gondwana*
621 *Res.* 28 (4), 1482–1499.

622 Chiu, H.Y., Chung, S.L., Wu, F.Y., Liu, D.Y., Liang, Y.H., Lin, Y.J., Iizuka, Y., Xie,
623 L.W., Wang, Y.B., Chu, M.F., 2009. Zircon U–Pb and Hf isotope constraints
624 from eastern Transhimalayan batholiths on the precollisional magmatic and
625 tectonic evolution in southern Tibet. *Tectonophysics* 477 (1–2), 3–19.

626 Chu, M.F., Chung, S.L., Song, B., Liu, D.Y., O'Reilly, S.Y., Pearson, N.J., 2006.
627 Zircon U–Pb and Hf isotope constraints on the Mesozoic tectonics and crustal
628 evolution of southern Tibet. *Geology* 34 (9), 745–748.

629 [Collins, A.S., Pisarevsky, S.A., 2005. Amalgamating eastern Gondwana: The](#)
630 [evolution of the circum-Indian orogens. *Earth Sci. Rev.* 71, 229–270.](#)

631 Coward, M.P., Kidd, W.F., Yun, P., Shackleton, R.M., Zhang, H., 1988. The structure
632 of the 1985 Tibet Geotraverse, Lhasa to Golmud. *Phil. Trans. Roy. Soc. Lond. A*
633 327, 307–336.

634 Dewey, J.F., Shackleton, R.M., Chang, C., Sun, Y., 1988. The tectonic evolution of
635 the Tibetan Plateau. *Phil. Trans. Roy. Soc. Lond. A* 327, 379–413.

636 Ding, H.X., Zhang, Z.M., Dong, X., Yan, R., Lin, Y.H., Jiang, H.Y., 2015. Cambrian
637 ultrapotassic rhyolites from the Lhasa terrane, south Tibet: Evidence for Andean-
638 type magmatism along the northern active margin of Gondwana. *Gondwana Res.*

639 27 (4), 1616–1629.

640 Ding, L., Kapp, P., Zhong, D., Deng, W., 2003. Cenozoic volcanism in Tibet:
641 Evidence for a transition from oceanic to continental subduction. *J. Petrol.* 44,
642 1833–1865.

643 Dong, X., Zhang, Z.M., Santosh, M., 2010. Zircon U–Pb chronology of the Nyingtri
644 Group, Southern Lhasa Terrane, Tibetan Plateau: Implications for Grenvillian
645 and Pan-African provenance and Mesozoic-Cenozoic metamorphism. *J. Geol.*
646 118 (6), 677–690.

647 Dong, X., Zhang, Z.M., Liu, F., Wang, W., Yu, F., Shen, K., 2011a. Zircon U–Pb
648 geochronology of the Nyainqêntanglha Group from the Lhasa terrane: New
649 constraints on the Triassic orogeny of the south Tibet. *J. Asian Earth Sci.* 42 (4),
650 732–739.

651 Dong, X., Zhang, Z.M., Santosh, M., Wang, W., Yu, F., Liu, F., 2011b. Late
652 Neoproterozoic thermal events in the northern Lhasa terrane, south Tibet: Zircon
653 chronology and tectonic implications. *J. Geodyn.* 52 (5), 389–405.

654 Dong, X., Zhang, Z.M., Liu, F., Wang, W., Yu, F., Lin, Y.H., Jiang, H.Y., He, Z.Y.,
655 2012. Genesis of the metamorphic rocks from southeastern Lhasa terrane and the
656 Mesozoic-Cenozoic orogenesis. *Acta Petrol. Sin.* 28 (6), 1765–1784 (in Chinese
657 with English abstract).

658 Dong, X., Zhang, Z.M., 2013. Genesis and tectonic significance of the Early Jurassic
659 magmatic rocks from the southern Lhasa terrane. *Acta Petrol. Sin.* 29 (6), 1933–
660 1948 (in Chinese with English abstract).

661 Dong, X., Zhang, Z.M., Liu, F., He, Z.Y., Lin, Y.H., 2014. Late Paleozoic intrusive
662 rocks from the southeastern Lhasa terrane, Tibetan Plateau, and their Late
663 Mesozoic metamorphism and tectonic implications. *Lithos* 198–199, 249–262.

664 Dong, X., Zhang, Z.M., 2015. Cambrian granitoids from the southeastern Tibetan
665 Plateau: Research on petrology and zircon Hf isotope. *Acta Petrol. Sin.* 31 (5),
666 1183–1199 (in Chinese with English abstract).

667 Emslie, R.F., 1978. Anorthosite massifs, rapakivi granites, and late Proterozoic rifting
668 of North America. *Precambrian Res.* 7 (1), 61–98.

669 Ernst, R.E., Pereira, E., Hamilton, M.A., Pisarevsky, S.A., Rodrigues, J., Tassinari,
670 C.C.G., Teixeira, W., Van-Dunem, V., 2013. Mesoproterozoic intraplate
671 magmatic ‘barcode’ record of the Angola portion of the Congo Craton: Newly
672 dated magmatic events at 1505 and 1110 Ma and implications for Nuna
673 (Columbia) supercontinent reconstructions. *Precambrian Res.* 230, 103–118.

674 Ernst, R.E., Okrugin, A.V., Veselovskiy, R.V., Kamo, S.L., Hamilton, M.A., Pavlov,
675 V., Söderlund, U., Chamberlain, K.R., Rogers, C., 2016. The 1501 Ma
676 kuonamka large igneous province of northern siberia: U–Pb geochronology,
677 geochemistry, and links with coeval magmatism on other crustal blocks. *Russ.*
678 *Geol. Geophys.* 57 (5), 653–671.

679 Ferry, J.M., Watson, E.B., 2007. New thermodynamic models and revised calibrations
680 for the Ti-in-zircon and Zr-in-rutile thermometers. *Contrib. Mineral. Petrol.* 154
681 (4), 429–437.

682 Guo, L., Zhang, H.F., Harris, N., Pan, F.B., Xu, W.C., 2011. Origin and evolution of

683 multistage felsic melts in eastern Gangdese belt: Constraints from U–Pb zircon
684 dating and Hf isotopic composition. *Lithos* 127 (1–2), 54–67.

685 Guo, L., Zhang, H.F., Harris, N., Parrish, R., Xu, W.C., Shi, Z.L., 2012. Paleogene
686 crustal anatexis and metamorphism in Lhasa terrane, eastern Himalayan syntaxis:
687 Evidence from U–Pb zircon ages and Hf isotopic compositions of the Nyingchi
688 Complex. *Gondwana Res.* 21 (1), 100–111.

689 Guo, L., Zhang, H.F., Harris, N., Xu, W.C., Pan, F.B., 2017. Detrital zircon U–Pb
690 geochronology, trace-element and Hf isotope geochemistry of the
691 metasedimentary rocks in the eastern Himalayan syntaxis: Tectonic and
692 paleogeographic implications. *Gondwana Res.* 41, 207–221.

693 Guo, L.S., Liu, Y.L., Liu, S.W., Cawood, P.A., Wang, Z.H., Liu, H.F., 2013.
694 Petrogenesis of Early to Middle Jurassic granitoid rocks from the Gangdese belt,
695 Southern Tibet: Implications for early history of the Neo-Tethys. *Lithos* 179,
696 320–333.

697 Guynn, J.H., Kapp, P., Pullen, A., Heizler, M., Gehrels, G., Ding, L., 2006. Tibetan
698 basement rocks near Amdo reveal “missing” mesozoic tectonism along the
699 Bangong suture, central Tibet. *Geology* 34 (6), 505–508.

700 Guynn, J., Kapp, P., George, E., Ding, L., 2012. U–Pb geochronology of terrane rocks
701 in central Tibet and paleogeographic implications. *J. Asian Earth Sci.* 43 (1), 23–
702 50.

703 Hansen, E.C., Ahmed, K., Harlov, D.E., 2002. Rb depletion in biotites and whole
704 rocks across an amphibolite to granulite-facies transition zone, Tamil Nadu,

705 South India. *Lithos* 64 (1), 29–47.

706 Harlov, D.E., Hansen, E.C., 2005. Oxide and sulphide isograds along a late Archean,
707 deep-crustal profile in Tamil Nadu, South India. *J. Metamorph. Geol.* 23 (4),
708 241–259.

709 Harlov, D.E., Tropper, P., Seifert, W., Nijland, T., Förster, H.J., 2006. Formation of
710 Al-rich titanite ($\text{CaTiSiO}_4\text{O}-\text{CaAlSiO}_4\text{OH}$) reaction rims on ilmenite in
711 metamorphic rocks as a function of $f\text{H}_2\text{O}$ and $f\text{O}_2$. *Lithos* 88, 72–84.

712 Harris, N.B.W., Xu, R.H., Lewis, C.L., Hawkesworth, C.L., Zhang, Y.Q., 1988a.
713 Isotope geochemistry of the 1985 Tibet Geotraverse, Lhasa to Golmud. *Phil.*
714 *Trans. Roy. Soc. Lond. A* 327, 263–285.

715 Harris, N.B.W., Holland, T.J.B., Tindle, A.G., 1988b. Metamorphic rocks of the 1985
716 Tibet Geotraverse, Lhasa to Golmud. *Phil. Trans. Roy. Soc. Lond. A* 327, 203–
717 213.

718 Hayden, L.A., Watson, E.B., 2007. Rutile saturation in hydrous siliceous melts and its
719 bearing on Ti-thermometry of quartz and zircon. *Earth Planet. Sci. Lett.* 258 (3–
720 4), 561–568.

721 Hayden, L.A., Watson, E.B., Wark, D.A., 2008. A thermobarometer for sphene
722 (titanite). *Contrib. Mineral. Petrol.* 155 (4), 529–540.

723 Holland, T.J.B., Blundy, J.D., 1994. Non-ideal interactions in calcic amphiboles and
724 their bearing on amphibole–plagioclase thermometry. *Contrib. Mineral. Petrol.*
725 116 (4), 433–447.

726 Hoskin, P.W.O., Black, L.P., 2000. Metamorphic zircon formation by solid-state

727 recrystallization of protolith igneous zircon. *J. Metamorph. Geol.* 18 (4), 423–
728 439.

729 Hoskin, P.W.O., Schaltegger, U., 2003. The composition of zircon and igneous and
730 metamorphic petrogenesis. *Rev. Mineral. Geochem.* 53 (1), 27–62.

731 Hou, Z.Q, Duan, L.F, Lu, Y.J, Zheng, Y.C, Zhu, D.C., Yang, Z.M., Yang, Z.S.,
732 Wang, B.D., Pei, Y.R., Zhao, Z.D., Mccuaig, T.C., 2015. Lithospheric
733 architecture of the Lhasa terrane and its control on ore deposits in the
734 Himalayan-Tibetan orogen. *Econ. Geol.* 110, 1541–1575.

735 Hu, D.G., Wu, Z.H., Jiang, W., Shi, Y.R., Ye, P.S., Liu, Q.S., 2005. SHRIMP zircon
736 U–Pb age and Nd isotopic study on the Nyainqêntanglha Group in Tibet. *Sci.*
737 *China* 48 (9), 1377–1386.

738 Hu, P.Y, Li, C., Wang, M., Xie, C.M, Wu, Y.W., 2013. Cambrian volcanism in the
739 Lhasa terrane, southern Tibet: Record of an early Paleozoic Andean-type
740 magmatic arc along the Gondwana proto-Tethyan margin. *J. Asian Earth Sci.* 77,
741 91–107.

742 Hu, P.Y., Zhai, Q.G., Wang, J., Tang, Y., Wang, H.T., Zhu, Z.C., W, H., 2018a.
743 Middle Neoproterozoic (~ 760 Ma) arc and back-arc system in the North Lhasa
744 terrane, Tibet, inferred from coeval N-MORB- and arc-type gabbros.
745 *Precambrian Res.* 316, 275–290.

746 Hu, P.Y., Zhai, Q.G., Wang, J., Tang, Y., Wang, H.T., Hou, K.J., 2018b. Precambrian
747 origin of the north Lhasa terrane, Tibetan Plateau: Constraint from early
748 Cryogenian back-arc magmatism. *Precambrian Res.* 313, 51–67.

- 749 Ji, W.Q., Wu, F.Y., Chung, S.L., Li, J.X., Liu, C.Z., 2009. Zircon U–Pb
750 geochronology and Hf isotopic constraints on petrogenesis of the Gangdese
751 batholith, southern Tibet. *Chem. Geol.* 262, 229–245.
- 752 Ji, W.Q., Wu, F.Y., Chung, S.L., Liu, C.Z., 2012. Identification of early
753 Carboniferous granitoids from southern Tibet and implications for terrane
754 assembly related to the Paleo-Tethyan evolution. *J. Geol.* 120 (5), 531–541.
- 755 Ji, W.Q., Wu, F.Y., Liu, C.Z., Zhang, H., 2017. Zircon U–Pb geochronology and Hf
756 isotopes of granitic rocks and river sands in the Nyingchi region, Tibet:
757 Constraints on evolution of the deep crust beneath the southeast Lhasa terrane. *J.*
758 *Asian Earth Sci.* 145, 613–625.
- 759 Kang, D.Y., Zhang, Z.M., Dong, X., Tian, Z.L., Xiang, H., Mo, X.X., 2019.
760 Anticlockwise *P-T-t* path and tectonic mechanism of metapelites from the
761 eastern Gangdese arc, southern Tibet. *Acta Petrol. Sin.* 35 (2), 349–362 (in
762 Chinese with English abstract).
- 763 Keto, L.S., Jacobsen, S.B., 1987. Nd and Sr isotopic variations of Early Paleozoic
764 ocean. *Earth Planet. Sci. Lett.* 84 (1), 27–41.
- 765 Kidd, W.F., Pan, Y.S., Chang, C.F., Coward, M.P., Dewey, J.F., Gansser, A., Molnar,
766 P., Shackleton, R.M., Sun, Y.J., 1988. Geological mapping of the 1985 Chinese–
767 British Tibetan (Xizang–Qinghai) Plateau geotraverse route. *Phil. Trans. Roy.*
768 *Soc. Lond. A* 327, 287–305.
- 769 Kröner, A., Santosh, M., Wong, J., 2012. Zircon ages and Hf isotopic systematics
770 reveal vestiges of Mesoproterozoic to Archaean crust within the late

- 771 Neoproterozoic-Cambrian high-grade terrain of southernmost India. *Gondwana*
772 *Res.* 21 (4), 876–886.
- 773 Leake, B.E., et al., 1997. Nomenclature of amphiboles: Report of the subcommittee
774 on amphiboles of the International Mineralogical Association. *Commission on*
775 *New Minerals and Mineral Names. Mineral. Mag.* 35, 219–246.
- 776 Leier, A.L., Kapp, P., Gehrels, G.E., DeCelles, P.G., 2007. Detrital zircon
777 geochronology of Carboniferous-Cretaceous strata in the Lhasa terrane, southern
778 Tibet. *Basin Res.* 19 (3), 361–378.
- 779 Li, G.W., Sandiford, M., Liu, X.H., Xu, Z.Q., Wei, L.J., Li, H.Q., 2014. Provenance
780 of Late Triassic sediments in central Lhasa terrane, Tibet and its implication.
781 *Gondwana Res.* 25 (4), 1680–1689.
- 782 Li, P., 1955. Primary understanding of geology, eastern Tibet. *Chin. Sci. Bull.* 7 (7),
783 62–71 (in Chinese).
- 784 Lin, Y.H., Zhang, Z.M., Dong, X., Xiang, H., Yan, R., 2013a, Early Mesozoic
785 metamorphism and tectonic significance of the eastern segment of the Lhasa
786 terrane, south Tibet. *J. Asian Earth Sci.* 78, 160–183.
- 787 Lin, Y.H., Zhang, Z.M., Dong, X., Shen, K., Lu, X., 2013b. Precambrian evolution of
788 the Lhasa terrane, Tibet: Constraint from the zircon U–Pb geochronology of the
789 gneisses. *Precambrian Res.* 237, 64–77.
- 790 Maniar, P.D., Piccoli, P.M., 1989. Tectonic discrimination of granitoids. *Geol. Soc.*
791 *Am. Bull.* 101 (5), 635–643.
- 792 McWilliams, M.O., 1981. Palaeomagnetism and Precambrian tectonic evolution of

793 Gondwana. In: Kroöner, A. (Ed.), Precambrian Plate Tectonics. Elsevier,
794 Amsterdam, pp. 649–687.

795 Meert, J.G., Van der Voo, R., Ayub, S., 1995. Paleomagnetic investigation of the
796 Neoproterozoic Gagwe lavas and Mbozi complex, Tanzania and the assembly of
797 Gondwana. Precambrian Res. 74 (4), 225–244.

798 Meert, J.G., Van der Voo, R., 1997. The assembly of Gondwana 800–550 Ma. J.
799 Geodyn. 23 (3–4), 223–235.

800 Meert, J.G., 2001. Growing Gondwana and rethinking Rodinia: A paleomagnetic
801 perspective. Gondwana Res. 4 (3), 279–288.

802 Meert, J.G., 2003. A synopsis of events related to the assembly of eastern Gondwana.
803 Tectonophysics 362, 1–40.

804 Meert, J.G., Torsvik, T.H., 2003. The making and unmaking of a supercontinent:
805 Rodinia revisited. Tectonophysics 375, 261–288.

806 Meng, Y.K., Dong, H.W., Cong, Y., Xu, Z.Q., Cao, H., 2016. The early-stage
807 evolution of the Neo-Tethys ocean: Evidence from granitoids in the middle
808 Gangdese batholith, southern Tibet. J. Geodyn. 94–95, 34–49.

809 Mo, X.X., Hou, Z.Q., Niu, Y.L., Dong, G.C., Qu, X.M., Zhao, Z.D., Yang, Z.M.,
810 2007. Mantle contributions to crustal thickening during continental collision:
811 Evidence from Cenozoic igneous rocks in southern Tibet. Lithos 96 (1–2), 225–
812 242.

813 Mukherjee, A., Das, S., 2002. Anorthosites, Granulites and the Supercontinent Cycle.
814 Gondwana Res. 5 (1), 147–156.

815 Nijland, T.G., Maijer, C., 1993. The regional amphibolite to granulite facies transition
816 at Arendal, Norway: Evidence for a thermal dome. *N. Jahrb. Mineral. Abh.* 165,
817 191–221.

818 Nijland, T.G., Visser, D., 1995. Provenance of the Bamble amphibolites, Norway.
819 *Proc. R. Neth. Acad. Arts Sci.* 98 (1–2), 69–88.

820 Nimaciren, Xie, Y.W., Sha, Z.L., Xiluolangjie, Qiangbazaxi, Peng, D.P.,
821 Gesangsuolang, Luosongzhandui, 2005. 1: 250, 000 geological report of Nagqu
822 County with geological map. Xizang Institute of Geological Survey, Lhasa, 103–
823 107 (in Chinese).

824 Palin, R.M., Searle, M.P., St-Onge, M.R., Waters, D.J., Roberts, N.M.W., Horstwood,
825 M.S.A., Parrish, R.R., Weller, O.M., Chen, S., Yang, J., 2014. Monazite
826 geochronology and petrology of kyanite- and sillimanite-grade migmatites from
827 the northwestern flank of the eastern Himalayan syntaxis. *Gondwana Res.* 26 (1),
828 323–347.

829 Palin, R.M., White, R.W., Green, E.C.R., Diener, J.F.A., Powell, R., Holland, T.J.B.,
830 2016. High-grade metamorphism and partial melting of basic and intermediate
831 rocks. *J. Metamorph. Geol.* 34, 871–892.

832 Pan, G.T., Ding, J., Yao, D.S., Wang, L.Q., 2004. Guidebook of 1:1,500,000 geologic
833 map of the Qinghai–Xizang (Tibet) plateau and adjacent areas. Cartographic
834 Publishing House, Chengdu, China, pp. 1–148 (in Chinese).

835 Pan, G.T., Mo, X.X., Hou, Z.Q., Zhu, D.C., Wang, L.Q., Li, G.M., Zhao, Z.D., Geng,
836 Q.R., Liao, Z.L., 2006. Spatial-temporal framework of the Gangdese Orogenic

837 Belt and its evolution. *Acta Petrol. Sin.* 22 (3), 521–533 (in Chinese with English
838 abstract).

839 Piper, J.D.A., 1976. Palaeomagnetic evidence for a Proterozoic super-continent. *Phil.*
840 *Trans. Roy. Soc. Lond. A* 280, 469–490.

841 Pullen, A., Kapp, P., Gehrels, G.E., DeCelles, P.G., Brown, E.H., Fabijanic, J.M.,
842 Ding, L., 2008. Gangdese retroarc thrust belt and foreland basin deposits in the
843 Damxung area, southern Tibet. *J. Asian Earth Sci.* 33 (5–6), 323–336.

844 Rogers, J.J.W., Santosh, M., 2002. Configuration of Columbia, a Mesoproterozoic
845 Supercontinent. *Gondwana Res.* 5 (1), 5–22.

846 Rollinson, H., 1993. *Using Geochemical Data: Evaluation, Pre-sentation,*
847 *Interpretation.* Longman, London. 215–263 pp.

848 Rubatto, D., Hermann, J., Berger, A., Engi, M., 2009. Protracted fluid-induced
849 melting during barroviaan metamorphism in the central Alps. *Contrib. Mineral.*
850 *Petrol.* 158 (6), 703–722.

851 Rubatto, D., 2017. Zircon: The Metamorphic Mineral. *Rev. Mineral. Geochem.* 83,
852 261–296.

853 Sadowski, G.R., Bettencourt, J.S., 1996. Mesoproterozoic tectonic correlations
854 between eastern Laurentia and the western border of the Amazon Craton.
855 *Precambrian Res.* 76 (3–4), 213–227.

856 Sawyer, E.W., 2001. Melt segregation in the continental crust: Distribution and
857 movement of melt in anatectic rocks. *J. Metamorph. Geol.* 19 (3), 291–309.

858 Sengör, A.M.C., Natal'in, B.A., 1996. Paleotectonics of Asia: Fragments of a

859 synthesis. In: Yin, A., Harrison, M.T. (Eds.), *The Tectonic Evolution of Asia*,
860 Cambridge University Press, pp. 486–640.

861 Silveira, E.M., Söderlund, U., Oliveira, E.P., Ernst, R.E., Menezes Leal, A.B., 2013.
862 First precise U–Pb baddeleyite ages of 1500 Ma mafic dykes from the São
863 Francisco Craton, Brazil, and tectonic implications. *Lithos* 174, 144–156.

864 Sun, S.S., McDonough, W.F., 1989. Chemical and isotope systematics of oceanic
865 basalts: Implications for mantle composition and processes. In: Saunders, A.D.
866 (Ed.), *Magmatism in Ocean Basins*. Geological Society of London Special
867 Publication, pp. 313–345.

868 Timmermann, H., Jamieson, R.A., Parrish, R.R., Culshaw, N.G., 2002. Coeval
869 migmatites and granulites, Muskoka domain, southwestern Grenville Province,
870 Ontario. *Can. J. Earth Sci.* 39 (2), 239–258.

871 [Veevers, J.J., 2004. Gondwanaland from 650–500 Ma assembly through 320 Ma](#)
872 [merger in Pangea to 185–100 Ma breakup: Supercontinental tectonics via](#)
873 [stratigraphy and radiometric dating. *Earth Sci. Rev.* 68, 1–132](#)

874 Weis, D., 1986. Genetic implications of Pb isotopic geochemistry in the Rogaland
875 anorthositic complex (southwest Norway). *Chem. Geol.* 57 (1), 181–199.

876 Weller, O.M., St-Onge, M.R., Searle, M.P., Waters, D.J., Rayner, N., Chen, S.,
877 Chung, S.L., Palin, R.M., 2015. Quantifying the P – T – t conditions of north–south
878 Lhasa terrane accretion: New insight into the pre-Himalayan architecture of the
879 Tibetan plateau. *J. Metamorph. Geol.* 33 (1), 91–113.

880 Xie, C.M., Li, C., Su, L., Wu, Y.W., Wang, M., Yu, H., 2010. LA–ICP–MS U–Pb

881 dating of zircon from granite–gneiss in the Amdo area, northern Tibet, China.
882 Geolo. Bull. Chin. 29 (12), 1737–1744 (in Chinese with English abstract).

883 Xie, R.W., Peng, X.J., Xiluelangjie, Bao, J.Y., Duan, G.X., He, C.H., Qiangbazhax,
884 Sha, S.L., Chen, Y.M., Chen, D.Q., Peng, D.P., 2007. 1:250, 000 geological
885 report of Zêtang Town with geological map. Geological Survey of Tibet
886 Autonomous Region Press, Lhasa, pp. 1–315 (in Chinese).

887 Xu, R.H., Schärer, U., Allègre, C.J., 1985. Magmatism and metamorphism in the
888 Lhasa block (Tibet): A geochronological study. *J. Geol.* 93(1), 41–57.

889 Xu, W.C., Zhang, H.F., Harris, N., Guo, L., Pan, F.B., Wang, S., 2013a.
890 Geochronology and geochemistry of Mesoproterozoic granitoids in the Lhasa
891 terrane, south Tibet: Implications for the early evolution of Lhasa terrane.
892 *Precambrian Res.* 236, 46–58.

893 Xu, W.C., Zhang, H.F., Harris, N., Guo, L., Pan, F.B., 2013b. Rapid Eocene erosion,
894 sedimentation and burial in the eastern Himalayan syntaxis and its geodynamic
895 significance. *Gondwana Res.* 23 (2), 715–725.

896 Yang, J.S., Xu, Z.Q., Li, Z.L., Xu, X.Z., Li, T.F., Ren, Y.F., Li, H.Q., Chen, S.Y.,
897 Robinson, P.T., 2009. Discovery of an eclogite belt in the Lhasa block, Tibet: A
898 new border for Paleo-Tethys? *J. Asian Earth Sci.* 34 (1), 76–89.

899 Yang, Z.M., Hou, Z.Q., Jiang, Y.F., Zhang, H.R., Song, Y.C., 2011. Sr-Nd-Pb and
900 zircon Hf isotopic constraints on petrogenesis of the Late Jurassic granitic
901 porphyry at Qulong, Tibet. *Acta Petrol. Sin.* 27 (7), 2003–2010 (in Chinese with
902 English abstract).

903 Yin, A., Harrison, T.M., 2000. Geologic evolution of the Himalayan–Tibetan orogen.
904 *Annu. Rev. Earth Planet. Sci.* 28, 211–280.

905 Yin, A., Nie, S., 1996. A Phanerozoic palinspastic reconstruction of China and its
906 neighboring regions. In: Yin, A., Harrison, M.T. (Eds.), *The Tectonic Evolution*
907 *of Asia*. Cambridge University Press, pp. 442–485.

908 Yin, G.G., Chen, Y.P., Su, X.J., Bao, J.Y., Hou, S.Y., Lu, Y., Duan, G.X., Zhang,
909 J.Y., Liu, Z., Xiao, L., 2003. 1:250,000 geological report of Nyingtri region with
910 geological map. Yunnan, Institute of Yunnan Geological Survey (in Chinese).

911 Zeng, L.S., Liu, J., Gao, L.E., Chen, F.Y., Xie, K.J., 2009. Early Mesozoic high-
912 pressure metamorphism within the Lhasa block, Tibet and implications for
913 regional tectonics. *Earth Sci. Front.* 16 (2), 140–151.

914 Zeng, Y.C., Chen, Q., Xu, J.F., Chen, J.L., Huang, F., Yu, H.X., Zhao, P.P., 2018.
915 Petrogenesis and geodynamic significance of neoproterozoic (~ 925 Ma) high-
916 Fe-Ti gabbros of the Rentso ophiolite, Lhasa terrane, central Tibet. *Precambrian*
917 *Res.* 314, 160–169.

918 Zhang, H.F., Xu, W.C., Guo, J.Q., Zong, K.Q., Cai, H.M., Yuan, H.L., 2007a. Zircon
919 U–Pb and Hf isotopic composition of deformed granite in the southern margin of
920 the Gangdese Belt, Tibet: Evidence for early Jurassic subduction of Neo-Tethyan
921 oceanic slab. *Acta Petrol. Sin.* 23 (6), 1347–1353 (in Chinese with English
922 abstract).

923 Zhang, H.F., Xu, W.C., Guo, J.Q., Zong, K.Q., Cai, H.M., Yuan, H.L., 2007b.
924 Indosinian orogenesis of the Gangdese terrane: Evidences from zircon U–Pb

925 dating and petrogenesis of granitoids. *Earth Sci. J. China Univ. Geosci.* 32 (2),
926 155–166 (in Chinese with English abstract).

927 Zhang, K.J., Zhang, Y.X., Li, B., Zhong, L.F., 2007. Nd isotopes of siliciclastic rocks
928 from Tibet, western China: Constraints on provenance and pre-Cenozoic tectonic
929 evolution. *Earth Planet. Sci. Lett.* 256 (3–4), 604–616.

930 Zhang, X.R., Shi, R.D., Huang, Q.S., Liu, D.L., Gong, X.H., Chen, S.S., Wu, K., Yi,
931 G.D., Sun, Y.L., Ding, L., 2014. Early Jurassic high-pressure metamorphism of
932 the Amdo terrane, Tibet: Constraints from zircon U-Pb geochronology of mafic
933 granulites. *Gondwana Res.* 26 (3–4), 975–985.

934 Zhang, Z.M., Zhao, G.C., Santosh, M., Wang, J.L., Dong, X., Liou, J.G., 2010. Two
935 stages of granulite facies metamorphism in the eastern Himalayan syntaxis, south
936 Tibet: Petrology, zircon geochronology and implications for the subduction of
937 Neo-Tethys and the Indian continent beneath Asia. *J. Metamorph. Geol.* 28 (7),
938 719–733.

939 Zhang, Z.M., Dong, X., Liu, F., Lin, Y.H., Yan, R., Santosh, M., 2012a. Tectonic
940 evolution of the Amdo terrane, central Tibet: Petrochemistry and zircon U–Pb
941 geochronology. *J. Geol.* 120 (4), 431–451.

942 Zhang, Z.M., Dong, X., Liu, F., Lin, Y.H., Yan, R., He, Z.Y., Santosh, M., 2012b.
943 The making of Gondwana: Discovery of 650 Ma HP granulites from the North
944 Lhasa, Tibet. *Precambrian Res.* 212–213, 107–116.

945 Zhang, Z.M., Dong, X., Xiang, H., Liou, J.G., Santosh, M., 2013. Building of the
946 deep Gangdese arc, South Tibet: Paleocene plutonism and granulite-facies

947 metamorphism. *J. Petrol.* 54 (12), 2547–2580.

948 Zhang, Z.M., Dong, X., Santosh, M., Zhao, G.C., 2014a. Metamorphism and tectonic
949 evolution of the Lhasa terrane, Central Tibet. *Gondwana Res.* 25 (1), 170–189.

950 Zhang, Z.M., Dong, X., Xiang, H., He, Z.Y., Liou, J.G., 2014b. Metagabbros of the
951 Gangdese arc root, south Tibet: Implications for the growth of continental crust
952 *Geochim. Cosmochim. Acta* 143, 268–284.

953 Zhang, Z.M., Dong, X., Xiang, H., Ding, H.X., He, Z.Y., Liou, J.G., 2015. Reworking
954 of the Gangdese magmatic arc, southeastern Tibet: Post-collisional
955 metamorphism and anatexis. *J. Metamorph. Geol.* 33 (1), 1–21.

956 Zhao, G.C., Sun, M., Wilde, S.A., Li, S.Z., 2003. Assembly, accretion, and break-up
957 of the Palaeo-Mesoproterozoic Columbia supercontinent: Record in the North
958 China Craton revisited. *Gondwana Res.* 6 (3), 417–434.

959 Zhu, D.C., Pan, G.T., Chung, S.L., Liao, Z.L., Wang, L.Q., Li, G.M., 2008. SHRIMP
960 zircon age and geochemical constraints on the origin of lower Jurassic volcanic
961 rocks from the Yeba formation, southern Gangdese, south Tibet. *Int. Geol. Rev.*
962 50 (5), 442–471.

963 Zhu, D.C., Mo, X.X., Niu, Y., Zhao, Z.D., Wang, L.Q., Liu, Y.S., Wu, F.Y., 2009a.
964 Geochemical investigation of Early Cretaceous igneous rocks along an east–west
965 traverse throughout the central Lhasa Terrane, Tibet. *Chem. Geol.* 268 (3–4),
966 298–312.

967 Zhu, D.C., Mo, X.X., Niu, Y.L., Zhao, Z.D., Wang, L.Q., Pan, G.T., Wu, F.Y., 2009b.
968 Zircon U–Pb dating and in-situ Hf isotopic analysis of Permian peraluminous

969 granite in the Lhasa terrane, southern Tibet: Implications for Permian collisional
970 orogeny and paleogeography. *Tectonophysics* 469 (1–4), 48–60.

971 Zhu, D.C., Zhao, Z.D., Niu, Y.L., Mo, X.X., Chung, S.L., Hou, Z.Q., Wang, L.Q.,
972 Wu, F.Y., 2011. The Lhasa Terrane: Record of a microcontinent and its histories
973 of drift and growth. *Earth Planet. Sci. Lett.* 301 (1–2), 241–255.

974 Zhu, D.C., Zhao, Z.D., Niu, Y.L., Dilek, Y., Wang, Q., Ji, W.H., Dong, G.C., Sui,
975 Q.L., Liu, Y.S., Yuan, H.L., Mo, X.X., 2012. Cambrian bimodal volcanism in
976 the Lhasa Terrane, southern Tibet: Record of an early Paleozoic Andean-type
977 magmatic arc in the Australian proto-Tethyan margin. *Chem. Geol.* 328, 290–
978 308.

979 Zhu, D.C., Zhao, Z.D., Niu, Y., Dilek, Y., Hou, Z.Q., Mo, X.X., 2013. The origin and
980 pre-Cenozoic evolution of the tibetan plateau. *Gondwana Res.* 23 (4), 1429–
981 1454.

982

983 **Figure captions:**

984 Figure 1. (a) Tectonic framework of the Tibetan Plateau (after [Zhu et al., 2013](#)),
985 showing the major tectonic subdivisions. NLT = Northern Lhasa subterrane, CLT =
986 Central Lhasa subterrane, SLT = Southern Lhasa subterrane, JSSZ = Jinsha Suture
987 Zone, LSSZ = Longmu Tso-Shuanghu Suture Zone, BNSZ = Bangong-Nujiang
988 Suture Zone, SNMZ = Shiquan River-Nam Tso Mmélange Zonezone, LMF =
989 Luobadui-Milashan Fault, IYZSZ = Indus-Yarlung Zangbo Suture Zone. Data sources

990 of the Precambrian magmatic rocks for Amdo: ~ 820 Ma and 500 Ma (Zhang et al.,
991 2012a), 852 Ma (Guynn et al., 2006), 532 Ma (Guynn et al., 2012); the CLT from
992 west to east: 492 Ma (Zhu et al., 2012), 525–510 Ma (Hu et al., 2013), 512 Ma (Ding
993 et al., 2015), 787 Ma (Hu et al., 2005), 897–886 Ma (Zhang et al., 2012b), 760 Ma
994 (Hu et al., 2018a), 822–806 Ma (Hu et al., 2018b), 925 Ma (Zeng et al., 2018), 1343–
995 ~~Ma and~~ 1250 Ma (Xu et al., 2013a; Chen et al., 2019), 1866 Ma (Chen et al., 2019);
996 the SLT: 496 Ma (Dong et al., 2010). (b) Geological sketch map of the Dongjiu area
997 in the SLT, the Paleoproterozoic data (~ 1780 Ma) from Lin et al. (2013b).-

998

999 Figure 2. ~~Field photographs of Dongjiu gneiss. (a) Outcrop of the Dongjiu gneiss. (b)~~
1000 ~~Closeup photo showing banded structure with millimeter-size white leucosome. Figure~~
1001 ~~3.~~ Photomicrographs of representative Dongjiu gneiss. (a) Biotite (Bt)- amphibole
1002 (~~Ampamp~~) gneiss, consisting of amphibole, plagioclase (Pl), K-feldspar (Kfs), biotite,
1003 quartz (Qz) and titanite (Ttn) rimming ilmenite (Ilm), with minor apatite (Ap). (b) Bt-
1004 amp gneiss, showing plagioclase with cusped extensions along quartz-quartz
1005 contacts. (c) and (d) Bt-amp gneiss, showing allanite (Aln) replaced by epidote (Ep)
1006 in rim, with zircon (Zrn) inclusions. (e) Bt gneiss, consisting of plagioclase, K-
1007 feldspar, biotite, quartz, with minor allanite replaced by epidote at rim; adjacent
1008 grains of quartz, plagioclase and K-feldspar ~~grains~~ are corroded. (f) Bt gneiss,
1009 showing adjacent plagioclase and biotite grains are corroded; narrow K-feldspar blebs
1010 at quartz-plagioclase contacts.

1011

1012 Figure [34](#). (a) Ab-An-Or classification for silicic rocks from Barker (1979). (b)
1013 A/CNK vs A/NK diagram from Maniar and Piccoli (1989). [The data of the Bomi](#)
1014 [Mesoproterozoic granitoids are after Xu et al. \(2013a\)](#).

1015

1016 Figure [4.5](#). (a) Chondrite-normalized REE and (b) Primitive-mantle-normalized trace
1017 element patterns for the Dongjiu gneiss. The data of [the](#) Bomi Mesoproterozoic
1018 granitoids are after Xu et al. (2013a). The normalization data are from Sun and
1019 McDonough (1989).

1020

1021 Figure [5.6](#). Zircon U–Pb concordia diagrams and chondrite-normalized REE patterns
1022 of [the](#) Dongjiu Bt-amp gneiss. (a), (c) and (e) Zircon U–Pb concordia diagrams, red
1023 and blue ellipses represent zircon core and rim ages, respectively. (b), (d) and (f)
1024 Chondrite-normalized REE patterns, showing CL images of representative zircon
1025 grains. Red and blue circles indicate zircon core and rim dating spots with ages in Ma,
1026 respectively. The normalization data are from Sun and McDonough (1989).

1027

1028 Figure [6.7](#). Zircon U–Pb concordia diagrams and chondrite-normalized REE patterns
1029 of [the Dongjiu Bt ~~gneiss.gneisses~~](#). (a) and (c) Zircon U–Pb concordia diagrams, red
1030 and blue ellipses represent zircon core and rim ages, respectively. (b) and (d)
1031 Chondrite-normalized REE patterns, showing CL images of representative zircon
1032 grains. Red and blue circles indicate zircon core and rim ages with ages in Ma,
1033 respectively. The normalization data are from Sun and McDonough (1989).

1034

1035 Figure [78](#). BSE images and photomicrographs of representative titanite for the
1036 Dongjiu Bt-amp gneiss. Representative titanite (a)–(h) for sample 169-1, (i)–(p) for
1037 sample 39-1. (a)–(d) and (i)–(l) Blue circles are spots for dating with ^{207}Pb corrected
1038 $^{206}\text{Pb}/^{238}\text{U}$ ages in Ma. (e)–(h) and (m)–(p) Most titanite including ilmenite, biotite,
1039 allanite, apatite, plagioclase, quartz and ~~minor~~ rutile.

1040

1041 Figure [89](#). Titanite U–Pb concordia diagrams of [the Dongjiu](#) Bt-amp gneiss.

1042

1043 Figure [910](#). Frequency histogram of Zr-in-titanite temperatures [for the Dongjiu Bt-](#)
1044 [amp gneiss](#).

1045

1046 [Figure 10. Zircon U vs Th contents diagram of the Dongjiu gneiss.](#)

1047

1048 Figure 11. Zircon U ~~vs Th diagram~~. ~~Figure 12. Zircon U-Pb age vs $\epsilon_{\text{Hf}}(t)$ diagram for~~
1049 the Dongjiu gneiss and [related rockssamples](#) from the Lhasa terrane. Data sources:
1050 SLT ~ 1500 Ma gneiss (our unpublished data); SLT granitoids ([Chu et al., 2006](#);
1051 [Zhang et al., 2007a](#); [Ji et al., 2009, 2012](#); [Yang et al., 2011](#); [Zhu et al. 2011](#); [Dong et](#)
1052 [al., 2013, 2014, 2015](#); [Guo et al., 2013](#); [Meng et al., 2016](#)); CLT granitoids ([Zhang et](#)
1053 [al., 2007b](#); [Zhu et al., 2009b, 2011, 2012](#); [Xu et al., 2013a](#); [Hu et al., 2018b](#); [Chen et](#)
1054 [al., 2019](#)); SLT Paleozoic strata ([Guo et al., 2017](#)); CLT Paleozoic strata ([Zhu et al.,](#)
1055 [2013](#); [Li et al., 2014](#)).

HIGHLIGHTS

The Mesoproterozoic rocks (1520–1506 Ma) are recognized in the southern Lhasa subterrane (SLT).

Bulk-rock Nd and zircon Hf isotopes show their derivation from the Paleoproterozoic material.

The Mesoproterozoic rocks metamorphosed at 605–590 Ma represent the Precambrian metamorphic basement of the Lhasa terrane.

Titanite *in situ* U-Pb dating gives more recent metamorphic age of ~ 26 Ma.

The SLT basement has been strongly reworked by mantle-derived magmatism and metamorphism since the Mesozoic.

1 **Reworked Precambrian metamorphic basement of the Lhasa**
2 **terrane, southern Tibet: Zircon/Titanite U–Pb geochronology,**
3 **Hf isotope and Geochemistry**

4
5 Dong Xin^{1,2}, Zhang Zeming¹, Niu Yaoling², Tian Zuolin¹, Zhang Liangliang³

6
7 1. Key Laboratory of Deep-Earth Dynamics of Ministry of Land and Resources, Institute of
8 Geology, Chinese Academy of Geological Sciences, Beijing, 100037, China

9 2. Department of Earth Sciences, Durham University, Durham, DH1 3LE, UK

10 3. State Key Laboratory of Geological Processes and Mineral Resources, and Institute of Earth
11 Sciences, China University of Geosciences, Beijing, 100083, China

12 **ABSTRACT**

13 Due to the paucity of exposure, the formation and evolution of the Precambrian
14 basement of the Lhasa terrane remain poorly known. Here we report zircon and
15 titanite *in situ* U–Pb ages, bulk-rock geochemical and zircon Hf isotopic data on the
16 orthogneisses from the Dongjiu area of the southern Lhasa subterrane (SLT), southern
17 Tibet. Geochemical data suggest that the protoliths of the biotite-amphibole gneiss
18 and biotite gneiss are granodiorite and granite, respectively. Inherited magmatic
19 zircon cores from these orthogneisses give protolith crystalline ages of 1520–1506
20 Ma, whereas the overgrown zircon rims give metamorphic ages of 605–590 Ma. The

21 Mesoproterozoic granitic rocks have bulk-rock $\epsilon_{\text{Nd}}(t)$ values of -3.6 to +0.1 and zircon
22 core $\epsilon_{\text{Hf}}(t)$ values of -4.5 to +2.6, which give similar T_{DM2} ages of 2.35–2.05 Ga and
23 2.54–2.10 Ga respectively, suggesting their derivation from partial melting of
24 Paleoproterozoic crustal material. The granitic rocks are also local provenance for the
25 Mesoproterozoic detrital zircons in the Paleozoic strata in the Lhasa terrane. Titanite
26 *in situ* U–Pb ages further indicate that the Dongjiu orthogneiss experienced more
27 recent metamorphism at ~ 26 Ma. The mineral assemblage and thermobarometry
28 calculations indicate that the Oligocene metamorphism occurred under medium-
29 pressure (MP) amphibolite-facies conditions (5.4–7.2 kbar, 691–765 °C). We propose
30 that the Dongjiu gneisses represent the Precambrian metamorphic basement of the
31 Lhasa terrane, but have been intensively reworked by metamorphism in the SLT in
32 response to the continued India-Asia convergence since the collision.

33

34 **Keywords:**

35 Zircon and Titanite *in situ* U–Pb dating; Mesoproterozoic; Precambrian metamorphic
36 basement; Reworking; Lhasa terrane

37

38 **1. Introduction**

39 Like much of the central and southeastern Asian geology, the Tibetan Plateau
40 formed via amalgamation of terranes during the Phanerozoic (Chang and Zheng,
41 1973; Allégre et al., 1984; Chang et al., 1986; Sengör and Natal'in, 1996; Yin and

42 [Nie, 1996](#)). However, our knowledge on the histories of these terranes prior to their
43 amalgamation remains limited. The early history of these terranes that make up the
44 Tibetan Plateau is obscured by the paucity of basement exposure, by the strong
45 reworking of basement rocks during the later thermal events, and by the
46 predominance of younger supracrustal rocks.

47 As the main tectonic component of the Tibetan Plateau, the Lhasa terrane has
48 been considered to be composed dominantly of Paleozoic to Mesozoic strata,
49 Mesozoic and Cenozoic igneous rocks and Precambrian basement (e.g., [Yin and](#)
50 [Harrison, 2000](#); [Pan et al., 2004, 2006](#)). The nature and spatial distribution of the
51 Precambrian basement beneath the entire terrane have been speculative. The limited
52 works on the basement to date suggest that the Lhasa terrane crust is relatively young
53 (< 2.0 Ga). U–Pb dating of zircons in gneissic rocks shows the presence of the
54 Neoproterozoic crystalline crust in the Amdo block (~ 850 Ma, [Guynn et al., 2006,](#)
55 [2012](#); [Zhang et al., 2012a](#)) and in the Xainza area in the central Lhasa subterrane
56 (CLT) (~ 925–760 Ma, [Hu et al., 2005](#); [Zhang et al., 2012b](#); [Hu et al., 2018a, b](#); [Zeng](#)
57 [et al., 2018](#)). There is also Proterozoic crystalline basement in the Bomi area in the
58 eastern CLT (ca. 1866 Ma, 1343–1250 Ma and 824 Ma, [Xu et al., 2013a](#); [Chen et al.,](#)
59 [2019](#)) ([Fig. 1a](#)). These ages represent the only known Precambrian crystalline
60 basement from the Lhasa terrane. Nd–Hf isotopic model ages have been used to
61 suggest that the crust of the Lhasa terrane may be older, perhaps even Archean. Bulk-
62 rock Nd isotope data on the Amdo Cambrian orthogneiss give Mesoproterozoic model
63 ages ([Harris et al., 1988a](#)), while bulk-rock Nd and zircon Hf isotopic data on the

64 Cretaceous granitoids of the Lhasa terrane yield Proterozoic and Archean model ages
65 ([Chiu et al., 2009](#); [Zhu et al., 2009a](#)). [Zhu et al. \(2011\)](#) suggest that the CLT was once
66 a microcontinent with Proterozoic and Archean basement rocks, whereas the southern
67 and northern parts of the Lhasa terrane are dominated by younger juvenile crust.
68 However, zircon Hf isotopic mapping for the Mesozoic-Cenozoic magmatic rocks
69 shows that the eastern segment of the northern Lhasa subterrane (NLT) is an ancient
70 block; the southern Lhasa subterrane (SLT) is not entirely a juvenile block with
71 inhomogeneity of crustal compositions ([Hou et al., 2015](#)). However, no Archean
72 rocks have been identified so far. It is possible that the enriched radiogenic isotopic
73 compositions could have resulted from the assimilation of melted sedimentary rocks
74 that were themselves sourced from older continents (e.g., Indian craton), rather than
75 from pre-Neoproterozoic basement of the Lhasa terrane itself ([Ding et al., 2003](#)).
76 Therefore, the true and complete constituent of the Precambrian basement beneath the
77 Lhasa terrane remains to be revealed.

78 In this paper, we report the results of petrological, geochronological and
79 geochemical studies on reworked Precambrian metamorphic basement rocks from the
80 Dongjiu area of the SLT ([Fig. 1](#)). The metamorphic rocks not only provide
81 information on their protolith, but also record two episodes of subsequent
82 metamorphism and Phanerozoic reworking of the Precambrian basement of the Lhasa
83 terrane.

84

85 **2. Geological setting and sample description**

86 **2.1. Geological setting**

87 The Lhasa terrane on the southern segment of the Tibetan Plateau is located
88 between the Qiangtang terrane and Himalayan belt, bounded by the Bangong-Nujiang
89 suture zone to the north and the Indus-Yarlung Zangbo suture zone to the south (Fig.
90 1a). From north to south, the Lhasa terrane has been divided into the northern, central
91 and southern subterrane, separated by the Shiquan River-Nam Tso mélangé zone to
92 the north and the Luobadui-Milashan fault to the south (Fig. 1a; Zhu et al., 2009a).

93 The NLT is characterized by the presence of juvenile crust and absence of a
94 Precambrian basement (cf. Pan et al., 2004; Zhu et al., 2011). The sedimentary cover
95 in the NLT is mainly Jurassic–Cretaceous with minor Triassic in age (e.g., Pan et al.,
96 2004, 2006; Nimaciren et al., 2005). Voluminous Mesozoic volcanic rocks are
97 exposed in this subterrane, and Mesozoic plutonic rocks are mainly confined to its
98 western and eastern segments generally as huge batholiths (e.g., Zhu et al., 2011).

99 The CLT is covered with the widespread Permo-Carboniferous metasedimentary
100 rocks, plus minor Ordovician, Silurian and Triassic strata (cf. Pan et al., 2004). The
101 volcanic rocks in this subterrane are mostly early Cretaceous in age with minor being
102 Permian. The Mesozoic plutonic rocks occur as batholiths of varying age (~ 215–88
103 Ma; cf. Zhu et al., 2011 and references therein). Cambrian volcanic rocks are
104 scattered in the west and middle of the CLT (Fig. 1a, Zhu et al., 2012; Hu et al., 2013;
105 Ding et al., 2015). The late Permian high-pressure eclogite and late Triassic–early

106 Jurassic metamorphic rocks are exposed in the middle and eastern parts of the CLT
107 (e.g., [Yang et al., 2009](#); [Zeng et al., 2009](#); [Dong et al., 2011a](#); [Lin et al., 2013a](#); [Cheng](#)
108 [et al., 2015](#); [Weller et al., 2015](#); [Chen et al., 2017](#)). The Nyainqêntanglha Group in the
109 middle part of the CLT has been interpreted as its Precambrian basement ([Li, 1955](#);
110 [Allégre et al., 1984](#); [Harris et al., 1988b](#); [Pan et al., 2004](#)). On the basis of zircon U–
111 Pb dating, the protoliths of the Nyainqêntanglha Group near Xainza area were
112 emplaced in the Neoproterozoic ([Fig. 1a](#), [Hu et al., 2005](#); [Zhang et al., 2012b](#); [Hu et](#)
113 [al., 2018a, b](#); [Zeng et al., 2018](#)). Recent petrological studies with zircon U–Pb age
114 data reveal that the rocks from the Xainza area are the relics of the Neoproterozoic (~
115 900 Ma) ocean crust metamorphosed subsequently at ~ 690–650 Ma ([Dong et al.,](#)
116 [2011b](#); [Zhang et al., 2012b](#)). Moreover, Xu and co-workers ([Xu et al., 2013a](#); [Chen et](#)
117 [al., 2019](#)) reported the presence of Proterozoic basement with crystallization ages of
118 ca. 1866 Ma, 1343–1250 Ma and 824 Ma from the Bomi complex in the southeastern
119 CLT. [Chen et al. \(2019\)](#) suggested that these Proterozoic gneisses revealed two
120 metamorphic events at ca. 625–600 Ma and 80 Ma. These new data confirm the
121 presence of a Precambrian metamorphic basement in the CLT.

122 The SLT is mainly composed of the Paleogene volcanic rocks, Cretaceous–
123 Tertiary intrusions, Triassic–Cretaceous volcano-sedimentary rocks and minor
124 medium- to high-grade metamorphic rocks (e.g., [Pan et al., 2004](#); [Zhu et al., 2008,](#)
125 [2013](#); [Zhang et al., 2014a](#)). The sedimentary cover in the SLT is largely restricted to
126 its eastern segment (cf. [Pan et al., 2004](#)). The Nyingchi complex in the eastern SLT
127 has been interpreted as the Precambrian basement ([Pan et al., 2004](#); [Yin et al., 2003](#);

128 [Xie et al., 2007](#)). However, more recent studies indicated that most protoliths of the
129 Nyingchi complex included both sedimentary and magmatic rocks of Cambrian (~
130 496 Ma), Devonian (~ 360 Ma), Cretaceous (~ 90 Ma) and Eocene (~ 55 Ma),
131 metamorphosed in the Mesozoic to Cenozoic ([Dong et al., 2010, 2012, 2014](#); [Guo et](#)
132 [al., 2011, 2012](#); [Palin et al., 2014](#); [Xu et al., 2013b](#); [Zhang et al., 2010, 2013, 2014a,](#)
133 [b, 2015](#)). Based on zircon U–Pb dating, [Lin et al. \(2013b\)](#) reported a metamorphic age
134 of ~ 600 Ma from the Nyingchi complex in the eastern SLT, with a protolith age of ~
135 1780 Ma. However, their samples are close to the northeast of the Eastern Himalayan
136 Syntaxis, and are widely intruded by the Mesozoic–Cenozoic granitoids or occur as
137 xenoliths within these granitoids ([Lin et al., 2013b](#)). Therefore, a Precambrian
138 crystalline basement may indeed be present at least locally in the SLT.

139 The present study area is located northwest of the Dongjiu area at the eastern
140 edge of the SLT, where metamorphic rocks and Cenozoic intrusive rocks are exposed
141 ([Fig. 1b](#)). The metamorphic rocks are offset by an east-west fault. The rocks north of
142 the fault include schists and gneisses that experienced amphibolite-facies
143 metamorphism at ~ 190 Ma ([Chen et al., 2017](#)). The studied samples are gneisses
144 collected south of the fault. These metamorphic rocks are all intruded by the Cenozoic
145 granites (~ 40–25 Ma; [Booth et al., 2004](#)).

146 **2.2. Sample description**

147 Sample details are given in [Table 1](#), including protolith type, location, mineral
148 assemblage, protolith and metamorphic ages, and metamorphic P – T conditions.

149 The biotite-amphibole (Bt-amp) gneisses consist of plagioclase (~30 vol%), K-
150 feldspar (~15 vol%), quartz (~35 vol%), amphibole (~10 vol%), biotite (~5 vol%),
151 titanite (~3 vol%), allanite (~1 vol%), and accessory phases including epidote,
152 ilmenite, apatite, rutile and zircon (Fig. 2a–d). The biotite (Bt) gneisses are comprised
153 of plagioclase (~20 vol%), K-feldspar (~35 vol%), quartz (~40 vol%), biotite (~4
154 vol%), and accessory minerals of allanite, epidote, apatite and zircon (Fig. 2e, f). The
155 foliation is defined by aligned biotite flakes and quartz-feldspar bands. Thereinto,
156 allanite occurs in two ways: those with epidote rims and zircon inclusions (Fig. 2c–e),
157 and those as inclusions within titanite (Fig. 7f, g, m, o, p). Most titanite grains rim
158 ilmenite, and some have inclusions of biotite, allanite, apatite, plagioclase, quartz or
159 minor rutile. The gneisses have a mineral assemblage of plagioclase + K-feldspar +
160 biotite + quartz + epidote ± amphibole ± titanite.

161 The studied gneisses underwent partial melting as revealed by the following
162 evidence: (1) feldspar grains with cusped extensions along quartz-quartz contacts
163 (Fig. 2b), (2) narrow trains of K-feldspar blebs along quartz-plagioclase contacts (Fig.
164 2a, f), (3) adjacent grains of quartz, feldspar and biotite are corroded (Fig. 2a, b, e, f).
165 These microstructures are interpreted as crystallization products of the former melt
166 (e.g., Sawyer, 2001; Brown, 2002; Timmermann et al., 2002).

167

168 **3. Analytical methods and results**

169 Analytical method details are given in [Supplementary Text 1](#), including

170 Cathodoluminescence (CL) images, back scattered electron (BSE) images and
171 analytical data on mineral major elements, bulk-rock major and trace elements, Sr–Nd
172 isotopes, zircon U–Pb dating, trace elements and Hf isotopes, and titanite *in situ* U–Pb
173 dating.

174 **3.1. Mineral major element data**

175 Major element compositions of plagioclase and amphibole in the Bt-amp gneiss
176 (samples 169-1 and 39-1) are given in [Supplementary Table 1](#) and [2](#), respectively.

177 Plagioclase grains in both samples are oligoclase, with An contents of 0.28–0.30.
178 Amphibole grains have 10.98–11.68 wt% CaO and 1.19–1.42 wt% Na₂O classified as
179 calcic amphibole ([Leake et al., 1997](#)).

180 **3.2. Bulk-rock major and trace element and Sr–Nd isotope data**

181 Bulk-rock major element, trace element and Sr–Nd isotopic compositions on the
182 studied samples are given in [Table 2](#).

183 The Bt-amp gneiss samples (169-1, 169-2 and 39-1) have 64.2–68.4 wt% SiO₂,
184 15.0–15.7 wt% Al₂O₃, 3.33–3.80 wt% CaO, 3.40–4.10 wt% Na₂O and 2.40–3.72 wt%
185 K₂O. The Bt gneiss samples (168-1 and 169-4) are characterized by higher SiO₂
186 (70.3–71.9 wt%) and K₂O (4.33–5.34 wt%), but lower Al₂O₃ (13.9–14.7 wt%), CaO
187 (1.85–2.06 wt%) and Na₂O (3.21–3.38 wt%). Using the Ab-An-Or classification for
188 silicic rocks ([Barker, 1979](#)), the Bt-amp gneisses are granodiorite whereas the Bt
189 gneisses are granite ([Fig. 3a](#)). These granitoid gneisses are metaluminous ([Fig. 3b](#)),

190 with the aluminum saturation indices ($A/CNK = \text{molecular Al}_2\text{O}_3 / (\text{CaO} + \text{Na}_2\text{O} +$
191 $\text{K}_2\text{O})$) of 0.95–1.02.

192 These orthogneisses are enriched in light rare earth elements (REE) and
193 relatively depleted in heavy REEs with highly fractionated REE patterns ($(\text{La}/\text{Yb})_N =$
194 15.3–143.5) and a weak negative Eu anomaly ($\text{Eu}/\text{Eu}^* = 0.62\text{--}0.87$) (Fig. 4a, Table
195 2). Furthermore, most samples display characteristic arc-like signature of negative
196 Nb, Ta and Ti anomalies (except for sample 169-2 without Ti anomaly due to low
197 REE contents, Fig. 4b).

198 For the analyzed four samples, their initial $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic ratios and $\epsilon_{\text{Nd}}(t)$
199 values calculated at $t = 1520$ Ma (see 3.3 below). The Bt-amp gneiss samples (169-1,
200 169-2 and 39-1) have initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of 0.7008–0.7036 and $\epsilon_{\text{Nd}}(t)$ values of -3.6
201 to +0.1, with model ages $T_{\text{DM}2} = 2.35\text{--}2.05$ Ga. The Bt gneiss sample (168-1) gives
202 $\epsilon_{\text{Nd}}(t) = -2.2$ and $T_{\text{DM}2} = 2.24$ Ga, with an abnormally low $^{87}\text{Sr}/^{86}\text{Sr}_{\text{initial}} = 0.6866$. This
203 unusual isotopic ratio has no petrogenetic significance because of the mobility of Rb,
204 which led to the excessive subtraction of $^{87}\text{Rb}/^{86}\text{Sr}$ ratio.

205 **3.3. Zircon U–Pb age and Hf isotope**

206 LA-ICP-MS zircon U–Pb dating and trace element analysis of five samples and
207 zircon Hf isotope compositions of four samples are given in Supplementary Tables 3
208 and 4, respectively.

209 Zircon grains from the five gneisses are colorless, subhedral–euhedral oblong or
210 prismatic with varying size of $\sim 100\text{--}200$ μm . CL images show that zircon grains have

211 a core–rim structure consisting of inherited cores with oscillatory zoning and dark
212 rims with weak or no zoning (Figs. 5 and 6). The analyzed spots on zircon cores from
213 two Bt-amp gneiss samples (169-1 and 169-2) and two Bt gneiss samples (168-1 and
214 169-4) yield weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ ages of 1519 ± 36 Ma ($n = 5$, MSWD = 0.016),
215 1520 ± 18 Ma ($n = 12$, MSWD = 0.85), 1516 ± 15 Ma ($n = 20$, MSWD = 0.046) and
216 1506 ± 6 Ma ($n = 16$, MSWD = 0.45), with upper intercept ages of 1544 ± 47 Ma,
217 1551 ± 23 Ma, 1544 ± 26 Ma and 1498 ± 6 Ma, respectively (Figs. 5a, c and 6a, c). All
218 analyzed spots on core domains have relatively high Th contents (57.7–927 ppm),
219 Th/U ratios (0.10–1.52) and REE contents (170–1576 ppm) with remarkable negative
220 Eu anomalies ($\text{Eu}/\text{Eu}^* = 0.07\text{--}0.55$) (Figs. 5b, d and 6b, d, Supplementary Tables 3).
221 Analyzed spots on zircon rims from three Bt-amp gneiss samples (169-1, 169-2 and
222 39-1) and one Bt gneiss sample (168-1) yield weighted mean $^{206}\text{Pb}/^{238}\text{U}$ ages of
223 605 ± 27 Ma ($n = 15$, MSWD = 0.96), 591 ± 3 Ma ($n = 14$, MSWD = 0.54) and 595 ± 2
224 Ma ($n = 21$, MSWD = 0.40), with lower intercept ages of 585 ± 11 Ma, 592 ± 18 Ma,
225 588 ± 6 Ma and 563 ± 10 Ma, respectively (Figs. 5a, c, e and 6a). Only one zircon rim
226 spot from sample 169-2 is obtained with $^{206}\text{Pb}/^{238}\text{U}$ age of 590 ± 2 Ma (Figs. 5c).
227 Compared with zircon cores, analyzed spots on rim domains have relatively low Th
228 contents (22.0–82.2 ppm), Th/U ratios (0.03–0.10) and REE contents (50.3–473
229 ppm), with weak or no negative Eu anomalies ($\text{Eu}/\text{Eu}^* = 0.21\text{--}1.86$) (Figs. 5b, d, f
230 and 6a, Supplementary Tables 3).

231 Therefore, the zircon LA–ICP–MS U–Pb analyses yield two age groups: 1520–
232 1506 Ma of weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age for zircon cores and 605–590 Ma of

233 weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age for zircon rims.

234 Fifty-three Hf isotopic analyses on zircon cores from two Bt-amp gneiss samples
235 (169-1 and 169-2) and two Bt gneiss samples (168-1 and 169-4) give initial
236 $^{176}\text{Hf}/^{177}\text{Hf}$ isotopic ratios of 0.281697–0.281891 and $\varepsilon_{\text{Hf}}(t)$ values ranging from -4.5
237 to +2.6, with two-stage model ages T_{DM2} of 2.54–2.10 Ga (Supplementary Tables 4).

238 **3.4. Titanite *in situ* U–Pb age**

239 Two titanite-rich gneiss samples (169-1 and 39-1) were selected for LA-ICP-MS
240 titanite *in situ* U–Pb dating. BSE images and photomicrographs of representative
241 titanite are shown in Fig. 7 and the titanite U–Pb dating and trace element data are
242 given in Supplementary Table 5.

243 Most titanite crystals are brown and subhedral–anhedral in shape with inclusions
244 of ilmenite, biotite, allanite, apatite, plagioclase, quartz and minor rutile (Fig. 7). BSE
245 images show that the titanite crystals mostly have patchy zoning. The analyzed spots
246 of titanite yield lower intercept ages are 25.1 ± 0.6 Ma for sample 169-1 (Fig. 8a) and
247 24.7 ± 0.5 Ma for sample 39-1 (Fig. 8b). After correction using ^{207}Pb , the weighted
248 mean $^{206}\text{Pb}/^{238}\text{U}$ ages are 26.2 ± 0.4 Ma ($n=40$, $\text{MSWD}=2.5$) and 26.0 ± 0.6 Ma ($n=29$,
249 $\text{MSWD}=3.1$) (Fig. 8).

250

251 **4. Metamorphic P – T conditions**

252 **4.1. Hbl-Pl-Q thermobarometry**

253 Amphibole–plagioclase thermometry (Holland and Blundy, 1994) and
254 amphibole–plagioclase–quartz barometry (Bhadra and Bhattacharya, 2007) are used
255 to calculate the metamorphic P – T condition of the Bt-amp gneisses. The amphibole–
256 plagioclase–quartz thermobarometry yields metamorphic P – T conditions of 6.2–7.2
257 kbar and 691–736 °C for sample 169-1, and 5.4–6.5 kbar and 716–765 °C for sample
258 39-1.

259 **4.2. Zr-in-titanite thermometry**

260 Titanite formation temperatures are estimated using the Zr-in-titanite
261 thermometry (T (°C) = $[7708 + 960P] / [10.52 - \log(\alpha_{\text{TiO}_2}) - \log(\alpha_{\text{SiO}_2}) - \log(\text{ppm Zr,}$
262 titanite)] – 273; Hayden et al., 2008). The activity of TiO_2 is assumed to be 0.5
263 (plausible lower limits in typical crustal rocks), with SiO_2 activity assumed as 1.0
264 (Hayden and Watson 2007; Ferry and Watson 2007). Based on amphibole–
265 plagioclase–quartz barometer, the metamorphic pressure conditions of the Bt-amp
266 gneisses are ~ 6 kbar. Zr concentrations range from 158 to 591 ppm in sample 169-1,
267 and from 276 ppm to 620 ppm in sample 39-1. The calculations of Zr-in-titanite
268 thermometry are 688–756 °C for sample 169-1 and 716–759 °C for sample 39-1
269 (Supplementary Table 5). The temperature data display a cluster at 700–750 °C
270 (64/69, Fig. 9), which is consistent with the temperature conditions obtained by the

271 amphibole–plagioclase thermometry.

272

273 **5. Discussion**

274 **5.1. Age interpretation**

275 Zircon LA-ICP-MS U–Pb dating shows two age groups of 1520–1506 Ma and
276 605–590 Ma. Most zircons of the studied Dongjiu gneisses show euhedral-prismatic
277 forms and display rounded terminations, which in some cases generate an ovoid
278 morphology. CL images show that all zircon grains have a core–rim structure, i.e.,
279 oscillatory-zoned core and rim with weak or no zoning (Figs. 5 and 6). The inherited
280 zircon cores yield concordant ages of 1520–1506 Ma without detrital age distribution
281 (analyses with concordance > 95%, Supplementary Tables 3). These zircon cores
282 have relatively high Th contents (usually > 50 ppm) with high Th/U ratios (≥ 0.1 , up
283 to 1) (Fig. 10) and REE patterns with remarkable negative Eu anomalies (Figs. 5b, d
284 and 6b, d). These properties are consistent with the zircons of magmatic origin (e.g.,
285 Hoskin and Schaltegger, 2003). Thus, the Mesoproterozoic age of ~ 1500 Ma given
286 by the zircon cores represents the protolith crystallization age of the gneisses. By
287 comparison, CL images show that zircon rims have weak or no zoning. Most zircon
288 rims occur as lobes with smooth or rough edges, and may overprint pre-existing
289 structures (Fig. 5b, f). All these characteristics suggest that zircon rims have
290 developed during metamorphic recrystallization near the solidus (Hoskin and Black,
291 2000; Rubatto, 2017). The zircon rims have lower Th contents (usually < 50 ppm) and

292 Th/U ratios (< 0.1) (Fig. 10) without remarkable negative Eu anomalies (Figs. 5b, d, f
293 and 6b), which are consistent with metamorphic zircon (e.g., Rubatto et al., 2009;
294 Rubatto, 2017). Based on the zircon internal structure, Th/U ratios and REE patterns,
295 we suggest that the zircon rims provide the metamorphic ages of 605–590 Ma for the
296 orthogneisses in the Dongjiu area.

297 Titanite crystals from two Bt-amp gneiss samples are subhedral–anhedral in
298 shape with metamorphic mineral inclusions of ilmenite, biotite, allanite, plagioclase,
299 quartz or minor rutile (Fig. 7). BSE images show that titanite crystals have patchy
300 zonation, characteristic of metamorphic titanite (Rubatto, 2017). Therefore, LA–ICP–
301 MS titanite *in situ* U–Pb dating indicates that these gneisses experienced Oligocene
302 metamorphism at ~ 26 Ma.

303 In summary, the protoliths of the gneisses from the Dongjiu area crystallized in
304 the Mesoproterozoic (1520–1506 Ma), and followed by subsequent metamorphism in
305 the Neoproterozoic (605–590 Ma) and more recently in the Oligocene (~ 26 Ma).

306 **5.2. Mesoproterozoic magmatism**

307 The Lhasa terrane, as the southernmost part of the Asian continent, experienced
308 intense deformation, magmatism and metamorphism related to the northward Neo-
309 Tethyan seafloor subduction in the Mesozoic and the India-Asia continental collision
310 in the Cenozoic (e.g., Zhu et al., 2011; Zhang et al., 2014a). Due to these strong
311 reworking processes, the Precambrian thermotectonic records are rarely reported (e.g.,
312 Dong et al., 2010, 2011b; Guynn et al., 2012; Zhang et al., 2012b; Xu et al., 2013a;

313 [Hu et al., 2018b](#); [Chen et al., 2019](#)).

314 Based on the zircon U–Pb geochronology, the inherited magmatic zircon cores of
315 the Dongjiu gneisses yield crystallization ages of 1520–1506 Ma (lack detrital
316 components; see above), indicate that the protoliths of Dongjiu gneisses are
317 Mesoproterozoic magmatic rocks. The bulk-rock chemical compositions of the
318 Dongjiu gneisses suggest that their protoliths are metaluminous granodiorite and
319 granite ([Fig. 3](#)), characteristic of arc-like signature with negative Nb, Ta and Ti
320 anomalies ([Fig. 4b](#)). The Mesoproterozoic granitic rocks have bulk-rock $\epsilon_{\text{Nd}}(t)$ values
321 of -3.6 to +0.1 and zircon $\epsilon_{\text{Hf}}(t)$ values of -4.5 to +2.6, with similar T_{DM2} ages of 2.35–
322 2.05 Ga and 2.54–2.10 Ga respectively, suggesting that the magmatic rocks are
323 derived from partial melting of Paleoproterozoic crustal material.

324 The coeval ~ 1500 Ma magmatic rocks are widespread in several continental
325 fragments, including West Africa, South America, North America, Australia, Baltica
326 (Northern Europe), Siberia and India. The rock types are mainly mafic dikes and sills
327 (e.g., [Ernst et al., 2013, 2016](#); [Silveira et al., 2013](#)), and massif-type anorthosites (e.g.,
328 [Emslie, 1978](#); [Weis, 1986](#); [Sadowski and Bettencourt, 1996](#); [Mukherjee and Das,](#)
329 [2002](#)). The Mesoproterozoic Era, dominated by the break-up of the Columbia
330 supercontinent and the formation of the Rodinia supercontinent, was an important
331 crust-forming period in many continents in Earth's history. The global
332 Mesoproterozoic magmatism has commonly been attributed to the rifting and
333 fragmentation of the Columbia supercontinent (e.g., [Rogers and Santosh, 2002](#); [Zhao](#)
334 [et al., 2003](#)). However, ~ 1.6–1.5 Ga metamorphic and magmatic rocks of the Central

335 Indian Tectonic Zone are the products of south-north Indian subcontinental collision
336 (e.g., Acharyya, 2003; Kröner et al., 2012). For the studied Mesoproterozoic granitic
337 rocks in the SLT, it is too difficult to discuss the tectonic setting in a global context
338 owing to their limited distribution and subsequent reworking.

339 The Mesoproterozoic inherited zircons in the Gangdese batholith (e.g., Zhu et al.,
340 2011; Ji et al., 2017), and detrital zircons from the sedimentary rocks of the
341 Carboniferous–Triassic strata (Leier et al., 2007; Pullen et al., 2008; Dong et al.,
342 2010; Zhu et al., 2013; Li et al., 2014; Guo et al., 2017) indicate that the
343 Mesoproterozoic magmatic rocks are probably more widely distributed than exposed
344 in the Lhasa terrane. Moreover, the metasedimentary rocks from the Nyingchi
345 complex in the SLT contain abundant ~1500 Ma detrital zircons (Guo et al., 2017).
346 The 1550–1450 Ma detrital zircons from the CLT Permian–Triassic strata define a
347 broad band of $\epsilon_{\text{Hf}}(t)$ values (-16.7 to +9.6; Fig. 11). By comparison, the coeval detrital
348 zircons from the SLT metasedimentary rocks have lower $\epsilon_{\text{Hf}}(t)$ values (-11.3 to +3.2;
349 Fig. 11). The studied Mesoproterozoic granitic rocks, with the coeval gneisses of the
350 southern Nyingchi complex (our unpublished data) have the similar zircon $\epsilon_{\text{Hf}}(t)$
351 values as the above, suggesting that they might be local sources for the
352 Mesoproterozoic detrital zircons of the Paleozoic strata (Fig. 11).

353 **5.3. Neoproterozoic and Oligocene metamorphism**

354 Based on zircon and titanite U–Pb geochronology, the Dongjiu orthogneisses
355 experienced two metamorphic events at 605–590 Ma recorded by zircon and 26 Ma

356 by titanite, respectively.

357 **5.3.1. Neoproterozoic metamorphism**

358 Due to the Oligocene metamorphism, the Neoproterozoic metamorphic minerals
359 are usually overprinted. The petrography shows that ilmenite is all surrounded by
360 titanite; rare rutile only occurs as inclusions within titanite; and allanite is rimed by
361 epidote including zircon grains (Figs. 2c, d and 7). Along with titanite formed in the
362 later metamorphism, we speculate that the mineral assemblage of the Neoproterozoic
363 metamorphism is represented as ilmenite and allanite. Lacking index metamorphic
364 minerals, it is difficult to calculate the detailed P - T conditions of the Neoproterozoic
365 metamorphism for the studied gneisses. However, the characteristics of zircon internal
366 structure and chemistry show that zircon rims of the Dongjiu gneisses likely form
367 under conditions near solidus. Rubatto et al. (2009) show that the metamorphic zircon
368 rims of metatonalite with the similar mineral assemblage to this study formed under
369 amphibolite-facies condition ($T = 620$ – 700 °C). For diorite bulk composition, recent
370 phase equilibrium modeling indicated that the H_2O -saturated (wet) solidus occurs
371 between ~ 650 – 700 °C and garnet becomes stable above ~ 8.5 kbar (e.g., Palin et al.,
372 2016). On the formation condition of zircon rim, bulk composition and lack of garnet,
373 we reason that the Dongjiu granitic gneisses underwent MP amphibolite-facies
374 metamorphism at 605–590 Ma.

375 According to the Gondwana-derived affinity, the ~ 600 Ma metamorphic event
376 of the Lhasa terrane is likely related to the assembly of Gondwana supercontinent

377 (e.g., [Meert, 2003](#); [Veevers, 2004](#); [Collins and Pisarevsky, 2005](#)). Early
378 palaeogeographic models based on limited data interpreted the presence of a single
379 super-continent throughout the Proterozoic ([Piper, 1976](#)). [McWilliams \(1981\)](#)
380 suggested that two Neoproterozoic continental masses, East Gondwana (India, East
381 Australia, Antarctica, Madagascar and Sri Lanka) and West Gondwana (Africa and
382 South America) collided along the Mozambique Belt to form Gondwana. From the
383 Rodinia fragments to the final amalgamation Gondwana, there have been many
384 accretionary terranes and collisional events ([Collins and Pisarevsky, 2005](#)). Although
385 more work is needed on details of such amalgamation. Meert and co-workers ([Meert,](#)
386 [et al., 1995](#); [Meert and Van der Voo, 1997](#); [Meert, 2001, 2003](#)) suggested a
387 multiphase assembly of two main periods of orogenesis, including an earlier East
388 African Orogeny (EAO) (~ 750–620 Ma) and a later Kuunga Orogeny (~ 570–530
389 Ma). The later orogeny marks the collision of Australia and Antarctica with the rest of
390 Gondwana and was subsequently correlated with a broad belt of orogenesis from the
391 Damara Orogen in the west to the Pinjarra Orogen in the east ([Meert, 2003](#)). They
392 proposed a Neoproterozoic continent consisting of Sri Lanka, Madagascar and India
393 colliding with a combined Congo/Kalahari (African) continent at ~ 750–620 Ma,
394 followed by Australia/East Antarctica colliding with the bulk of Gondwana at ~ 570–
395 530 Ma ([Meert, 2003](#); [Meert and Torsvik, 2003](#)). However, [Boger and Miller \(2004\)](#)
396 proposed that the EAO evolved as an accretionary orogeny and was partially
397 superimposed by a ~ 590–560 Ma orogen created by the collision of combined India,
398 Madagascar and part of Antarctica land masses with eastern Africa along the

399 Mozambique suture. In their model, Australia–Antarctica collided with India along
400 the Kuunga suture at ~ 535–520 Ma. Until now, the Precambrian metamorphic events
401 of the Lhasa terrane are only reported in the Nyainqêntanglha Group in the central
402 CLT (~ 690–650 Ma, [Dong et al., 2011b](#); [Zhang et al., 2012b](#)), the Bomi complex in
403 the eastern CLT (~ 625–600 Ma, [Chen et al., 2019](#)), and the Nyingchi complex in the
404 eastern SLT (~ 600 Ma, [Lin et al., 2013b](#) and this study). The Nyainqêntanglha Group
405 experienced an early granulite-facies peak-metamorphism at ~ 690–650 Ma, and late
406 amphibolite-facies retrogression at ~ 480 Ma ([Dong et al., 2011b](#); [Zhang et al.,](#)
407 [2012b](#)). [Zhang et al. \(2012b, 2014a\)](#) suggested that the Neoproterozoic metamorphism
408 occurred during the assembly of East and West Gondwana within the EAO. For all
409 other Precambrian metamorphic events, only the Nyingchi complex is speculated to
410 experience MP amphibolite-facies metamorphism without knowing exact P – T
411 conditions due to the Cenozoic metamorphic reworking. Therefore, this study
412 suggests that the ~ 600 Ma metamorphism events recorded in the Nyingchi complex
413 in the eastern SLT and the Bomi complex in the eastern CLT are likely response to
414 the assembly of Gondwana supercontinent.

415 **5.3.2. Oligocene metamorphism and melting**

416 In this study, titanite formed at ca. 26 Ma is observed either mostly rimming
417 ilmenite or as separate grains. Titanite can be in contact with a variety of minerals,
418 e.g., amphibole, biotite, plagioclase and epidote, and contains inclusions of biotite,
419 allanite, plagioclase and quartz ([Fig. 7](#)). The formation of titanite rims on the ilmenite

420 could be explained in terms of reactions such as: ilmenite + allanite + K-feldspar +
421 quartz = titanite + anorthite + annite + H₂O (Harlov et al., 2006; Angiboust and
422 Harlov, 2017). Titanite rimming ilmenite is commonly present in the amphibolite-
423 facies rocks (e.g., Nijland and Maijer, 1993; Nijland and Visser, 1995; Hansen et al.,
424 2002; Harlov and Hansen, 2005). The mineral assemblage (plagioclase + K-feldspar +
425 biotite + quartz + epidote ± amphibole ± titanite) also indicates that the later
426 Oligocene metamorphism occurred at amphibolite-facies condition. Hbl-Pl-Q
427 thermobarometry shows that the Dongjiu gneisses experienced peak *P–T* conditions
428 of 5.4–7.2 kbar and 691–765 °C. Zr-in-titanite thermometry yields the similar *T*
429 conditions of 688–759 °C at ~ 6 kbar. Moreover, the microstructure proves that these
430 studied gneisses record the presence of melt. Therefore, we suggest that the prior melt
431 represents the product of the Oligocene metamorphism, and the Dongjiu gneisses
432 underwent MP amphibolite-facies metamorphism and melting at ca. 26 Ma. In the
433 southern part of the studied area, the coeval metamorphic rocks of the Nyingchi
434 complex have also been reported to take place under amphibolite-facies conditions
435 (e.g., Zhang et al., 2010; Dong et al., 2012; Palin et al., 2014; Kang et al., 2019).

436 **5.4. The nature of the Precambrian basement of the Lhasa terrane**

437 The spatial distribution and nature of the Precambrian basement beneath the
438 entire Lhasa terrane have been speculative. Due to medium- to high-grade
439 metamorphism, the Nyainqêntanglha Group in the CLT and the Nyingchi complex in
440 the SLT have been regarded as the Precambrian metamorphic basement (Xu et al.

441 1985; Dewey et al. 1988; Harris 1988b; Hu et al. 2005). However, adequate age
442 constraints are lacking. Based on zircon Hf isotope data, Zhu et al (2011) suggested
443 that the CLT has ancient basement rocks of Proterozoic and Archean ages with NLT
444 and SLT being younger and juvenile crust (Phanerozoic) accreted towards the CLT.

445 The Amdo basement, consisting of orthogneisses and mafic granulites, is
446 reported to represent the Precambrian basement of the Lhasa terrane (Xu et al., 1985;
447 Coward et al., 1988; Kidd et al., 1988; Pan et al., 2004). The gneisses have
448 crystallization ages of Neoproterozoic (~820 Ma; Zhang et al., 2012a) and Cambro-
449 Ordovician (540–460 Ma; Xu et al., 1985; Xie et al., 2010; Guynn et al., 2012; Zhang
450 et al., 2012a). The mafic granulites have undergone peak granulite-facies
451 metamorphism at ~ 190 Ma and retrogressed under amphibolite-facies conditions at ~
452 180 Ma (e.g., Xu et al., 1985; Guynn et al., 2006; Zhang et al., 2012a; Zhang XR et
453 al., 2014). Therefore, the Amdo gneiss represents a Neoproterozoic crystallization
454 basement, which undergoes metamorphism in the early Jurassic.

455 The existence of a Precambrian basement in the CLT has been previously
456 inferred using older inherited zircon ages of the gneiss (Allégre et al., 1984) and the
457 bulk-rock Nd isotope composition from sedimentary rocks (Zhang KJ et al., 2007).
458 Recently reported old rocks are the ca. 925–748 Ma granitoids and gabbros of the
459 Nyainqêntanglha Group in the Xianza area west of Nam Tso Lake (Hu et al., 2005;
460 Zhang et al., 2012b; Hu et al., 2018 a, b; Zeng et al., 2018). These rocks have
461 experienced granulite-facies peak-metamorphism at ca. 690–650 Ma (Dong et al.,
462 2011b; Zhang et al., 2012b). Some studies suggest that the Neoproterozoic magmatic

463 rocks are crust of the Mozambique Ocean (Zhang et al., 2012b; Zeng et al., 2018), but
464 others propose that these rocks formed in a back-arc setting (Hu et al., 2018 a, b). In
465 addition, the Bomi complex consists of the Proterozoic magmatic rocks formed at ca.
466 1866 Ma, 1343–1250 Ma and 824 Ma, and undergoes metamorphism at ca. 625–600
467 Ma and 80 Ma (Xu et al., 2013a; Chen et al., 2019). Thereinto, the Paleoproterozoic
468 and Neoproterozoic granitoid gneisses show geochemical affinity of volcanic arc
469 granites (Chen et al., 2019); the Mesoproterozoic granite gneisses have an aluminous
470 A-type granite affinity (Xu et al., 2013a). However, there is no constraint on the
471 metamorphic condition. Therefore, the CLT indeed has Proterozoic basement.

472 In the SLT, the Nyingchi complex has been interpreted to represent slivers of a
473 Precambrian basement of the Lhasa terrane (e.g., Pan et al., 2004; Xie et al., 2007;
474 Yin et al., 2003). However, more recent studies suggested that most high-grade
475 metamorphic rocks in the eastern SLT underwent Mesozoic to Cenozoic
476 metamorphism and their protoliths included both sedimentary and magmatic rocks
477 with various protolith ages (Dong et al., 2010, 2012, 2014; Guo et al., 2011, 2012,
478 2017; Palin et al., 2014; Xu et al., 2013b; Zhang et al., 2010, 2013, 2014a, 2014b,
479 2015). Here, the Dongjiu gneisses, as a part of the Nyingchi complex, have a protolith
480 crystalline age of 1520–1506 Ma, and experienced amphibolite-facies metamorphism
481 at 605–590 Ma, representing a Precambrian metamorphic basement of the SLT.
482 Moreover, the studied Mesoproterozoic granitic rocks have T_{DM2} of 2.54–2.10 Ga,
483 along with Meso- to Paleoproterozoic zircon Hf model ages of Cambrian and
484 Devonian–Carboniferous granitoids (Ji et al., 2012; Dong et al., 2014, 2015),

485 implying the presence of an older early Paleoproterozoic crust yet unidentified in the
486 SLT.

487 Excluding the ca. 1780 Ma xenoliths reported by Lin et al. (2013b), the ~ 1500
488 Ma granitic gneisses from the Dongjiu area here are the oldest rocks reported of the
489 SLT. The zircon Hf and bulk-rock Nd isotopes give similar T_{DM2} ages up to 2.5 Ga,
490 suggesting that the Mesoproterozoic granitic rocks are derived from melting of the
491 Paleoproterozoic crustal material. Moreover, the ~ 1500 Ma gneisses from the
492 southern Nyingchi complex give Paleoproterozoic zircon Hf model ages (Fig. 11, our
493 unpublished data). By comparison, the Proterozoic granitoids from the Bomi complex
494 in the CLT have similar zircon Hf T_{DM2} ages ranging from 2.5 to 1.3 Ga (Xu et al.,
495 2013a; Chen et al., 2019). Furthermore, the magmatic rocks (before 360 Ma) from
496 both the SLT and CLT have the same ranges of zircon $\epsilon_{Hf}(t)$ values and model ages
497 (Fig. 11). Therefore, we suggest that the SLT and CLT share a common Precambrian
498 basement.

499 **5.5. Reworking of the Precambrian basement of the Lhasa terrane**

500 Although both SLT and CLT share a common Precambrian basement, the strong
501 thermal events (including metamorphism and mainly mantle-derived magmatism) as a
502 consequence of the northward subduction of the Neo-Tethyan seafloor beneath the
503 Lhasa terrane and the subsequent India-Asia continental collision have intensively
504 reworked the Precambrian basement.

505 Since the early Mesozoic, important mantle contributions have caused the

506 drastically elevated zircon $\epsilon_{\text{Hf}}(t)$ of the magmatic rocks from the SLT (Fig 11).
507 However, their zircon $\epsilon_{\text{Hf}}(t)$ values vary significantly (up to 20 units from ~ -5 to $+15$;
508 Fig. 11), indicating the presence of old basement. The input of mantle material not
509 only contributed to juvenile continental crust growth (e.g., Mo et al., 2007; Zhu et al.,
510 2011), but also reworked the Precambrian basement of the SLT. In contrast, the
511 granitoids from the CLT exhibit negative zircon $\epsilon_{\text{Hf}}(t)$ and old T_{DM2} ages, suggesting
512 that they are mainly derived from partial melting of ancient continental crust.
513 Therefore, the basement of the CLT underwent weaker reworking, preserving more
514 rocks with Nd-Hf isotopes characteristic of ancient continental crust than the SLT.

515 This study shows that the Precambrian metamorphic basement of the Lhasa
516 terrane has also undergone more recent metamorphism at ~ 26 Ma. Due to similar
517 metamorphic conditions, it is difficult to distinguish mineral assemblages as the result
518 of recent metamorphism from those of the Neoproterozoic metamorphism, except for
519 the preserved inclusions of ilmenite and allanite. The main mineral assemblage of
520 plagioclase + K-feldspar + biotite + quartz + epidote \pm amphibole \pm titanite is the
521 product of the Oligocene metamorphism. The coeval metamorphic rocks have been
522 widely reported in the south part of the Nyingchi complex (e.g., Zhang et al., 2010,
523 2014a; Guo et al., 2011; Dong et al., 2012; Palin et al., 2014; Kang et al., 2019).
524 Zhang et al. (2015) suggested that the crustal shortening and thickening resulting from
525 the continental collision and continued convergence is the very tectonic mechanism
526 for the Oligocene reworking of the Lhasa terrane crust.

527

528 **6. Conclusion**

529 (1) The protoliths of the Dongjiu orthogneisses in the SLT are granodiorite and
530 granite emplaced at 1520–1506 Ma, which provide source materials for the
531 Paleozoic metasedimentary rocks in the Lhasa terrane. The Mesoproterozoic
532 granitoids have derived from partial melting of earlier Paleoproterozoic crustal
533 material.

534 (2) The Mesoproterozoic orthogneisses from the Dongjiu area have experienced the
535 Neoproterozoic (605–590 Ma) metamorphism, and therefore represent the
536 Precambrian metamorphic basement of the SLT.

537 (3) The Dongjiu gneisses also underwent the Oligocene (26 Ma) metamorphism
538 under MP amphibolite-facies conditions as the result of crustal shortening and
539 thickening in response to the continued India-Asia continental convergence.

540 (4) The CLT and SLT share a common Precambrian metamorphic basement, but the
541 SLT basement has been strongly reworked by mantle-derived magmatism and
542 metamorphism since the Mesozoic.

543

544 **Acknowledgments**

545 We want to thank two anonymous journal referees and Editor Guochun Zhao for
546 their constructive comments, which have helped improve the quality of this paper.

547 This study was supported by the National Natural Science Foundation of China
548 (grants 41872070 and 91855210) and the China Geological Survey (grants

549 DD20160122 and DD20190057). Xin Dong acknowledges the China Scholarship
550 Council for funding a 12-month research at Durham University, UK (CSC NO.
551 201809110024). We thank Dr. Zhenyu He, Hua Xiang and Fenghua Liang for their
552 support of this work; Dr. Zhengbin Gou and Huixia Ding for taking part in field work,
553 and Ph.D. students Yanhong Chen and Fangyu Shen for helpful discussion.

554

555 **References**

- 556 Acharyya, S.K., 2003. The Nature of Mesoproterozoic Central Indian Tectonic Zone
557 with Exhumed and Reworked Older Granulites. *Gondwana Res.* 6 (2), 197–214.
- 558 Allégre, C.J., et al., 1984. Structure and evolution of the Himalaya–Tibet orogenic
559 belt. *Nature* 307, 17–22.
- 560 Angiboust, S., Harlov, D., 2017. Ilmenite breakdown and rutile-titanite stability in
561 metagranitoids: Natural observations and experimental results. *Am. Mineral.* 102
562 (8), 1696–1708.
- 563 Barker, F., 1979. Trondhjemite: definition environment and hypothesis of origin. In:
564 Barker F (Ed) *Trondhjemites dacites and related rocks*. Elsevier, Amsterdam, pp.
565 1–12.
- 566 Bhadra, S., Bhattacharya, A., 2007. The barometer tremolite + tschermakite + 2 albite
567 = 2 pargasite + 8 quartz: constraints from experimental data at unit silica activity,
568 with application to garnet-free natural assemblages. *Am. Mineral.* 92 (4), 491–
569 502.

570 Boger, S.D., Miller, J.M., 2004. Terminal suturing of Gondwana and the onset of the
571 Ross–Delamerian Orogeny: The cause and effect of an Early Cambrian
572 reconfiguration of plate motions. *Earth Planet. Sci. Lett.* 219, 35–48.

573 Booth, A.L., Zeitler, P.K., Kidd, W.S.F., Wooden, J., Liu, Y.P., Idleman, B., Hren,
574 M., Chamberlain, C.P., 2004. U–Pb zircon constraints on the tectonic evolution
575 of southeastern Tibet, Namche Barwa area. *Am. J. Sci.* 304 (10), 889–929.

576 Brown, M., 2002. Retrograde processes in migmatites and granulites revisited. *J.*
577 *Metamorph. Geol.* 20 (1), 25–40.

578 Chang, C.F., et al., 1986. Preliminary conclusions of the Royal Society and
579 Academia-Sinica 1985 Geotraverse of Tibet. *Nature* 323, 501–507.

580 Chang, C.F., Zheng, S.L., 1973. Tectonic features of the Mount Jolmo Lungma region
581 in southern Tibet, China. *Chin. J. Geol.* 1 (1), 1–12.

582 Chen, L.R, Xu, W.C., Zhang, H.F., Zhao, P.L., Guo, J.L., Luo, B.J., Guo, L., Pan,
583 F.B., 2019. Origin and early evolution of the Lhasa Terrane, South Tibet:
584 Constraints from the Bomi Gneiss Complex. *Precambrian Res.* 331, 105360.

585 Chen, Z.J., Tian, Z.L., Zhang, Z.M., Dong, X., 2017. Early Jurassic metamorphism of
586 the eastern segment of the Lhasa terrane in south Tibet and its tectonic
587 significance. *Int. Geol. Rev.* 59 (14), 1–17.

588 Cheng, H., Liu, Y., Vervoort, J.D., Lu, H., 2015. Combined U–Pb, Lu–Hf, Sm–Nd
589 and Ar–Ar multichronometric dating on the Bailang eclogite constrains the
590 closure timing of the Paleo-Tethys Ocean in the Lhasa terrane, Tibet. *Gondwana*
591 *Res.* 28 (4), 1482–1499.

592 Chiu, H.Y., Chung, S.L., Wu, F.Y., Liu, D.Y., Liang, Y.H., Lin, Y.J., Iizuka, Y., Xie,
593 L.W., Wang, Y.B., Chu, M.F., 2009. Zircon U–Pb and Hf isotope constraints
594 from eastern Transhimalayan batholiths on the precollisional magmatic and
595 tectonic evolution in southern Tibet. *Tectonophysics* 477 (1–2), 3–19.

596 Chu, M.F., Chung, S.L., Song, B., Liu, D.Y., O'Reilly, S.Y., Pearson, N.J., 2006.
597 Zircon U–Pb and Hf isotope constraints on the Mesozoic tectonics and crustal
598 evolution of southern Tibet. *Geology* 34 (9), 745–748.

599 Collins, A.S., Pisarevsky, S.A., 2005. Amalgamating eastern Gondwana: The
600 evolution of the circum-Indian orogens. *Earth Sci. Rev.* 71, 229–270.

601 Coward, M.P., Kidd, W.F., Yun, P., Shackleton, R.M., Zhang, H., 1988. The structure
602 of the 1985 Tibet Geotraverse, Lhasa to Golmud. *Phil. Trans. Roy. Soc. Lond. A*
603 327, 307–336.

604 Dewey, J.F., Shackleton, R.M., Chang, C., Sun, Y., 1988. The tectonic evolution of
605 the Tibetan Plateau. *Phil. Trans. Roy. Soc. Lond. A* 327, 379–413.

606 Ding, H.X., Zhang, Z.M., Dong, X., Yan, R., Lin, Y.H., Jiang, H.Y., 2015. Cambrian
607 ultrapotassic rhyolites from the Lhasa terrane, south Tibet: Evidence for Andean-
608 type magmatism along the northern active margin of Gondwana. *Gondwana Res.*
609 27 (4), 1616–1629.

610 Ding, L., Kapp, P., Zhong, D., Deng, W., 2003. Cenozoic volcanism in Tibet:
611 Evidence for a transition from oceanic to continental subduction. *J. Petrol.* 44,
612 1833–1865.

613 Dong, X., Zhang, Z.M., Santosh, M., 2010. Zircon U–Pb chronology of the Nyingtri

614 Group, Southern Lhasa Terrane, Tibetan Plateau: Implications for Grenvillian
615 and Pan-African provenance and Mesozoic-Cenozoic metamorphism. *J. Geol.*
616 118 (6), 677–690.

617 Dong, X., Zhang, Z.M., Liu, F., Wang, W., Yu, F., Shen, K., 2011a. Zircon U–Pb
618 geochronology of the Nyainqêntanglha Group from the Lhasa terrane: New
619 constraints on the Triassic orogeny of the south Tibet. *J. Asian Earth Sci.* 42 (4),
620 732–739.

621 Dong, X., Zhang, Z.M., Santosh, M., Wang, W., Yu, F., Liu, F., 2011b. Late
622 Neoproterozoic thermal events in the northern Lhasa terrane, south Tibet: Zircon
623 chronology and tectonic implications. *J. Geodyn.* 52 (5), 389–405.

624 Dong, X., Zhang, Z.M., Liu, F., Wang, W., Yu, F., Lin, Y.H., Jiang, H.Y., He, Z.Y.,
625 2012. Genesis of the metamorphic rocks from southeastern Lhasa terrane and the
626 Mesozoic-Cenozoic orogenesis. *Acta Petrol. Sin.* 28 (6), 1765–1784 (in Chinese
627 with English abstract).

628 Dong, X., Zhang, Z.M., 2013. Genesis and tectonic significance of the Early Jurassic
629 magmatic rocks from the southern Lhasa terrane. *Acta Petrol. Sin.* 29 (6), 1933–
630 1948 (in Chinese with English abstract).

631 Dong, X., Zhang, Z.M., Liu, F., He, Z.Y., Lin, Y.H., 2014. Late Paleozoic intrusive
632 rocks from the southeastern Lhasa terrane, Tibetan Plateau, and their Late
633 Mesozoic metamorphism and tectonic implications. *Lithos* 198–199, 249–262.

634 Dong, X., Zhang, Z.M., 2015. Cambrian granitoids from the southeastern Tibetan
635 Plateau: Research on petrology and zircon Hf isotope. *Acta Petrol. Sin.* 31 (5),

636 1183–1199 (in Chinese with English abstract).

637 Emslie, R.F., 1978. Anorthosite massifs, rapakivi granites, and late Proterozoic rifting
638 of North America. *Precambrian Res.* 7 (1), 61–98.

639 Ernst, R.E., Pereira, E., Hamilton, M.A., Pisarevsky, S.A., Rodriques, J., Tassinari,
640 C.C.G., Teixeira, W., Van-Dunem, V., 2013. Mesoproterozoic intraplate
641 magmatic ‘barcode’ record of the Angola portion of the Congo Craton: Newly
642 dated magmatic events at 1505 and 1110 Ma and implications for Nuna
643 (Columbia) supercontinent reconstructions. *Precambrian Res.* 230, 103–118.

644 Ernst, R.E., Okrugin, A.V., Veselovskiy, R.V., Kamo, S.L., Hamilton, M.A., Pavlov,
645 V., Söderlund, U., Chamberlain, K.R., Rogers, C., 2016. The 1501 Ma
646 kuonamka large igneous province of northern siberia: U–Pb geochronology,
647 geochemistry, and links with coeval magmatism on other crustal blocks. *Russ.*
648 *Geol. Geophys.* 57 (5), 653–671.

649 Ferry, J.M., Watson, E.B., 2007. New thermodynamic models and revised calibrations
650 for the Ti-in-zircon and Zr-in-rutile thermometers. *Contrib. Mineral. Petrol.* 154
651 (4), 429–437.

652 Guo, L., Zhang, H.F., Harris, N., Pan, F.B., Xu, W.C., 2011. Origin and evolution of
653 multistage felsic melts in eastern Gangdese belt: Constraints from U–Pb zircon
654 dating and Hf isotopic composition. *Lithos* 127 (1–2), 54–67.

655 Guo, L., Zhang, H.F., Harris, N., Parrish, R., Xu, W.C., Shi, Z.L., 2012. Paleogene
656 crustal anatexis and metamorphism in Lhasa terrane, eastern Himalayan syntaxis:
657 Evidence from U–Pb zircon ages and Hf isotopic compositions of the Nyingchi

658 Complex. *Gondwana Res.* 21 (1), 100–111.

659 Guo, L., Zhang, H.F., Harris, N., Xu, W.C., Pan, F.B., 2017. Detrital zircon U–Pb
660 geochronology, trace-element and Hf isotope geochemistry of the
661 metasedimentary rocks in the eastern Himalayan syntaxis: Tectonic and
662 paleogeographic implications. *Gondwana Res.* 41, 207–221.

663 Guo, L.S., Liu, Y.L., Liu, S.W., Cawood, P.A., Wang, Z.H., Liu, H.F., 2013.
664 Petrogenesis of Early to Middle Jurassic granitoid rocks from the Gangdese belt,
665 Southern Tibet: Implications for early history of the Neo-Tethys. *Lithos* 179,
666 320–333.

667 Guynn, J.H., Kapp, P., Pullen, A., Heizler, M., Gehrels, G., Ding, L., 2006. Tibetan
668 basement rocks near Amdo reveal “missing” mesozoic tectonism along the
669 Bangong suture, central Tibet. *Geology* 34 (6), 505–508.

670 Guynn, J., Kapp, P., George, E., Ding, L., 2012. U–Pb geochronology of terrane rocks
671 in central Tibet and paleogeographic implications. *J. Asian Earth Sci.* 43 (1), 23–
672 50.

673 Hansen, E.C., Ahmed, K., Harlov, D.E., 2002. Rb depletion in biotites and whole
674 rocks across an amphibolite to granulite-facies transition zone, Tamil Nadu,
675 South India. *Lithos* 64 (1), 29–47.

676 Harlov, D.E., Hansen, E.C., 2005. Oxide and sulphide isograds along a late Archean,
677 deep-crustal profile in Tamil Nadu, South India. *J. Metamorph. Geol.* 23 (4),
678 241–259.

679 Harlov, D.E., Tropper, P., Seifert, W., Nijland, T., Förster, H.J., 2006. Formation of

680 Al-rich titanite ($\text{CaTiSiO}_4\text{O}-\text{CaAlSiO}_4\text{OH}$) reaction rims on ilmenite in
681 metamorphic rocks as a function of $f\text{H}_2\text{O}$ and $f\text{O}_2$. *Lithos* 88, 72–84.

682 Harris, N.B.W., Xu, R.H., Lewis, C.L., Hawkesworth, C.L., Zhang, Y.Q., 1988a.
683 Isotope geochemistry of the 1985 Tibet Geotraverse, Lhasa to Golmud. *Phil.*
684 *Trans. Roy. Soc. Lond. A* 327, 263–285.

685 Harris, N.B.W., Holland, T.J.B., Tindle, A.G., 1988b. Metamorphic rocks of the 1985
686 Tibet Geotraverse, Lhasa to Golmud. *Phil. Trans. Roy. Soc. Lond. A* 327, 203–
687 213.

688 Hayden, L.A., Watson, E.B., 2007. Rutile saturation in hydrous siliceous melts and its
689 bearing on Ti-thermometry of quartz and zircon. *Earth Planet. Sci. Lett.* 258 (3–
690 4), 561–568.

691 Hayden, L.A., Watson, E.B., Wark, D.A., 2008. A thermobarometer for sphene
692 (titanite). *Contrib. Mineral. Petrol.* 155 (4), 529–540.

693 Holland, T.J.B., Blundy, J.D., 1994. Non-ideal interactions in calcic amphiboles and
694 their bearing on amphibole–plagioclase thermometry. *Contrib. Mineral. Petrol.*
695 116 (4), 433–447.

696 Hoskin, P.W.O., Black, L.P., 2000. Metamorphic zircon formation by solid-state
697 recrystallization of protolith igneous zircon. *J. Metamorph. Geol.* 18 (4), 423–
698 439.

699 Hoskin, P.W.O., Schaltegger, U., 2003. The composition of zircon and igneous and
700 metamorphic petrogenesis. *Rev. Mineral. Geochem.* 53 (1), 27–62.

701 Hou, Z.Q, Duan, L.F, Lu, Y.J, Zheng, Y.C, Zhu, D.C., Yang, Z.M., Yang, Z.S.,

702 Wang, B.D., Pei, Y.R., Zhao, Z.D., Mccuaig, T.C., 2015. Lithospheric
703 architecture of the Lhasa terrane and its control on ore deposits in the
704 Himalayan-Tibetan orogen. *Econ. Geol.* 110, 1541–1575.

705 Hu, D.G., Wu, Z.H., Jiang, W., Shi, Y.R., Ye, P.S., Liu, Q.S., 2005. SHRIMP zircon
706 U–Pb age and Nd isotopic study on the Nyainqêntanglha Group in Tibet. *Sci.*
707 *China* 48 (9), 1377–1386.

708 Hu, P.Y., Li, C., Wang, M., Xie, C.M., Wu, Y.W., 2013. Cambrian volcanism in the
709 Lhasa terrane, southern Tibet: Record of an early Paleozoic Andean-type
710 magmatic arc along the Gondwana proto-Tethyan margin. *J. Asian Earth Sci.* 77,
711 91–107.

712 Hu, P.Y., Zhai, Q.G., Wang, J., Tang, Y., Wang, H.T., Zhu, Z.C., W, H., 2018a.
713 Middle Neoproterozoic (~ 760 Ma) arc and back-arc system in the North Lhasa
714 terrane, Tibet, inferred from coeval N-MORB- and arc-type gabbros.
715 *Precambrian Res.* 316, 275–290.

716 Hu, P.Y., Zhai, Q.G., Wang, J., Tang, Y., Wang, H.T., Hou, K.J., 2018b. Precambrian
717 origin of the north Lhasa terrane, Tibetan Plateau: Constraint from early
718 Cryogenian back-arc magmatism. *Precambrian Res.* 313, 51–67.

719 Ji, W.Q., Wu, F.Y., Chung, S.L., Li, J.X., Liu, C.Z., 2009. Zircon U–Pb
720 geochronology and Hf isotopic constraints on petrogenesis of the Gangdese
721 batholith, southern Tibet. *Chem. Geol.* 262, 229–245.

722 Ji, W.Q., Wu, F.Y., Chung, S.L., Liu, C.Z., 2012. Identification of early
723 Carboniferous granitoids from southern Tibet and implications for terrane

724 assembly related to the Paleo-Tethyan evolution. *J. Geol.* 120 (5), 531–541.

725 Ji, W.Q., Wu, F.Y., Liu, C.Z., Zhang, H., 2017. Zircon U–Pb geochronology and Hf
726 isotopes of granitic rocks and river sands in the Nyingchi region, Tibet:
727 Constraints on evolution of the deep crust beneath the southeast Lhasa terrane. *J.*
728 *Asian Earth Sci.* 145, 613–625.

729 Kang, D.Y., Zhang, Z.M., Dong, X., Tian, Z.L., Xiang, H., Mo, X.X., 2019.
730 Anticlockwise *P-T-t* path and tectonic mechanism of metapelites from the
731 eastern Gangdese arc, southern Tibet. *Acta Petrol. Sin.* 35 (2), 349–362 (in
732 Chinese with English abstract).

733 Keto, L.S., Jacobsen, S.B., 1987. Nd and Sr isotopic variations of Early Paleozoic
734 ocean. *Earth Planet. Sci. Lett.* 84 (1), 27–41.

735 Kidd, W.F., Pan, Y.S., Chang, C.F., Coward, M.P., Dewey, J.F., Gansser, A., Molnar,
736 P., Shackleton, R.M., Sun, Y.J., 1988. Geological mapping of the 1985 Chinese–
737 British Tibetan (Xizang–Qinghai) Plateau geotraverse route. *Phil. Trans. Roy.*
738 *Soc. Lond. A* 327, 287–305.

739 Kröner, A., Santosh, M., Wong, J., 2012. Zircon ages and Hf isotopic systematics
740 reveal vestiges of Mesoproterozoic to Archaean crust within the late
741 Neoproterozoic-Cambrian high-grade terrain of southernmost India. *Gondwana*
742 *Res.* 21 (4), 876–886.

743 Leake, B.E., et al., 1997. Nomenclature of amphiboles: Report of the subcommittee
744 on amphiboles of the International Mineralogical Association. Commission on
745 New Minerals and Mineral Names. *Mineral. Mag.* 35, 219–246.

746 Leier, A.L., Kapp, P., Gehrels, G.E., DeCelles, P.G., 2007. Detrital zircon
747 geochronology of Carboniferous-Cretaceous strata in the Lhasa terrane, southern
748 Tibet. *Basin Res.* 19 (3), 361–378.

749 Li, G.W., Sandiford, M., Liu, X.H., Xu, Z.Q., Wei, L.J., Li, H.Q., 2014. Provenance
750 of Late Triassic sediments in central Lhasa terrane, Tibet and its implication.
751 *Gondwana Res.* 25 (4), 1680–1689.

752 Li, P., 1955. Primary understanding of geology, eastern Tibet. *Chin. Sci. Bull.* 7 (7),
753 62–71 (in Chinese).

754 Lin, Y.H., Zhang, Z.M., Dong, X., Xiang, H., Yan, R., 2013a, Early Mesozoic
755 metamorphism and tectonic significance of the eastern segment of the Lhasa
756 terrane, south Tibet. *J. Asian Earth Sci.* 78, 160–183.

757 Lin, Y.H., Zhang, Z.M., Dong, X., Shen, K., Lu, X., 2013b. Precambrian evolution of
758 the Lhasa terrane, Tibet: Constraint from the zircon U–Pb geochronology of the
759 gneisses. *Precambrian Res.* 237, 64–77.

760 Maniar, P.D., Piccoli, P.M., 1989. Tectonic discrimination of granitoids. *Geol. Soc.*
761 *Am. Bull.* 101 (5), 635–643.

762 McWilliams, M.O., 1981. Palaeomagnetism and Precambrian tectonic evolution of
763 Gondwana. In: Kroöner, A. (Ed.), *Precambrian Plate Tectonics*. Elsevier,
764 Amsterdam, pp. 649–687.

765 Meert, J.G., Van der Voo, R., Ayub, S., 1995. Paleomagnetic investigation of the
766 Neoproterozoic Gagwe lavas and Mbozi complex, Tanzania and the assembly of
767 Gondwana. *Precambrian Res.* 74 (4), 225–244.

- 768 Meert, J.G., Van der Voo, R., 1997. The assembly of Gondwana 800–550 Ma. *J.*
769 *Geodyn.* 23 (3–4), 223–235.
- 770 Meert, J.G., 2001. Growing Gondwana and rethinking Rodinia: A paleomagnetic
771 perspective. *Gondwana Res.* 4 (3), 279–288.
- 772 Meert, J.G., 2003. A synopsis of events related to the assembly of eastern Gondwana.
773 *Tectonophysics* 362, 1–40.
- 774 Meert, J.G., Torsvik, T.H., 2003. The making and unmaking of a supercontinent:
775 Rodinia revisited. *Tectonophysics* 375, 261–288.
- 776 Meng, Y.K., Dong, H.W., Cong, Y., Xu, Z.Q., Cao, H., 2016. The early-stage
777 evolution of the Neo-Tethys ocean: Evidence from granitoids in the middle
778 Gangdese batholith, southern Tibet. *J. Geodyn.* 94–95, 34–49.
- 779 Mo, X.X., Hou, Z.Q., Niu, Y.L., Dong, G.C., Qu, X.M., Zhao, Z.D., Yang, Z.M.,
780 2007. Mantle contributions to crustal thickening during continental collision:
781 Evidence from Cenozoic igneous rocks in southern Tibet. *Lithos* 96 (1–2), 225–
782 242.
- 783 Mukherjee, A., Das, S., 2002. Anorthosites, Granulites and the Supercontinent Cycle.
784 *Gondwana Res.* 5 (1), 147–156.
- 785 Nijland, T.G., Maijer, C., 1993. The regional amphibolite to granulite facies transition
786 at Arendal, Norway: Evidence for a thermal dome. *N. Jahrb. Mineral. Abh.* 165,
787 191–221.
- 788 Nijland, T.G., Visser, D., 1995. Provenance of the Bamble amphibolites, Norway.
789 *Proc. R. Neth. Acad. Arts Sci.* 98 (1–2), 69–88.

790 Nimaciren, Xie, Y.W., Sha, Z.L., Xiluolangjie, Qiangbazaxi, Peng, D.P.,
791 Gesangsuolang, Luosongzhandui, 2005. 1: 250, 000 geological report of Nagqu
792 County with geological map. Xizang Institute of Geological Survey, Lhasa, 103–
793 107 (in Chinese).

794 Palin, R.M., Searle, M.P., St-Onge, M.R., Waters, D.J., Roberts, N.M.W., Horstwood,
795 M.S.A., Parrish, R.R., Weller, O.M., Chen, S., Yang, J., 2014. Monazite
796 geochronology and petrology of kyanite- and sillimanite-grade migmatites from
797 the northwestern flank of the eastern Himalayan syntaxis. *Gondwana Res.* 26 (1),
798 323–347.

799 Palin, R.M., White, R.W., Green, E.C.R., Diener, J.F.A., Powell, R., Holland, T.J.B.,
800 2016. High-grade metamorphism and partial melting of basic and intermediate
801 rocks. *J. Metamorph. Geol.* 34, 871–892.

802 Pan, G.T., Ding, J., Yao, D.S., Wang, L.Q., 2004. Guidebook of 1:1,500,000 geologic
803 map of the Qinghai–Xizang (Tibet) plateau and adjacent areas. Cartographic
804 Publishing House, Chengdu, China, pp. 1–148 (in Chinese).

805 Pan, G.T., Mo, X.X., Hou, Z.Q., Zhu, D.C., Wang, L.Q., Li, G.M., Zhao, Z.D., Geng,
806 Q.R., Liao, Z.L., 2006. Spatial-temporal framework of the Gangdese Orogenic
807 Belt and its evolution. *Acta Petrol. Sin.* 22 (3), 521–533 (in Chinese with English
808 abstract).

809 Piper, J.D.A., 1976. Palaeomagnetic evidence for a Proterozoic super-continent. *Phil.*
810 *Trans. Roy. Soc. Lond. A* 280, 469–490.

811 Pullen, A., Kapp, P., Gehrels, G.E., DeCelles, P.G., Brown, E.H., Fabijanic, J.M.,

812 Ding, L., 2008. Gangdese retroarc thrust belt and foreland basin deposits in the
813 Damxung area, southern Tibet. *J. Asian Earth Sci.* 33 (5–6), 323–336.

814 Rogers, J.J.W., Santosh, M., 2002. Configuration of Columbia, a Mesoproterozoic
815 Supercontinent. *Gondwana Res.* 5 (1), 5–22.

816 Rollinson, H., 1993. *Using Geochemical Data: Evaluation, Pre-sentation,*
817 *Interpretation.* Longman, London. 215–263 pp.

818 Rubatto, D., Hermann, J., Berger, A., Engi, M., 2009. Protracted fluid-induced
819 melting during barroviaan metamorphism in the central Alps. *Contrib. Mineral.*
820 *Petrol.* 158 (6), 703–722.

821 Rubatto, D., 2017. Zircon: The Metamorphic Mineral. *Rev. Mineral. Geochem.* 83,
822 261–296.

823 Sadowski, G.R., Bettencourt, J.S., 1996. Mesoproterozoic tectonic correlations
824 between eastern Laurentia and the western border of the Amazon Craton.
825 *Precambrian Res.* 76 (3–4), 213–227.

826 Sawyer, E.W., 2001. Melt segregation in the continental crust: Distribution and
827 movement of melt in anatectic rocks. *J. Metamorph. Geol.* 19 (3), 291–309.

828 Sengör, A.M.C., Natal'in, B.A., 1996. Paleotectonics of Asia: Fragments of a
829 synthesis. In: Yin, A., Harrison, M.T. (Eds.), *The Tectonic Evolution of Asia,*
830 *Cambridge University Press,* pp. 486–640.

831 Silveira, E.M., Söderlund, U., Oliveira, E.P., Ernst, R.E., Menezes Leal, A.B., 2013.
832 First precise U–Pb baddeleyite ages of 1500 Ma mafic dykes from the São
833 Francisco Craton, Brazil, and tectonic implications. *Lithos* 174, 144–156.

834 Sun, S.S., McDonough, W.F., 1989. Chemical and isotope systematics of oceanic
835 basalts: Implications for mantle composition and processes. In: Saunders, A.D.
836 (Ed.), *Magmatism in Ocean Basins*. Geological Society of London Special
837 Publication, pp. 313–345.

838 Timmermann, H., Jamieson, R.A., Parrish, R.R., Culshaw, N.G., 2002. Coeval
839 migmatites and granulites, Muskoka domain, southwestern Grenville Province,
840 Ontario. *Can. J. Earth Sci.* 39 (2), 239–258.

841 Veevers, J.J., 2004. Gondwanaland from 650–500 Ma assembly through 320 Ma
842 merger in Pangea to 185–100 Ma breakup: Supercontinental tectonics via
843 stratigraphy and radiometric dating. *Earth Sci. Rev.* 68, 1–132

844 Weis, D., 1986. Genetic implications of Pb isotopic geochemistry in the Rogaland
845 anorthositic complex (southwest Norway). *Chem. Geol.* 57 (1), 181–199.

846 Weller, O.M., St-Onge, M.R., Searle, M.P., Waters, D.J., Rayner, N., Chen, S.,
847 Chung, S.L., Palin, R.M., 2015. Quantifying the P – T – t conditions of north–south
848 Lhasa terrane accretion: New insight into the pre-Himalayan architecture of the
849 Tibetan plateau. *J. Metamorph. Geol.* 33 (1), 91–113.

850 Xie, C.M., Li, C., Su, L., Wu, Y.W., Wang, M., Yu, H., 2010. LA–ICP–MS U–Pb
851 dating of zircon from granite–gneiss in the Amdo area, northern Tibet, China.
852 *Geolo. Bull. Chin.* 29 (12), 1737–1744 (in Chinese with English abstract).

853 Xie, R.W., Peng, X.J., Xiluelangjie, Bao, J.Y., Duan, G.X., He, C.H., Qiangbazhax,
854 Sha, S.L., Chen, Y.M., Chen, D.Q., Peng, D.P., 2007. 1:250, 000 geological
855 report of Zêtang Town with geological map. Geological Survey of Tibet

856 Autonomous Region Press, Lhasa, pp. 1–315 (in Chinese).

857 Xu, R.H., Schärer, U., Allègre, C.J., 1985. Magmatism and metamorphism in the
858 Lhasa block (Tibet): A geochronological study. *J. Geol.* 93(1), 41–57.

859 Xu, W.C., Zhang, H.F., Harris, N., Guo, L., Pan, F.B., Wang, S., 2013a.
860 Geochronology and geochemistry of Mesoproterozoic granitoids in the Lhasa
861 terrane, south Tibet: Implications for the early evolution of Lhasa terrane.
862 *Precambrian Res.* 236, 46–58.

863 Xu, W.C., Zhang, H.F., Harris, N., Guo, L., Pan, F.B., 2013b. Rapid Eocene erosion,
864 sedimentation and burial in the eastern Himalayan syntaxis and its geodynamic
865 significance. *Gondwana Res.* 23 (2), 715–725.

866 Yang, J.S., Xu, Z.Q., Li, Z.L., Xu, X.Z., Li, T.F., Ren, Y.F., Li, H.Q., Chen, S.Y.,
867 Robinson, P.T., 2009. Discovery of an eclogite belt in the Lhasa block, Tibet: A
868 new border for Paleo-Tethys? *J. Asian Earth Sci.* 34 (1), 76–89.

869 Yang, Z.M., Hou, Z.Q., Jiang, Y.F., Zhang, H.R., Song, Y.C., 2011. Sr-Nd-Pb and
870 zircon Hf isotopic constraints on petrogenesis of the Late Jurassic granitic
871 porphyry at Qulong, Tibet. *Acta Petrol. Sin.* 27 (7), 2003–2010 (in Chinese with
872 English abstract).

873 Yin, A., Harrison, T.M., 2000. Geologic evolution of the Himalayan–Tibetan orogen.
874 *Annu. Rev. Earth Planet. Sci.* 28, 211–280.

875 Yin, A., Nie, S., 1996. A Phanerozoic palinspastic reconstruction of China and its
876 neighboring regions. In: Yin, A., Harrison, M.T. (Eds.), *The Tectonic Evolution*
877 *of Asia*. Cambridge University Press, pp. 442–485.

878 Yin, G.G., Chen, Y.P., Su, X.J., Bao, J.Y., Hou, S.Y., Lu, Y., Duan, G.X., Zhang,
879 J.Y., Liu, Z., Xiao, L., 2003. 1:250,000 geological report of Nyingtri region with
880 geological map. Yunnan, Institute of Yunnan Geological Survey (in Chinese).

881 Zeng, L.S., Liu, J., Gao, L.E., Chen, F.Y., Xie, K.J., 2009. Early Mesozoic high-
882 pressure metamorphism within the Lhasa block, Tibet and implications for
883 regional tectonics. *Earth Sci. Front.* 16 (2), 140–151.

884 Zeng, Y.C., Chen, Q., Xu, J.F., Chen, J.L., Huang, F., Yu, H.X., Zhao, P.P., 2018.
885 Petrogenesis and geodynamic significance of neoproterozoic (~ 925 Ma) high-
886 Fe-Ti gabbros of the Rentso ophiolite, Lhasa terrane, central Tibet. *Precambrian*
887 *Res.* 314, 160–169.

888 Zhang, H.F., Xu, W.C., Guo, J.Q., Zong, K.Q., Cai, H.M., Yuan, H.L., 2007a. Zircon
889 U–Pb and Hf isotopic composition of deformed granite in the southern margin of
890 the Gangdese Belt, Tibet: Evidence for early Jurassic subduction of Neo-Tethyan
891 oceanic slab. *Acta Petrol. Sin.* 23 (6), 1347–1353 (in Chinese with English
892 abstract).

893 Zhang, H.F., Xu, W.C., Guo, J.Q., Zong, K.Q., Cai, H.M., Yuan, H.L., 2007b.
894 Indosinian orogenesis of the Gangdese terrane: Evidences from zircon U–Pb
895 dating and petrogenesis of granitoids. *Earth Sci. J. China Univ. Geosci.* 32 (2),
896 155–166 (in Chinese with English abstract).

897 Zhang, K.J., Zhang, Y.X., Li, B., Zhong, L.F., 2007. Nd isotopes of siliciclastic rocks
898 from Tibet, western China: Constraints on provenance and pre-Cenozoic tectonic
899 evolution. *Earth Planet. Sci. Lett.* 256 (3–4), 604–616.

900 Zhang, X.R., Shi, R.D., Huang, Q.S., Liu, D.L., Gong, X.H., Chen, S.S., Wu, K., Yi,
901 G.D., Sun, Y.L., Ding, L., 2014. Early Jurassic high-pressure metamorphism of
902 the Amdo terrane, Tibet: Constraints from zircon U-Pb geochronology of mafic
903 granulites. *Gondwana Res.* 26 (3–4), 975–985.

904 Zhang, Z.M., Zhao, G.C., Santosh, M., Wang, J.L., Dong, X., Liou, J.G., 2010. Two
905 stages of granulite facies metamorphism in the eastern Himalayan syntaxis, south
906 Tibet: Petrology, zircon geochronology and implications for the subduction of
907 Neo-Tethys and the Indian continent beneath Asia. *J. Metamorph. Geol.* 28 (7),
908 719–733.

909 Zhang, Z.M., Dong, X., Liu, F., Lin, Y.H., Yan, R., Santosh, M., 2012a. Tectonic
910 evolution of the Amdo terrane, central Tibet: Petrochemistry and zircon U–Pb
911 geochronology. *J. Geol.* 120 (4), 431–451.

912 Zhang, Z.M., Dong, X., Liu, F., Lin, Y.H., Yan, R., He, Z.Y., Santosh, M., 2012b.
913 The making of Gondwana: Discovery of 650 Ma HP granulites from the North
914 Lhasa, Tibet. *Precambrian Res.* 212–213, 107–116.

915 Zhang, Z.M., Dong, X., Xiang, H., Liou, J.G., Santosh, M., 2013. Building of the
916 deep Gangdese arc, South Tibet: Paleocene plutonism and granulite-facies
917 metamorphism. *J. Petrol.* 54 (12), 2547–2580.

918 Zhang, Z.M., Dong, X., Santosh, M., Zhao, G.C., 2014a. Metamorphism and tectonic
919 evolution of the Lhasa terrane, Central Tibet. *Gondwana Res.* 25 (1), 170–189.

920 Zhang, Z.M., Dong, X., Xiang, H., He, Z.Y., Liou, J.G., 2014b. Metagabbros of the
921 Gangdese arc root, south Tibet: Implications for the growth of continental crust

922 Geochim. Cosmochim. Acta 143, 268–284.

923 Zhang, Z.M., Dong, X., Xiang, H., Ding, H.X., He, Z.Y., Liou, J.G., 2015. Reworking
924 of the Gangdese magmatic arc, southeastern Tibet: Post-collisional
925 metamorphism and anatexis. *J. Metamorph. Geol.* 33 (1), 1–21.

926 Zhao, G.C., Sun, M., Wilde, S.A., Li, S.Z., 2003. Assembly, accretion, and break-up
927 of the Palaeo-Mesoproterozoic Columbia supercontinent: Record in the North
928 China Craton revisited. *Gondwana Res.* 6 (3), 417–434.

929 Zhu, D.C., Pan, G.T., Chung, S.L., Liao, Z.L., Wang, L.Q., Li, G.M., 2008. SHRIMP
930 zircon age and geochemical constraints on the origin of lower Jurassic volcanic
931 rocks from the Yeba formation, southern Gangdese, south Tibet. *Int. Geol. Rev.*
932 50 (5), 442–471.

933 Zhu, D.C., Mo, X.X., Niu, Y., Zhao, Z.D., Wang, L.Q., Liu, Y.S., Wu, F.Y., 2009a.
934 Geochemical investigation of Early Cretaceous igneous rocks along an east–west
935 traverse throughout the central Lhasa Terrane, Tibet. *Chem. Geol.* 268 (3–4),
936 298–312.

937 Zhu, D.C., Mo, X.X., Niu, Y.L., Zhao, Z.D., Wang, L.Q., Pan, G.T., Wu, F.Y., 2009b.
938 Zircon U–Pb dating and in-situ Hf isotopic analysis of Permian peraluminous
939 granite in the Lhasa terrane, southern Tibet: Implications for Permian collisional
940 orogeny and paleogeography. *Tectonophysics* 469 (1–4), 48–60.

941 Zhu, D.C., Zhao, Z.D., Niu, Y.L., Mo, X.X., Chung, S.L., Hou, Z.Q., Wang, L.Q.,
942 Wu, F.Y., 2011. The Lhasa Terrane: Record of a microcontinent and its histories
943 of drift and growth. *Earth Planet. Sci. Lett.* 301 (1–2), 241–255.

944 Zhu, D.C., Zhao, Z.D., Niu, Y.L., Dilek, Y., Wang, Q., Ji, W.H., Dong, G.C., Sui,
945 Q.L., Liu, Y.S., Yuan, H.L., Mo, X.X., 2012. Cambrian bimodal volcanism in
946 the Lhasa Terrane, southern Tibet: Record of an early Paleozoic Andean-type
947 magmatic arc in the Australian proto-Tethyan margin. *Chem. Geol.* 328, 290–
948 308.

949 Zhu, D.C., Zhao, Z.D., Niu, Y., Dilek, Y., Hou, Z.Q., Mo, X.X., 2013. The origin and
950 pre-Cenozoic evolution of the tibetan plateau. *Gondwana Res.* 23 (4), 1429–
951 1454.

952

953 **Figure captions:**

954 Figure 1. (a) Tectonic framework of the Tibetan Plateau (after [Zhu et al., 2013](#)),
955 showing the major tectonic subdivisions. NLT = Northern Lhasa subterrane, CLT =
956 Central Lhasa subterrane, SLT = Southern Lhasa subterrane, JSSZ = Jinsha Suture
957 Zone, LSSZ = Longmu Tso-Shuanghu Suture Zone, BNSZ = Bangong-Nujiang
958 Suture Zone, SNMZ = Shiquan River-Nam Tso Mélange Zone, LMF = Luobadui-
959 Milashan Fault, IYZSZ = Indus-Yarlung Zangbo Suture Zone. Data sources of the
960 Precambrian magmatic rocks for Amdo: ~ 820 Ma and 500 Ma ([Zhang et al., 2012a](#)),
961 852 Ma ([Guynn et al., 2006](#)), 532 Ma ([Guynn et al., 2012](#)); the CLT from west to east:
962 492 Ma ([Zhu et al., 2012](#)), 525–510 Ma ([Hu et al., 2013](#)), 512 Ma ([Ding et al., 2015](#)),
963 787 Ma ([Hu et al., 2005](#)), 897–886 Ma ([Zhang et al., 2012b](#)), 760 Ma ([Hu et al.,](#)
964 [2018a](#)), 822–806 Ma ([Hu et al., 2018b](#)), 925 Ma ([Zeng et al., 2018](#)), 1343–1250 Ma

965 (Xu et al., 2013a; Chen et al., 2019), 1866 Ma (Chen et al., 2019); the SLT: 496 Ma
966 (Dong et al., 2010). (b) Geological sketch map of the Dongjiu area in the SLT, the
967 Paleoproterozoic data (~ 1780 Ma) from Lin et al. (2013b).

968

969 Figure 2. Photomicrographs of representative Dongjiu gneiss. (a) Biotite (Bt)-
970 amphibole (Amp) gneiss, consisting of amphibole, plagioclase (Pl), K-feldspar (Kfs),
971 biotite, quartz (Qz) and titanite (Ttn) rimming ilmenite (Ilm), with minor apatite (Ap).
972 (b) Bt-amp gneiss, showing plagioclase with cusped extensions along quartz-quartz
973 contacts. (c) and (d) Bt-amp gneiss, showing allanite (Aln) replaced by epidote (Ep)
974 in rim, with zircon (Zrn) inclusions. (e) Bt gneiss, consisting of plagioclase, K-
975 feldspar, biotite, quartz, with minor allanite replaced by epidote at rim; adjacent
976 grains of quartz, plagioclase and K-feldspar are corroded. (f) Bt gneiss, showing
977 adjacent plagioclase and biotite grains are corroded; narrow K-feldspar blebs at
978 quartz-plagioclase contacts.

979

980 Figure 3. (a) Ab-An-Or classification for silicic rocks from Barker (1979). (b) A/CNK
981 vs A/NK diagram from Maniar and Piccoli (1989). The data of the Bomi
982 Mesoproterozoic granitoids are after Xu et al. (2013a).

983

984 Figure 4. (a) Chondrite-normalized REE and (b) Primitive-mantle-normalized trace
985 element patterns for the Dongjiu gneiss. The data of the Bomi Mesoproterozoic
986 granitoids are after Xu et al. (2013a). The normalization data are from Sun and

987 McDonough (1989).

988

989 Figure 5. Zircon U–Pb concordia diagrams and chondrite-normalized REE patterns of
990 the Dongjiu Bt-amp gneiss. (a), (c) and (e) Zircon U–Pb concordia diagrams, red and
991 blue ellipses represent zircon core and rim ages, respectively. (b), (d) and (f)
992 Chondrite-normalized REE patterns, showing CL images of representative zircon
993 grains. Red and blue circles indicate zircon core and rim dating spots with ages in Ma,
994 respectively. The normalization data are from Sun and McDonough (1989).

995

996 Figure 6. Zircon U–Pb concordia diagrams and chondrite-normalized REE patterns of
997 the Dongjiu Bt gneiss. (a) and (c) Zircon U–Pb concordia diagrams, red and blue
998 ellipses represent zircon core and rim ages, respectively. (b) and (d) Chondrite-
999 normalized REE patterns, showing CL images of representative zircon grains. Red
1000 and blue circles indicate zircon core and rim ages with ages in Ma, respectively. The
1001 normalization data are from Sun and McDonough (1989).

1002

1003 Figure 7. BSE images and photomicrographs of representative titanite for the Dongjiu
1004 Bt-amp gneiss. Representative titanite (a)–(h) for sample 169-1, (i)–(p) for sample 39-
1005 1. (a)–(d) and (i)–(l) Blue circles are spots for dating with ^{207}Pb corrected $^{206}\text{Pb}/^{238}\text{U}$
1006 ages in Ma. (e)–(h) and (m)–(p) Most titanite including ilmenite, biotite, allanite,
1007 apatite, plagioclase, quartz and minor rutile.

1008

1009 Figure 8. Titanite U–Pb concordia diagrams of the Dongjiu Bt-amp gneiss.

1010

1011 Figure 9. Frequency histogram of Zr-in-titanite temperatures for the Dongjiu Bt-amp
1012 gneiss.

1013

1014 Figure 10. Zircon U vs Th contents diagram of the Dongjiu gneiss.

1015

1016 Figure 11. Zircon U-Pb age vs $\epsilon_{\text{Hf}}(t)$ diagram for the Dongjiu gneiss and related rocks
1017 from the Lhasa terrane. Data sources: SLT ~ 1500 Ma gneiss (our unpublished data);
1018 SLT granitoids (Chu et al., 2006; Zhang et al., 2007a; Ji et al., 2009, 2012; Yang et
1019 al., 2011; Zhu et al. 2011; Dong et al., 2013, 2014, 2015; Guo et al., 2013; Meng et
1020 al., 2016); CLT granitoids (Zhang et al., 2007b; Zhu et al., 2009b, 2011, 2012; Xu et
1021 al., 2013a; Hu et al., 2018b; Chen et al., 2019); SLT Paleozoic strata (Guo et al.,
1022 2017); CLT Paleozoic strata (Zhu et al., 2013; Li et al., 2014).

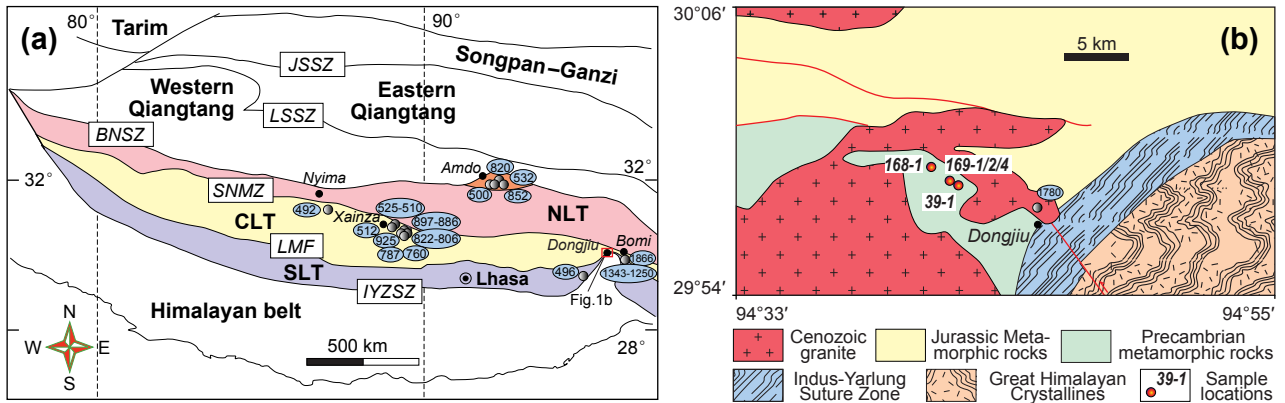


Figure 1

(a) Tectonic framework of the Tibetan Plateau, showing the major tectonic subdivisions. NLT = Northern Lhasa subterranean, CLT = Central Lhasa subterranean, SLT = Southern Lhasa subterranean, JSSZ = Jinsha Suture Zone, LSSZ = Longmu Tso-Shuanghu Suture Zone, BNSZ = Bangong-Nujiang Suture Zone, SNMZ = Shiquan River-Nam Tso Mélange Zone, LMF = Luobadui-Milashan Fault, IYZSZ = Indus-Yarlung Zangbo Suture Zone. (b) Geological sketch map of the Dongjiu area in the SLT.

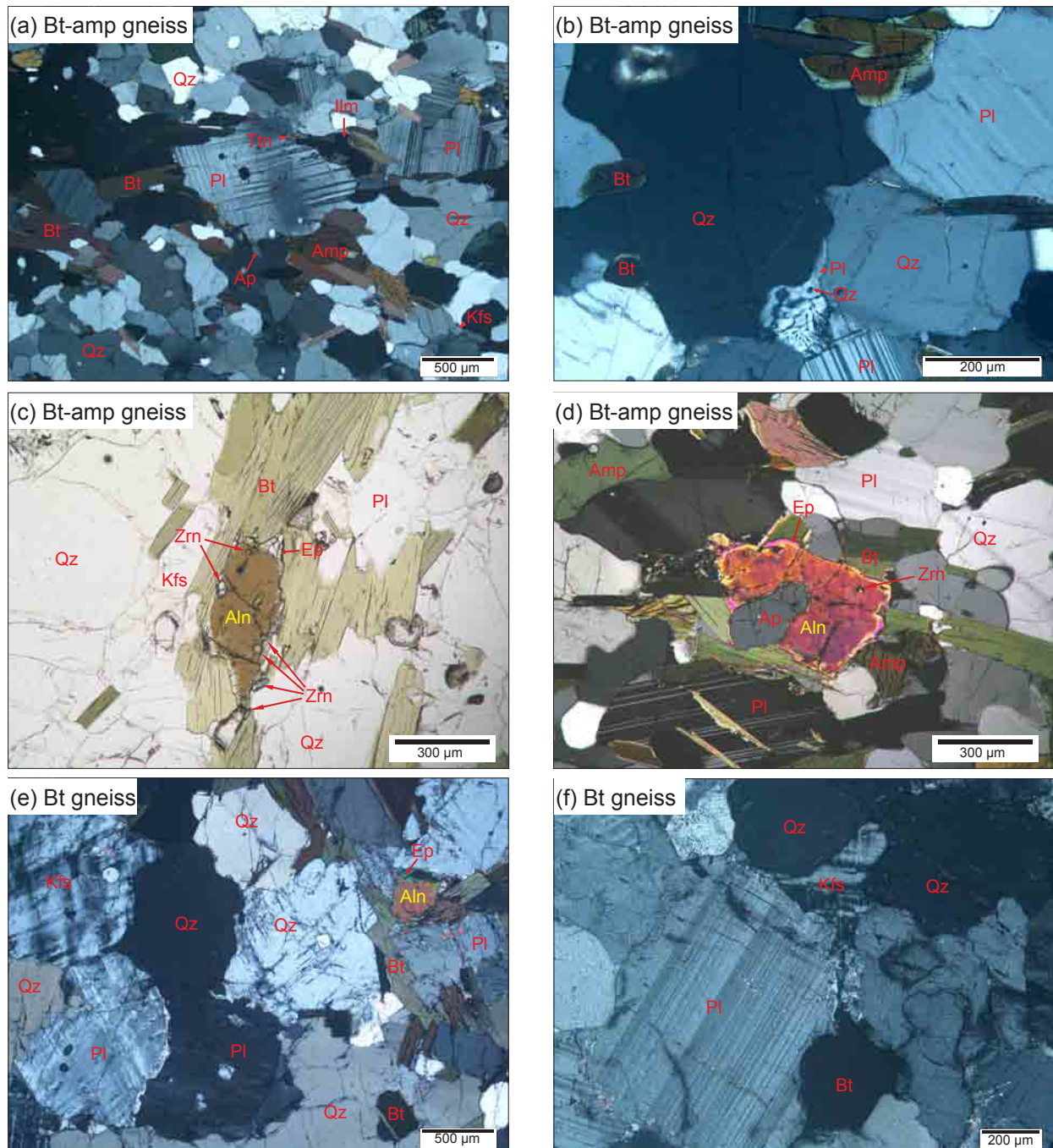


Figure 2. Photomicrographs of representative Dongjiu gneiss.

(a) Biotite (Bt)- amphibole (amp) gneiss, consisting of amphibole, plagioclase (Pl), K-feldspar (Kfs), biotite, quartz (Qz) and titanite (Ttn) rimming ilmenite (Ilm), with minor apatite (Ap).

(b) Bt-amp gneiss, showing plagioclase with cusped extensions along quartz-quartz contacts.

(c) and (d) Bt-amp gneiss, showing allanite (Aln) replaced by epidote (Ep) in rim, with zircon (Zrn) inclusions.

(e) Bt gneiss, consisting of plagioclase, K-feldspar, biotite, quartz, with minor allanite replaced by epidote at rim; adjacent quartz, plagioclase and K-feldspar grains are corroded.

(f) Bt gneiss, showing adjacent plagioclase and biotite grains are corroded; narrow K-feldspar blebs at quartz-plagioclase contacts.

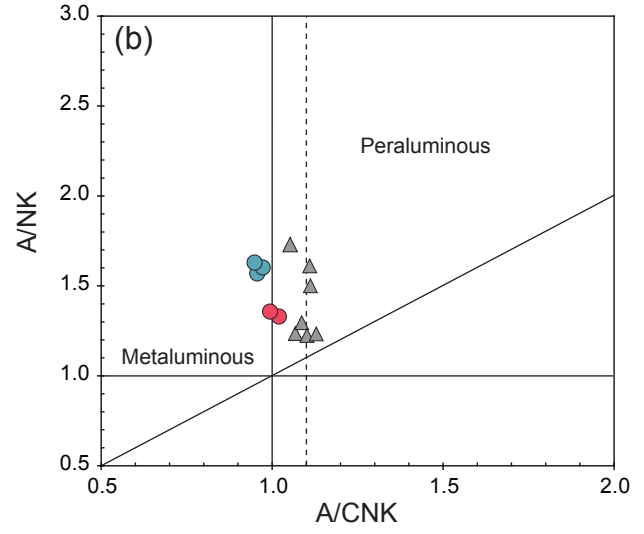
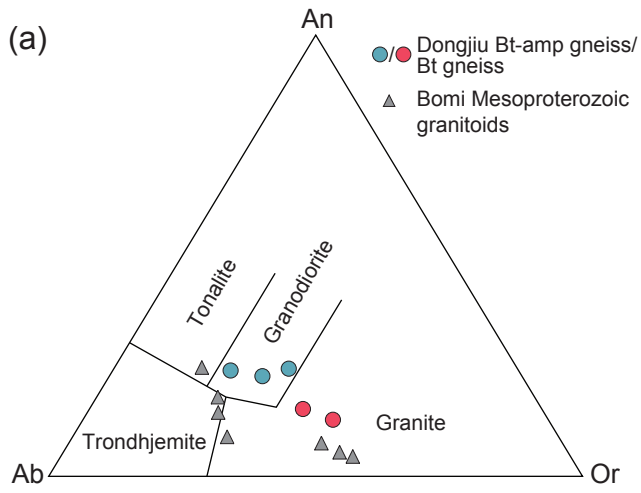


Figure 3

(a) Ab-An-Or classification for silicic rocks.
 (b) A/CNK vs A/NK diagram.

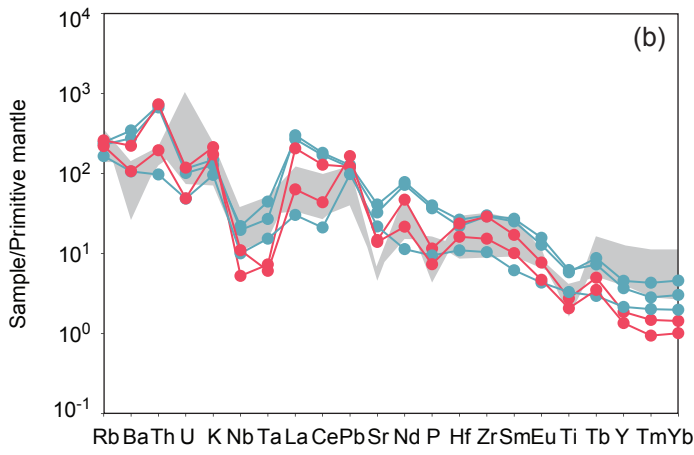
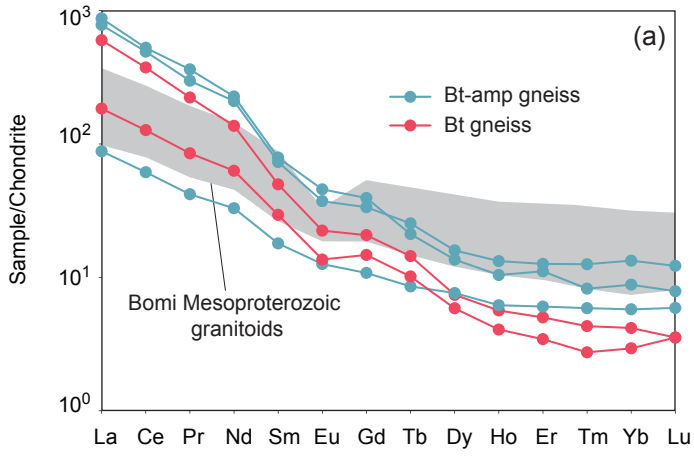


Figure 4

(a) Chondrite-normalized REE.

(b) Primitive-mantle-normalized trace element patterns for the Dongjiu gneiss.

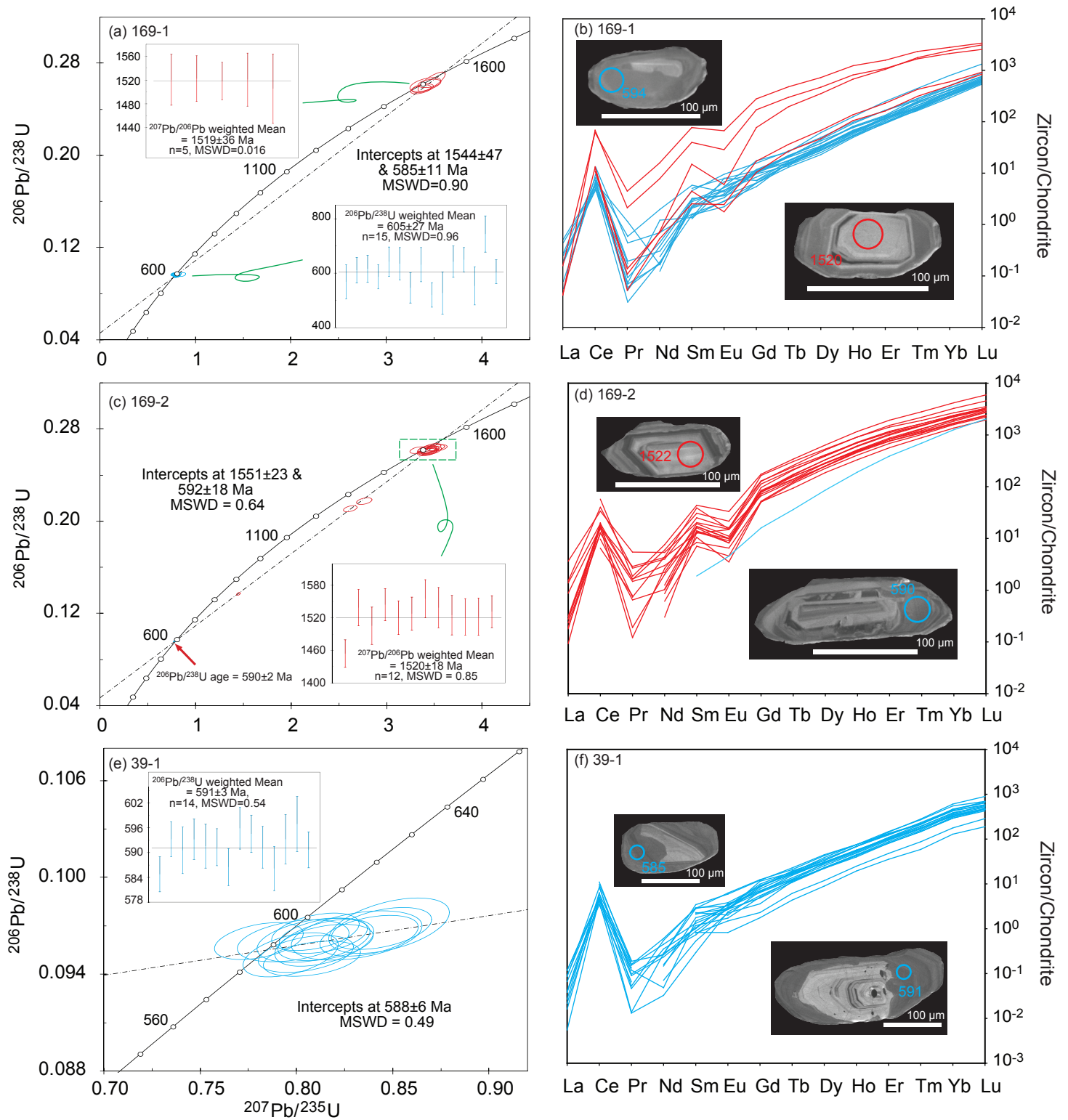


Figure 5. Zircon U–Pb concordia diagrams and chondrite-normalized REE patterns of the Dongjiu Bt-amp gneiss. (a), (c) and (e) Zircon U–Pb concordia diagrams, red and blue ellipses represent zircon core and rim ages, respectively. (b), (d) and (f) Chondrite-normalized REE patterns, showing CL images of representative zircon grains. Red and blue circles indicate zircon core and rim dating spots with ages in Ma, respectively.

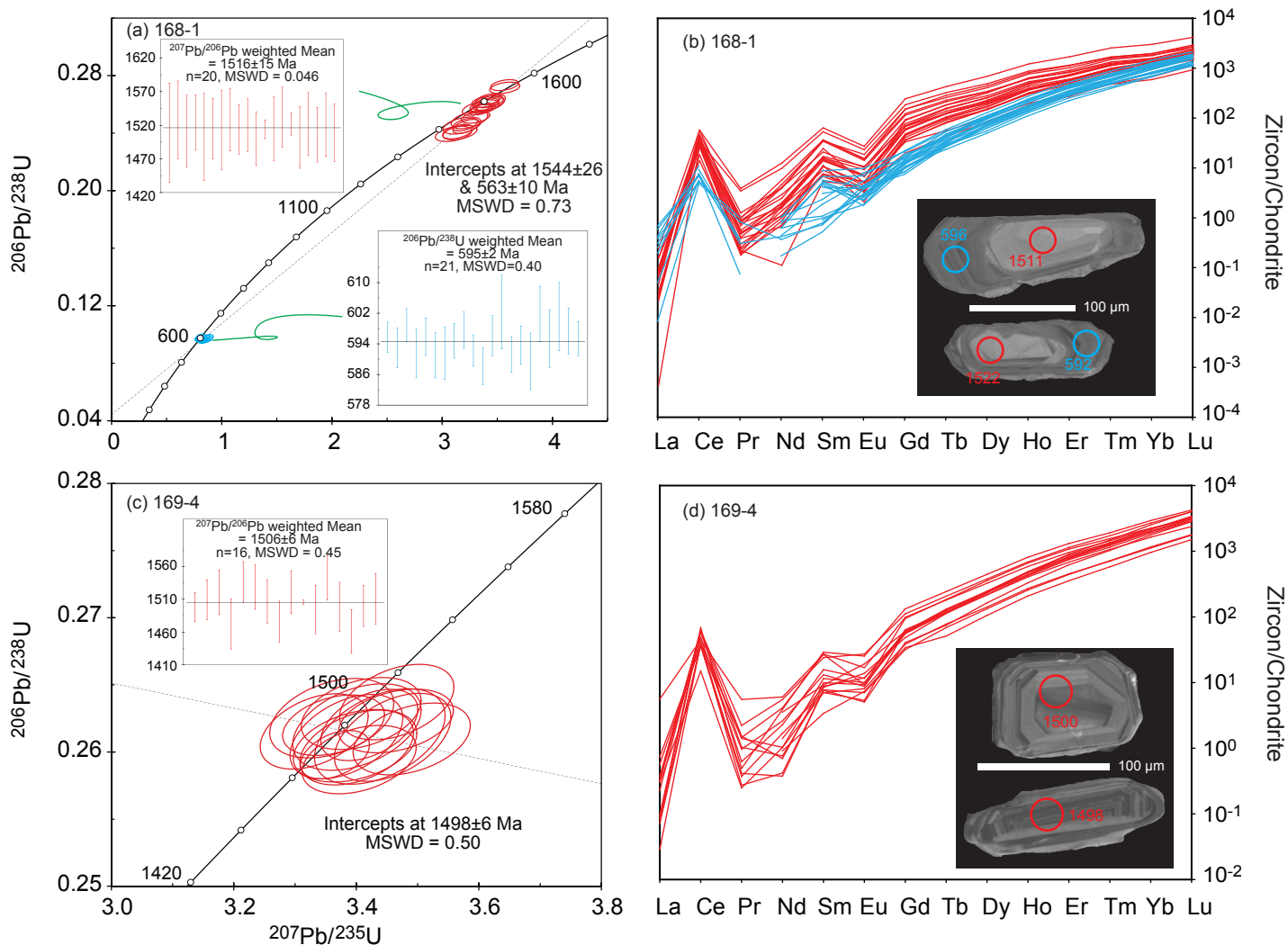


Figure 6. Zircon U–Pb concordia diagrams and chondrite-normalized REE patterns of the Dongjiu Bt gneiss.

(a) and (c) Zircon U–Pb concordia diagrams, red and blue ellipses represent zircon core and rim ages, respectively.

(b) and (d) Chondrite-normalized REE patterns, showing CL images of representative zircon grains. Red and blue circles indicate zircon core and rim ages with ages in Ma, respectively.

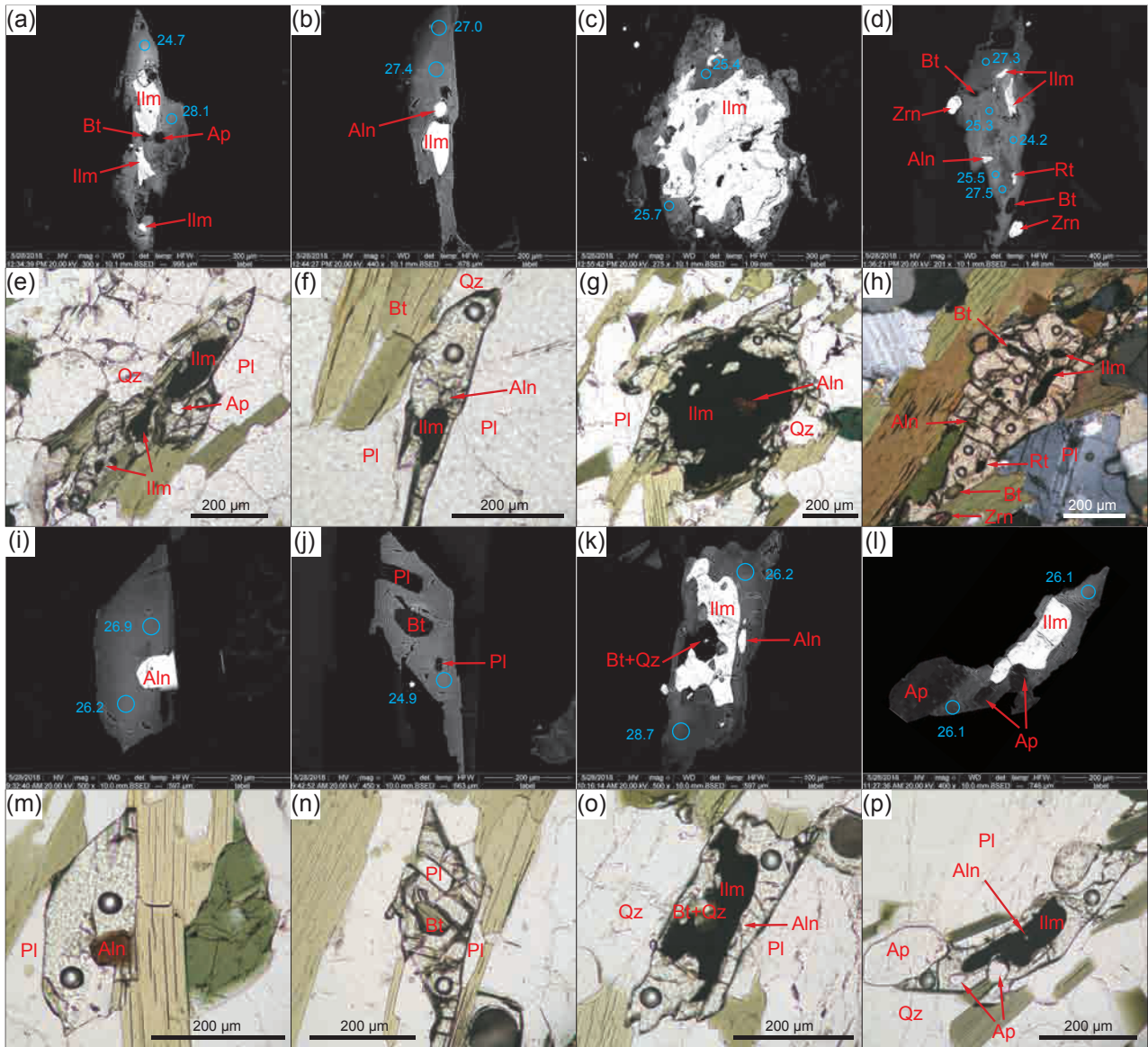


Figure 7. BSE images and photomicrographs of representative titanite for the Dongjiu Bt-amp gneiss.

Representative titanite (a)–(h) for sample 169-1, (i)–(p) for sample 39-1. (a)–(d) and (i)–(l) Blue circles are spots for dating with ^{207}Pb corrected $^{206}\text{Pb}/^{238}\text{U}$ ages in Ma. (e)–(h) and (m)–(p) Most titanite including ilmenite, biotite, allanite, apatite, plagioclase, quartz and minor rutile.

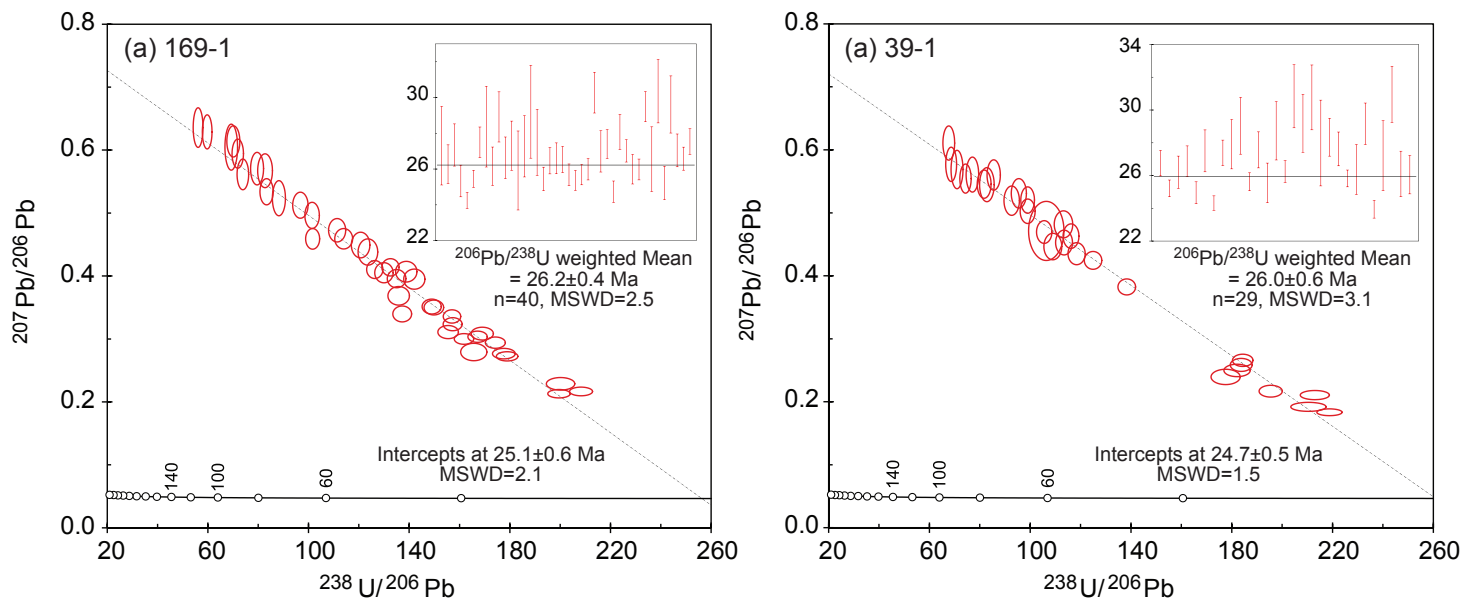


Figure 8. Titanite U-Pb concordia diagrams of the Dongjiu Bt-amp gneiss.

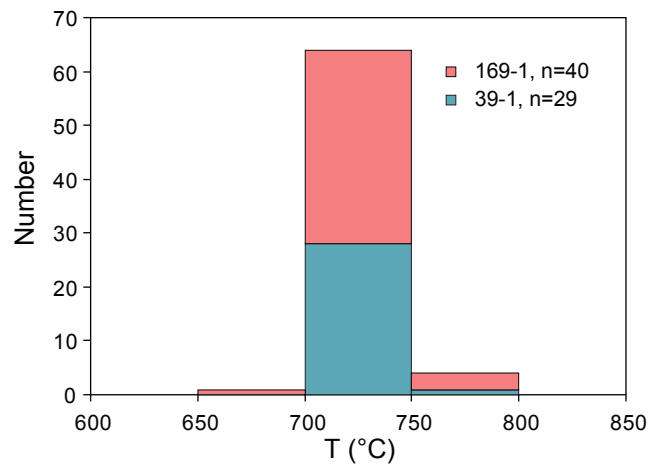


Figure 9. Frequency histogram of Zr-in-titanite temperatures for the Dongjiu Bt-amp gneiss

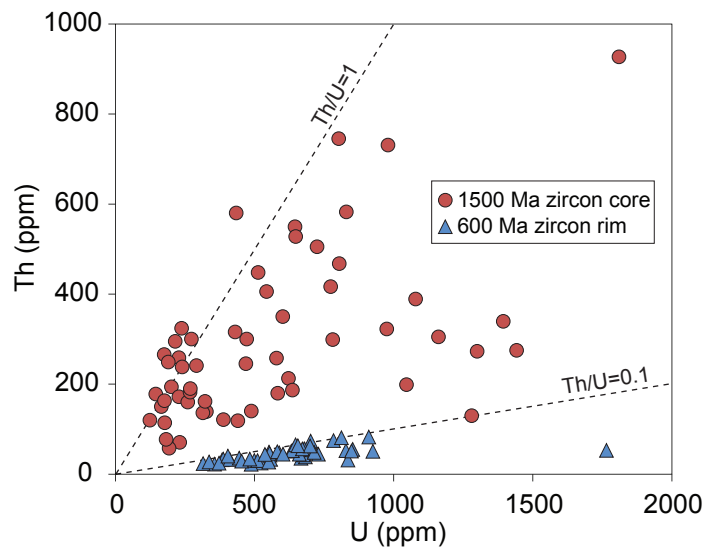


Figure 10. Zircon U vs Th contents diagram of the Dongjiu gneiss

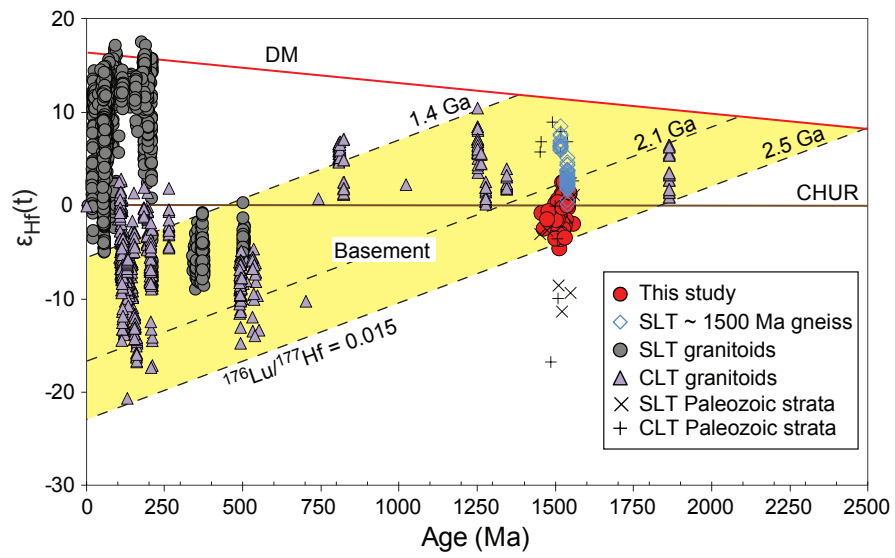


Figure 11. Zircon U-Pb age vs $\epsilon_{\text{Hf}}(t)$ diagram for the Dongjiu gneiss and related rocks from the Lhasa terrane

CONFLICT OF INTEREST

Xin Dong and all co-authors confirm that there are no known conflicts of interest associated with this publication (Title: Reworked Precambrian metamorphic basement of the Lhasa terrane, southern Tibet: Zircon/Titanite U–Pb geochronology, Hf isotope and Geochemistry) and there has been no significant financial support for this work that could have influenced its outcome.