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Two Types of mafic rocks in southern Tibet: A mark of tectonic setting change from Neo-Tethyan oceanic crust subduction to Indian continental crust subduction

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ABSTRACT

We collated existing data for the Eocene Langshan mafic rocks (Eocene mafic rocks) and the Miocene potassic–ultrapotassic mafic rocks (Miocene mafic rocks) in southern Tibet to investigate the tectonic transition from Neo-Tethyan oceanic crust subduction to Indian continental crust subduction. The Eocene mafic rocks have high Na_2O contents (K_2O/Na_2O = 0.03–0.2) and show OIB-like trace element patterns (e.g., positive Nb and Ta anomalies) and depleted radiogenic Sr–Nd isotope compositions ($^{87}Sr/^{86}Sr$ of apatite = 0.7031, $\varepsilon Nd_{(t)}$ = +5.1 to +6.1). In contrast, the Miocene mafic rocks have high K_2O contents (K_2O/Na_2O = 1.9–8.5) and exhibit arc-like trace element patterns (enrichment in LILEs and depletion in HFSEs) and enriched radiogenic Sr–Nd isotope compositions ($^{87}Sr/^{86}Sr$ = 0.7115–0.7362, $\varepsilon Nd_{(t)}$ = −16 to −12.4). The mantle source for the Eocene mafic rocks was generated by reactions between asthenospheric mantle wedge and felsic melts from subducted Neo-Tethyan oceanic crust (outside the field of rutile stability). In contrast, the mantle source of the Miocene mafic rocks was generated by reactions between asthenospheric (or lithospheric) mantle wedge and felsic melts from subducted Indian continental crust. Taking into account the regional tectonic evolution, we propose that break-off of the Neo-Tethyan oceanic slab and roll-back and/or break-off of the Indian continental slab were the most likely geodynamic mechanisms that led to the production of the Eocene and Miocene mafic rocks, respectively. Therefore, the transition from the Eocene to Miocene mafic rocks in southern Tibet provides an opportunity to understand the tectonic transition from Neo-Tethyan oceanic to Indian continental crust subduction.

1. Introduction

The subduction of continental crust in continental collisional orogens follows the subduction of oceanic crust to mantle depths, closure of the oceanic basin, and eventual continent–continent collision (e.g., Ernst, 2005; Castro et al., 2013; Gerya, 2014; Dash et al., 2015). These sequential processes are significant not only for high-pressure (HP) to ultrahigh-pressure (UHP) metamorphism of subducted crustal rocks (e.g., Chopin, 2003; Ernst and Liou, 2008; Zheng et al., 2012) but also for the recycling of crustal materials into the deep mantle (e.g., Zindler and Hart, 1986; Willbold and Stracke, 2010; Zheng, 2012; Zhao et al., 2013). In an orogen formed by continent–continent collision, the subduction of oceanic crust would have predated the subduction of continental crust, and because oceanic crust subjected to eclogite-facies metamorphism has a high density, it can pull the continental crust into the mantle where it experiences UHP metamorphism (Forsyth and Uyeda, 1975). Thus, in this scenario, both oceanic and continental crustal materials would be recycled into the mantle during continent–continent collision. It is assumed that oceanic crust undergoes metamorphic dehydration during subduction and that aqueous fluids derived from the subducted oceanic crust alter the peridotite of the overlying mantle wedge, thus generating the mantle source for oceanic arc basalts (e.g., Kelemen et al., 2003; Schmidt and Poli, 2003; Spandler and Pirard, 2013). In this process, the residual oceanic crust is subducted farther into the deep mantle to provide the mantle source for intraplate oceanic island basalts (OIBs), which are enriched in high-field-strength elements (e.g., Nb and Ta) and have depleted Sr–Nd isotopic values (Hofmann and White, 1982; Hofmann, 1997; Stracke et al., 2003; Chauvel et al., 2008). The subducted continental crust may become dehydrated and partially melted at depths of 80–130 km in a

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continental subduction zone (e.g., Zhang et al., 2008; Chen et al., 2013a, 2013b; Hermann et al., 2013). Thus, the fluids or melts derived from the subducted continental crust would also metasomatize the peridotite of the mantle wedge that overlies the continental slab (Zheng et al., 2012). An enriched mantle (ultramafic metasomatite), generated by reactions between mantle peridotite and the hydrous felsic melts derived from the partial melting of the deeply subducted continental crust, provides a likely source of the post-collisional potassic–ultrapotassic mafic rocks that are found in continent–continent collisional orogens, and these mafic rocks exhibit arc-like trace element patterns and enriched Sr–Nd isotope compositions (Prelević et al., 2008, 2013; Guo et al., 2013, 2015; Zhao et al., 2013, 2015). The existence of two types of crust–mantle interaction (i.e., oceanic crust–mantle and continental crust–mantle) during continent–continent collision means that the geochemical transition from OIB-like basalts to post-collisional potassic–ultrapotassic mafic rocks could provide a window into the processes involved during these two types of slab–mantle interaction.

The Tibetan Plateau is an ideal location to investigate processes associated with continent–continent collision (Allégre et al., 1984; Molnar et al., 1993). For example, southern Tibet records the subduction of Neo-Tethyan oceanic lithosphere, the subsequent collision of the Indian and Asian continents, and subduction of the India continental lithosphere (e.g., Chung et al., 2005). However, it is commonly difficult to identify the processes associated with the transition from the subduction of the Neo-Tethyan oceanic crust to the subduction of the Indian continent during the evolution of this orogen (Chung et al., 2005 and references therein). Recently, the Eocene (~45 Ma) Langshan mafic rocks (gabbros) have been discovered in the Gyangze region of southern Tibet and have been shown to have clear OIB-like characteristics (Ji et al., 2016). Unlike these OIB-like magmatic rocks, which are of limited extent in southern Tibet, the Miocene (23–8 Ma) post-collisional potassic–ultrapotassic mafic rocks are widely distributed within the Lhasa Block of southern Tibet (Turner et al., 1996; Miller et al., 1999; Ding et al., 2003; Williams et al., 2004; Zhao et al., 2009).

In this study, we collated existing data on the Langshan mafic rocks (gabbros) (herein, Eocene mafic rocks) and the Miocene (23–8 Ma) Xuruco Lake–Dangre Yongcuo Lake (XDY) potassic–ultrapotassic mafic rocks (herein, Miocene mafic rocks) in southern Tibet to investigate (1) the mantle source of both group of rocks and (2) whether the transition from Eocene to Miocene mafic rocks records the tectonic evolution from subduction of Neo-Tethyan oceanic crust to subduction of Indian continental crust.

2. Geology of the study area

The Tibetan Plateau comprises the Songpan–Gangzi, Qiangtang, Lhasa, and Himalaya blocks from north to south. The Lhasa block is bounded by the Bangong–Nujiang suture zone (BNSZ) to the north and the Indus–Yarlung Zangbo suture zone (IYZSZ) to the south (Fig. 1a). The BNSZ formed from the Middle Jurassic to the Early Cretaceous (Yin and Harrison, 2000; Kapp et al., 2007; Zhu et al., 2011, 2013, 2016; Pan et al., 2012; Zhang et al., 2012; Fan et al., 2014) and the IYZSZ formed from the Late Cretaceous to the early Paleogene (Dewey et al., 1988; Klootwijk et al., 1992; Tapponnier et al., 2001; Leech et al., 2005; Royden et al., 2008; Najman et al., 2010; Ma et al., 2014; W. Huang et al., 2015). The Lhasa terrane has been subdivided into southern, central, and northern subterranes, separated by the Luobadui–Milashan Fault and Shiquan River–Nam Tso Mélange Zone (Fig. 1a; Zhu et al., 2011, 2013). The Himalaya block comprises three main units: the Tethyan Himalaya, the High Himalaya, and the Lesser Himalaya, separated by the South Tibet detachment system and the Main Central thrust (Fig. 1b; Yin and Harrison, 2000; Yin, 2006).

The Cenozoic magmatic rocks in southern Tibet (Lhasa and Himalaya blocks) consist mainly of the Linzizong volcanics, Miocene (18–12 Ma) adakites, post-collisional potassic–ultrapotassic mafic rocks (23–8 Ma), and Oligocene–Miocene (30–10 Ma) leucogranites along with minor middle Eocene (46–42 Ma) granites (Mo et al., 2007, 2008; Zhao et al., 2009; Guo et al., 2013; Wu et al., 2015; Liu et al., 2016). The studied Eocene mafic rocks are located in the northeast of Gyangze in the eastern Tethyan Himalaya. These rocks intrude the Late Cretaceous to early Tertiary Zongzhuo Formation, which consists mainly of sandstone, siltstone, and shale (Fig. 1c; Ji et al., 2016). The studied Miocene mafic rocks are located within the XDY rift, which contains lava flows, plugs, and dykes, forming a N–S-trending, 130-km-long, magmatic belt extending from the Garwa volcanic field in the north, through the Yaqian, Mibale, and Yiqian volcanic fields, to the Chazi volcanic field in the south (Fig. 1d; Guo et al., 2013).

3. Magma sources

The data used in this study for the Eocene mafic rocks were obtained from Ji et al. (2016), and the data for the Miocene mafic rocks were obtained from Liao et al. (2002), Ding et al. (2003, 2006), Gao et al. (2007), Zhao et al. (2009), Guo et al. (2013). To exclude crustal contamination and obvious fractional crystallization, we used only those samples with MgO > 6.5 wt%. Details regarding data selection are given in Supplementary text 1. The ages and geochemistry of the studied rocks are presented in Supplementary Table 1.

The Eocene mafic rocks (MgO = 7.2–10.4 wt%) have high Na_2O contents (Na_2O = 3.2–4.5 wt%; K_2O/Na_2O = 0.03–0.2, Fig. 2a and b). These rocks are enriched in LREEs with positive Nb–Ta anomalies (Fig. 3a and b) and have depleted Sr–Nd isotopic compositions ($^{87}Sr/^{86}Sr_{(i)}$ for apatite = 0.7031, $\varepsilon Nd_{(t)}$ = +5.1 to +6.1) (Fig. 4; Supplement Table 1), resembling OIB-like magmas. Previous researchers have proposed that the likely mantle sources of OIBs are lithospheric mantle with amphibole-bearing metasomatic veins, asthenospheric mantle, or a mantle plume (White and Hofmann, 1982; Hofmann, 1997; Niu and O'Hara, 2003; Pilet et al., 2008; Willbold and Stracke, 2010; Stracke, 2012). According to the model of recycled lithospheric mantle with amphibole-bearing metasomatic veins (Niu and O'Hara, 2003; Pilet et al., 2008), the high Nb–Ta values are inherited from Nb-rich minerals in the veins. Moreover, the Nb-rich minerals could also host Zr and Hf, thereby yielding positive Zr and Hf anomalies, which are not observed for the Eocene mafic rocks in a primitive-mantle-normalized incompatible-trace-element spidergram (Fig. 3b). The Rongniduo (central Lhasa subterrane) Paleocene (~64 Ma) pseudoleucite phonolitic rocks may represent metasomatized lithospheric mantle, but these rocks have more enriched Sr–Nd isotopic compositions ($^{87}Sr/^{86}Sr_{(i)}$ = 0.7064–0.7062; $\varepsilon Nd_{(t)}$ = −1.5 to +0.4; Qi et al., 2018) than the Eocene mafic rocks ($^{87}Sr/^{86}Sr_{(i)}$ of apatite = 0.7031, $\varepsilon Nd_{(t)}$ = +5.1 to +6.1, Fig. 4). Furthermore, the absence of a large igneous province (LIP) and the low calculated mantle potential temperature (Tp, 1400 °C; Ji et al., 2016) beneath southern Tibet argue against the presence of a mantle plume in the area. Thus, the lithospheric mantle and mantle plume models cannot explain the source of the Eocene mafic rocks.

It is probable, therefore, that the Eocene mafic rocks originated from the asthenospheric mantle. However, decompressional melting of normal asthenospheric mantle would have produced mid-ocean-ridge basalts (MORBs), which are characterized typically by depletion in melt-mobile incompatible trace elements such as LILEs and LREEs, and pertinent radiogenic isotopes (e.g., Salters and Stracke, 2004; Workman and Hart, 2005). In contrast, the Eocene mafic rocks are generally enriched in melt-mobile incompatible trace elements (e.g., LREEs), and they are not depleted in HFSEs (Fig. 3a and b). Such geochemical features are similar to those of OIBs but differ significantly from those of normal MORB. This difference indicates that normal asthenospheric mantle cannot have served directly as the source of the Eocene mafic rocks. Nevertheless, recycled oceanic crust, with or without sediments, is considered by many workers to be a probable end-member component in the mantle source of OIBs (e.g., White and Hofmann, 1982; Hofmann, 1997; Chauvel et al., 2008; Stracke, 2012). We suggest that

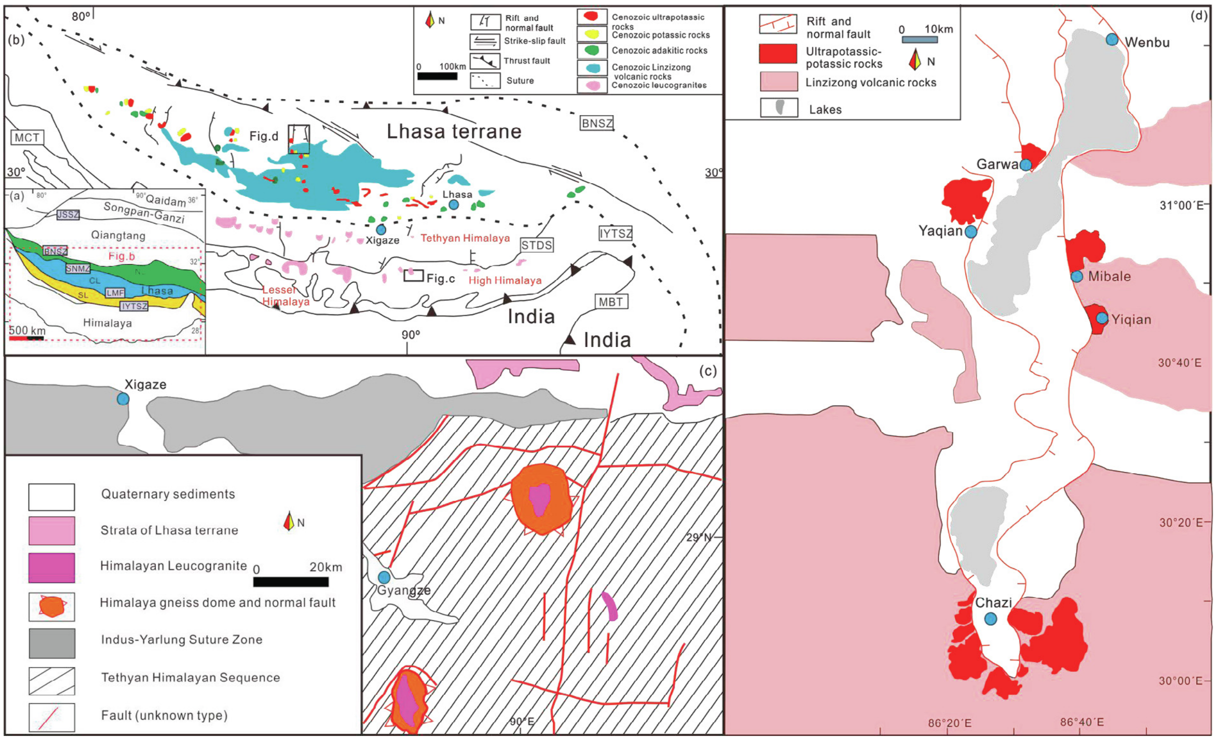

Fig. 1. (a) Tectonic outline of the Tibetan Plateau showing the study area (after Zhu et al., 2011). (b) Geological map of southern Tibet (after Chung et al., 2009), with Cenozoic magmatism after Ma et al. (2017a,b). JSSZ = Jinsha Suture Zone; BNSZ = Bangong–Nujiang Suture Zone; SNMZ = Shiquanhe–Nam Tso Mélange Zone; LMF = Luobadui–Milashan Fault; IYZSZ = Indus–Yarlung Zangbo Suture Zone. NL = Northern Lhasa subterrane; CL = Central Lhasa subterrane; SL = Southern Lhasa subterrane; MBT = Main Boundary Thrust; MCT = Main Central Thrust; STDS = South Tibet Detachment System. (c) Geological map of the Gyangze area, southern Tibet (after Ji et al., 2016). (d) Geological map showing the distribution of post-collisional potassic–ultrapotassic mafic rocks in the XDY rift region (after Guo et al., 2013).

the other component in the mantle source of the Eocene mafic rocks was oceanic crust, based on the following considerations. Firstly, the Eocene mafic rocks with high $(Ta/U)_N$ (1.4–1.7) and $(Nb/Th)_N$ (1.4–1.7) values indicate a contribution from subducted oceanic crust in their mantle source (Fig. 5a; Supplementary Table 1). As slab dehydration occurs during the subduction of oceanic crust, water-soluble elements (e.g., Th, U, Ba, Rb, Cs, and Sr) are supplied to the arc magmas, whereas HFSEs (i.e., Nb and Ta) remain in the residual oceanic crust (Porter and White, 2009). The involvement of such residual oceanic crust with $(Ta/U)_N > 1$ and $(Nb/Th)_N > 1$ in the mantle source can explain the excess Nb and Ta in both E-MORBs and OIBs (Niu and Batiza, 1997). Secondly, during the subduction of oceanic crust in the rutile stability field, the aqueous solutions that are first released from the subducted oceanic crust are commonly enriched in fluid-mobile incompatible trace elements such as LILEs, LREEs, and Pb, but depleted in Nb, Ta, and Ti. Fluid-fluxed mantle wedge peridotites are generated above the subducted slab, and their partial melting produces oceanic arc basalts (OABs) (Kelemen et al., 2003; Schmidt and Poli, 2003). Consequently, the OABs are characterized by arc-like trace element patterns, with low Nb/U and TiO_2/Al_2O_3 values relative to MORB. However, compared with OABs, the Eocene mafic rocks have high Nb/U (47–57) and TiO_2/Al_2O_3 (0.20–0.24) ratios, which indicate that their mantle source contained a contribution from recycled oceanic crust with the breakdown of rutile (Fig. 5b; Supplementary Table 1). Thirdly, on a primitive-mantle-normalized variation diagram (Fig. 3b), the Eocene mafic rocks have positive Nb and Ta anomalies and are depleted in strongly incompatible elements (Rb, Ba, Th, and U). The geochemical characteristics of the Eocene mafic rocks are consistent with those of HIMU-type OIBs, which are usually the product of a mantle source containing recycled dehydrated oceanic crust (e.g., Stracke et al., 2005). The Eocene mafic rocks have relatively depleted Sr–Nd isotopic compositions ($^{87}Sr/^{86}Sr_{(i)}$ of apatite = 0.7031, $\varepsilon Nd_{(t)}$ = +5.1 to +6.1), which requires the recycled oceanic crust in their mantle source to be relatively young. The Eocene mafic rocks are located close to the IYZSZ (Fig. 1c), which marks the closure of the Neo-Tethys (e.g., Yin and Harrison, 2000). Therefore, the recycled component that was involved in the mantle source of the Eocene mafic rocks was probably the subducted Neo-Tethyan oceanic crust. We therefore propose that the mantle source of the Eocene mafic rocks was asthenospheric mantle wedge peridotite with recycled Neo-Tethyan oceanic crust.

The Miocene mafic rocks have high MgO (6.6–10.8 wt%) and K_2O (4.5–9.9 wt%; K_2O/Na_2O = 1.9–8.5) values (Fig. 2a and b; Supplementary Table 1). These rocks are highly enriched in LREEs and LILEs, significant depleted in Nb and Ta (Fig. 3a and b), and have extremely enriched Sr–Nd isotopic compositions ($^{87}Sr/^{86}Sr_{(i)}$ = 0.7115–0.7362, $\varepsilon Nd_{(t)}$ = −16 to −12.4) (Fig. 4; Supplementary Table 1). The arc-like trace element patterns and enriched Sr–Nd isotope compositions of these potassic–ultrapotassic mafic rocks indicate that they originated from an enriched mantle source, and the enrichment has been explained as either due to (1) an ancient (Mesoproterozoic) metasomatic event (Turner et al.,1996; Miller et al., 1999; Williams et al., 2004), or (2) source contamination during the more recent subduction of Neo-Tethyan oceanic crust or Indian continental crust (e.g., Ding et al., 2003; Gao et al., 2007; Guo et al., 2013). With regard to the first possibility, the inference of an ancient mantle source is based mainly on the Proterozoic Nd (0.9–1.3 Ga) and older Pb (2.2–3.5 Ga) model ages for the potassic–ultrapotassic mafic rocks (e.g., Turner et al., 1996; Miller et al., 1999; Williams et al., 2004). However, an ancient enriched mantle remained chemically isolated and physically intact beneath Tibet throughout the Phanerozoic, and it is unlikely to have been involved in the complex Phanerozoic tectonic and magmatic evolution of Tibet (e.g., Ding et al., 2003). With regard to the second possibility, Prelević et al. (2008) collated isotopic data for post-collisional mafic

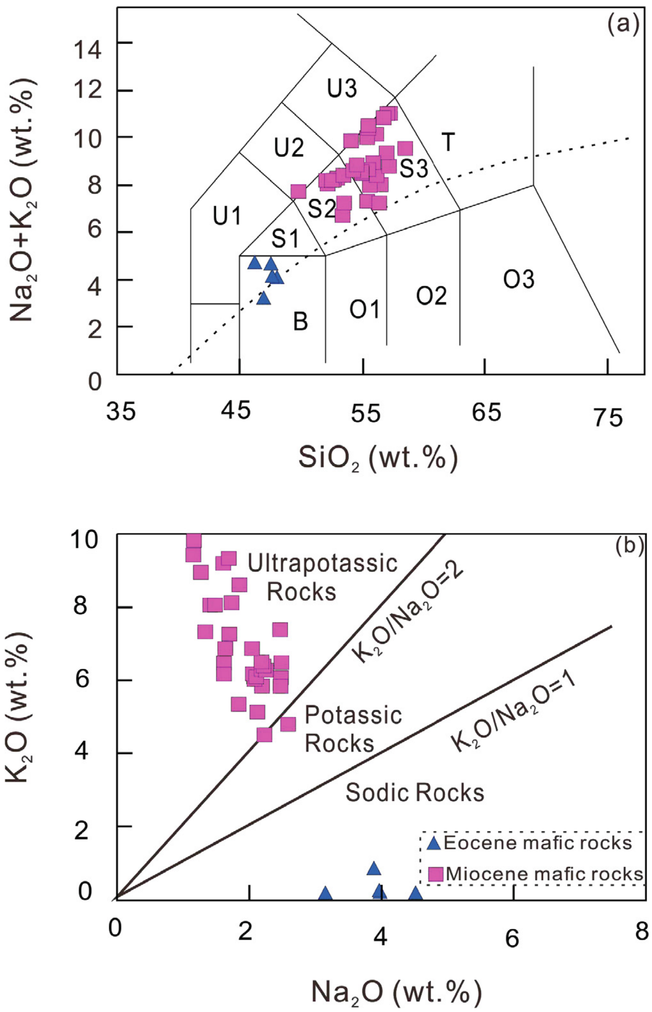

Fig. 2. (a) $Na_2O + K_2O$ (wt.%) versus SiO_2 (wt.%) diagram for the Eocene and Miocene mafic rocks; classification boundaries are from Le Bas et al. (1986). Rock types are as follows: B, basalt; S1, trachybasalt; S2, basaltic trachyandesite; S3, trachyandesite; T, trachyte; U1, tephrite; U2, phonotephrite; U3, tephriphonolite; O1, basaltic andesite; O2, andesite; and O3, dacite. (b) K_2O (wt.%) versus Na_2O (wt.%) diagram for the Eocene and Miocene mafic rocks. The classification of ultrapotassic, potassic, and sodic rocks in K_2O/Na_2O compositional space follows Foley et al. (1987). The data for the Eocene mafic rocks are from Ji et al. (2016); data for the Miocene mafic rocks are from Liao et al. (2002), Ding et al. (2003, 2006), Gao et al. (2007), Zhao et al. (2009), and Guo et al. (2013).

lavas in the Mediterranean area and the Alpine–Himalayan belt and suggested that the enriched isotope signatures in the mantle source were due to the involvement of recent subducted sediments rather than an ancient enriched mantle. We therefore favor the second possibility that the mantle source of the Miocene mafic rocks was enriched during the recent subduction events.

However, it has been argued that prior to enrichment, the mantle source of the Miocene mafic rocks was either asthenospheric (Gao et al., 2007; Guo et al., 2013, 2015; Cheng and Guo, 2017; Hao et al., 2018) or lithospheric mantle (Ding et al., 2003; Zhao et al., 2009; Liu et al., 2014, 2015; Huang et al., 2015). Unfortunately, no mantle xenoliths were brought to the surface by the lavas during the Neo-Tethyan oceanic subduction, so the evolution of the lithospheric mantle beneath southern Tibet remains enigmatic. As the lithospheric mantle wedge beneath southern Tibet, represented by the 94 Ma Zhengga gabbros, had already been enriched during the Neo-Tethyan oceanic subduction but retained depleted isotopic values ($^{87}Sr/^{86}Sr_{(i)}$ = 0.7043–0.7048, $\varepsilon Nd_{(t)}$ = +1.7 to +4.1, $\varepsilon Hf_{(t)}$ = +6.5 to +11.1; Fig. 4; Ma et al.,

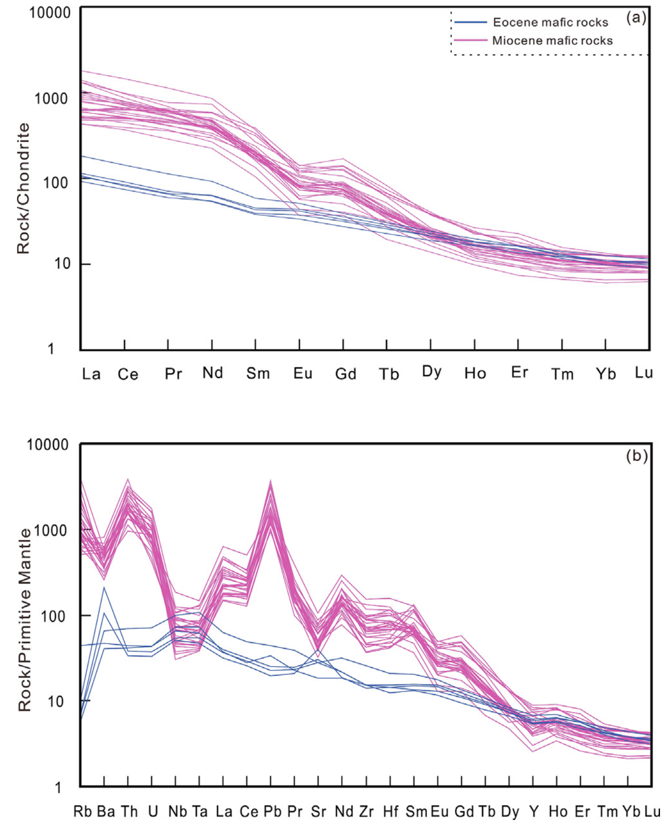

Fig. 3. (a) Chondrite-normalized REE patterns, and (b) primitive-mantle-normalized incompatible element diagrams for the Eocene and Miocene mafic rocks. Normalizing values are from Sun and McDonough (1989). Data sources are as for Fig. 2.

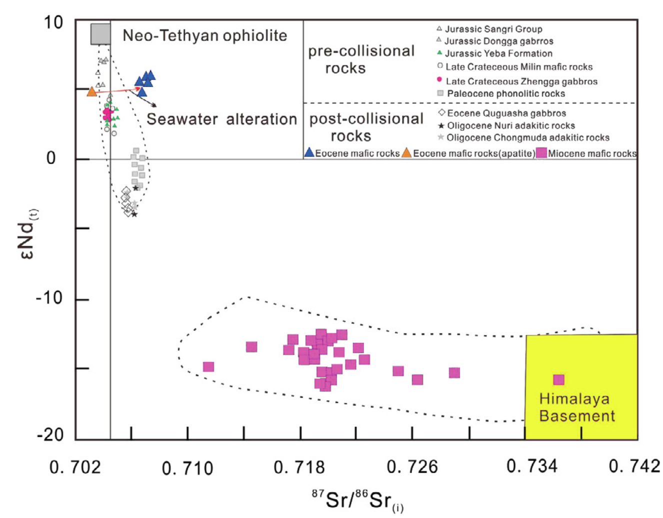

Fig. 4. $\varepsilon Nd_{(t)}$ versus $^{87}Sr/^{86}Sr_{(i)}$ diagram for the Eocene and Miocene mafic rocks. Data sources are as follows: Jurassic Yeba Formation, Zhu et al. (2008); Jurassic Sangri Group, Kang et al. (2014); Jurassic Dongga gabbros, Wang et al. (2017); Late Cretaceous Zhengga gabbros, Ma et al. (2013a); Late Cretaceous Milin mafic rocks, Ma et al. (2013b); Paleocene phonolitic rocks, Qi et al. (2018); Eocene Quguasha gabbros, Ma et al. (2017a); Oligocene Chongmuda adakitic rocks, Jiang et al. (2014); Oligocene Nuri adakitic rocks, Chen et al. (2015); Himalaya basement, Richards et al. (2005); and Neo-Tethyan ophiolite, Qiu et al. (2007). Data sources are as for Fig. 2.

2013a), it is difficult, and beyond the aim of this paper, to identify whether the mantle source of the Miocene mafic rocks, prior to enrichment, was asthenospheric or lithospheric mantle wedge beneath

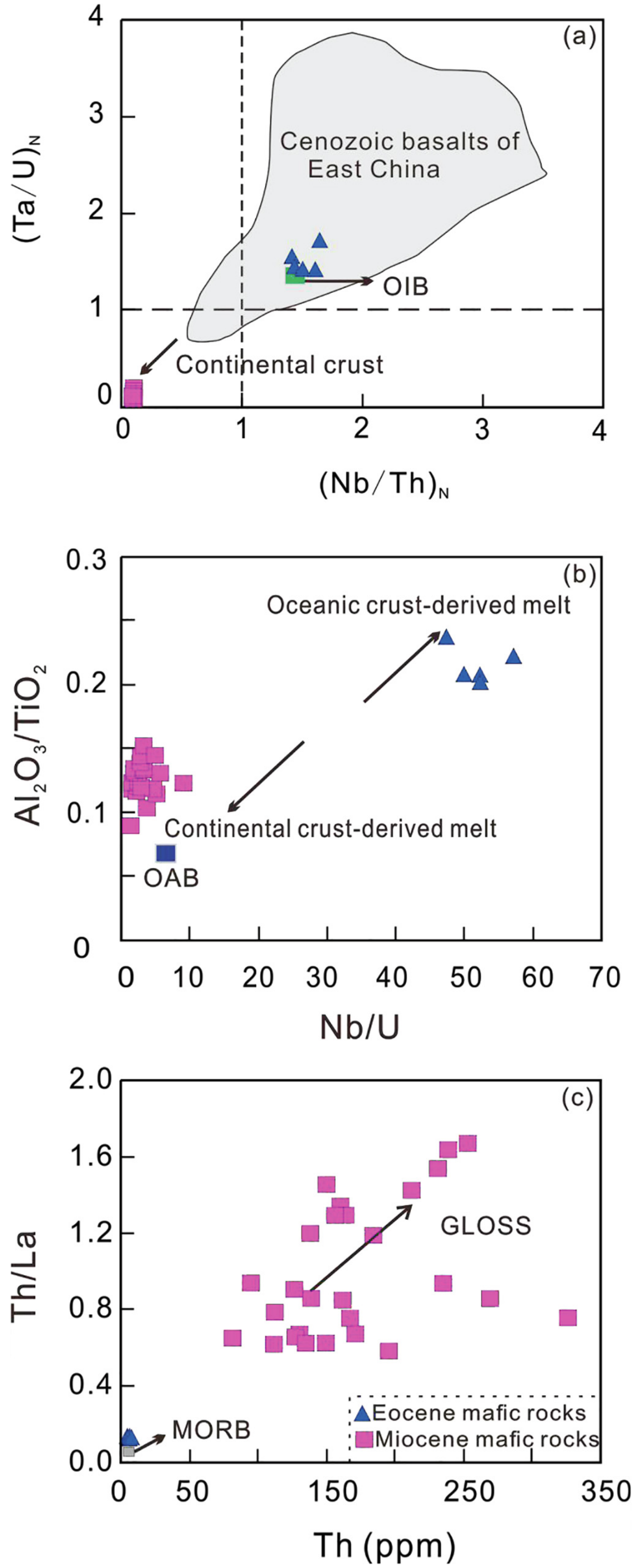

Fig. 5. (a) $(Th/U)_N$ versus $(Nb/Th)_N$, (b) Al_2O_3/TiO_2 versus Nb/U, and (c) Th/La versus Th (ppm) diagrams for the Eocene and Miocene mafic rocks. The reference fields for Cenozoic basalts of East China are from Guo et al. (2016). The data for GLOSS (global subducted sediments) are from Plank and Langmuir (1998). The data for MORB, OIB, OAB, and continental crust are from Sun and McDonough (1989), Niu and Batiza (1997), Kelemen et al. (2003), and Rudnick and Gao (2003), respectively. The sources of other data are as for Fig. 2.

southern Tibet.

The Miocene mafic rocks have high contents of K_2O and Th (81–327 ppm), high Th/La (0.4–1.7) ratios (Fig. 5c; Supplementary Table 1), and enriched Sr–Nd isotope values (Fig. 4), and these require recycled sediments to have played a role in producing the enriched component in the mantle source. Current views on the origin of the enriched component in the mantle source of the Miocene mafic rocks involve either oceanic pelagic sediments or ancient Indian continental crustal materials (Ding et al., 2003; Gao et al., 2007; Zhao et al., 2009; Guo et al., 2013, 2015; Liu et al., 2014, 2015; Huang et al., 2015; Cheng and Guo, 2017; Hao et al., 2018). We prefer the latter option based on the following considerations. (1) The pre-collisional enriched asthenospheric and lithospheric mantle wedges beneath the southern Lhasa subterrane during the subduction of Neo-Tethyan oceanic crust are represented respectively by the Late Cretaceous (~93 Ma) Milin norites and hornblendites in the southern Lhasa subterrane (Ma et al., 2013b) and the Paleocene (~64 Ma) Rongniduo pseudoleucite phonolitic rocks in the central Lhasa subterrane (Qi et al., 2018), but these rocks have more depleted Sr–Nd isotopic compositions compared with the Miocene mafic rocks (Fig. 4). Given that the changes in the chemical and isotopic compositions of magmas generally record changes in tectonic processes (e.g., Chu et al., 2011), we propose that the shift from the relatively depleted pre-collisional mantle (represented by the Milin and Rongniduo rocks) to the relatively enriched post-collisional mantle (represented by the Miocene mafic rocks) was induced by the subduction of Indian continental crust, which could have provided the enriched components from continental sediments. (2) Previous studies of the Early Jurassic basalts of the Yeba Formation the Sangri Group, and the Dongga gabbros in the southern Lhasa subterrane, which formed when the Neo-Tethyan oceanic crust was undergoing subduction, have shown that their mantle source was enriched by melts or fluids derived from subducted oceanic crust rather than from subducted oceanic sediments (Zhu et al., 2008; Kang et al., 2014; Wang et al., 2017). Moreover, after compiling data for the ~492–64 Ma mafic rocks of southern Tibet to characterize the isotopic evolutionary trend of the local mantle, Hao et al. (2018) inferred that the subduction of Neo-Tethyan oceanic crust introduced isotopically depleted components rather than enriched components into the local mantle. Their work also demonstrated that the local mantle beneath this area was more likely to have been enriched by melts or fluids derived from the Neo-Tethyan basaltic oceanic crust (with depleted Sr–Nd isotopic values) than from melts or fluids derived from oceanic sediments (with highly enriched Sr–Nd isotopic values) during subduction. Thus, if subducted Neo-Tethyan oceanic sediments were not the main cause of enrichment in the mantle beneath southern Tibet when the Neo-Tethyan oceanic crust was being subducted, their contribution to the mantle should have been even less after the cessation of subduction. Therefore, the extreme enrichment of the local mantle below southern Tibet during the Miocene, as represented by the Miocene mafic rocks, resulted from the addition of some other component, such as Indian continental crust. (3) Detailed trace element and Sr–Nd isotopic modeling has indicated that the mantle source of the potassic–ultrapotassic mafic rocks in southern Tibet could have been a hybrid source consisting of a depleted (asthenospheric or lithospheric) mantle wedge and less than 10% melts and/or fluids derived from the Indian continental crust (Guo et al., 2013; Ma et al., 2017b; Hao et al., 2018). We propose, therefore, that the mantle source of the Miocene mafic rocks was the depleted (asthenospheric or lithospheric) mantle wedge together with some recycled Indian continental crust. However, we should bear in mind that a contribution from oceanic sediments in the mantle source of the Miocene mafic rocks cannot be totally excluded, and further research is needed to evaluate this fully.

4. Transition from sodic OIB-like magmas to potassic–ultrapotassic mafic rocks

Recent studies have ascribed the change from sodic OIB-like basalts (mafic dikes) to potassic mafic intrusive rocks in the Hong'an–Dabie orogens of east-central China to mantle sources with different types of recycled crustal material (oceanic crust versus continental crust) (Dai et al., 2012, 2015, 2017; Zhao et al., 2013, 2015; Zheng et al., 2015; Zheng and Chen, 2016). These rocks are related to the closure of the Paleo-Tethys, which involved first the subduction of Paleo-Tethyan oceanic crust and subsequently the subduction of South China continental crust, and both oceanic and continental crustal materials would have been recycled into the mantle during the continent–continent collision. The mantle source (metasomatites) of the Hong'an sodic OIB-like basalts (mafic dikes) was generated by reaction of the peridotite of the mantle wedge with felsic melts that originated from the earlier-subducted Paleo-Tethyan oceanic crust. In contrast, the mantle source (metasomatites) of the Dabie potassic mafic rocks was generated by reaction of the peridotite with felsic melts derived from subducted South China continental crust. The partial melting of these two types of metasomatites produced the contrasting OIB-like basalts (mafic dikes) and potassic mafic intrusive rocks in the Hong'an–Dabie orogens (Dai et al., 2012, 2015, 2017; Zhao et al., 2013, 2015; Zheng et al., 2015; Zheng and Chen, 2016). The recycling of continental and oceanic crust into the mantle source has also been used to explain the coexistence of two types of alkaline rock along the northern margin of the Sino-Korean craton (Zhu et al., 2017). We suggest here that in southern Tibet, the change from the Eocene to the Miocene mafic rocks can also be attributed to mantle sources that contained different types of recycled crustal material (oceanic crust versus continental crust), based on the following observations.

Experimental studies have shown that the reaction between fertile peridotite and melts derived from MORB-eclogite can produce metasomatites that could be the proximal source of sodic OIB-like basalts (e.g., Kogiso et al., 1998; Mallik and Dasgupta, 2012). The Na-rich mantle (metasomatites) could be the result of the melt–rock reactions involving the assimilation of mantle clinopyroxene, olivine, and spinel by the oceanic-crust-derived melts as well as the fractional crystallization of sodic amphibole and orthopyroxene in those melts (Prouteau et al., 2001; Xiong et al., 2006). Direct evidence for such metasomatism involving oceanic-crust-derived melts and the creation of a Na-rich mantle comes from ultramafic xenoliths found in arc volcanics. For example, Kepezhinskas et al. (1995) found that some mantle xenoliths in volcanic arc rocks from north Kamchatka (Russia) contain the metasomatic mineral phases sodic amphibole, clinopyroxene, and plagioclase, as well as veins that are rich in Na. Recycled oceanic crust would be subjected to partial melting at mantle depths of > 120 km where felsic melts would be produced that are enriched in LREEs but not depleted in Nb and Ta due to the breakdown of rutile (Ringwood, 1990; Zheng, 2012). Furthermore, recycled oceanic crust has depleted Sr–Nd radiogenic isotope compositions. Thus, partial melting of a mantle source with recycled oceanic crust would generate melts with sodic OIB-style trace-element patterns showing enrichment in LREEs, no depletion in HFSEs, and depleted Sr–Nd isotope compositions.

Experimental studies have shown that the partial melting of fertile peridotite fluxed by hydrous sediments can generate potassic or ultrapotassic magmas (Mallik et al., 2015). Reaction of mantle peridotite with K-rich melts derived from metasediments would transform mantle olivine into orthopyroxene as well as hydrous minerals such as K-rich amphibole and phlogopite, leading to elevated K_2O/Na_2O ratios in the mantle sources and the production of metasomatites such as amphibole- and phlogopite-rich garnet (or spinel) peridotite or pyroxenite (e.g., Sekine and Wyllie, 1982; Castro et al., 2010, 2013). The abundance of melt-mobile incompatible trace elements and radiogenic Sr–Nd isotope compositions in mafic igneous rocks is controlled primarily by the nature of the crustal components involved in their mantle sources (Zheng, 2012). Sediment-derived melts are usually enriched in LILEs, depleted in HFSEs, and have enriched Sr–Nd isotope compositions, and they transfer these geochemical signatures to mantle metasomatites. Therefore, potassic–ultrapotassic rocks that have their source in such mantle metasomatites will inherit these features.

The Eocene Na_2O-rich mafic rocks have OIB-like trace element patterns and relatively depleted Sr–Nd isotopic compositions, and their mantle source would have been formed by the reaction of recycled Neo-Tethyan oceanic crust with the peridotites of the southern Tibetan asthenospheric mantle wedge. They are therefore the product of slab–mantle interactions during the subduction of Neo-Tethyan oceanic crust prior to the subduction of Indian continental crust. In contrast, the Miocene K_2O-rich mafic rocks have arc-like trace element patterns and enriched Sr–Nd isotope compositions. Their mantle source (metasomatites) would have been formed by the reaction of felsic melts derived from subducted Indian continental crust with the peridotites of the southern Tibetan (asthenospheric or lithospheric) mantle wedge. They are therefore the product of slab–mantle interactions during the subduction of Indian continental crust. The two different kinds of metasomatite mantle sources of the Eocene and Miocene mafic rocks could have been preserved in the mantle wedge for up to 100 Myr, depending on the time span of the subsequent thermal events (Zhao et al., 2013, 2015; Zheng et al., 2015).

The thermal event that produced the Eocene mafic rocks can be attributed to slab break-off of the subducted Neo-Tethyan oceanic crust at 55–45 Ma, based on the following evidence. (1) Slab break-off forms a relatively narrow, linear zone of magmatism along a suture (e.g., Kohn and Parkinson, 2002; Mahéo et al., 2002), and it has been shown that the early Tertiary magmatic rocks are confined to a narrow linear zone along the southern margin of the Lhasa Block (e.g., Chung et al., 2005; Lee et al., 2009). (2) Slab break-off would cause pronounced topographic uplift, which is consistent with the concomitant topographic uplift of southern Tibet during the Eocene (Chung et al., 1998, 2005; Kohn and Parkinson, 2002; Ding et al., 2014; Rowley et al., 2015; Zhu et al., 2017). (3) The decrease in the India–Asian convergence rate at ca. 45 Ma (from 8–10 to 4–6 cm/yr) can also be explained by a loss of slab pull due to slab break-off at this time (Lee and Lawver, 1995; Bercovici et al., 2015). (4) The ~ 53 Ma exhumation of ultrahigh-pressure rocks, now exposed in the NW Himalaya, has also been attributed to the process of Neo-Tethyan oceanic slab break-off (Leech et al., 2005). (5) The break-off of the Neo-Tethyan oceanic slab may have triggered the upwelling of asthenospheric mantle, thus causing extensive mantle and crustal melting and facilitating the so-called magmatic "flare-up" at ca. 55–50 Ma in southern Tibet (Wen et al., 2008; Ji et al., 2009; Zhu et al., 2015).

In contrast, the Miocene mafic rocks and coeval calc-alkalic lavas were erupted within or adjacent to N–S graben during 25–8 Ma (Coulon et al., 1986; Turner et al., 1996; Miller et al., 1999; Williams et al., 2004), and this volcanic and tectonic activity was triggered by regional E–W extension. Both convective removal of a lithospheric root beneath the plateau (Turner et al., 1996; Chung et al., 2005) and roll-back and/or break-off of the subducted Indian continental slab (Miller et al., 1999; Mahéo et al., 2002, 2009; DeCelles et al., 2011) have been proposed to explain the post-collisional magmatism in southern Tibet. Based on the following lines of evidence, we favor the proposition that upwelling asthenospheric mantle, caused by roll-back and/or break-off of the Indian continental slab, generated the thermal event that produced the Miocene mafic rocks in southern Tibet. (1) The Gangdese Oligocene–Miocene intrusive rocks are distributed within a narrow ~ 1500-km-long belt along the IYZSZ (e.g., Chung et al., 2005). (2) There is an increasing proportion of the Indian continental component in the mantle source, from north to south, together with a southwards-decreasing trend in the age of the Miocene mafic rocks within XDY rift (Ding et al., 2003; Guo et al., 2013).

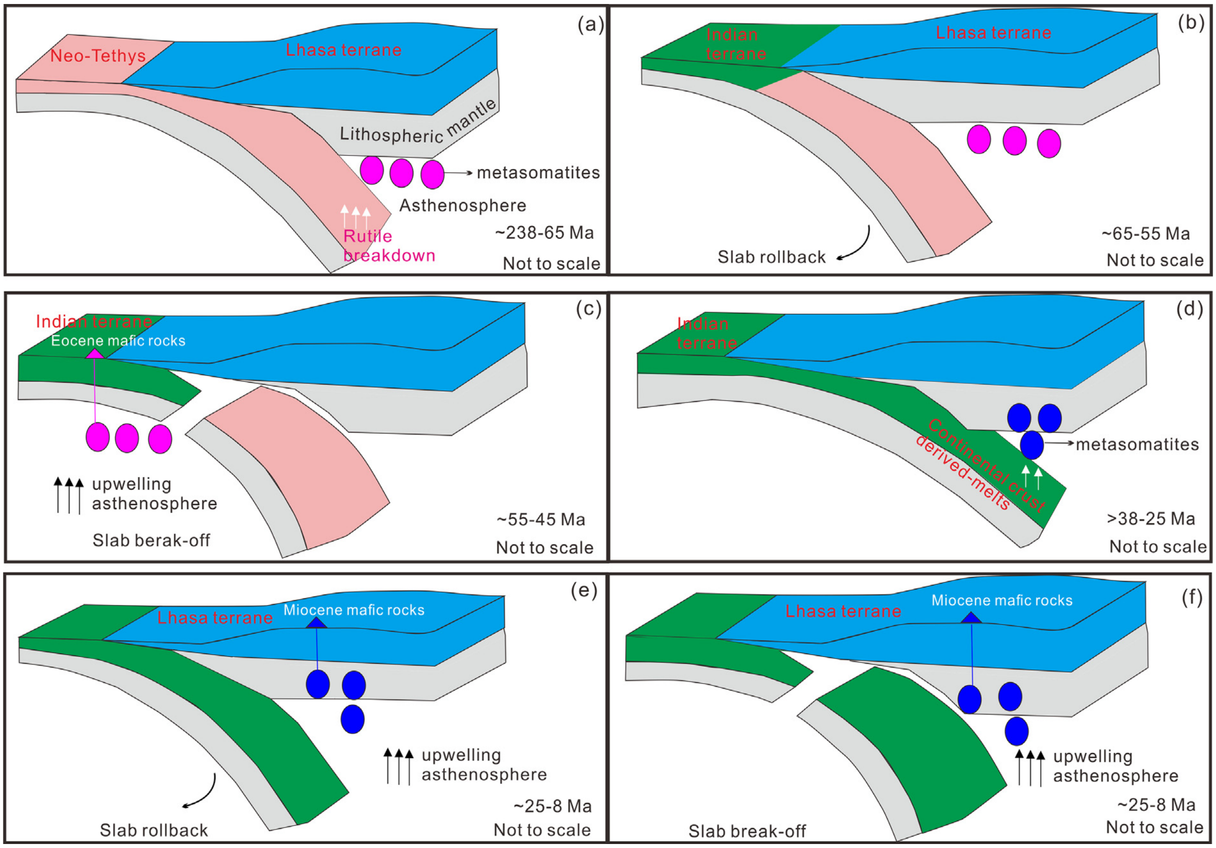

Fig. 6. Schematic illustration of the tectonic evolution of southern Tibet since the Middle–Late Triassic. (a) Subduction of Neo-Tethyan oceanic lithosphere at 238–65 Ma. (b) Initial collision of the Indian and Asian continents, and slab rollback of Neo-Tethyan oceanic slab at 60–55 Ma. (c) Break-off of subducted Neo-Tethyan oceanic slab at 55–45 Ma. (d) Northwards subduction of Indian continental crust at > 38–25 Ma. (e and f) Roll-back and/or break-off of subducted Indian continental slab at 25–8 Ma.

5. Implications for the tectonic evolution from oceanic crust to continental crust subduction

It has previously been thought that the Late Triassic–Early Jurassic (210–174 Ma) magmatic belt in southern Tibet recorded the onset of the subduction of Neo-Tethyan oceanic crust (Zhang et al., 2007; Yang et al., 2008; Zhu et al., 2008, 2011; Ji et al., 2009; L. Guo et al., 2013; Kang et al., 2014; Song et al., 2014, Meng et al., 2015). However, the recent discovery of Middle–Late Triassic (237–212 Ma) volcanic rocks in the southern Lhasa subterrane has revealed that the northwards subduction of Neo-Tethyan oceanic lithosphere beneath the Lhasa Terrane started prior to 237 Ma (Wang et al., 2016). The IYZSZ marks the closure of the Neo-Tethys, which took place when the Indian continental landmass collided with Asia. As continental collision is a complex process, involving a number of concomitant geological events, different scientists in particular research domains have concluded that the timing of initial India–Asia collision ranged between 70 and 34 Ma (Ding et al., 2017 and references therein). Most researchers have proposed that the initial collision occurred at ~65–55 Ma based on the cessation of Xigaze forearc sedimentation (ca. 58–54 Ma; Orme et al., 2014), geochronological and geochemical data for the Linzizong volcanic rocks and coeval intrusive rocks in the Gangdese arc (ca. 55 Ma; Zhu et al., 2015), the abrupt change in sediment provenance recorded in the Xigaze forearc basin (> 59 Ma; Hu et al., 2016), and the onset of India–Asia terrestrial faunal exchange (ca. 54 Ma; Clementz et al., 2011). Considering the southwards migration of magmatism from ~30.5°N to ~29.5°N, together with the abrupt decrease in the rate of India–Asia convergence between ~69 and 53 Ma (from 12–17 to 10 cm/yr; Lee and Lawver, 1995), we propose a model of interaction between initial continental collision and slab roll-back of Neo-Tethyan oceanic crust to account for the above observations in the southern Lhasa terrane. This is because slab roll-back could have enhanced asthenospheric corner flow and supplied a prolonged heat source for producing the early Paleocene magmatism and coeval metamorphism during the early stage of continental collision in this region (Chung et al., 2005; Wen et al., 2008; Lee et al., 2009; Zhu et al., 2017; Ma et al., 2017b). Following India–Asia collision, break-off of the subducted Neo-Tethyan oceanic slab occurred during the Eocene (55–45 Ma; Section 4), probably weakening the lithospheric mantle. This would have provided suitable conditions for subduction of the Indian continent because the break-off of the subducted Neo-Tethyan oceanic crust would have provided the pulling force for the subduction of the Indian continent. Geophysical studies have shown that the Indian lithosphere was subducted under the Lhasa Terrane as far as the Bangong–Nujiang Suture (Nábělek et al., 2009). The following lines of evidence indicate that the subduction of the Indian continental lithosphere beneath Asia occurred before ca. 38 Ma, thus following break-off of the Neo-Tethyan oceanic slab. Firstly, in the southern Lhasa subterrane, the early Oligocene adakitic rocks (~30 Ma) with enriched Sr–Nd isotope values require the involvement of Indian continental components in their mantle source, which suggests that the Indian continental crustal materials were subducted into the middle–lower crust of the southern Lhasa subterrane before the early Oligocene (Fig. 4; Jiang et al., 2014; Chen et al., 2015). Secondly, it has been proposed that the late Eocene (~35 Ma) Quguosha gabbros in the southern Lhasa Block were generated by partial melting of lithospheric mantle that had already been enriched by subducted Indian continental crust (Fig. 4; Ma et al., 2017a). Lastly, the late Eocene–Oligocene (38–24 Ma) ultrahigh-pressure (UHP) eclogites in the western Himalaya and the coeval high-pressure (HP) granulite facies and mediumpressure (MP) amphibolite-facies metamorphic rocks in the eastern Himalaya also provide evidence that the Indian continental crust had already been subducted into the middle–lower crust of southern Tibet at the time of their formation (Mukherjee et al., 2003; Xu et al., 2010; Zhang et al., 2010). The youngest documented magmas of southern Tibet are the potassic–ultrapotassic volcanic rocks, adakitic plutons, and Himalayan leucogranites of Oligocene–Miocene age (25–8 Ma), and these rocks may have been related to roll-back and/or break-off of the subducted Indian continental lithospheric slab, as proposed in Section 4.

Thus, we propose the following generalized five-stage process to explain the Eocene mafic rocks and the Miocene mafic rocks of the southern Tibetan orogen. In stage 1 (~238–65 Ma), the northwards subduction of Neo-Tethyan oceanic lithosphere beneath the mantle wedge of the southern Lhasa subterrane probably occurred during the Middle–Late Triassic, and as eclogite (basaltic protolith) predominates in the subducted oceanic crust, its partial melting with the breakdown of rutile is capable of generating felsic melts without Nb–Ta depletion. The reaction of such felsic melts with peridotite in the asthenospheric mantle wedge would have generated OIB-type mantle domains (metasomatites) beneath southern Tibet (Fig. 6a). Stage 2 (~65–55 Ma) was marked by the initial collision of the Indian and Asian continents and slab rollback of Neo-Tethyan oceanic crust (Fig. 6b). In stage 3 (~55–45 Ma), upwelling of the asthenosphere, triggered by break-off of the subducted Neo-Tethyan oceanic slab, would have heated the metasomatites produced in stage 1 to form the Eocene mafic rocks of southern Tibet (Fig. 6c). In stage 4 (> 38–25 Ma), continental collision was generally preceded by the subduction of dense oceanic lithosphere, and this was followed by the subduction of light continental lithosphere. Meanwhile, break-off of the subducted Neo-Tethyan oceanic slab during the Eocene (~55–45 Ma) probably caused weakening of the lithospheric mantle, thus providing suitable conditions for subduction of the Indian continent. The reaction between the felsic melts derived from subducted Indian continental crust and the overlying peridotite of southern Tibetan (asthenospheric or lithospheric) mantle wedge would have yielded a fertile, enriched mantle (metasomatites) below this region (Fig. 6d). During stage 5 (23–8 Ma), roll-back and/or break-off of the north-dipping slab of Indian continental crust would have triggered asthenospheric upwelling, which would have heated and partially melted the metasomatites produced in stage 4 to develop the Miocene mafic rocks of southern Tibet (Fig. 6e–f). Thus, the transition in the southern Tibet orogen from the Eocene mafic rocks to the Miocene mafic rocks provides a record of the tectonic evolution of an orogen that was at first dominated by the subduction of Neo-Tethyan oceanic crust and which was subsequently dominated by the subduction of Indian continental crust.

6. Conclusions

The Eocene mafic rocks (gabbros) and Miocene Xuruco Lake–Dangre Yongcuo Lake potassic–ultrapotassic mafic rocks in southern Tibet exhibit significantly different geochemical features, which indicates that they originated from two types of mantle source. The Eocene mafic rocks exhibit OIB-like trace element patterns and depleted Sr–Nd radiogenic isotope compositions, consistent with a mantle source that was generated by the reaction of felsic melts derived from subducted Neo-Tethyan oceanic crust with peridotites of southern Tibetan asthenospheric mantle wedge. In contrast, the Miocene mafic rocks show arc-like trace element patterns and enriched Sr–Nd radiogenic isotope compositions, indicating a mantle source that was generated by the reaction of felsic melts derived from subducted Indian continental crust with peridotites of (asthenospheric or lithospheric) mantle wedge beneath southern Tibet. Thus, the contrasting geochemical features of the Eocene mafic rocks and the Miocene mafic rocks in southern Tibet can be attributed to two types of slab–mantle interaction (i.e., oceanic crust–mantle versus continental crust–mantle) in this collisional orogen. The transition from the Eocene mafic rocks to the Miocene mafic rocks in southern Tibet therefore records the tectonic evolution of this orogen from a regime of Neo-Tethyan oceanic crust subduction to a regime of Indian continental crust subduction.

Declaration of Competing Interest

The authors declared that they have no conflicts of interest to this work.

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Appendix A. Supplementary material

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