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

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## Abstract

Understanding the processes of tectonic erosion and crustal relamination during continental collision has important implications for the growth and differentiation of the continental crust. The discrepancy in isotopic compositions between the pre- and syn-collision magmatic rocks from the Gangdese belt in south Tibet provides an opportunity for studying these processes during the India-Asian collision. The Nyingchi granites and Confluence hornblende gabbros from the eastern Gangdese belt have zircon U−Pb ages of ca. 50 Ma. The Nyingchi granites have high Sr/Y and $(Dy/Yb)_N$ ratios, indicating that the magma was generated under eclogite-facies conditions. Their Sr−Nd−Pb−Hf isotopic compositions require significant incorporation of ancient supracrustal materials from the Gangdese belt and the Indian continent. The Confluence hornblende gabbros display arc-like trace element patterns but have enriched Sr−Nd−Pb−Hf isotopic compositions compared with those from the Jurassic−Cretaceous arc magmatic rocks, indicating significant input of ancient components into their mantle sources. The occurrence of the Cenozoic felsic metamorphic rocks in the lower crust of the Gangdese belt allows us to propose that the Nyingchi high Sr/Y granites were derived from partial melting of relaminated crustal materials which were removed from the Gangdese belt by tectonic erosion and the subducted Indian continent. The Confluence gabbros were sourced from lithospheric mantle which was metasomatized by inputs from relaminated crustal materials derived from the Gangdese belt and the subducted Indian continent. The estimated tectonic erosion rate is 150−188 $km^3$/km/my, indicating significant crustal loss occurred during continental collision. Our study demonstrates that tectonic erosion and crustal relamination play an important role in the refinement of the composition of continental crust during continental

collision.

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

## 1. Introduction

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

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

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

In this study, we report zircon U−Pb ages, whole-rock major, trace element and Sr−Nd isotope, in-situ zircon Hf isotope and feldspar Pb isotope data for the Eocene Confluence gabbros and Nyingchi granites in the eastern Gangdese belt. Our results show that the Nyingchi high Sr/Y granites were derived from partial melting of both relaminated Gangdese crustal materials, removed by tectonic erosion, and the subducted Indian crustal materials. The Confluence gabbros were sourced from the lithospheric mantle which was metasomatized by felsic melts derived from relaminated crustal materials. Our study implies that significant tectonic erosion occurs during continental collision. The eroded felsic crustal materials may be relaminated to the base of the upper plate, which plays an important role in crustal refinement during the process of continent-continent collision.

## 2. Geological background and samples

The Lhasa terrane of southern Tibet is separated from the Qiangtang terrane to the north by the Bangong−Nujiang suture and from the Himalayas to the south by the Indus−Yarlung Tsangpo suture (Fig. 1A). The Lhasa terrane is underlain by Proterozoic basement with juvenile crust accreted towards its southern and northern margins (Zhu et al., 2011). The Gangdese belt in the southern Lhasa terrane is dominated by the Triassic−Tertiary Gangdese batholith and the Paleogene Linzizong volcanic succession, with minor Triassic−Cretaceous volcano−sedimentary rocks (Mo et al., 2007; Pan et al., 2006). The batholith is composed of a variety of lithologies including gabbro, diorite, granodiorite to granite (Harris et al., 1988; Ji et al., 2009; Wen et al., 2008; Xu et al., 1985). Zircon U−Pb dating results revealed that the Gangdese magmatism began in Middle-Late Triassic and lasted until Miocene, with four magmatic flare-up events at 205−150 Ma, 100−80 Ma, 65−40 Ma, and 30−10 Ma (Ji et al., 2009; Wang et al., 2016; Wen et al., 2008; Zhu et al., 2011). The 65−40 Ma magmatic flare-up event is generally attributed to the rollback and break-off of the Neo-Tethyan oceanic slab after the India-Asian collision (Ji et al., 2009; Lee et al., 2012; Wen et al., 2008; Zhu et al., 2015). Most Triassic−Cretaceous arc magmatic rocks have positive $\varepsilon_{Nd}(t)$ and $\varepsilon_{Hf}(t)$ values and low initial $^{87}Sr/^{86}Sr$ ratios, indicating that their magmas were derived from partial melting of the asthenospheric mantle or of juvenile crust under the Gangdese arc (Harris et al., 1988; Ji et al., 2009; Zhu et al., 2011). By contrast, the Paleogene-Eocene magmatic rocks show clearly negative excursion of $\varepsilon_{Nd}(t)$ and $\varepsilon_{Hf}(t)$ values, which was attributed to the involvement of the ancient Indian crust (Chu et al., 2011; Ji et al., 2009; Ma et al., 2014) or to the assimilation of the basement of the Lhasa terrane (Zhao et al., 2011; Zhu et al., 2017a). In addition, the magmatism during the Paleogene-Eocene flare-up shows significant geochemical variations in magma compositions, including calc-alkaline, low-K, shoshonitic, peraluminous, and adakitic-type rocks (Guo et al., 2011; Ji et al., 2017; Lee et al., 2012; Zhang et al., 2010a, 2013).

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

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

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

## 3. Results

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

## 3.1 Zircon U−Pb Ages

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

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

## 3.2 Whole-rock Major and trace element compositions

Whole-rock major and trace element data for the Confluence hornblende gabbros and Nyingchi granites are presented in Table S1. The Confluence hornblende gabbros have $SiO_2$ concentrations ranging from 44.85 *wt.* % to 53.06 *wt.*%. All gabbro samples are rich in $Na_2O$ with $K_2O/Na_2O$ of 0.43−0.84. Except for sample T1336, the other samples plot in the alkaline field on the total alkaline-silica (TAS) diagram (Fig. 3A; Middlemost, 1994). All gabbro samples fall in the high-K calc-alkaline to shoshonitic fields on the $K_2O$−$SiO_2$ diagram (Fig. 3B; Peccerillo and Taylor, 1976). Their MgO (3.25−6.38 *wt.*%) and Mg# (43−54) are rather low compared with mantle-derived primary magmas, with corresponding low Cr (1.24−49.8 ppm) and Ni (1.27−12.7 ppm), and high concentrations of strongly incompatible trace elements (e.g., Rb =12.1−67.6 ppm, Th = 0.43−7.08 ppm). The MgO, $TFe_2O_3$ (total iron as $Fe_2O_3$), Cr and Ni contents and $(Gd/Yb)_N$ decrease as $SiO_2$ increases from ca. 44 *wt.*% to ca. 48 *wt.*%, but slightly increase for $SiO_2$ higher than 48 *wt.*% (Fig. 4). The $Al_2O_3$, $P_2O_5$ and Sr concentrations increase with $SiO_2$ contents between from ca. 44 *wt.*% to ca. 48 *wt.*%, but decrease profoundly for $SiO_2$ contents higher than 48 *wt.*% (Fig. 4). The CaO concentration is characterized by an initial steep decrease followed by a modest decrease as $SiO_2$ increases from ca. 44 *wt.*% to ca. 54 *wt.*% (Fig. 4). The Confluence hornblende gabbros exhibit fractionated rare earth element (REE) patterns [$(La/Yb)_N$ = 3.7−9.7] and weak negative Eu anomalies with Eu/Eu* = 0.76−0.93 (Fig. 5A). Their primitive mantle-normalized trace element distribution patterns are characterized by positive anomalies in Rb, K, Th, U and Pb, but negative anomalies in Nb, Ta, P, Zr, Hf and Ti (Fig. 5B).

The Nyingchi granites show a relatively narrow range in many major element concentrations (Fig. 4), with high $SiO_2$ (70.74–75.86 *wt*.%), $Al_2O_3$ (12.93–15.7 *wt*.%), and CaO (2.01–3.74 *wt*.%), but low $Fe_2O_3$ (0.94–2.91 *wt*.%) and MgO (0.29–0.88 *wt*.%). All samples plotted in the subalkaline granite field on the TAS diagram (Fig. 3A). They have variable $K_2O$ of 1.06–5.15 *wt*.% and plot in the low-K, calc-alkaline, and shoshonitic fields on the $K_2O$–$SiO_2$ diagram (Fig. 3B), with $K_2O/Na_2O$ ratios of 0.26–1.11 (Table S1). They are weakly peraluminous with A/CNK values of 1.03–1.07 (Table S1). The Nyingchi granites are characterized by strongly enrichment of LREEs relative to HREEs on the chondrite-normalized REE diagram (Fig. 5C), with high $(La/Yb)_N$ (38–153) and $(Dy/Yb)_N$ ratios (2.0–6.1), and negative to positive Eu anomalies (Eu/Eu* = 0.48–1.57). The Nyingchi granites have high Sr (522–638 ppm), low Y (5.25–12.5 ppm) and Yb (0.30–0.74 ppm), and thus high Sr/Y ratios (48–121). All Nyingchi granite samples plot in the adakite fields of Sr/Y–Y and $(La/Yb)_N$–$(Yb)_N$ diagrams (Fig. 6A and 6B; Defant and Drummond, 1990; Drummond and Defant, 1990). They define a positive correlation between $(La/Yb)_N$ and $(Dy/Yb)_N$ (Fig. 6C). Most Nyingchi granite samples have high Nb/Ta ratios relative to the bulk continental crust and lower crust (Fig. 6D). For the trace-element spider diagram, Nyingchi granites exhibit enrichment of Th, K, Pb, and Sr, and depletion in Nb, Ta, Zr, Hf and Ti relative to their neighboring elements (Fig. 5D).

### 3.3 Sr–Nd–Hf–Pb isotopic compositions

Whole-rock Sr–Nd isotopic data for the Confluence hornblende gabbros and Nyingchi granites are reported in Table S1 and illustrated in Fig. 7. Initial isotopic compositions were calculated at 50 Ma for all studied samples. The Confluence gabbros record a narrow range of values for both initial $^{87}$Sr/$^{87}$Sr (0.705650−0.706074) and $^{147}$Nd/$^{144}$Nd (0.512404−0.512468) (Fig. 7), corresponding to $\varepsilon_{Nd}$(t) values of -3.3 to -2.1. The Nyingchi granites provide a moderate range of initial $^{87}$Sr/$^{87}$Sr (0.707054−0.708162) and $^{147}$Nd/$^{144}$Nd (0.512232−0.512327) (Fig. 7), corresponding to $\varepsilon_{Nd}$(t) values of -6.7 to -4.8.

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

Fresh plagioclase from the Confluence gabbros and K-feldspar from the Nyingchi granites were selected for *in situ* Pb isotope analyses. The results are listed in the supplementary Table S4 and illustrated in Fig. 9. The plagioclase from the Confluence gabbro samples T1332, T1334, T1336, and T1339 yield the following ranges of values: $^{206}$Pb/$^{204}$Pb = 18.524−18.750, $^{207}$Pb/$^{204}$Pb = 15.499−15.685, $^{208}$Pb/$^{204}$Pb = 38.529−39.015, $^{207}$Pb/$^{206}$Pb = 0.834−0.840 and $^{208}$Pb/$^{206}$Pb = 2.076−2.086 (Table S4; Fig. 9). By contrast, the K-feldspar from the Nyingchi granites generally have lower $^{206}$Pb/$^{204}$Pb = 18.307−18.643, $^{207}$Pb/$^{204}$Pb = 15.378−15.618, $^{208}$Pb/$^{204}$Pb = 38.246−38.821 and higher $^{207}$Pb/$^{206}$Pb = 0.838−0.842, $^{208}$Pb/$^{206}$Pb =2.082−2.092 than those of the Confluence gabbros (Table S4; Fig. 9). To constrain the magma sources of the Nyingchi granites and the Confluence gabbros, the plagioclase from the mafic granulite samples (16GT022 and 16GT023) in the lower crust section of the eastern Gangdese belt (Guo et al., 2013) were also selected for *in situ* Pb isotope analyses. The plagioclases from the granulites have lower $^{206}Pb/^{204}Pb$ = 18.355−18.470, $^{207}Pb/^{204}Pb$ = 15.511−15.736, and $^{208}Pb/^{204}Pb$ = 38.309−38.605, and higher $^{207}Pb/^{206}Pb$ = 0.842−0.855 and $^{208}Pb/^{206}Pb$ = 2.085−2.102 compared with those of the Nyingchi granites and the Confluence gabbros (Table S4; Fig. 9).

## 4. Discussion

### 4.1 Origin of the Eocene Nyingchi high Sr/Y granites

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

High Sr/Y magmatic rocks may be generated by partial melting of subducted oceanic or continental crust (e.g., Defant and Drummond, 1990; Wang et al., 2008b), partial melting of thickened or delaminated lower continental crust (e.g., Atherton and Petford, 1993; Chung et al., 2003; Kay and Kay, 1993; Xu et al., 2002), fractional crystallization from parental basaltic magmas with or without crustal assimilation (e.g., Castillo, 2012; Macpherson et al., 2006), and by magma mixing (e.g., Guo et al., 2007). The low Mg# values (38−42), Cr (0.46−6.49 ppm) and Ni (1.91−4.11 ppm) abundances of the Nyingchi granites are distinct from the adakitic rocks derived from partial melting of subducted oceanic crust and delaminated lower crust, which generally have high Mg#, Cr and Ni concentrations due to melt-peridotite interactions during the melt ascent through the mantle (Defant and Drummond, 1990; Wang et al., 2008b; Xu et al., 2002). The Nyingchi granites are unlikely to have been directly derived from fractional crystallization of the coeval Confluence mafic magma because of the different Sr−Nd−Pb−Hf isotopic compositions (Fig. 7−9). Furthermore, no correlations between Sr/Y, $(Dy/Yb)_N$ ratios and $SiO_2$ has been observed (Fig. 6E and 6F). The petrogenetic model of magma mixing can be ruled out because the Nyingchi granites have high $SiO_2$ concentrations (70.74−75.86 *wt*.%) and lack field and petrographic evidence of magma mixing.

The Nyingchi high Sr/Y granites have high initial $^{87}Sr/^{86}Sr$ ratios (0.70705−0.70816) and negative $\varepsilon_{Nd}(t)$ (−6.7 to −4.8) and $\varepsilon_{Hf}(t)$ values (-11.8 to -10.1), which are similar to those of the thickened lower crust-derived high Sr/Y rocks in the collisional orogens (e.g., Liu et al., 2010; Wang et al., 2005). However, the eastern Gangdese belt is likely to have a juvenile lower crust prior to the India-Asian collision as inferred from the following: (1) the Triassic−Cretaceous Gangdese arc magmatic rocks, including the Late Cretaceous lower crust-derived adakitic rocks (Wen et al., 2008), have depleted Sr−Nd−Hf isotopic compositions (Harris et al., 1988; Ji et al., 2009; Zhu et al., 2011) (Fig. 7 and 8); (2) Late Cretaceous mafic granulites and ultramafic-mafic cumulates from the exposed Gangdese arc lower crust also display depleted Sr−Nd−Hf isotopic compositions (Fig. 8; Guo et al., 2013; Ma et al., 2013a; Zhang et al., 2014). Because of the juvenile nature of this lower crust, the enriched isotopic geochemistry of the Nyingchi granites indicates that they could not be directly derived from partial melting of the lower crust. Ancient crustal components are required to contribute to the magma sources following the India-Asian collision. Previous studies show that the Eocene high Sr/Y granites in the central Gangdese belt resulted from partial melting of the thickened lower crust (Chu et al., 2011; Guan et al., 2012; Ma et al., 2014; Zhu et al., 2017b), and that ancient Indian crustal materials were involvement into their magma sources after India-Asian collision (Chu et al., 2011; Ma et al., 2014).

The potential isotopically enriched sources for the Nyingchi granites include the subducted Indian continental crust and ancient crustal materials from the Nyingchi Complex in the eastern Gangdese belt. In the eastern Himalayan syntaxis area, the Zhibai and Duoxiongla gneisses and migmatites from the Greater Himalayan Sequence which represent the subducted Indian continental crust have extremely high initial $^{87}Sr/^{86}Sr$ ratios (0.74524−0.98165 at 50 Ma) and negative $\varepsilon_{Nd}$(50 Ma) (−19.8 to −10.0) and $\varepsilon_{Hf}$(50 Ma) (−42 to −27) values (Fig. 7; Guo et al., 2017; Zhang et al., 2010a), which preclude an origin directly from subducted Indian crust for the Nyingchi granites. The results of isotopic mixing models between the Indian crustal materials and juvenile lower crust of the Gangdese belt also cannot account for the Sr−Nd isotopic compositions of the Nyingchi granites (Fig. 7). By contrast, mixing of 20-35% ancient gneisses from the Nyingchi Complex (Zhang et al., 2015) with 65-80% depleted mafic lower crust of the Gangdese belt can generate the isotopic features of the Nyingchi granites (Fig. 7). Pb isotopes are sensitive indicators of involvement of ancient crustal materials because of the shorter half-life of $^{238}$U, $^{235}$U, and $^{232}$Th isotopes compared with those of $^{147}$Sm and $^{87}$Rb isotopes. The Pb isotopic compositions suggest that the Nyingchi granites were derived from melting of both the Gangdese and Indian continental crustal materials (Fig. 9). The reason why the Sr and Nd isotopes are ineffective to identify the Indian crustal materials is probably that the involvement of the Indian crustal materials is limited to change the Pb isotopic compositions but to change the Sr-Nd isotopic compositions. Therefore, we propose that the high Sr/Y Nyingchi granites were generated by the introduction of the Nyingchi gneisses from the overlying Gangdese crust through tectonic erosion and the subducted Indian continental crust. Both the ancient Indian crustal materials and the Gangdese crustal materials were carried into the subduction channel. The mixed crustal materials were transported to the lower crust or mantle depths in the channel and partially melted under eclogite-facies conditions. The melts could have risen through buoyancy and either relaminated the lower crust or intruded the upper Gangdese arc crust to form the Nyingchi high Sr/Y granites.

## 4.2 Petrogenesis of the Confluence hornblende gabbros

### 4.2.1 Evaluation of crustal contamination and fractionation

The ca. 50 Ma Confluence hornblende gabbros display arc-like trace element patterns (Fig. 5B). In addition, their enriched Sr−Nd−Hf−Pb isotopic compositions are different from those of the mafic arc magmatism in the eastern Gangdese belt (Fig. 7−9; Ma et al., 2013a). These geochemical signatures could result from (1) crustal assimilation during magma ascent and/or magma chamber processes, (2) partial melting of lithospheric mantle metasomatized by enriched crustal materials, or (3) a combination of both processes. The relatively limited range of whole-rock Sr−Nd and zircon Hf isotopic compositions (Fig. 7 and 8) and absence of correlations for the studied samples in the diagrams of $(^{87}Sr/^{86}Sr)_i$ versus $SiO_2$ or $(^{147}Nd/^{144}Nd)_i$ versus $SiO_2$ (not shown) indicate that crustal assimilation did not play a significant role during magma evolution of the Confluence gabbros. Therefore, these geochemical signatures of the Confluence gabbros would have been inherited from their mantle sources without significant crustal assimilation.

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

#### 4.2.2 Mantle source and enrichment processes

Due to the evolved geochemical composition of the Confluence gabbros, neither the degree of mantle melting, nor the composition of primary mantle melts could not be precisely evaluated. Nevertheless, the low La/Yb (5.4−13.1) and Dy/Yb (1.8−2.3) ratios of the gabbros suggest that their primary melts were not in equilibrium with garnet and formed at a relatively shallow level of the mantle in the spinel peridotite stability field. The Confluence hornblende gabbros have high $K_2O$ and LILE contents, indicating that they were derived from partial melting of a $K_2O$, LILE and $H_2O$-rich mantle. Phlogopite and amphibole are the main $K_2O$ and $H_2O$ phase in the mantle. In the $K_2O/MgO$ versus $CaO/Al_2O_3$ diagram (Fig. 10A), most hornblende gabbro samples match the major element composition of experimental melts of phlogopite- and/or amphibole-bearing spinel peridotite and mixed peridotite + felsic granitoid sources (Couzinié et al., 2016, and references therein). This suggests that the primary melts were derived from partial melting of a phlogopite- and/or amphibole-bearing spinel peridotite or of a spinel mantle peridotite metasomatized by felsic granitic melts.

While the Jurassic−Cretaceous mafic arc magmatic rocks in the eastern Gangdese belt have depleted Sr−Nd−Pb−Hf isotopic composition (Gariépy et al., 1985; Harris et al., 1988; Ji et al., 2009; Zhu et al., 2008, 2011), the Eocene Confluence gabbros display enriched Sr−Nd−Pb−Hf isotopic characteristics (Fig. 7−9). This indicates that the lithospheric mantle was metasomatized by ancient crustal materials shortly after the India-Asian collision. The Sr−Nd−Pb isotopic compositions of the Confluence gabbros are in a similar situation to those of the Nyingchi granites. A simple modeling for source contamination indicates that mixing the depleted upper mantle peridotite with about 15-20% of the ancient crustal materials (the Nyingchi gneisses) from the eastern Gangdese belt can explain the present Sr−Nd isotopic features of the gabbros (Fig. 7). However, the incorporation of material from the Nyingchi gneisses into the mantle beneath the Gangdese arc cannot account for the Pb isotopic composition of these gabbros (Fig. 9). The Confluence gabbros have lower $^{207}$Pb/$^{206}$Pb and $^{208}$Pb/$^{206}$Pb ratios than those of the Gangdese batholith, the lower crust of the Gangdese arc, the Lhasa basement and the Eocene Nyingchi high Sr/Y granites (Fig. 9). This requires an involvement of Indian crustal materials which have low $^{207}$Pb/$^{206}$Pb and $^{208}$Pb/$^{206}$Pb ratios (Fig. 9; Gariépy et al., 1985). Therefore, we suggest that the crustal components in the mantle source results from influx of felsic melts from melting of the Indian plate together with components from partial melting of the eroded crustal materials from the Gangdese belt (Fig. 11). This metasomatized mantle region provides a ready source for potassic magma during the late stages of lithosphere convergence related to extension and mantle upwelling (Castro, 2014). The composition of the bulk continental crust (Rudnick and Gao, 2003) is taken to represent the felsic melts because both upper and lower crust materials were involved in the subduction channel through tectonic erosion and continental subduction (Fig. 11B). The modeling results show that the melts can be generated from 15−25% partial melting of a hybrid source consisting of 75−90% depleted mantle and 10−25% of the felsic component (Fig. 10B), which is consistent with the result of the binary Sr−Nd isotopic mixing model (Fig. 7).

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

### 4.3 Tectonic erosion during the India-Asian continental collision

As stated above, the magma sources of the ca. 50 Ma Nyingchi high Sr/Y granites involved significant ancient crustal materials from the Nyingchi Complex which predominantly is composed of metagranitoids and metasedimentary rocks. However, these ancient crustal materials were not subject to high-grade metamorphism until the India-Asian continental collision (Dong et al., 2012; Guo et al., 2011, 2012, 2017; Wang et al., 2008a; Zhang et al., 2010b, 2013, 2015). The metagranitoids have protolith ages ranging from Paleoproterozoic (ca. 1782 Ma), Cambrian (ca. 496 Ma), Mesozoic (165-83 Ma) to Cenozoic (65-38 Ma) (Dong et al., 2012; Guo et al., 2012; Lin et al., 2013; Zhang et al., 2013, 2015). The protoliths of Mesozoic-Cenozoic metagranitoids resulted from the subduction of Neo-Tethyan oceanic slab or from the collision of India-Asian continents (Guo et al., 2012; Zhang et al., 2013, 2015). The protoliths of the metasedimentary rocks from the Nyingchi complex include Neoproterozoic, Late Paleozoic, Mesozoic, and Cenozoic sedimentary rocks (Guo et al., 2011, 2017; Xu et al., 2013; Zhang et al., 2008). Inherited detrital zircon from the Mesozoic-Cenozoic metasedimentary rocks yielded age peaks at 95-60 Ma and 171-138 Ma (Xu et al., 2013; Zhang et al., 2008, 2015), which is consistent with the age spectra of the Gangdese arc magmatic rocks, indicating that their protoliths were probably deposited in the forearc basin. The felsic metamorphic rocks from the Nyingchi Complex underwent granulite-facies metamorphism and protracted crustal anatexis from 63 Ma to 41 Ma, and amphibolite-facies metamorphism from 35 Ma to 23 Ma (Dong et al., 2012; Guo et al., 2011, 2012; Lin et al., 2013; Wang et al., 2008b; Xu et al., 2013; Zhang et al., 2013, 2015). Their metamorphic ages are close to their protolith ages, indicating that these supracrustal rocks underwent rapidly burial and metamorphism after the Indian-Asian collision. In addition, the existence of abundant Early Cenozoic inherited zircons in the Oligocene high Sr/Y granites indicates significant reworking of the Gangdese crust (Ding and Zhang, 2019; Zhang et al., 2008; Zheng et al., 2012).

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

After the closure of Neo-Tethys Ocean, material from the leading edge of the Indian continent was dragged into the subduction channel. The buoyant continental crust probably enhanced the mechanical coupling between the subducted and overlying continents, inducing pervasive abrasion of the overriding plate (Fig. 11). Arc magmatic fronts commonly form 200−250 km inboard of the trench axis (Scholl and von Huene, 2010). The direct contact between the Gangdese batholith and Indian continent requires the removal of the former forearc in the eastern Gangdese belt since India-Asian collision at ca. 60 Ma. (Fig. 1). If we assume that the former Gangdese forearc was similar to the modern Andean forearc in its dimensions and geometry, the width of forearc was 200−250 km just prior to the India-Asian collision (Fig. 11A). An average crustal thickness of 45 km is used to estimate the rate of long-term loss of crustal materials from the upper plate (Clift and Vannucchi, 2004). If the loss of forearc is ascribed entirely to tectonic erosion, the calculated long-term erosion rates are 150−188 $km^3$/km/my, which is higher than those observed in most modern ocean-margin subduction zones (30−115 $km^3$/km/my) (Clift and Vannucchi, 2004; Scholl and von Huene, 2007, 2009; Stern, 2011). Our result suggests that significant crustal loss by tectonic erosion occurred during the continental collision.

### 4.4 Crustal relamination and its implications

During continental collision, felsic crustal materials derived from both the subducted plate (by anatexis) and from the upper plate (by tectonic erosion) can be relaminated to the base of the upper plate and eventually form a part of the upper plate, whereas the mafic crustal materials are recycled into the mantle (Hacker et al., 2011, 2015; Maierova et al., 2018). These crustal materials can be carried into lower crust or mantle and undergo partial melting to produce adakitic melts (Stern, 2011). Some felsic melts could react with the overlying wedge peridotite and serve as metasomatic agents for crust-mantle interaction in the continental subduction channel (Stern, 2011; Willbold and Stracke, 2010). Our study shows that the Eocene Nyingchi high Sr/Y granites in the eastern Gangdese belt were derived from partial melting of relaminated crustal materials, and the Eocene Confluence gabbro was sourced from lithospheric mantle metasomatized by relaminated crustal melts (Fig. 11B). The Cretaceous lower crust of the Gangdese arc was dominated by mafic granulite and ultramafic/mafic cumulates (Guo et al., 2013; Ma et al., 2013b; Zhang et al., 2010b, 2014). By contrast, the substantial occurrence of felsic granulite-/amphibolite-facies metamorphic rocks in the lower crustal section of the Gangdese arc (Dong et al., 2012; Guo et al., 2012, 2017; Xu et al., 2013; Zhang et al., 2010b, 2015) further indicates that substantial amounts of felsic crustal materials were relaminated to the base of the upper plate during the India-Asian collision. In addition, the whole-rock $\varepsilon_{Nd}(t)$ and zircon $\varepsilon_{Hf}(t)$ values of the magmatic rocks exhibit clearly negative excursions (Fig. 7 and 8) during the Eocene (ca. 50 Ma) magmatic flare-up event in the Gangdese belt (Chu et al., 2011; Ji et al., 2009; Ma et al., 2014). We propose that these negative excursions result from relamination of ancient crustal materials removed from the Gangdese belt by tectonic erosion and from subducted Indian continental crust. As a result, crustal relamination rejuvenated the supply of melt-fertile lithosphere and ignited the Eocene flare-up event (Ducea and Barton, 2007; Ducea et al., 2015). The substantial addition of felsic rocks into the lower crust probably shifted the lower crust composition of the Gangdese arc from basaltic to andesitic. Our study demonstrates that crustal relamination plays an important role in refinement of the continental crust composition (Castro et al., 2013; Hacker et al., 2011, 2015; Kelemen and Behn, 2016;

Vogt et al., 2013).

## 5. Conclusions

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

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