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1 **Tectonic erosion and crustal relamination during the India-Asian continental**
2 **collision: insights from Eocene magmatism in the southeastern Gangdese belt**

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11 **Abstract**

12 Understanding the processes of tectonic erosion and crustal relamination during
13 continental collision has important implications for the growth and differentiation of the
14 continental crust. The discrepancy in isotopic compositions between the pre- and syn-collision
15 magmatic rocks from the Gangdese belt in south Tibet provides an opportunity for studying
16 these processes during the India-Asian collision. The Nyingchi granites and Confluence
17 hornblende gabbros from the eastern Gangdese belt have zircon U–Pb ages of ca. 50 Ma. The
18 Nyingchi granites have high Sr/Y and $(Dy/Yb)_N$ ratios, indicating that the magma was generated
19 under eclogite-facies conditions. Their Sr–Nd–Pb–Hf isotopic compositions require significant
20 incorporation of ancient supracrustal materials from the Gangdese belt and the Indian continent.
21 The Confluence hornblende gabbros display arc-like trace element patterns but have enriched
22 Sr–Nd–Pb–Hf isotopic compositions compared with those from the Jurassic–Cretaceous arc
23 magmatic rocks, indicating significant input of ancient components into their mantle sources.
24 The occurrence of the Cenozoic felsic metamorphic rocks in the lower crust of the Gangdese
25 belt allows us to propose that the Nyingchi high Sr/Y granites were derived from partial melting
26 of relaminated crustal materials which were removed from the Gangdese belt by tectonic
27 erosion and the subducted Indian continent. The Confluence gabbros were sourced from
28 lithospheric mantle which was metasomatized by inputs from relaminated crustal materials
29 derived from the Gangdese belt and the subducted Indian continent. The estimated tectonic
30 erosion rate is 150–188 km³/km/my, indicating significant crustal loss occurred during
31 continental collision. Our study demonstrates that tectonic erosion and crustal relamination play
32 an important role in the refinement of the composition of continental crust during continental

33 collision.

34

35 **Keywords:** tectonic erosion; relamination; continental collision; Gangdese belt; magmatism

36

37 **1. Introduction**

38 Tectonic erosion, which removes crustal materials from the upper plate above the lower
39 subducting plate, occurs at all convergent plate boundaries and is a key process in destroying
40 continental crust (e.g., Clift and Vannucchi, 2004; Scholl and von Huene, 2010; Stern, 2011;
41 von Huene and Scholl, 1991). The crustal materials removed from the overriding plate by
42 tectonic erosion could be relaminated to the base of the upper plate and eventually form a part
43 of the upper plate (Hacker et al., 2011, 2015), or could be carried into deep mantle (e.g.,
44 Willbold and Stracke, 2010). Understanding these processes of tectonic erosion and crustal
45 relamination has important implications for the chemical and physical differentiation of the
46 Earth, particularly the compositional evolution of the continental crust (Castro et al., 2013; Clift
47 and Vannucchi, 2004; Hacker et al., 2011, 2015; Kelemen and Behn, 2016; Scholl and von
48 Huene, 2009, 2010; Vogt et al., 2013). The subduction zones and continental collision belts
49 represent locations in which continental crust is formed and modified by physical and chemical
50 processes. It is therefore important to determine how large masses of crustal materials may be
51 added to, or removed from, the crust during continental collision.

52 The Gangdese belt in southern Tibet was an Andean arc caused by the northward
53 subduction of the Neo-Tethyan oceanic lithosphere before the India-Asian collision (Yin and
54 Harrison, 2000). The widespread Triassic-Cretaceous arc magmatic rocks have low initial

55 $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and positive $\epsilon_{\text{Nd}}(t)$ and $\epsilon_{\text{Hf}}(t)$ values, indicating that the crust of the Gangdese
56 belt is juvenile (Harris et al., 1988; Ji et al., 2009; Xu et al., 1985; Zhu et al., 2011). By contrast,
57 the Paleogene–Miocene magmatic rocks display large variation in Sr–Nd–Hf isotopic
58 composition and show clearly negative excursions of $\epsilon_{\text{Nd}}(t)$ and $\epsilon_{\text{Hf}}(t)$ values (Chu et al., 2011;
59 Ji et al., 2009; Ma et al., 2014; Zhao et al., 2011). These excursions represent the incorporation
60 of older crustal material into the magma; however the mechanisms responsible are controversial.
61 The negative excursions have been ascribed to the inputs of ancient Indian crustal materials
62 (Chu et al., 2011; Ji et al., 2009; Ma et al., 2014) or assimilation of ancient basement of the
63 Lhasa terrane (Zhao et al., 2011; Zhu et al., 2017a). Since the Indian continent, ancient basement
64 and juvenile lower crust of the Gangdese belt have distinct isotopic compositions (e.g., Gariépy
65 et al., 1985; Harris et al., 1988; Ji et al., 2009; Zhang et al., 2004; Zhu et al., 2011), they should
66 be trackable in the syn- and post-collisional magmatic rocks. This provides an opportunity to
67 investigate tectonic erosion and crustal relamination during the India–Asian continental
68 collision.

69 In this study, we report zircon U–Pb ages, whole-rock major, trace element and Sr–Nd
70 isotope, in-situ zircon Hf isotope and feldspar Pb isotope data for the Eocene Confluence
71 gabbros and Nyingchi granites in the eastern Gangdese belt. Our results show that the Nyingchi
72 high Sr/Y granites were derived from partial melting of both relaminated Gangdese crustal
73 materials, removed by tectonic erosion, and the subducted Indian crustal materials. The
74 Confluence gabbros were sourced from the lithospheric mantle which was metasomatized by
75 felsic melts derived from relaminated crustal materials. Our study implies that significant
76 tectonic erosion occurs during continental collision. The eroded felsic crustal materials may be

77 relaminated to the base of the upper plate, which plays an important role in crustal refinement
78 during the process of continent-continent collision.

79

80 **2. Geological background and samples**

81 The Lhasa terrane of southern Tibet is separated from the Qiangtang terrane to the north
82 by the Bangong–Nujiang suture and from the Himalayas to the south by the Indus–Yarlung
83 Tsangpo suture (Fig. 1A). The Lhasa terrane is underlain by Proterozoic basement with juvenile
84 crust accreted towards its southern and northern margins (Zhu et al., 2011). The Gangdese belt
85 in the southern Lhasa terrane is dominated by the Triassic–Tertiary Gangdese batholith and the
86 Paleogene Linzizong volcanic succession, with minor Triassic–Cretaceous
87 volcano–sedimentary rocks (Mo et al., 2007; Pan et al., 2006). The batholith is composed of a
88 variety of lithologies including gabbro, diorite, granodiorite to granite (Harris et al., 1988; Ji et
89 al., 2009; Wen et al., 2008; Xu et al., 1985). Zircon U–Pb dating results revealed that the
90 Gangdese magmatism began in Middle-Late Triassic and lasted until Miocene, with four
91 magmatic flare-up events at 205–150 Ma, 100–80 Ma, 65–40 Ma, and 30–10 Ma (Ji et al.,
92 2009; Wang et al., 2016; Wen et al., 2008; Zhu et al., 2011). The 65–40 Ma magmatic flare-up
93 event is generally attributed to the rollback and break-off of the Neo-Tethyan oceanic slab after
94 the India-Asian collision (Ji et al., 2009; Lee et al., 2012; Wen et al., 2008; Zhu et al., 2015).
95 Most Triassic–Cretaceous arc magmatic rocks have positive $\epsilon_{Nd}(t)$ and $\epsilon_{Hf}(t)$ values and low
96 initial $^{87}Sr/^{86}Sr$ ratios, indicating that their magmas were derived from partial melting of the
97 asthenospheric mantle or of juvenile crust under the Gangdese arc (Harris et al., 1988; Ji et al.,
98 2009; Zhu et al., 2011). By contrast, the Paleogene-Eocene magmatic rocks show clearly

99 negative excursion of $\epsilon_{Nd}(t)$ and $\epsilon_{Hf}(t)$ values, which was attributed to the involvement of the
100 ancient Indian crust (Chu et al., 2011; Ji et al., 2009; Ma et al., 2014) or to the assimilation of
101 the basement of the Lhasa terrane (Zhao et al., 2011; Zhu et al., 2017a). In addition, the
102 magmatism during the Paleogene-Eocene flare-up shows significant geochemical variations in
103 magma compositions, including calc-alkaline, low-K, shoshonitic, peraluminous, and adakitic-
104 type rocks (Guo et al., 2011; Ji et al., 2017; Lee et al., 2012; Zhang et al., 2010a, 2013).

105 The eastern Gangdese belt in the western margin of the Namche Barwa syntaxis (Fig. 1B)
106 mainly consists of the high-grade metamorphic Nyingchi Complex and Mesozoic–Cenozoic
107 (165–22 Ma) granitoids (Booth et al., 2004; Dong et al., 2012; Guo et al., 2011, 2012, 2013; Ji
108 et al., 2017; Zhang et al., 2008, 2010a, 2010b, 2013, 2014, 2015). The Nyingchi Complex
109 represents the exposed middle-lower crust of the Gangdese arc and is composed of mafic and
110 felsic granulites, amphibolites, migmatites, orthogneisses, paragneisses and marble (Guo et al.,
111 2012, 2013; Zhang et al., 2010b, 2013, 2014, 2015). The mafic granulites from the Nyingchi
112 Complex have protolith ages of 82–95 Ma and metamorphic ages of 90–68 Ma (Guo et al., 2013;
113 Zhang et al., 2010b, 2014). Their protoliths have depleted Sr–Nd–Hf isotopic compositions that
114 are typical of arc magmatic rocks (Guo et al., 2013; Zhang et al., 2014). The protoliths of the
115 felsic granulites-facies and amphibolite-facies metamorphic rocks include Mesozoic–Cenozoic
116 sedimentary rocks and 65–38 Ma Gangdese granitoids which have large variation in Sr–Nd–Hf
117 isotopic compositions (Guo et al., 2011; Zhang et al., 2010b, 2013, 2015). These felsic rocks
118 underwent granulite-facies metamorphism and protracted crustal anatexis from 67 Ma to 41 Ma,
119 and amphibolite-facies metamorphism from 35 Ma to 26 Ma (Dong et al., 2012; Guo et al.,
120 2011, 2012; Wang et al., 2008a; Zhang et al., 2010b, 2013, 2015). The granitoids in the

121 Nyingchi area have a wide range of crystallization ages from 165 to 22 Ma, and mainly formed
122 during the periods 67-44 Ma and 28-22 Ma (Guo et al., 2011, 2012; Ji et al., 2017; Liu, 2012;
123 Zhang et al., 2008, 2010a).

124 The studied Confluence hornblende gabbro and Nyingchi granite samples were collected
125 in the eastern Gangdese belt near the confluence of the Yarlung Tsangpo and Nyang rivers (Fig.
126 1B). Both the hornblende gabbros and granites intruded the high-grade metamorphic Nyingchi
127 Complex and were cut by the Oligocene two-mica granites with sharply cross-cutting contacts
128 (Supplementary Figure S1). The hornblende gabbro samples show medium to coarse-grained
129 texture and consist mainly of amphibole (50–55 vol. %), plagioclase (35–40 vol. %), biotite (3–
130 8 vol. %), and clinopyroxene (1–3 vol. %), with accessory zircon, apatite, and magnetite
131 (Supplementary Figure S2A). The Nyingchi granites are coarse-grained with gneissic textures
132 and are composed of plagioclase (30–40 vol.%), K-feldspar (25–30 vol.%), quartz (25–30
133 vol.%), and biotite (5–10 vol.%) with accessory zircon, apatite, epidote, and Fe–Ti oxide
134 (Supplementary Figure S2B).

135

136 **3. Results**

137 Analytical methods are detailed in the supplementary materials. Whole-rock major and
138 trace element and Sr–Nd isotope data for the Nyingchi granites and the Confluence hornblende
139 gabbros are provided in the supplementary Table S1. Laser ablation inductively coupled plasma
140 mass spectrometry (LA–ICP–MS) zircon U–Pb geochronology, zircon Hf isotope data, and in-
141 situ feldspar Pb isotope data for the Nyingchi granites and the Confluence hornblende gabbros
142 are documented in the supplementary Tables S2–S4, respectively.

143

144 **3.1 Zircon U–Pb Ages**

145 LA–ICP–MS zircon U–Pb isotope data are presented in Appendix Table S2. Zircon grains
146 from two Confluence hornblende gabbro samples T1339 and 14GT004 have similar
147 morphological and textural features. They are euhedral or subhedral in shape, range in length
148 from 100 to 400 μm with aspect ratios of 1:1–4:1. They show broad oscillatory zoning in the
149 CL images (Fig. 2A and 2B), which is consistent with the magmatic zircon in mafic rocks (Corfu
150 et al., 2003). The analyzed zircon grains from two samples have variable U (72.4–2088 ppm)
151 and Th (24.1–1456 ppm) concentrations, with high Th/U ratios of 0.26–1.70 (Table S2).
152 Nineteen analyses of sample T1339 yield $^{206}\text{Pb}/^{238}\text{U}$ ages ranging from 48.1 to 51.4 Ma with a
153 weighted mean of 49.4 ± 0.5 Ma (MSWD = 0.68; Fig. 2A). Seventeen analyses of sample
154 14GT004 yield $^{206}\text{Pb}/^{238}\text{U}$ ages ranging from 49.1 to 52.5 Ma with a weighted mean of $50.3 \pm$
155 0.5 Ma (MSWD = 1.8; Fig. 2B).

156 Zircon grains from the Nyingchi granites (sample T774) are euhedral, 150–300 μm in
157 length, and have aspect ratios of 2:1–3:1. They show well–defined oscillatory zoning in the CL
158 images (Fig. 2C). Some zircon grains display inherited zircon cores. Twenty analyses were
159 conducted on 19 zircon grains. These zircons have Th of 31.8–416 ppm and U of 42.4–1104
160 ppm, with high Th/U ratios of 0.29–1.26 (Table S2). Nineteen analyses on zircon grains with
161 oscillatory zoning yield $^{206}\text{Pb}/^{238}\text{U}$ ages ranging from 49.1 to 53.4 Ma with a weighted mean of
162 50.4 ± 0.9 Ma (MSWD = 2.2; Fig. 2C). An inherited core yields a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1643 ± 89
163 Ma (Table S2).

164

165 **3.2 Whole-rock Major and trace element compositions**

166 Whole-rock major and trace element data for the Confluence hornblende gabbros and
167 Nyingchi granites are presented in Table S1. The Confluence hornblende gabbros have SiO₂
168 concentrations ranging from 44.85 wt. % to 53.06 wt.%. All gabbro samples are rich in Na₂O
169 with K₂O/Na₂O of 0.43–0.84. Except for sample T1336, the other samples plot in the alkaline
170 field on the total alkaline-silica (TAS) diagram (Fig. 3A; Middlemost, 1994). All gabbro
171 samples fall in the high-K calc-alkaline to shoshonitic fields on the K₂O–SiO₂ diagram (Fig.
172 3B; Peccerillo and Taylor, 1976). Their MgO (3.25–6.38 wt.%) and Mg# (43–54) are rather low
173 compared with mantle-derived primary magmas, with corresponding low Cr (1.24–49.8 ppm)
174 and Ni (1.27–12.7 ppm), and high concentrations of strongly incompatible trace elements (e.g.,
175 Rb = 12.1–67.6 ppm, Th = 0.43–7.08 ppm). The MgO, TFe₂O₃ (total iron as Fe₂O₃), Cr and Ni
176 contents and (Gd/Yb)_N decrease as SiO₂ increases from ca. 44 wt.% to ca. 48 wt.%, but slightly
177 increase for SiO₂ higher than 48 wt.% (Fig. 4). The Al₂O₃, P₂O₅ and Sr concentrations increase
178 with SiO₂ contents between from ca. 44 wt.% to ca. 48 wt.%, but decrease profoundly for SiO₂
179 contents higher than 48 wt.% (Fig. 4). The CaO concentration is characterized by an initial steep
180 decrease followed by a modest decrease as SiO₂ increases from ca. 44 wt.% to ca. 54 wt.% (Fig.
181 4). The Confluence hornblende gabbros exhibit fractionated rare earth element (REE) patterns
182 [(La/Yb)_N = 3.7–9.7] and weak negative Eu anomalies with Eu/Eu* = 0.76–0.93 (Fig. 5A).
183 Their primitive mantle-normalized trace element distribution patterns are characterized by
184 positive anomalies in Rb, K, Th, U and Pb, but negative anomalies in Nb, Ta, P, Zr, Hf and Ti
185 (Fig. 5B).

186 The Nyingchi granites show a relatively narrow range in many major element

187 concentrations (Fig. 4), with high SiO₂ (70.74–75.86 wt.%), Al₂O₃ (12.93–15.7 wt.%), and CaO
188 (2.01–3.74 wt.%), but low Fe₂O₃ (0.94–2.91 wt.%) and MgO (0.29–0.88 wt.%). All samples
189 plotted in the subalkaline granite field on the TAS diagram (Fig. 3A). They have variable K₂O
190 of 1.06–5.15 wt.% and plot in the low-K, calc-alkaline, and shoshonitic fields on the K₂O–SiO₂
191 diagram (Fig. 3B), with K₂O/Na₂O ratios of 0.26–1.11 (Table S1). They are weakly
192 peraluminous with A/CNK values of 1.03–1.07 (Table S1). The Nyingchi granites are
193 characterized by strongly enrichment of LREEs relative to HREEs on the chondrite-normalized
194 REE diagram (Fig. 5C), with high (La/Yb)_N (38–153) and (Dy/Yb)_N ratios (2.0–6.1), and
195 negative to positive Eu anomalies (Eu/Eu* = 0.48–1.57). The Nyingchi granites have high Sr
196 (522–638 ppm), low Y (5.25–12.5 ppm) and Yb (0.30–0.74 ppm), and thus high Sr/Y ratios
197 (48–121). All Nyingchi granite samples plot in the adakite fields of Sr/Y–Y and (La/Yb)_N–
198 (Yb)_N diagrams (Fig. 6A and 6B; Defant and Drummond, 1990; Drummond and Defant, 1990).
199 They define a positive correlation between (La/Yb)_N and (Dy/Yb)_N (Fig. 6C). Most Nyingchi
200 granite samples have high Nb/Ta ratios relative to the bulk continental crust and lower crust
201 (Fig. 6D). For the trace-element spider diagram, Nyingchi granites exhibit enrichment of Th,
202 K, Pb, and Sr, and depletion in Nb, Ta, Zr, Hf and Ti relative to their neighboring elements (Fig.
203 5D).

204

205 **3.3 Sr–Nd–Hf–Pb isotopic compositions**

206 Whole-rock Sr–Nd isotopic data for the Confluence hornblende gabbros and Nyingchi
207 granites are reported in Table S1 and illustrated in Fig. 7. Initial isotopic compositions were
208 calculated at 50 Ma for all studied samples. The Confluence gabbros record a narrow range of

209 values for both initial $^{87}\text{Sr}/^{87}\text{Sr}$ (0.705650–0.706074) and $^{147}\text{Nd}/^{144}\text{Nd}$ (0.512404–0.512468)
210 (Fig. 7), corresponding to $\epsilon_{\text{Nd}}(t)$ values of -3.3 to -2.1. The Nyingchi granites provide a moderate
211 range of initial $^{87}\text{Sr}/^{87}\text{Sr}$ (0.707054–0.708162) and $^{147}\text{Nd}/^{144}\text{Nd}$ (0.512232–0.512327) (Fig. 7),
212 corresponding to $\epsilon_{\text{Nd}}(t)$ values of -6.7 to -4.8.

213 The results of *in situ* zircon Lu-Hf isotopes were listed in supplementary Table S3 and
214 illustrated in Fig. 8. Zircons from the gabbro sample T1339 have $\epsilon_{\text{Hf}}(t)$ values of +0.1 to +1.8
215 (Fig. 8) with two stage Hf model ages of 1008–1111 Ma (Table S3). Zircons from the gabbro
216 sample 14GT004 have $\epsilon_{\text{Hf}}(t)$ values of -0.7 to +2.7 (Fig. 8) with two stage Hf model ages of
217 797–1164 Ma (Table S3). Zircons from the granite sample T774 have negative $\epsilon_{\text{Hf}}(t)$ values of
218 -11.8 to -10.1 (Fig. 8) with two stage Hf model ages of 1764–1869 Ma (Table S3).

219 Fresh plagioclase from the Confluence gabbros and K-feldspar from the Nyingchi granites
220 were selected for *in situ* Pb isotope analyses. The results are listed in the supplementary Table
221 S4 and illustrated in Fig. 9. The plagioclase from the Confluence gabbro samples T1332, T1334,
222 T1336, and T1339 yield the following ranges of values: $^{206}\text{Pb}/^{204}\text{Pb} = 18.524\text{--}18.750$,
223 $^{207}\text{Pb}/^{204}\text{Pb} = 15.499\text{--}15.685$, $^{208}\text{Pb}/^{204}\text{Pb} = 38.529\text{--}39.015$, $^{207}\text{Pb}/^{206}\text{Pb} = 0.834\text{--}0.840$ and
224 $^{208}\text{Pb}/^{206}\text{Pb} = 2.076\text{--}2.086$ (Table S4; Fig. 9). By contrast, the K-feldspar from the Nyingchi
225 granites generally have lower $^{206}\text{Pb}/^{204}\text{Pb} = 18.307\text{--}18.643$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.378\text{--}15.618$,
226 $^{208}\text{Pb}/^{204}\text{Pb} = 38.246\text{--}38.821$ and higher $^{207}\text{Pb}/^{206}\text{Pb} = 0.838\text{--}0.842$, $^{208}\text{Pb}/^{206}\text{Pb} = 2.082\text{--}2.092$
227 than those of the Confluence gabbros (Table S4; Fig. 9). To constrain the magma sources of the
228 Nyingchi granites and the Confluence gabbros, the plagioclase from the mafic granulite samples
229 (16GT022 and 16GT023) in the lower crust section of the eastern Gangdese belt (Guo et al.,
230 2013) were also selected for *in situ* Pb isotope analyses. The plagioclases from the granulites

231 have lower $^{206}\text{Pb}/^{204}\text{Pb} = 18.355\text{--}18.470$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.511\text{--}15.736$, and $^{208}\text{Pb}/^{204}\text{Pb} =$
232 $38.309\text{--}38.605$, and higher $^{207}\text{Pb}/^{206}\text{Pb} = 0.842\text{--}0.855$ and $^{208}\text{Pb}/^{206}\text{Pb} = 2.085\text{--}2.102$ compared
233 with those of the Nyingchi granites and the Confluence gabbros (Table S4; Fig. 9).

234

235 **4. Discussion**

236 **4.1 Origin of the Eocene Nyingchi high Sr/Y granites**

237 The Eocene Nyingchi granites have low Y (5.25–12.5 ppm) and HREE (Yb = 0.30–0.74
238 ppm) abundances, high Sr (522–638 ppm) abundances, and high Sr/Y (48–121), (La/Yb)_N (38–
239 153) and (Dy/Yb)_N ratios (2.0–6.1), which are similar to those of the adakitic rocks (Fig. 6A
240 and 6B; Defant and Drummond, 1990). Garnet is the only rock-forming mineral that can
241 substantially fractionate middle REE and heavy REE. Positively correlated high (Dy/Yb)_N and
242 (La/Yb)_N ratios (Fig. 6C) imply that the dominant role of garnet in fractionating REE of the
243 Nyingchi granites during partial melting. Elevated Sr abundances and a lack of correlation
244 between CaO and Eu/Eu* (not shown) rule out plagioclase as a residual phase in the restite or
245 a prominent mineral during crystal fractionation. Rutile has high partition coefficients for Nb
246 and Ta and generally partition Ta over Nb (Green and Pearson 1987; Foley et al., 2000). The
247 presence of rutile in the residue would result in high Nb/Ta of melts (Foley et al., 2002). The
248 Nyingchi high Sr/Y granites show variable and high Nb/Ta ratios (Fig. 6D), indicating that rutile
249 was stable in the residue (Foley et al., 2002). Therefore, their primary melts with high Sr/Y,
250 (Dy/Yb)_N and Nb/Ta ratios were in equilibrium with garnet and rutile in the absence of
251 plagioclase and thus were generated under eclogite-facies conditions.

252 High Sr/Y magmatic rocks may be generated by partial melting of subducted oceanic or

253 continental crust (e.g., Defant and Drummond, 1990; Wang et al., 2008b), partial melting of
254 thickened or delaminated lower continental crust (e.g., Atherton and Petford, 1993; Chung et
255 al., 2003; Kay and Kay, 1993; Xu et al., 2002), fractional crystallization from parental basaltic
256 magmas with or without crustal assimilation (e.g., Castillo, 2012; Macpherson et al., 2006), and
257 by magma mixing (e.g., Guo et al., 2007). The low Mg# values (38–42), Cr (0.46–6.49 ppm)
258 and Ni (1.91–4.11 ppm) abundances of the Nyingchi granites are distinct from the adakitic rocks
259 derived from partial melting of subducted oceanic crust and delaminated lower crust, which
260 generally have high Mg#, Cr and Ni concentrations due to melt-peridotite interactions during
261 the melt ascent through the mantle (Defant and Drummond, 1990; Wang et al., 2008b; Xu et al.,
262 2002). The Nyingchi granites are unlikely to have been directly derived from fractional
263 crystallization of the coeval Confluence mafic magma because of the different Sr–Nd–Pb–Hf
264 isotopic compositions (Fig. 7–9). Furthermore, no correlations between Sr/Y, (Dy/Yb)_N ratios
265 and SiO₂ has been observed (Fig. 6E and 6F). The petrogenetic model of magma mixing can be
266 ruled out because the Nyingchi granites have high SiO₂ concentrations (70.74–75.86 wt.%) and
267 lack field and petrographic evidence of magma mixing.

268 The Nyingchi high Sr/Y granites have high initial ⁸⁷Sr/⁸⁶Sr ratios (0.70705–0.70816) and
269 negative ε_{Nd}(t) (–6.7 to –4.8) and ε_{Hf}(t) values (–11.8 to –10.1), which are similar to those of the
270 thickened lower crust-derived high Sr/Y rocks in the collisional orogens (e.g., Liu et al., 2010;
271 Wang et al., 2005). However, the eastern Gangdese belt is likely to have a juvenile lower crust
272 prior to the India-Asian collision as inferred from the following: (1) the Triassic–Cretaceous
273 Gangdese arc magmatic rocks, including the Late Cretaceous lower crust-derived adakitic rocks
274 (Wen et al., 2008), have depleted Sr–Nd–Hf isotopic compositions (Harris et al., 1988; Ji et al.,

275 2009; Zhu et al., 2011) (Fig. 7 and 8); (2) Late Cretaceous mafic granulites and ultramafic-
276 mafic cumulates from the exposed Gangdese arc lower crust also display depleted Sr–Nd–Hf
277 isotopic compositions (Fig. 8; Guo et al., 2013; Ma et al., 2013a; Zhang et al., 2014). Because
278 of the juvenile nature of this lower crust, the enriched isotopic geochemistry of the Nyingchi
279 granites indicates that they could not be directly derived from partial melting of the lower crust.
280 Ancient crustal components are required to contribute to the magma sources following the
281 India-Asian collision. Previous studies show that the Eocene high Sr/Y granites in the central
282 Gangdese belt resulted from partial melting of the thickened lower crust (Chu et al., 2011; Guan
283 et al., 2012; Ma et al., 2014; Zhu et al., 2017b), and that ancient Indian crustal materials were
284 involvement into their magma sources after India-Asian collision (Chu et al., 2011; Ma et al.,
285 2014).

286 The potential isotopically enriched sources for the Nyingchi granites include the subducted
287 Indian continental crust and ancient crustal materials from the Nyingchi Complex in the eastern
288 Gangdese belt. In the eastern Himalayan syntaxis area, the Zhibai and Duoxiongla gneisses and
289 migmatites from the Greater Himalayan Sequence which represent the subducted Indian
290 continental crust have extremely high initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (0.74524–0.98165 at 50 Ma) and
291 negative $\epsilon_{\text{Nd}}(50 \text{ Ma})$ (–19.8 to –10.0) and $\epsilon_{\text{Hf}}(50 \text{ Ma})$ (–42 to –27) values (Fig. 7; Guo et al.,
292 2017; Zhang et al., 2010a), which preclude an origin directly from subducted Indian crust for
293 the Nyingchi granites. The results of isotopic mixing models between the Indian crustal
294 materials and juvenile lower crust of the Gangdese belt also cannot account for the Sr–Nd
295 isotopic compositions of the Nyingchi granites (Fig. 7). By contrast, mixing of 20–35% ancient
296 gneisses from the Nyingchi Complex (Zhang et al., 2015) with 65–80% depleted mafic lower

297 crust of the Gangdese belt can generate the isotopic features of the Nyingchi granites (Fig. 7).
298 Pb isotopes are sensitive indicators of involvement of ancient crustal materials because of the
299 shorter half-life of ^{238}U , ^{235}U , and ^{232}Th isotopes compared with those of ^{147}Sm and ^{87}Rb
300 isotopes. The Pb isotopic compositions suggest that the Nyingchi granites were derived from
301 melting of both the Gangdese and Indian continental crustal materials (Fig. 9). The reason why
302 the Sr and Nd isotopes are ineffective to identify the Indian crustal materials is probably that
303 the involvement of the Indian crustal materials is limited to change the Pb isotopic compositions
304 but to change the Sr-Nd isotopic compositions. Therefore, we propose that the high Sr/Y
305 Nyingchi granites were generated by the introduction of the Nyingchi gneisses from the
306 overlying Gangdese crust through tectonic erosion and the subducted Indian continental crust.
307 Both the ancient Indian crustal materials and the Gangdese crustal materials were carried into
308 the subduction channel. The mixed crustal materials were transported to the lower crust or
309 mantle depths in the channel and partially melted under eclogite-facies conditions. The melts
310 could have risen through buoyancy and either relaminated the lower crust or intruded the upper
311 Gangdese arc crust to form the Nyingchi high Sr/Y granites.

312

313 **4.2 Petrogenesis of the Confluence hornblende gabbros**

314 **4.2.1 Evaluation of crustal contamination and fractionation**

315 The ca. 50 Ma Confluence hornblende gabbros display arc-like trace element patterns (Fig.
316 5B). In addition, their enriched Sr-Nd-Hf-Pb isotopic compositions are different from those of
317 the mafic arc magmatism in the eastern Gangdese belt (Fig. 7-9; Ma et al., 2013a). These
318 geochemical signatures could result from (1) crustal assimilation during magma ascent and/or

319 magma chamber processes, (2) partial melting of lithospheric mantle metasomatized by
320 enriched crustal materials, or (3) a combination of both processes. The relatively limited range
321 of whole-rock Sr–Nd and zircon Hf isotopic compositions (Fig. 7 and 8) and absence of
322 correlations for the studied samples in the diagrams of $(^{87}\text{Sr}/^{86}\text{Sr})_i$ versus SiO_2 or $(^{147}\text{Nd}/^{144}\text{Nd})_i$
323 versus SiO_2 (not shown) indicate that crustal assimilation did not play a significant role during
324 magma evolution of the Confluence gabbros. Therefore, these geochemical signatures of the
325 Confluence gabbros would have been inherited from their mantle sources without significant
326 crustal assimilation.

327 The mantle-derived primary magmas generally show $\text{Mg}\# > 65$. The Confluence
328 hornblende gabbros have low $\text{Mg}\#$ (38–42), indicating that significant fractional crystallization
329 had occurred after the formation of the primary magma. The studied gabbro samples define
330 kinked trends on the plots of major and trace elements against SiO_2 (Fig. 4). The associated
331 decrease in MgO , TFe_2O_3 and Ni contents with increasing SiO_2 is due to olivine removal, while
332 the decrease of CaO and Cr can be explained by the crystallization and removal of
333 clinopyroxene from the magmas. The early decrease of $(\text{Gd}/\text{Yb})_N$ suggest that the fractionation
334 of hornblende. The Al_2O_3 , P_2O_5 , and Sr contents firstly increase and then decrease, indicating
335 that the plagioclase and apatite are late crystallizing phases in the Confluence gabbros.
336 Therefore, the parental magma of the Confluence gabbros underwent fractional crystallization
337 at depth involving an early fractionation assemblage of olivine + clinopyroxene + hornblende
338 and a later assemblage of plagioclase + apatite.

339

340 **4.2.2 Mantle source and enrichment processes**

341 Due to the evolved geochemical composition of the Confluence gabbros, neither the
342 degree of mantle melting, nor the composition of primary mantle melts could not be precisely
343 evaluated. Nevertheless, the low La/Yb (5.4–13.1) and Dy/Yb (1.8–2.3) ratios of the gabbros
344 suggest that their primary melts were not in equilibrium with garnet and formed at a relatively
345 shallow level of the mantle in the spinel peridotite stability field. The Confluence hornblende
346 gabbros have high K₂O and LILE contents, indicating that they were derived from partial
347 melting of a K₂O, LILE and H₂O-rich mantle. Phlogopite and amphibole are the main K₂O and
348 H₂O phase in the mantle. In the K₂O/MgO versus CaO/Al₂O₃ diagram (Fig. 10A), most
349 hornblende gabbro samples match the major element composition of experimental melts of
350 phlogopite- and/or amphibole-bearing spinel peridotite and mixed peridotite + felsic granitoid
351 sources (Couzinié et al., 2016, and references therein). This suggests that the primary melts
352 were derived from partial melting of a phlogopite- and/or amphibole-bearing spinel peridotite
353 or of a spinel mantle peridotite metasomatized by felsic granitic melts.

354 While the Jurassic–Cretaceous mafic arc magmatic rocks in the eastern Gangdese belt have
355 depleted Sr–Nd–Pb–Hf isotopic composition (Gariépy et al., 1985; Harris et al., 1988; Ji et al.,
356 2009; Zhu et al., 2008, 2011), the Eocene Confluence gabbros display enriched Sr–Nd–Pb–Hf
357 isotopic characteristics (Fig. 7–9). This indicates that the lithospheric mantle was
358 metasomatized by ancient crustal materials shortly after the India-Asian collision. The Sr–Nd–
359 Pb isotopic compositions of the Confluence gabbros are in a similar situation to those of the
360 Nyingchi granites. A simple modeling for source contamination indicates that mixing the
361 depleted upper mantle peridotite with about 15–20% of the ancient crustal materials (the
362 Nyingchi gneisses) from the eastern Gangdese belt can explain the present Sr–Nd isotopic

363 features of the gabbros (Fig. 7). However, the incorporation of material from the Nyingchi
364 gneisses into the mantle beneath the Gangdese arc cannot account for the Pb isotopic
365 composition of these gabbros (Fig. 9). The Confluence gabbros have lower $^{207}\text{Pb}/^{206}\text{Pb}$ and
366 $^{208}\text{Pb}/^{206}\text{Pb}$ ratios than those of the Gangdese batholith, the lower crust of the Gangdese arc, the
367 Lhasa basement and the Eocene Nyingchi high Sr/Y granites (Fig. 9). This requires an
368 involvement of Indian crustal materials which have low $^{207}\text{Pb}/^{206}\text{Pb}$ and $^{208}\text{Pb}/^{206}\text{Pb}$ ratios (Fig.
369 9; Gariépy et al., 1985). Therefore, we suggest that the crustal components in the mantle source
370 results from influx of felsic melts from melting of the Indian plate together with components
371 from partial melting of the eroded crustal materials from the Gangdese belt (Fig. 11). This
372 metasomatized mantle region provides a ready source for potassic magma during the late stages
373 of lithosphere convergence related to extension and mantle upwelling (Castro, 2014). The
374 composition of the bulk continental crust (Rudnick and Gao, 2003) is taken to represent the
375 felsic melts because both upper and lower crust materials were involved in the subduction
376 channel through tectonic erosion and continental subduction (Fig. 11B). The modeling results
377 show that the melts can be generated from 15–25% partial melting of a hybrid source consisting
378 of 75–90% depleted mantle and 10–25% of the felsic component (Fig. 10B), which is consistent
379 with the result of the binary Sr–Nd isotopic mixing model (Fig. 7).

380 In summary, the Eocene Confluence gabbros were derived from partial melting of the
381 phlogopite- and/or amphibole-bearing spinel peridotite, formed by contamination of the mantle
382 by limited amounts of crustal materials that were subducted during the early stages of the India-
383 Asian collision.

384

385 **4.3 Tectonic erosion during the India-Asian continental collision**

386 As stated above, the magma sources of the ca. 50 Ma Nyingchi high Sr/Y granites involved
387 significant ancient crustal materials from the Nyingchi Complex which predominantly is
388 composed of metagranitoids and metasedimentary rocks. However, these ancient crustal
389 materials were not subject to high-grade metamorphism until the India-Asian continental
390 collision (Dong et al., 2012; Guo et al., 2011, 2012, 2017; Wang et al., 2008a; Zhang et al.,
391 2010b, 2013, 2015). The metagranitoids have protolith ages ranging from Paleoproterozoic (ca.
392 1782 Ma), Cambrian (ca. 496 Ma), Mesozoic (165-83 Ma) to Cenozoic (65-38 Ma) (Dong et
393 al., 2012; Guo et al., 2012; Lin et al., 2013; Zhang et al., 2013, 2015). The protoliths of
394 Mesozoic-Cenozoic metagranitoids resulted from the subduction of Neo-Tethyan oceanic slab
395 or from the collision of India-Asian continents (Guo et al., 2012; Zhang et al., 2013, 2015). The
396 protoliths of the metasedimentary rocks from the Nyingchi complex include Neoproterozoic,
397 Late Paleozoic, Mesozoic, and Cenozoic sedimentary rocks (Guo et al., 2011, 2017; Xu et al.,
398 2013; Zhang et al., 2008). Inherited detrital zircon from the Mesozoic-Cenozoic
399 metasedimentary rocks yielded age peaks at 95-60 Ma and 171-138 Ma (Xu et al., 2013; Zhang
400 et al., 2008, 2015), which is consistent with the age spectra of the Gangdese arc magmatic rocks,
401 indicating that their protoliths were probably deposited in the forearc basin. The felsic
402 metamorphic rocks from the Nyingchi Complex underwent granulite-facies metamorphism and
403 protracted crustal anatexis from 63 Ma to 41 Ma, and amphibolite-facies metamorphism from
404 35 Ma to 23 Ma (Dong et al., 2012; Guo et al., 2011, 2012; Lin et al., 2013; Wang et al., 2008b;
405 Xu et al., 2013; Zhang et al., 2013, 2015). Their metamorphic ages are close to their protolith
406 ages, indicating that these supracrustal rocks underwent rapidly burial and metamorphism after

407 the Indian-Asian collision. In addition, the existence of abundant Early Cenozoic inherited
408 zircons in the Oligocene high Sr/Y granites indicates significant reworking of the Gangdese
409 crust (Ding and Zhang, 2019; Zhang et al., 2008; Zheng et al., 2012).

410 Previous studies proposed that crustal shortening and thickening resulted in the Oligocene
411 reworking of the Gangdese crust (Ding and Zhang, 2019; Zhang et al., 2015). If this
412 interpretation is true, at least 50% crustal shortening of the Gangdese crust is required to enable
413 upper crustal rocks (e.g., granitoids generally intruded at depths from 5 to 15 km) to be
414 subjected to amphibolite- or granulite-facies metamorphism during the Eocene and Oligocene.
415 This is at variance with the limited shortening are unlikely to have descended of the Gangdese
416 belt after the India-Asian collision (Mo et al., 2007). Furthermore, the supracrustal sediments
417 are unlikely to have descended to the depths of the lower crust through crustal shortening in
418 less than 40 Myr. Structurally, the simplest interpretation for these metagranitoids and
419 metasedimentary rocks is that they were underplated by tectonic erosion during India-Asian
420 collision (Xu et al., 2013; Zhang et al., 2008, 2015). According to the tectonic erosion model
421 (Scholl and von Huene, 2010), the subduction of buoyant Indian continental crust would
422 enhance the front and basal erosion of the forearc of the Gangdese belt. The tectonic erosion
423 invokes collapse and accommodation of upper plate materials into the subduction channel
424 which hybridized the ancient crustal materials from the Indian continent and ancient upper-
425 middle and juvenile lower crustal materials from the Gangdese crust (Fig. 11). The mixed
426 crustal materials were transported to lower crust or mantle depths by subduction and partially
427 melted under eclogite-facies conditions.

428 After the closure of Neo-Tethys Ocean, material from the leading edge of the Indian

429 continent was dragged into the subduction channel. The buoyant continental crust probably
430 enhanced the mechanical coupling between the subducted and overlying continents, inducing
431 pervasive abrasion of the overriding plate (Fig. 11). Arc magmatic fronts commonly form 200–
432 250 km inboard of the trench axis (Scholl and von Huene, 2010). The direct contact between
433 the Gangdese batholith and Indian continent requires the removal of the former forearc in the
434 eastern Gangdese belt since India-Asian collision at ca. 60 Ma. (Fig. 1). If we assume that the
435 former Gangdese forearc was similar to the modern Andean forearc in its dimensions and
436 geometry, the width of forearc was 200–250 km just prior to the India-Asian collision (Fig.
437 11A). An average crustal thickness of 45 km is used to estimate the rate of long-term loss of
438 crustal materials from the upper plate (Clift and Vannucchi, 2004). If the loss of forearc is
439 ascribed entirely to tectonic erosion, the calculated long-term erosion rates are 150–188
440 km³/km/my, which is higher than those observed in most modern ocean-margin subduction
441 zones (30–115 km³/km/my) (Clift and Vannucchi, 2004; Scholl and von Huene, 2007, 2009;
442 Stern, 2011). Our result suggests that significant crustal loss by tectonic erosion occurred during
443 the continental collision.

444

445 **4.4 Crustal relamination and its implications**

446 During continental collision, felsic crustal materials derived from both the subducted plate
447 (by anatexis) and from the upper plate (by tectonic erosion) can be relaminated to the base of
448 the upper plate and eventually form a part of the upper plate, whereas the mafic crustal materials
449 are recycled into the mantle (Hacker et al., 2011, 2015; Maierova et al., 2018). These crustal
450 materials can be carried into lower crust or mantle and undergo partial melting to produce

451 adakitic melts (Stern, 2011). Some felsic melts could react with the overlying wedge peridotite
452 and serve as metasomatic agents for crust-mantle interaction in the continental subduction
453 channel (Stern, 2011; Willbold and Stracke, 2010). Our study shows that the Eocene Nyingchi
454 high Sr/Y granites in the eastern Gangdese belt were derived from partial melting of relaminated
455 crustal materials, and the Eocene Confluence gabbro was sourced from lithospheric mantle
456 metasomatized by relaminated crustal melts (Fig. 11B). The Cretaceous lower crust of the
457 Gangdese arc was dominated by mafic granulite and ultramafic/mafic cumulates (Guo et al.,
458 2013; Ma et al., 2013b; Zhang et al., 2010b, 2014). By contrast, the substantial occurrence of
459 felsic granulite-/amphibolite-facies metamorphic rocks in the lower crustal section of the
460 Gangdese arc (Dong et al., 2012; Guo et al., 2012, 2017; Xu et al., 2013; Zhang et al., 2010b,
461 2015) further indicates that substantial amounts of felsic crustal materials were relaminated to
462 the base of the upper plate during the India-Asian collision. In addition, the whole-rock $\epsilon_{\text{Nd}}(t)$
463 and zircon $\epsilon_{\text{Hf}}(t)$ values of the magmatic rocks exhibit clearly negative excursions (Fig. 7 and
464 8) during the Eocene (ca. 50 Ma) magmatic flare-up event in the Gangdese belt (Chu et al.,
465 2011; Ji et al., 2009; Ma et al., 2014). We propose that these negative excursions result from
466 relamination of ancient crustal materials removed from the Gangdese belt by tectonic erosion
467 and from subducted Indian continental crust. As a result, crustal relamination rejuvenated the
468 supply of melt-fertile lithosphere and ignited the Eocene flare-up event (Ducea and Barton,
469 2007; Ducea et al., 2015). The substantial addition of felsic rocks into the lower crust probably
470 shifted the lower crust composition of the Gangdese arc from basaltic to andesitic. Our study
471 demonstrates that crustal relamination plays an important role in refinement of the continental
472 crust composition (Castro et al., 2013; Hacker et al., 2011, 2015; Kelemen and Behn, 2016;

473 Vogt et al., 2013).

474

475 **5. Conclusions**

476 In the eastern Gangdese belt, the Eocene Nyingchi high Sr/Y granites were derived from
477 partial melting of relaminated crustal materials which contained the Gangdese crustal materials,
478 removed by tectonic erosion, and subducted Indian crustal materials. The Eocene Confluence
479 gabbros were sourced from the lithospheric mantle which was metasomatized by relaminated
480 crustal melts and by melting of the Indian plate forming the footwall of the subduction zone.
481 Our results suggest (1) that significant crustal loss by tectonic erosion occurred during the India-
482 Asian continental collision and (2) more felsic rocks rise buoyantly to be relaminated to the
483 base of the upper plate, a process which probably plays an important role in refinement of the
484 composition of the continental crust.

485

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497

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