Middle–Late Triassic bimodal intrusive rocks from the Tethyan Himalaya in South Tibet: Geochronology, petrogenesis and tectonic implications

Yong Huang,⁎, Hua-wen Cao, Guang-ming Li, Stefanie M. Brueckner, Zhi Zhang, Lei Dong, Zuo-wen Dai, Liu Lu, Yu-bin Li

Chengdu Center, China Geological Survey, Chengdu 610086, China
Department of Geosciences, Auburn University, 2050 Beard-Eaves-Coliseum, Auburn, AL 36849, USA
Chengdu University of Technology, Chengdu 610059, China
Tibet Institute of Geological Survey, Lhasa 850012, China

Abstract

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This paper presents new geochronological and geochemical (whole-rock major and trace elements and Sr–Nd–Pb isotopes) data on intrusive rocks exposed in the Qiongduojiang area, the northern part of the Tethyan Himalaya. The Qiongduojiang intrusive rocks are mainly composed of mafic rocks (diabase and gabbro) with subordinate felsic rocks (monzonite), indicating bimodal component characteristics. In zircon U-Pb dating of monzonite, diabase and gabbro samples, the weighted mean ages of magma emplacement were determined to be 230.5 ± 2.9 Ma to 227.4 ± 4.7 Ma, showing Middle–Late Triassic magmatic activity in the northern part of the Himalayan belt. The monzonitic rocks share most of the geochemical features of A-type granites, and their Nd isotopic compositions are consistent with those of coeval diabase rocks. This suggests that they are likely generated by mantle-derived magmas, which had assimilated significant amounts of continental crust. The gabbro samples exhibit the geochemical composition of ocean island basalt (OIB) features and therefore assumingly originate from a depleted mantle source with insignificant crustal contamination. In contrast, the diabase samples display enriched mid-ocean ridge basalt (E-MORB) features and were derived from spinel bearing peridotite that was metasomatized by OIB-like components with limited crustal contamination. The Qiongduojiang bimodal magmas can be considered as the products of the opening of the Neo-Tethyan ocean. Considering the magmatic petrology, paleomagnetism and paleontology data, we further propose that the Neo-Tethyan ocean began opening before ~230 Ma.

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1. Introduction

Recent studies have found a close association between the formation and evolution of the Tibetan Plateau and the rifting and northward-drift of a series of Gondwana-original terranes towards the southern margin of the Eurasia plate from the Late Paleozoic Period onwards. These processes were accompanied by the gradual contraction and/or opening of the Paleo-, Meso- and Neo-Tethys (Ding et al., 2014; Ji et al., 2009; Lang et al., 2014; Meng et al., 2016a; Meng et al., 2016b; Song et al., 2014; Wang et al., 2016; Wang et al., 2017; Wei et al., 2017; Zhu et al., 2008a; Zou et al., 2017) (Fig. 1). In fact, Early Mesozoic magmatic rocks are relatively rare in the Lhasa terrane, where most of the magmatism is Cretaceous and Cenozoic. The Early Mesozoic magmatic rocks distributed in the Gangdese magma belt constrained the opening time of the Neo-Tethyan ocean prior to the Late Triassic period.

In this study, we newly report the zircon U-Pb ages, whole-rock geochemical data and Sr–Nd–Pb isotopic data from the Middle–Late Triassic intrusive rocks in the Tethyan Himalaya belt. Our aims are to constrain the opening time of the Neo-Tethyan ocean and Early Mesozoic tectonic evolution of the Tethyan Himalaya belt. The Qiongduojiang intrusive rocks are characterised by bimodal
components, indicating that the opening of the Neo-Tethyan ocean commenced in the Middle Triassic period.

2. Geological background and samples

The Tibetan Plateau is dominated by several blocks or microplates (terranes). From north to south, the four main continental terranes are the Songpan–Ganje, the Qiangtang, the Lhasa, and the Himalaya (Fig. 1B). These terranes are separated by the Jinsha suture, the Bangong–Nujang suture, and the Indus–Tsangpo suture, respectively (Yin and Harrison, 2000). The Himalayan orogen is bounded to the north by the Indus–Tsangpo suture (IYS; Fig. 1B), which resulted from the northwards drift of the Indian Plate and its collision with the Asian Plate ca. 55–50 Ma (Ding et al., 2016; Najman et al., 2017; Rage et al., 1995; Zhuang et al., 2015). The Himalayan orogeny belt includes four major tectonic domains (Yin and Harrison, 2000): (1) the Tethyan Himalaya (THS), (2) the Greater Himalaya (GHC), (3) the Lesser Himalaya (LHS) and (4) the Sub–Himalaya (SHS). The THS consists of Lower Paleozoic to Eocene clastic and carbonate rocks deposited on the northern Indian passive margin bounded by the IYS and South Detachment System (STDS). The GHC is delimited between the South Tibet Detachment System and the Main Central Thrust, and includes a Neoproterozoic to Ordovician high-grade metasedimentary sequence (Ali and Atchison, 2005; Robinson and Martin, 2014). The LHS is bounded by the Main Boundary Thrust and the Main Central Thrust, and consists of Paleoproterozoic–Cambrian low-grade metamorphosed siliciclastic rocks (Upset and Le Fort, 1999). The SHS consists of Neogene alluvial sedimentary rocks representing an overfilled stage of the Himalayan foreland basin.

Researchers have divided the evolutionary history of magmatism in the Himalayan terrane into three major phases: (1) 145–130 Ma, (2) 45–40 Ma and (3) 37–10 Ma. The 145–130 Ma rocks are exposed in the THS, and are dominated by dismembered mafic lava flows, sills, and dikes. The Early Cretaceous igneous rocks were coeval with the Bunbury basalt in southwestern Australia. They were proposed as the remnants of a large igneous province (the Comei–Bunbury LIP), which may represent the earliest activity of the Kerguelen mantle plume (Huang et al., 2018; Zhu et al., 2008b; Zhu et al., 2009). The 45–40 Ma rocks are dominated by two-mica granites with adakitic affinities and mafic rocks. The granites are mainly restricted to the Yardoi and Ramba domes and might be derived from partial melting of amphibolite under thickened crustal conditions (Aikman et al., 2008; Zeng et al., 2014). However, the geochemical characteristics of the Eocene mafic rocks are similar to those of HIMU (high μ)-type oceanic island basalt that might have derived from asthenosphere related to subducted Neo-Tethyan slab breakoff (Ji et al., 2016). The 37–10 Ma rocks are dominated by two-mica leucogranites, and by leucogranites bearing biotite, tourmaline and garnet. These rocks were mainly emplaced into a series of gneiss domes, clastic and carbonate strata. There are two belts of Cenozoic leucogranites: the Higher Himalayan leucogranites to the south and the Tethyan Himalayan leucogranites to the north. The grain size varies from fine to coarse, and most of the grains are peraluminous (Le Fort et al., 1987; Le Fort and Cronin, 1988; Searle et al., 2009).

Unlike previous reports of magmatic events, this study report Middle–Late Triassic magmas explored largely within the Qiongduojiaogang area (Fig. 2). These rocks are emplaced into the Triassic Nieru Formation, which consists of thick clastic turbidites, fine-grained sandstone and slate, and are exposed to the south of the southern Renbu mélangé exposure (Li et al., 2004). The Nieru Formation is dominated by south-directed imbricate thrust slices. The folds are mainly isoclinal and overturned with interlimb angles >45°. The axial planes of inverted folds dip northwards at moderate to steep angles and the northern limbs of anticlines or southern limbs of synclines are usually overturned. The dikes dominated by mafic rocks (diabase and gabbro) with minor felsic rocks (monzonte) which are locally concordant, in-trude in Nieru Formation (Fig. 2). The width of these dikes predominantly range from 2 to 5 m (Fig. 3). The Qiongduojiaogang felsic rocks have a fine-to-medium grained granitoid texture and consist mainly of plagioclase (30–40%), K-feldspar (25–35%), quartz (5–10%) and amphibole (5–10%), with minor biotite (5%) and magnetite (<5%) (Fig. 3e, f).

Zircons were collected from the outcrops in the region and were used for U-Pb age determinations. The samples from the different location of the same dikes were collected for bulk-rock geochemistry and Sr-Nd-Pb isotope analysis. The U-Pb zircon geochronology of these rocks (described below) indicates an emplacement time in the Middle to Late Triassic (230.5–227.4 Ma).
3. Analysis methods

3.1. Zircon U-Pb dating

Zircons were separated from crushed whole-rock samples and purified by careful hand picking. The handpicked zircon grains were mounted in epoxy resin and then polished to a smooth, flat surface. The internal structures of the zircons were revealed in cathodoluminescence (CL) images. The U-Pb isotopes in the zircons were measured by inductively coupled plasma mass spectrometry (ICP–MS) (Agilent 7700×, Agilent, USA) coupled with a Geolas Pro 193-nm laser system (Coherent, USA). The ICP–MS analyses were performed at the China University of Geosciences with a spot diameter of ca. 32 μm. As the standard for U-Pb dating, we used 91500-standard zircon (two analyses for every five sample analyses). As the external and internal standards for the elemental compositions, we adopted...
MUD and Si, respectively. During the zircon U-Pb analyses, the equipment was monitored using the standard zircon Plesovice. Common Pb correction was carried out in a dedicated EXCEL program (Andersen, 2002). The zircon–weighted mean age was calculated by ICPMSDataCal (Liu et al., 2010), and the concordia diagrams were plotted by Isoplots (Ludwig, 2003). The uncertainties of the data points were given as ±1σ. The 207Pb/206Pb ages were used for >1000 Ma zircons, and the 206Pb/238U ages for younger zircons. The zircon U-Pb isotopic results exclude analyses with >10% discordance between the 206Pb/238U and 207Pb/206Pb ages and/or a 1σ age error exceeding 3.0%.

3.2. Bulk-rock geochemistry

Quantitative analyses of the major and trace element contents in the whole-rock samples were conducted at the Beijing Research Institute of Uranium Geology. After removing the weathered surfaces of the samples, we chipped off fresh portions of the rocks and powdered them to a mesh size of approximately 200 μm in a tungsten carbide ball mill. The analytical procedures were similar to those in Gao et al. (2003). The major oxides were analysed in an Axios MAX X-ray fluorescence spectrometer, with an analytical uncertainty below 5%. The trace elements were analysed by a Perkin–Elmer Nexion 300D ICP-MS. The analytical precision of this instrument generally exceeds 1% for elements with concentrations above 200 ppm, and 1–3% for those below 200 ppm.

3.3. Sr–Nd–Pb isotopes

Whole-rock Sr–Nd–Pb isotopes were chemically separated and quantified at the Beijing Research Institute of Uranium Geology. Approximately 200 mg of rock powder was dissolved in an acid mixture (HF + HNO3) for 48 h in a Teflon beaker. All samples were prepared in duplicate. The digests were dried, dissolved in hydrochloric acid, heated in closed vials at 160 °C for 1 h and evaporated to dryness. This procedure was repeated twice. The Sr and Nd were then separated and purified by conventional cation-exchange techniques. The initial 87Sr/86Sr ratios and εNd(t) values at the time of crystallization were calculated from the zircon U-Pb ages and the Rb, Sr, Sm and Nd contents. When calculating the εNd(t) values, we assumed the model composition of a chondritic uniform reservoir at the estimated age. The TDM1 and TDM2 values are the estimated ages of extraction from the depleted mantle according to the one-stage and two-stage crustal pre-histories, respectively, as assumed by DePaolo (1988) and DePaolo et al. (1991). The precision of the calculated initial 87Sr/86Sr values is limited by the errors in the parent/daughter ratios calculated from the geochemical data. Nevertheless, in most cases, errors as high as ±10% in the Rb/Sr ratio introduce uncertainties below 0.0001 in the initial 87Sr/86Sr values (Dolgopolova et al., 2013), and a 10% error in the Nd isotopes causes an uncertainty of about 0.4–0.7 in the εNd(t) values. The measured Pb isotopic ratios were corrected for the instrumental mass fractionation of 0.1 amu-1 by referencing to repeat analyses of the standard NBS-981.

4. Results

4.1. Zircon U-Pb ages

The U-Pb ages of zircons separated from three samples are listed in Supplementary Table S1. The zircons from monzonite (G16318) are euhedral–subhedral, ~100–200 μm long, and short to long prismatic, with aspect ratios of 1:1–3:1. Most of these zircons are transparent, colourless to pale brown and show little to obvious oscillatory zoning (Fig. 4). Zircons from diabase (G16324) are mostly prismatic and subhedral in shape, and ~100–300 μm long, with length-to-width ratios of 1.5:1–3:1. Most of these grains are zoneless or zoned in sectors (Fig. 4). Zircons from gabbro (G16348) are subhedral in...
shape, and ~50–200 μm long, with length-to-width ratios of 1:1–3:1. Their zoning is oscillatory, although some of the zircons have inherited cores. The U-Pb ages of the zircons are plotted in Fig. 4. The zircons from sample G16318 date from 2621 to 2818.6 Ma, with Th/U ratios ranging from 0.1 to 2.3 (Table 1). With the exception of plots 2, 12, and 30, the concordances of the analysed spots exceed 90%. The weighted mean of the eight youngest spots is 2274 ± 4.7 Ma (MSWD = 0.02), which can be interpreted as the crystallization age of the monzonite (Fig. 4a). The other analyses of the zircons yield 206Pb/238U ages from 2818.6 Ma to 4283.3 Ma, representing the inherited ages. The U-Pb ages of samples G16324 and G16348 were estimated from 30 and 28 zircon grains, respectively. The weighted mean of the six youngest spots in G16324, 2297.4 ± 4.3 Ma (MSWD = 0.04), can be interpreted as the crystallization age of diabase (Fig. 4b). Meanwhile, the weighted mean of the eight youngest spots in G16348, 2305.2 ± 2.9 Ma (MSWD = 0.05), can be interpreted as the crystallization age of gabbro (Fig. 4c). Although the three samples were extracted from different rock types, their ages are indistinguishable within the uncertainties. The mean age of the three samples (ca. 2292 Ma) corresponds to the formation time of the Middle–Late Triassic magmas.

4.2. Bulk-rock geochemistry

The major and trace elements in the analysed samples are listed in Table 1. Narrow ranges of SiO2 (57.02–58.31 wt%), TiO2, Al2O3, and Fe2O3 are given in Table 2.
(0.99–1.03 wt%), and K₂O + Na₂O (6.25–6.38 wt%) were found in the monzonite samples. On the total alcalis vs. silica (TAS) diagram, all samples show sub-alkaline features. The rocks plot in the monzonite field (Fig. 5a). In the K₂O vs. SiO₂ diagram, the rocks show medium-K calc-alkaline affinity. The monzonite rocks are relatively enriched in light rare earth elements (LREEs) and display flat heavy REE patterns with moderately negative Eu anomalies (0.70–0.74). On the primitive mantle-normalized diagram, their patterns are markedly depleted in Ba, Zr, Hf and Ti. These rocks have high 10,000 ⁴⁰Ar/⁴⁰Kr ages of the zircons, are 18.54–18.61 Ma (Table S3, Figs. 7a, b). The initial ⁸⁷Sr/⁸⁶Sr ratios fall between 0.71201 and 0.71226, and share the geochemical characteristics of A-type granitoids as defined by Eby (1990). Monzonite rocks plot within the A-type granite field (Fig. 8). Two genetic models for A-type granites were proposed: (a) fractional crystallization of mafic magmas that experienced significant assimilation of continental crust (Bacon and Druitt, 1988; Grove and Donnelly-Nolan, 1986; Ingle et al., 2002), and (b) melting of ensialic continental crust (anatectic) in an intraplate environment (Bullen and Clynne, 1990; Cox, 1972; Roberts and Clemens, 1993; Tepper et al., 1993). In the first model, the A-type granites exhibit constant Nd isotopic composition with coeval mafic rocks, whereas the second model predicts negative εNd(t) values, different from those of coeval mafic rocks. The Qiongduojiang monzonitic rocks show negative εNd(t) values (−2.6 to −3.9), high initial ⁸⁷Sr/⁸⁶Sr ratios (0.71201–0.71226), and high ⁴⁰K/⁴⁰Ar-Pb composition (18.54–18.61). These properties clearly differ from those of coeval gabbro rocks but negative εNd(t) values are consistent with those of diabase rocks (see below) (Table S3, Figs. 7a, b). The Nd isotopic composition of monzonite indicates that it may have derived from coeval diabase magma. The high MgO (3.39%–3.62%) and low SiO₂ (57.02%–58.31%) content of monzonite also suggest that it is likely to be derived from the mafic rock. Furthermore, the monzonite has undergone very significant fractionation. The high MgO (3.39%–3.62%) and low SiO₂ (57.02%–58.31%) content of monzonite also suggest that it is likely to be derived from the mafic rock. Furthermore, the monzonite has undergone very significant fractionation. The Qiongduojiang monzonitic rocks are enriched in LREE, depleted in Ti, and their εNd(t) values are negative (Figs. 6a and b, 9d). The Nb/U (20.8–24.3), Nd/Pb (1.07–1.48) and Nb/La (0.98–1.07) values are apparently lower than those of mafic-derived magma, but similar to those of ensialic continental crust (Fig. 9a, b and c). Therefore, the monzonite rocks could have assimilated significant amounts of continental crust during the magma evolution. This idea is supported by the LA-ICP-MS age data of the inherited zircons. Given the uniform geochemical compositions of the major and trace elements and the relatively homogeneous initial ⁸⁷Sr/⁸⁶Sr ratio, the
Qiongduojiang monzonite rocks must have derived from a relatively homogeneous magma, meaning that the assimilation was extremely well-mixed in the magma. These samples have negative Eu and Ti anomalies (δEu = 0.70–0.74), indicating that the source rocks were partially melted within the stability field of plagioclase and Ti-bearing minerals (rutile/titanite).
In summary, the monzonite rocks are most likely generated by mantle-derived magmas and underwent apparently crustal contamination during the magma evolution.

5.2. Petrogenesis of mafic rocks

The REE amounts, trace element patterns and Sr–Nd–Pb isotopic compositions apparently differ between the gabbro and diabase samples (Fig. 6, Tables S2, and S3), suggesting that these mafic rocks were derived from distinct mantle sources.

Because the Qiongduojiang mafic rocks intruded the Tethyan Himalaya, the continental crust might have been contaminated during the magma ascent and intrusion. Furthermore, the Nb/U, Nd/Pb and Nb/La ratios can be sensitive indicators of crustal contamination (Hofmann, 2014). Crustal contamination should drive the magma composition towards that of continental crust. However, no such trend was identified for the gabbroic samples (Fig. 9a, b and c), indicating that the gabbro may have experienced insignificant crustal contamination. Furthermore, the most compelling evidence that crustal contamination exert distinct effects would be a correlation between the isotopic ratios of Sr and Nd and the chemical compositions with a fractionation indicator (e.g. SiO₂). Such a correlation would imply that the isotopic composition was changed during differentiation, while the magma was ascending and emplacing in the crust. The εNd(t) variations in the gabbros are uncorrelated with SiO₂, indicating negligible crustal contamination in the gabbros (Fig. 9d).

The gabbroic rocks are enriched in LREE, large-ion lithophilic elements (LILE) and high field-strength elements (HFSE) (Fig. 6c, d). On the primitive mantle-normalized diagram, the gabbroic rocks display positive Nb, Ta anomalies and no notably negative Ti anomalies, consistent with OIB characteristics (Sun and McDonough, 1989) (Fig. 6d). In addition, the Nb/U ratios (55.2–60.5) are equivalent to the mean ratios of “non-EM-type” OIB (52 ± 15; Hofmann, 2014). This view is supported by the FeO/MgO ratios and TiO₂ values, which are plotted in the OIB regions (Fig. 10b).

Fractional crystallization is commonly responsible for the petrologic and geochemical variations among the different intrusive rocks in the orogenic zone (e.g., Pearce et al., 1990). In the sampled gabbro rocks, the MgO was positively correlated with Cr and Ni, indicating clinopyroxene and/or olivine fractionation (Fig. 11e, f). The zero or negative correlations between TiO₂, FeO and MgO suggest an insignificant contribution of fractionation or negligible accumulation of Fe-Ti oxides in the magmas (Fig. 11b, c). The negative correlation between V and MgO indicates that hornblende was also a non-major fractionating phase (Fig. 11g). The absence of Eu anomalies (δEu = 0.96–1.04) in the REE pattern suggests that no plagioclase fractionation occurred in the mantle magmas (Fig. 7c).

Importantly, the gabbroic rocks display relatively depleted isotopic composition with low 206Pb/204Pb (15.49–15.57), 87Sr/86Sr (0.70512–0.70532), and depleted εNd(t) = 3.9–6.3 indicating a depleted mantle source. The alkaline OIB characteristics require enriched components in the mantle source (Ji et al., 2016), either from recycled oceanic crust containing various continental materials, or from metasomatic processes (Hofmann, 2014). The local subcontinental lithospheric mantle belonged to the former Indian passive continental margin, which was poor in metasomatic fluids, as indicated by the absence of potassic–ultrapotassic rocks in the region (Chung et al., 2005). Furthermore, ancient isotopic compositions are found in the Himalayan basement (Zeng et al., 2011). Thus, the Qiongduojiang gabbros could not have derived from the local lithospheric mantle, but derived from the asthenosphere instead.

The diabase rocks have lower εNd(t) and higher 87Sr/86Sr values than the gabbros (Table S2). The REE pattern and trace element compositions of the diabase samples suggest a derivation from the mantle wedge, consistent with their derivation from the asthenosphere.
characteristics of diabase are strongly consistent with those of enriched mid-ocean ridge basalt (E-MORB), except for the enrichment of Sr and depletion of Zr and Hf from/to the primitive mantle (Fig. 6e). This finding is further supported by the FeO/MgO ratios and TiO$_2$ values (Fig. 10b). The low Nb/U, Nd/Pb, and Nb/La ratios indicate that crustal components were involved in the diabase petrogenesis (Fig. 9a, b, c). However, the weakly positive Nb, Ta and Ti relative to the primitive mantle are abnormal, indicating limited involvement of the crustal components (Fig. 6f). Instead, the excess Fe-Ti oxides could have elevated the ratios of Nb, Ta, Zr and Hf relative to other trace elements (Klemme et al., 2006; Nielsen and Beard, 2000). The zero or negative correlations between TiO$_2$, FeO and MgO suggest an insignificant contribution of fractionation of Fe-Ti oxides in the magmas (Fig. 11). Therefore, the weakly enriched Nb and Ta can be interpreted as the primary signatures of the mantle source. Crustal contamination played no major role during the generation of the Qiongduojiang diabase rocks, which is in contrast to the genesis of the monzonites in the region. Moreover, according to the mixing calculations, the addition of crustal components and/or fluids in any proportion into the initial magma cannot explain the $\varepsilon_{Nd}(t)$ and (La/Nb)$_{MORB}$ values of the Qiongduojiang diabase rocks (Fig. 10a). The enrichment of Nb and Ta in mafic melts has been interpreted by three hypotheses: (1) partial melting of an OIB type asthenosphere (Zhou et al., 2009), (2) source mixing of a depleted N-MORB type mantle with OIB-like components (Castillo, 2008; Castillo et al., 2007; Saccani et al., 2013, 2014) and (3) partial melting of a lithosphere mantle metasomatized by OIB-like components (Paslick et al., 1995). In most of the Qiongduojiang diabase samples, the Nb/Pb values were lower than in OIB- and MORB-type mantles..
indicating that diabase petrogenesis was not driven by partial melting of an OIB-type asthenosphere and source mixing of a depleted N-MORB-type mantle with OIB-like components (Fig. 9b). The relatively low $\varepsilon_{\text{Nd}}(t)$ and high $^{87}\text{Sr}/^{86}\text{Sr}$ ratios further suggest that the diabase samples were derived from partial melting of a lithosphere mantle metasomatized by OIB-like components.

As previously mentioned, crustal contamination played a non-major role in the generation of Qiongduojiang mafic rocks. To understand the petrogenesis mechanism, it is important to detect the lithological features of the mantle sources. These lithological features can be fingerprinted using the ratios of the first-row transition elements (e.g., the Zn/Fe$_i$ ($\times10^4$) values) when these are available (Le Roux et al., 2010, 2011). These ratios usefully distinguish between peridotite-derived melt (Zn/Fe$_i$ ($\times10^4$) = 9 ± 1) and pyroxenite-derived melt (Zn/Fe$_i$ ($\times10^4$) = 13–20). However, fractional crystallization of clinopyroxene and magnetite increases the Zn/Fe$_i$ ratio in mafic melts (e.g., Le Roux et al., 2010, 2011). Because the fractionations of Fe-Ti oxides were unimportant in the generation of Qiongduojiang gabbro and diabase rocks (as discussed in the previous section), the relatively high Zn/Fe$_i$ ($\times10^4$) values in the gabbro rocks (typically 12.1–17.1) indicate their origin from pyroxenite rather than peridotite (Fig. 13a). As indicated by the lower Zn/Fe$_i$ ratios in diabase than in gabbro rocks, the mantle source lithology is peridotite (Fig. 13a). Additionally, the La/Yb and Sm/Yb ratios in the gabbro samples are relatively high (9.0–11.2 and 2.1–2.4, respectively): lower than in the garnet + spinel lherzolite melting curve, but higher than in the spinel lherzolite melting curve (Fig. 13b). This suggests that the parental magma originated from a mantle source of spinel + minor garnet. The La/Yb and Sm/Yb values are lower in the diabase rocks and plot in the spinel lherzolite melting curve (Fig. 13b).

In summary, we propose that the gabbro rocks were derived from spinel + minor-garnet-bearing pyroxenite with no crustal contamination, whereas the diabase rocks were derived from spinel-bearing peridotite that was metasomatized by OIB-like components with limited crustal contamination.

5.3. Tectonic background

Our zircon geochronology and whole-rock geochemical data provide the first evidence of Middle–Late Triassic bimodal intrusive rocks in the Tethyan Himalayan belt. The Qiongduojiang intrusive rocks are characterised by bimodal composition (monzonite, diabase, and gabbro). Bimodal magmatic suites are generally formed in extensional settings such as back-arc basins, post-collisions and within-plate settings (Bonin, 2004; Ikeda and Yuasa, 1989; Pin and Paquette, 1997). Considering their A-type granite characteristics, the felsic rocks from the Qiongduojiang bimodal suite were commonly generated in an extensional environment. This inference is supported by the monzonite
samples, which fall in the within-plate magma field on the Y vs. Nb diagram (Fig. 12a). The gabbro samples also plot in the within-plate magma field, clearly distinguishing them from volcanic arc magma (Fig. 12b).

The Mesozoic magmatic events (~210–170 Ma) of southern margin of the Gangdese belt have been well documented and imply a continuous E–W trending Later Triassic magmatic belt (Huang et al., 2015; Ma et al., 2017; Meng et al., 2016a; Song et al., 2014; Zou et al., 2017) (Fig. 1B). These rocks exhibit relatively uniform Nd-Hf isotopic compositions (zircon $\varepsilon_{\text{Nd}}(t) = +5.20$ to $+7.74$ and $\varepsilon_{\text{Hf}}(t) = +9.6$ to $+15.9$), negative Nb, Ta and Ti anomalies, enriched LREEs and LILEs, and depleted HFSEs. Therefore, these rocks crystallized in magmas generated in an active continental margin, which records the earliest northward Neo-Tethyan subduction (Meng et al., 2016b; Wang et al., 2016). However, results from this study are the first to report the occurrence of Middle to Late Triassic (230.5–227.4 Ma) intrusive rocks, which are ~20 Ma older than those in South Gangdese. Geochronological data from monzonite, gabbro and diabase show no distinction in their age within the error and have a combined mean age of ca. 229.2 Ma corresponding to the timing of the formation of Middle to Late Triassic magmas. Therefore, the Qiongduojiang region witnessed a major magmatic event during the Middle to Late Triassic (Ladinian to Carnian period), which assumingly is related to the opening of the Neo-Tethyan ocean.

Previous paleontological and paleomagnetic studies support our geochronological and geochemical data of the region (Li et al., 2016; Zhu et al., 2006). The radiolarian fauna in the radiolarian cherts from the middle section of the Indus–Tsangpo suture show also ages of Middle to Late Triassic period (Zhu et al., 2006). The geochemical features of the radiolarians are consistent with their deposition in a continental margin basin. The Middle–Late Triassic association of the radiolarian chert and turbidites, along with their geochemical characteristics, indicate the existence of a strong rifting within a marginal basin in the belt of the Yarlung Zangbo River (Zhu et al., 2006). The paleomagnetic data for the Lhasa terrane also suggest that it drifted away from the northern margin of Gondwana in the Late Triassic with an average drift rate of ~5 cm/yr and moved ~40° in latitude (~4500 km) northward until it collided with the Qiangtang terrane (Li et al., 2016). We note that pre-drift rifting, typically accommodating a few hundreds of kilometres of extension, may have started before the Late Triassic. In conjunction with the magmatic petrology, paleomagnetic data, and paleontology evidences, we consider that the Qiongduojiang intrusive rocks were generated in a rift setting related to the opening of the Neo-Tethys in the Middle to Late Triassic (Baxter et al., 2009; Baxter et al., 2011; Lang et al., 2014; Li et al., 2015; Li et al., 2016; Song et al., 2014; Wang et al., 2016; Zhu et al., 2006).

6. Conclusions

The main conclusions of the study are as follows.

1. Based on zircon U-Pb dating, we deduced that the bimodal intrusive rocks in the Qiongduojiang area formed between 230.5 and 227.4 Ma, indicating the occurrence of Middle–Late Triassic magmatism within the Tethyan Himalayan belt.

2. The felsic monzonitic rocks exhibit A-type granite affinities and are assumingly generated by mantle-derived magmas and apparently underwent crustal contamination during the magma evolution. The gabbroic rocks exhibited OIB-type characteristics.
and originated from a garnet + minor spinel-bearing mantle, whereas the diabase rocks originated from a spinel-bearing mantle, and originated from a garnet + minor spinel-bearing mantle, or a garnet + minor spinel-bearing mantle source metasomatized by OIB-like components.

The presence of bimodal intrusive rocks revealed that the opening of the Neo-Tethyan ocean occurred prior to ~230 Ma.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.lithos.2018.08.002.

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