

Sequential melting of deep crustal sources in a rift system: An example from the Southern Tibet

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ABSTRACT

How the continental crust responds geochemically to progressive extension is one of the interesting questions. The Southern Tibet Rift System (STRS) is one of the active extensional structures. The Yardoi gneiss dome, located within STRS, consists of at least four suites of Miocene granites. As crystallization ages become younger, they are characterized by decrease in $\epsilon_{\text{Nd}}(t)$ and Sr/Y, but increase in $^{87}\text{Sr}/^{86}\text{Sr}(t)$ and Rb/Sr. Such temporal trends could be explained by sequential partial melting of first the mafic lower crustal rocks and then progressively shallower metasedimentary rocks. Together with literature data, from north to south along STRS, as the extension proceeds and the heat moves upward, sequential partial melting is common to produce Miocene magmatic rocks. The processes documented in the southern Tibet might be common in other extensional provinces and provides a new insight to unravel the mechanisms for the generation of geochemical variations in contemporaneous granites.

24

25 **Keywords:** sequential melting, high Sr/Y ratios, granites, extension, rift, the southern
26 Tibet

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28 INTRODUCTION

29 In various tectonic settings, impingement of a thermal pulse could be induced by
30 breakoff of a subducting slab, extension and rifting or delamination of a dense
31 thickened continental lithosphere ([Gorti, 2009](#); [Rychert et al., 2012](#)). All these
32 processes could gradually warm up the continental crust, and eventually trigger partial
33 melting of different fertile components and produce granitic melts with vastly
34 different mineral and chemical signatures depending on the pressure and temperature
35 conditions achieved. In the upwelling regions associated with continental rifting, the
36 depth of melting decreases with time ([Wendlandt and Morgan, 1982](#)), which
37 conceptually could be proceeded by sequential melting. Sequential melting of a
38 vertical column of continental crust triggered by the ascent of a thermal pulse has
39 been suggested to generate co-existing granitic rocks with distinct mineral assemblage
40 and isotope compositions ([Holtz and Barbey, 1991](#); [Nabelek et al., 1992](#); [Greenfield et al., 1998](#);
41 [Gutiérrez-Alonso et al., 2011](#); [Carvalho et al., 2012](#)). However, how the
42 geochemical nature of granitic melts changes through such a process is still poorly
43 documented. The Southern Tibet Rift System (STRS), one of the active extensional
44 structures in the southern Tibet, is composed of a series of nearly north-south trending
45 rift valleys from the Lhasa terrain down to the Himalayan belt, and represents ongoing

46 E-W orogen-parallel extension (Taylor and Yin, 2009; Nagy et al., 2015). Instability
47 analysis suggests that the mantle lithosphere must have been involved in E-W
48 extension (Yin, 2000). In the Lhasa terrain, extension has induced partial melting of
49 the enriched subcontinental lithosphere (SCLM) as well as the thickened lower crust
50 (Chung et al., 2003; Hou et al., 2004; Liu et al., 2014; Guo et al., 2019). In the
51 Himalayan belt, East-West extension could be dated back to ~19 Ma (Mitsuishi et al.,
52 2012; Zhang et al., 2012; Nagy et al., 2015) and resulted in the exhumation of a
53 number of gneiss domes in the Tethyan Himalaya (Xu et al., 2013; Wang et al., 2018).
54 If such process is common to all the branches of STRS from north to south, then it is
55 conceivable that the basement rocks in the Himalayan belt should experience
56 progressive heating as the extension proceeds. Whether such a heating could induce
57 partial melting of lower crustal rocks is one of the interesting questions deserved
58 careful investigations. How the intermediate to lower crustal rocks response
59 physically as well as geochemically to such extension is one of the poorly constrained
60 problems. The Yardoi gneiss dome, located within the Sangri-Cuona rift, one of the
61 branches of STRS (Fig. 1A, Taylor et al., 2009), could have experienced progressive
62 heating due to extension and exhumation and provides us an excellent opportunity to
63 address the questions posed above.

64 In this contribution, we present geochemical as well as geochronological data of
65 four suites of Miocene granites from the Yardoi gneiss dome. These data together with
66 literature data from the Nariyongcuo and the Cuona within the Sangri-Cuona rift, and
67 from those rift valleys in the Lhasa terrane, are used to paint a detailed picture of the

68 variations in the melting reactions of deep crustal rocks within STRS.

69 **GEOLOGICAL SETTING**

70 The Yardoi gneiss dome (YGD) is located within the Sangri-Cuona rift and in the
71 easternmost of the Tethyan Himalaya (Fig. 1A). From the core to the margin, it
72 consists of Eocene granites (Zeng et al. 2015) in the core, high-grade metamorphic
73 rocks, mediate-grade garnet graphite schist and intruding Oligocene and Miocene
74 granitic dykes (Zeng et al. 2011) toward the margin, followed by the overlying
75 Tethyan sedimentary rocks (Fig. 1B). In addition, minor sheared two-mica granitic
76 rocks of ages ~43-44 Ma occur in the Dala and Quedang area and subvolcanic
77 porphyritic leucogranite dikes or plugs of ages 41.4 Ma (Zeng et al., 2015) occur
78 along the E-W trending valley from Qiaga to Longzi (Fig. 1B). The Eocene granitic
79 rocks were derived from partial melting of amphibolite under thickened crustal
80 conditions (Zeng et al., 2011; Hou et al., 2012). In the mantle, some meter-wide
81 leucogranitic dykes recorded U–Pb ages of 20~17 Ma (Gao et al., 2020), whereas, the
82 geochemical nature and the formation mechanism have not been described before. We
83 sampled four suites of granite T0394, T0725-LG, TYS-10, and T0468 as shown in Fig.
84 1B. They consist of quartz, plagioclase, muscovite, K-feldspar and accessory phases
85 of zircon, apatite, and monazite (Fig. S1). Except T0468, other granites contain 5%
86 biotite.

87 **RESULTS**

88 All the zircons from the four suites of granites show oscillatory zoning.
89 Weighted mean ages are 20.4 ± 0.4 Ma, 18.9 ± 0.2 Ma, 17.7 ± 0.1 Ma, 17.1 ± 0.1 Ma

for T0394, T0725-LG, TYS-10, and T0468, respectively (Fig. S2, data for T0394 are from Zeng et al., 2019). Though the zircons have low Th/U ratios (<0.25 , Table S1), the well-developed oscillatory zoning indicates that they were crystallized from granitic melt, therefore, we interpret these ages as the timing of crystallization for these granites.

The four suites of granites have similar geochemical natures in major elements (Fig. S3, data for the granite T0394 are from Zeng et al., 2019) and are characterized by (1) high SiO_2 (71.6–76.2 wt%), Al_2O_3 (13.7–16.3 wt%) and Na_2O (4.2–5.9 wt%); (2) low K_2O (1.1–3.7 wt%), CaO (0.7–1.8 wt%), FeO (<1.4 wt%), MgO , P_2O_5 ; and (3) relatively high $\text{Na}_2\text{O}/\text{K}_2\text{O}$ (1.19–5.10) and high A/CNK (1.06–1.31) ratios, which indicate that they are Na-rich and peraluminous granite. As compared to the other samples, T0468 have relatively higher SiO_2 , but lower CaO , FeO^* and P_2O_5 (Fig. S3).

In primitive mantle–normalized spider diagrams (Fig. S4), T0394, T0725-LG and TYS-10 share similar geochemical characteristics, with striking negative anomalies in Nb, Ta, P, Ti, and Y along with slightly positive anomalies in Sr. In contrast, T0468 samples are characterized by striking negative anomalies in P and Ti alongside slightly negative anomalies in Nb, Sr, Zr and Y. Except sample T0468, the others have relatively high Sr (316–536 ppm) and La (8.0–13.8 ppm), but low Y (2.2–6.7 ppm) and Yb (<0.6 ppm), and thus relatively high Sr/Y ratios (52.2–181.6) and La/Yb ratios (18.0–38.5). In the Sr/Y–Y and La/Yb–Yb diagram, all three suites of granite are plotted within the adakite field (Fig. 2). In particular, most samples in T0468 have lower Sr/Y ratios (<30.4) at similar Y concentrations (Fig. 2A), and lower

112 La/Yb ratios (<18.2) at similar Yb concentrations (Fig. 2B), respectively. In
113 additional, trace element ratios of Rb/Sr, Nb/Ta and Zr/Hf are apparently different.
114 T0468 have high Rb/Sr (0.7–2.4) and low Zr/Hf (15.8–26.2), Nb/Ta (4.5–8.7).
115 Compared to T0468, others are characterized by lower Rb/Sr ratios (<0.3), but higher
116 Zr/Hf (22.3–32.7) and Nb/Ta (6.9–15.5). Interestingly, as crystallization ages become
117 younger, Sr/Y ratios decrease, but Rb/Sr ratios increase (Fig. 2C, D).

118 All the granites are enriched in light REEs (LREE) and depleted in heavy REEs
119 (HREE), however, T0468 have relatively lower contents of LREE than others, and
120 more weakly degree of fractionation LREE over HREE (Fig. S4). The Eu anomalies
121 display significant difference. T0468 are characterized by pronounced negative Eu
122 anomalies ($\text{Eu}/\text{Eu}^* < 0.56$) and negative Nd anomalies ($\text{Nd}/\text{Nd}^* = 0.81\text{--}0.90$), whereas,
123 others have relatively higher and variable Eu anomalies ($\text{Eu}/\text{Eu}^* = 0.90\text{--}1.25$) and
124 limited negative Nd anomalies ($\text{Nd}/\text{Nd}^* = 0.85\text{--}0.96$) (Table S2).

125 The granites display a large variation in Sr and Nd isotope ratios, but all feature
126 relatively radiogenic $^{87}\text{Sr}/^{86}\text{Sr}(\text{t})$ (0.7091–0.7149) and unradiogenic $\epsilon_{\text{Nd}}(\text{t})$ (–11.1 to
127 –7.7; Fig. 3). There is regularity in variations of Sr and Nd isotope ratios for YGD
128 Miocene granites. As crystallization ages become younger, $\epsilon_{\text{Nd}}(\text{t})$ value decrease, but
129 $^{87}\text{Sr}/^{86}\text{Sr}(\text{t})$ increase (Fig. 3C, 3D).

130 DISCUSSION

131 The data presented above demonstrate that except sample T0468, the other three
132 Miocene granites in the YGD are Na-rich and peraluminous granite with high Sr/Y
133 and La/Yb ratios. Compared with the others, T0468 have different geochemical

134 natures and are characterized by (1) higher SiO₂, lower CaO, FeO*, TiO₂ and P₂O₅; (2)
135 higher Rb and Ta, lower Sr, LREE, Zr, and Ti, thus higher Rb/Sr but lower Sr/Y,
136 La/Yb, Zr/Hf and Nb/Ta ratios; (3) pronounced negative Eu anomalies and negative
137 Nd anomalies. These differences (Fig. S4) and systematic relationships in major and
138 trace elements (Fig. S5) suggest that T0468 had suffered from various degrees of
139 fractional crystallization of plagioclase, zircon, monazite, apatite, and Ti-rich mineral
140 phases, which is common to the Himalaya high silica leucogranites (Liu et al., 2019),
141 whereas, others seem to be more primitive and represent the more faithful melt
142 compositions. In addition, T0468 shows a large variation in Rb/Sr ratios, but no linear
143 relationship between Rb/Sr and ⁸⁶Sr/⁸⁷Sr ratios (Fig. S5), which indicates that
144 fractional crystallization has negligible effects on their Sr-Nd isotope compositions.

145 E-W extension in the southern Tibet results in the formation of adakitic and
146 potassic-ultrapotassic magmatic rocks (Chung et al., 2003). The adakitic magmas
147 were formed by a complex mechanism involving partial melting of mafic materials in
148 a thickened lower crust with input of enriched mantle and upper crust components
149 (Hou et al., 2004). Potassic-ultrapotassic rocks were derived from a metasomatized
150 subcontinental lithospheric mantle (SCLM) with additional contributions from
151 thickened juvenile lower crust or ancient basement (Liu et al., 2014). This
152 lower-crustal melting required a significantly elevated geotherm, which is attributed
153 to removal of the tectonically thickened lithospheric mantle at depth (Chung et al.,
154 2003), followed by E-W extension setting associated with Miocene plateau uplift (Liu
155 et al., 2014). The YGD is located within the Sangri-Cuona rift (Fig. 1A, Taylor et al.,

156 2009) and the basement rocks should have experienced progressive heating as the
 157 extension proceeds. As compare to above rocks in the Lhasa block, the four suites of
 158 Yardoi Miocene granites are characterized by intermediate $\epsilon_{\text{Nd}}(t)$ and $^{87}\text{Sr}/^{86}\text{Sr}(t)$ (Fig.
 159 3A). As compare to the nearly contemporaneous granites in the Himalayan orogenic
 160 belt, the Yardoi Miocene granites have different Sr–Nd isotope compositions, in
 161 contrast with similar Sr but elevated Nd isotope compositions to those in the Eocene
 162 granites (Fig. 3B). Therefore, the Miocene granites in the YGD could be derived from
 163 partial melting of lower crustal material during E–W extension. Occurrence of primary
 164 high Sr/Y granites in an orogenic belt requires a mafic source component in deeper
 165 crustal levels. Mafic materials that are responsible for these granites include (1)
 166 subcontinental mantle; (2) lower crustal mafic materials (amphibolite or recently
 167 underplated basaltic material); or (3) subducting Indian continental slab. The
 168 geochemical natures of low MgO (<0.65 wt %), Cr (<21 ppm), Ni (<12 ppm) in these
 169 Yardoi Miocene granites rule out mantle materials as their sources. The relatively
 170 elevated Sr isotope compositions with $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of 0.7091~0.7149 and negative
 171 $\epsilon_{\text{Nd}}(t)$ of -11.1~-7.7 could be explained by they represent melts derived from mafic
 172 components in the subducting Indian continental slab (Fig. 3). The close match in Sr
 173 and Nd isotope compositions between the Yardoi Miocene granites and the
 174 amphibolites are consistent with their derivation primarily from amphibolite (Fig. 3B).
 175 In addition, as crystallization ages become younger, from 20.4 Ma to 17.1 Ma, $\epsilon_{\text{Nd}}(t)$
 176 value decrease but $^{87}\text{Sr}/^{86}\text{Sr}(t)$ increase (Fig. 3C, 3D). The systemic variations in the
 177 age of formation and the Sr–Nd isotope compositions suggest that there are at least

178 two types of source rocks. These granites should be produced by mixing of
179 amphibolite-derived melts with metasediment-derived melts. As the extension
180 proceeds, source regimes change from more deeply seated amphibolite toward to
181 shallower metasedimentary rocks. This also could explain the variations in their Sr/Y
182 and Rb/Sr ratios (Fig. 2C, 2D).

183 Recently, other Miocene high Sr/Y granites were reported in other gneiss domes
184 within the Himalayan belt (Ji et al., 2019; Lin et al., 2020). They have similar Sr–Nd
185 isotope compositions to the Miocene granites in the YGD (Fig. 3A). Occurrences of
186 Miocene high Sr/Y granites imply that the Himalayan belt could have experienced a
187 major episode of melting of lower crustal rock. Additionally, the Miocene granite in
188 the YGD are high-temperature ones (~850 °C, Gao et al., 2020). Meanwhile, Miocene
189 ultrahigh temperature metamorphism is reported in the Himalaya belt (900–970 °C,
190 Wang et al., 2021). These high-temperature geological events require an extra heat
191 source which would probably be provided by upwelling of asthenospheric mantle
192 accompanied the E-W extension (Gao et al., 2020; Wang et al., 2021; Shi et al., 2020).
193 Therefore, partial melting of the lower crust was most likely triggered by Miocene
194 E-W extension in southern Tibet with heat source from the upwelling of
195 asthenospheric mantle.

196 Sequential partial melting is a model proposed by Holtz and Barbey (1991) who
197 explained the genesis of granitic partial melts segregated from the same melting zone
198 during progressive heating. Early crustal thickening followed by later extension and
199 mantle upwelling could induce similarly progressive heating and trigger progressive

200 partial melting, which are characterized by early melting at elevated pressure
201 conditions overtaken by progressive much shallower melting (Gutiérrez-Alonso et al.,
202 2011; Carvalho et al., 2012). From north to south along Sangri-Cuona rift, different
203 granites with various geochemical natures were derived from mafic rock, fluid-absent
204 melting and fluid-fluxed melting of metasediment (Fig 4A, Gao et al., 2017).
205 Therefore, similar to those processes after the slab breakoff (Atherton and Ghani,
206 2002; Magni et al., 2017), as the extension proceeds and the heat conduction moves
207 upward into the shallower level, sequential partial melting of first subcontinental
208 lithospheric mantle, then the mafic lower crustal rocks and finally progressively
209 shallower metasedimentary rocks could produce similar variations in the chemical as
210 well as isotopic compositions in the Miocene magmatic rocks within the STRS (Fig.
211 4B). The above processes might be common in other extensional provinces (e.g., East
212 Africa rift, Basin and Range Province) and provides a new insight to unravel the
213 mechanisms for the generation of the geochemical and isotopic variations in nearly
214 contemporaneous granitic rocks.

215

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223 **Data Availability Statement**

224 Data are published separately and are available under the

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229 **Figure 1.** A: Simplified geologic map of the Himalayan orogenic belt, southern Tibet.
230 B: Simplified geological map of the Yardoi area. STRS: Southern Tibet Rift System;
231 NHGD: Northern Himalayan Gneiss Dome.

232
233 **Figure 2.** Trace elements characteristics of the Yardoi Miocene leucogranites.

234
235 **Figure 3.** A: Sr–Nd isotope systematics of the magmatic rocks lied in NSTR,
236 containing Miocene high Sr/Y granite from the Yardoi, Mayum ([Lin et al., 2020](#)),
237 Kunday ([King et al., 2007](#)) and Bendui ([Ji et al., 2019](#)) in the Himalayan belt, adakitic
238 intrusives ([Hou et al., 2004](#)) and the ultrapotassic and potassic rocks ([Liu et al., 2014](#))
239 in the Lhasa terrain. B: Sr–Nd isotope systematics of the Eocene granites and other
240 Miocene granites, as well as amphibolite and metapelite in the Himalayan orogenic
241 belt ([Zeng et al., 2015](#)). C-D: The relationship between crystallization ages and Sr–Nd
242 isotope compositions of the Yardoi Miocene granite.

243
244 **Figure 4.** A: Sr–Nd isotope systematics of the ~20 Ma granites from north to south
245 within Sangri-Cuona rift (date from [Gao et al., 2019](#) and our unpublished data). B: the
246 model for the magmatism induced by E–W extension within the NSTR. YTS:
247 Yalung-Tsangpo suture; STDS: Southern Tibet Detachment System; MCT: Main
248 Central Thrust.

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250 Supplemental Material. Figures S1- S5, and Table S1- S2.

251

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