Melt evolution of upper mantle peridotites and mafic dikes in the northern ophiolite belt of the western Yarlung Zangbo suture zone (southern Tibet)

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ABSTRACT

The Yarlung Zangbo suture zone (YZSZ) in southern Tibet separates India and its northern passive margin units in the south from Eurasia and its active continental margin units (e.g., Gangdese magmatic arc of the Lhasa block) to the north (Fig. 1). It has been traditionally interpreted as one of the major suture zones in the Earth that formed during the India-Asia continental collision, following the terminal closure of the Neotethys (Aitchison et al., 2011; Hu et al., 2016). Mafic-ultramafic rock assemblages in different ophiolite massifs and mélanges along the YZSZ have been studied extensively during the past 30 years (i.e., Miller et al., 2003; Liu et al., 2010; Bezard et al., 2011; Dai et al., 2011; Guilmette et al., 2012; Hébert et al., 2012; Guo et al., 2015; Li et al., 2015; Niu et al., 2015; Lian et al., 2016, 2017; Feng et al., 2017). Geodynamic models explaining the geochemical evolution of the YZSZ ophiolites, their tectonic origin of magmatic construction within a broad Neotethys oceanic realm, and the paleography of this Mesozoic–Cenozoic ocean basin vary significantly (Hébert et al., 2012; Dai et al., 2013; C. Liu et al., 2014; Liu et al., 2015a; Gong et al., 2016; Lian et al., 2016; Xiong et al., 2016). These variations stem largely from (1) widespread, contractional, strike-slip and extensional deformation along and across the YZSZ that occurred during and after the initial India-Asia collision that significantly modified the primary structures and the original distribution of lithological units; (2) original heterogeneities in upper mantle compositions and in their crustal derivatives in the oceanic lithosphere, which developed in different tectonic settings within the Neotethys Ocean basin; and (3) major changes in intrabasin tectonics and continental margin evolution of the Neotethys Ocean along its >3000 km length from the west to the east.

In this study we have investigated an ophiolitic mélangé, upper mantle peridotites, and their mafic dike intrusions, which occur discontinuously in an east-west zone, making up the northern belt (NB) near the western end of the YZSZ (Fig. 1), where they are tectonically sandwiched between the Gangdese magmatic arc (north) and the Zhongba terrane (south). The NB ophiolites are tectonically juxtaposed against an accretionary prism complex of the late Mesozoic active continental margin of Eurasia, providing a critical spatial-temporal link between the magmatic development of the ophiolites and the Eurasian active margin tectonics in the Early Cretaceous. We present new geochemical, geochronological (U-Pb zircon ages), and isotopic data from mafic dike intrusions in two peridotite massifs, and the results of our non-modal batch and aggregated fractional partial melting modeling of these peridotites and mafic dikes in order to constrain their melt evolution and melt-residua genetic relationships. Our data and interpretations, together with a new tectonic model, provide important insights into the geodynamic development of the western YZSZ.

REGIONAL GEOLOGY AND STRUCTURE OF THE WESTERN YZSZ

The YZSZ is divided into three structurally different segments along its nearly 2000-km-long east-west trend (Fig. 1). The eastern segment extends from Xigaze to the Eastern Himalaya syntaxis (or Namche Barwa...
Figure 1. Simplified geological map of the Himalaya and southern Tibet, showing the distribution of the Tethyan ophiolites, ophiolitic mélanges, and high-pressure (HP) rocks along the Yarlung Zangbo suture zone (modified after Xu et al., 2015, and references therein). GCT—Great Counter thrust; GT—Gangdese thrust; KKF—Karakorum fault; MBT—Main Boundary thrust; MCT—Main Central thrust; MFT—Main Front thrust; NBS—Namche Barwa syntaxis; NPS—Nanga Parbat syntaxis; STD—South Tibet detachment. Ophiolite massifs: BR—Baer; CBZ—Cuobuzha; DB—Dongbo; DJW—Dajiweng; DQ—Dangqiong; GZ—Gongzhu; JD—Jiding; KZ—Kazhan; LBS—Lubusa; ND—Nidar; PR—Purang; SG—Saga; SL—Shangla; SP—Spongthang; SS—Sangsang; XGGB—Xiugugabu; XGZ—Xigaze; ZB—Zhongba; ZD—Zedang; ZG—Zhaga; ZL—Zhalai.
syntax, NBS) in the east, and the western segment extends from Saga to the Ladakh batholith in the northwest (Fig. 1). The eastern YSZS is strongly affected by north–south–oriented contractional deformation, and the primary contacts between the Gangdese magmatic belt (Lhasa block), the YSZS, and the Tethyan Himalaya sequence in and across this segment have been largely modified by backthrusting and backfolding that developed during and after the India-Asia collision (Xu et al., 2015). South-vergent thrust faults within the central YSZS are superimposed by nearly east-west–extending normal faults and northeast-southwest– and northwest-southeast–oriented oblique-slip fault systems that continue into the Gangdese magmatic belt in the north and the Tethyan Himalaya sequence in the south. The central segment of the suture zone is also juxtaposed against the Xigaze forearc group sequence in the north that does not exist in the other two segments to the east and the west (Fig. 1).

Previously formed contractual structures in the western YSZS have been significantly modified and deformed by the dextral Karakorum fault and its splays (Fig. 1). The suture zone tectonic units here are juxtaposed against the continental Zhongba terrane.

The northwest-southeast–oriented, ~900-km-long and ~100-km-wide Zhongba terrane divides the western YSZS into the NB and southern belt (SB) (Fig. 1). The Zhongba terrane consists of metamorphosed, early Paleozoic–Mesozoic pelitic and carbonate rocks (Fig. 2), and is dissected by northwest-southeast–extending dextral, oblique-slip fault systems. The NB is juxtaposed against the Gangdese magmatic belt along the northwest-southwest–extending Karakorum fault zone and its local splays. The SB and its peridotite massifs tectonically overlies the Tethyan Himalaya sequence in the south.

Ophiolites within the NB are made mainly of large peridotite massifs, which occur discontinuously as lensoidal bodies in a serpentinite matrix mélangé. Major peridotite massifs within the NB include the Dajiweng, Kazhan, Baer, Cuobuzha, Zhalai, Gongzhu, and Saga ophiolite massifs (Fig. 1), which are commonly ~0.5–2 km in width and ~5–20 km in length. Ophiolitic subunits in these massifs include upper mantle peridotites, cumulate to layered gabbros, and massive lavas that are locally interlayered with submarine shale, radiolarian chert, and siliceous limestone. Pillow lavas and sheeted dikes have not been observed in any of the massifs within the NB along the western YSZS. The upper mantle peridotites are composed predominantly of serpentinized lherzolite and harzburgite in the Baer, Gongzhu, and Zhalai massifs (Lian et al., 2016, 2017; Zheng et al., 2017), and clinopyroxene harzburgite and harzburgite with minor dunite-chromitite occurrences in the Cuobuzha and Kazhan massifs (Liu et al., 2015c; Feng et al., 2015; Lian et al., 2016, 2017). Northwest-southeast–striking dolerite, clinopyroxenite, and microgabbro dikes crosscut these peridotites in almost all ophiolite massifs in the NB.

Ophiolites in the SB occur as much larger peridotite massifs (i.e., Dongbo, 400 km²; Purang, 650 km²; Xiugugaba, 700 km²; Dangjiong, 300 km²) that are intruded by mafic dike swarms and overlain by volcanogenic sedimentary rock sequences. These peridotite massifs are locally thrust northward onto the Zhongba terrane, and southward over an ophiolitic mélangé and the Tethyan Himalaya Sequence by bivergent thrust fault kinematics (Figs. 1 and 2). Peridotites are composed of lherzolite and harzburgite in the Xiugugaba (Bezard et al., 2011), Zhaga (also called South Gongzhucuo; L. Zhang et al., 2016), and eastern Purang massifs (Miller et al., 2003; Zhou et al., 2014; Li et al., 2015), and harzburgite with minor lherzolite and dunite in the Dongbo, Zhongba, and western Purang massifs (Fig. 2; Dai et al., 2011; Xu et al., 2011; C. Liu et al., 2014; Niu et al., 2015). Disseminated and massive chromitite deposits are commonly associated with dunite occurrences within the harzburgites in the SB massifs. Geochemical and petrogenetic modeling of the melt evolution of the Purang and Dongbo peridotites has shown that they were the products of partial melting of garnet-bearing spinel lherzolites in the subcontinental lithospheric mantle below northern India or beneath the Zhongba terrane (Liu et al., 2015a).

**TECTONIC ARCHITECTURE ACROSS THE NORTHERN BELT**

We examined the petrological architecture and the internal structure of the NB and the tectonic entities adjacent to the western YSZS along several north–south profiles between longitude 80°E and 81°E. We summarize here the three major tectonic units that are pertinent to the geology of the western YSZS.

**Ophiolite Massifs**

We have studied two of the most important ophiolite massifs (Baer and Cuobuzha) in the NB of the western YSZS (Fig. 2). These two massifs are separated by different strands of the northwest-southeast–extending Karakorum fault zone. The Baer massif is juxtaposed against carbonaceous shale-siltstone units of the Zhongba terrane in the south and Triassic slate and metasandstone units of the terrane in the north along strike-slip faults (Fig. 3A). Lower Cretaceous silicic tuffaceous rocks of the Zhongba terrane occur in a >300-m-wide, fault-bounded sliver within the Baer massif. We define the peridotite exposures to the north and to the south of this sliver as the North Baer and South Baer massifs, respectively. Intensely altered quartz-listwanite commonly occurs as an ~10-m-thick metasomatic cover at the surface of the serpentinized peridotites. The peridotites in both massifs are intruded by microgabbro and dolerite dikes. These dikes are common ~0.5–1.5 m in thickness and have well-developed chilled margins against their ultramafic host rocks. Previous in situ zircon dating of several of these dolerite and microgabbro dikes in the North Baer submassif yielded crystallization ages ranging from 128 Ma to 126 Ma (Liu et al., 2015b; Zheng et al., 2017). However, Liu et al. (2015b) reported the zircon U-Pb age of 128.1 ± 2.1 Ma yielded by merely 6 zircon grains with the SHRIMP (sensitive high-resolution ion microprobe) method; Zheng et al. (2017) reported 2 laser ablation–inductively coupled plasma–mass spectroscopy (LA-ICP-MS) zircon ages of 126.3 ± 2.4 and 125.6 ± 2.4 Ma, but their zircon ages span a large range, including 145, 139, 135–119, 117 Ma (Zheng et al., 2017). Moreover, the whole-rock geochemical data from Zheng et al. (2017), especially the heavy rare earth element (HREE) contents, are not only much lower than those of samples from the same location in North Baer (12Y61, this study), but all the mafic dikes from Dajiweng (Zhang et al., 2005), North Baer (Liu et al., 2015b), South Baer (this study), Cuobuzha (Liu et al., 2015c; this study) in the NB, and from Purang (Liu et al., 2010; Liu et al., 2011; Liu et al., 2013; Miller et al., 2003) and Xiugugaba (Bezard et al., 2011) in the SB. The age and geochemical data from Zheng et al. (2017), therefore, are not 100% reliable. In this study we collected additional dike rocks from both the North and South Baer massifs for new geochemical and isotopic analyses and for U-Pb zircon dating.

The Cuobuzha massif, ~20 km southeast of the Baer massif, is 0.4–1.3 km wide and ~6 km long in the NB, and consists mainly of peridotites intruded by 1–3-m-wide dolerite and microgabbro dike swarms. Microgabbroic dikes are locally to 10 m in width and have coarser grained centers. Peridotites are composed of clinopyroxene harzburgite, depleted harzburgite, and minor dunite. Previous in situ U-Pb zircon dating of 1–3-m-wide dolerite and microgabbro dikes rocks from the Cuobuzha massif yielded crystallization ages of 126 Ma and 127 Ma, respectively (Liu et al., 2015c). In this study we present new isotope analyses for the 1–3-m-wide microgabbro dike rocks, and for U-Pb zircon dating of a 5–10-m-wide microgabbro dike (31°22′52.88″N, 80°02′40.48″E, 4986 m) intruding the Cuobuzha peridotite.
Figure 2. Simplified geological map of the western part of the Yarlung Zangbo suture zone, showing the locations of two geological profiles (Fig. 3) and main tectonic units from north to south, consisting of Gangdese arc, northern ophiolite belt, Zhongba terrane, southern ophiolite belt, and Tethyan Himalaya. The eastern and western Purang submassifs are divided by the western margin of Lake Yungbwa.
Accretionary Prism Complex

The Cuobuzha massif is bound to the north by an ~1-km-wide chaotic turbiditic assemblage, composed of pelitic and carbonate rocks, tectonically interleaved with andesitic volcanic-volcaniclastic rocks and massive alkaline basaltic lava flows, which are locally stratigraphically overlain by radiolarian chert, siliceous limestone, and siliceous and silty shale (Figs. 3B, 3C). These rock assemblages are repeated in southwest-vergent thrust sheets and commonly show tight, asymmetric, and southwest-overturned folds. Sandstone, siltstone, and shale make up a turbiditic sequence, also containing blocks of andesitic volcanic rocks, reminiscent of External Ligurian mélanges from the northern Apennines and of modern chaotic deposits documented from active continental margins (Remitti et al., 2011; Festa et al., 2010, 2012). Alkaline basaltic rocks occur within the turbiditic chaotic assemblage as blocks or thrust sheets of 2–3-m-thick, vesicular massive lava flows directly overlain by hyaloclastites and chert. The compositions, chemostratigraphy, and lithological makeup of these alkaline lava–sedimentary rock associations are analogous to those of seamounts, which occur widely in the modern Pacific Rim accretionary prism complexes (Cawood et al., 2009) and in ancient, exhumed accretionary prism complexes within the Tethyan orogenic belt (i.e., Codegone et al., 2012; Sarifakioglu et al., 2017).

The structural anatomy and the lithological units in the turbiditic chaotic assemblage to the north of the Cuobuzha ophiolite massif are reminiscent of active continental margin accretionary prisms (Anma et al., 2011). We thus interpret this assemblage as a Cretaceous accretionary prism of the Gangdese magmatic arc and the associated trench system of the Eurasian active continental margin.

Gangdese Magmatic Arc Units

The accretionary prism complex is juxtaposed against the plutonic-volcanic rocks of the Gangdese magmatic arc along a network of west-northwest–east-southeast–oriented, subparallel dextral faults (Figs. 1 and

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**Figure 3.** (A) Geological profile of the Baer massif. (B) Geological profile of the Cuobuzha massif. (C) Panoramic view of profile B across the northern belt of the western Yarlung Zangbo suture zone.
Medium- to coarse-grained diorite-granodiorite rocks close to these faults show a strong mineral fabric defined by the lineation (112°) of magmatic biotite and hornblende. Lineation-parallel, fine-grained gabbro dikes intrude the diorite-granodiorite rocks and are in turn cut by subparallel, 2–3-m-wide aplite dikes (Fig. 3B). These structural relationships in the outcrop suggest tectonically controlled emplacement of the mafic and felsic intrusions in the southern edge of the Gangdese magmatic arc. Gabbros show compositional zoning, defined by their increased clinopyroxene contents toward the south.

These intrusive rocks are overlain by a magmatic breccia along a gently south-dipping normal fault (Fig. 3B). Highly angular and poorly sorted clasts in this breccia range in size from 5 to 20 cm, and are made of diorite, granodiorite, granite, gabbro, aplite, and andesitic rocks, all derived from the magmatic arc. The matrix of the breccia is mainly lithic sandstone-siltstone. The age of this breccia is unknown, but its tectonic occurrence on top of the magmatic arc plutonic rocks suggests that the timing of its formation may signal an important episode of extensional unroofing along the southern edge of the Gangdese magmatic arc.

ANALYTICAL METHODS

U-Pb Zircon Dating

Zircon grains are separated from a dolerite dike sample (12YL54–9) in the North Baer submassif, from a dolerite dike sample (12YL61–9) in the North Baer submassif, and from a microgabbro dike sample (13YL30–30) in the Cuobuzha massif for U-Pb dating. Zircons were extracted by an analytical method involving the use of laser ablation and inductively coupled plasma mass spectrometry (LA-ICP-MS) at the Institute of Mineral Resources, Chinese Academy of Geological Sciences (Beijing). Laser sampling was performed by a New Wave UP123 LA system. The spot size was set to 35 µm. The ablated material was carried into the ICP-MS by helium and argon gas streams. Time-dependent drifts of U-Th-Pb isotopic ratios were corrected by reference zircon GJ-1 as external standards (Hou et al., 2007). The Plešovice zircon was calibrated as another standard for unknown samples (Sláma et al., 2008). Isotopic ratios and element concentrations of zircons, concordia ages, and diagrams were calculated by Isoplot/Ex (3.00; Ludwig, 2003). The results are listed in Table 1.

Whole-Rock Major and Trace Element Geochemistry

We analyzed six dolerite dike samples (12YL54–9–30) from the South Baer submassif and seven dolerite dike samples (12YL61–2–8) from the North Baer submassif for major and trace element chemistry. Samples were prepared by removing the oxidized surface and visible secondary materials, then by crushing these cleaned samples to ~200 mesh. Major elements were analyzed by X-ray fluorescence spectrometry at the Chinese Academy of Geological Sciences (Beijing). The analytical accuracy is estimated to be 1% relative for SiO₂, 2% relative for the other oxides. Trace elements, including REEs, were determined by ICP-MS. Analytical uncertainties are estimated to be 10% for trace elements with abundances <10 ppm, and ~5% for those >10 ppm. Loss on ignition was determined by gravimetric techniques in which the sample is heated in a closed container and the water vapor is collected in a separate tube, condensed, and then weighed. The detection limit for H₂O and CO₂ is 0.01 wt%. The major and trace element compositions are given in Table 2.

Sr, Nd, and Pb Isotope Analyses

Sr, Nd, and Pb isotope analyses of five microgabbro samples (12YL60–7–12) from the North Baer submassif and five microgabbro samples (12YL74–2–6) from the Cuobuzha massif were performed on a VG 354 mass spectrometer with five collectors at the Center of Modern Analysis, Nanjing University, China. Rh, Sr, Sm, Nd, U, Th, and Pb were separated and purified through standard ion exchange techniques. The Sr and Nd isotopic ratios were normalized against ⁸⁶Sr/⁸⁶Sr = 0.1194 and ¹⁴⁶Nd/¹⁴⁴Nd = 0.7219, respectively. Sr standard NBS-987 yielded ⁸⁶Sr/⁸⁶Sr = 0.710233 ± 0.000006 (2σ) and Nd standard La Jolla gave ¹⁴³Nd/¹⁴⁴Nd = 0.511863 ± 0.000006 (2σ). Pb isotopic ratios were corrected by Pb standard NBS981: ²⁰⁶Pb/²⁰⁴Pb = 16.941 ± 0.008, ²⁰⁷Pb/²⁰⁴Pb = 15.487 ± 0.0011, ²⁰⁸Pb/²⁰⁴Pb = 36.715 ± 0.009. The analytical procedures for Nd, Pb, and Sr isotopic measurements were described in detail by Wang et al. (2007). The Sr-Nd-Pb isotopes data are listed in Table 3.

RESULTS OF ZIRCON GEOCHRONOLOGY

CL images of zircon grains from dolerite dike samples from the South and North Baer submassifs and a microgabbro dike sample from the Cuobuzha massif (Fig. 4) show subhedral habits with long prismatic to tabular and faceted edges. Grain sizes range from 60 to 150 µm in length, and the analyzed zircons exhibit weak oscillatory zoning and no mineral inclusions. Some of the Cuobuzha zircons are rimmed by metasomatic margins that are <2–10 µm wide. Zircons from the South Baer submassif are relatively fresh, and their Th/U ratios vary between 1.55 and 5.31 with an average of 2.90; 0.66–2.04 with an average of 1.49 for Cuobuzha and 0.41–1.77 with an average of 0.67 for North Baer zircon grains (Table 1). These CL images and Th/U ratios are comparable to those of magmatic zircons (Rubatto, 2002; Grimes et al., 2009). In a ²⁰⁷Pb/²³⁵U against ²⁰⁶Pb/²³⁸U concordia diagram (Fig. 5), in situ zircon grains from samples 12YL54–9 (South Baer), 12YL61–9 (North Baer), and 13YL30–30 (Cuobuzha) show weighted average ²⁰⁶Pb/²³⁸U ages of 122.1 ± 0.5 Ma, 124.8 ± 1.4 Ma, and 128.5 ± 1.6 Ma, respectively.

GEOCHEMICAL AND ISOTOPIC CHARACTERIZATION OF MAFIC DIKES

Major and Trace Element Geochemistry

Dolerite dike rocks analyzed for geochemistry commonly display porphyritic or ophitic textures. The majority of all these dike rocks consist mainly of subhedral to anhedral grains of subhedral to anhedral tabular plagioclase (modal ~45%–50%), clinopyroxene (~5%), and green to greenish-brown altered hornblende (modal ~40%–45%) with magnetite, ilmenite, and chlorite as accessory phases (~5%).

Dolerite dike samples (12YL61) from the North Baer submassif are characterized by higher SiO₂ (48.82–51.65 wt%), MgO (8.76–12.58 wt%), and total alkaline (3.84–5.24 wt%), and lower FeO total (9.66–7.40 wt%), K₂O (0.72–0.87 wt%), and Al₂O₃ (15.44–15.58 wt%), respectively. These TiO₂ contents are lower than those of typical ocean island basalt (OIB; 2.87 wt%), and normal mid-oceanic ridge basalt (N-MORB; 1.27 wt%) values (Sun and McDonough, 1989). Mg numbers [Mg# = 100 Mg/(Mg + Fe₉₅)]
| Spot     | Th (ppm) | U (ppm) | Th/U  | 206Pb/238U ± 1σ   | 207Pb/235U ± 1σ   | 208Pb/232U ± 1σ (Ma) |
|----------|----------|----------|-------|-------------------|-------------------|----------------------|
| 12YL54-9-1 | 111.31   | 67.46    | 1.65  | 0.13121 ± 0.00296 | 0.01894 ± 0.00017 | 120.94 ± 1.09        |
| 12YL54-9-2 | 315.47   | 184.56   | 1.71  | 0.12901 ± 0.00268 | 0.01891 ± 0.00019 | 120.78 ± 1.21        |
| 12YL54-9-3 | 85.02    | 94.82    | 0.90  | 0.12401 ± 0.00439 | 0.01892 ± 0.00036 | 120.84 ± 2.28        |
| 12YL54-9-4 | 123.81   | 64.58    | 1.92  | 0.13426 ± 0.00635 | 0.01920 ± 0.00026 | 122.63 ± 1.62        |
| 12YL54-9-5 | 93.02    | 61.36    | 1.52  | 0.13107 ± 0.00608 | 0.01925 ± 0.00030 | 122.94 ± 1.89        |
| 12YL54-9-6 | 172.90   | 85.01    | 2.03  | 0.12919 ± 0.00187 | 0.01906 ± 0.00014 | 123.94 ± 1.37        |
| 12YL54-9-7 | 83.44    | 63.34    | 1.30  | 0.13046 ± 0.00314 | 0.01906 ± 0.00020 | 121.69 ± 1.28        |
| 12YL54-9-8 | 131.45   | 64.31    | 2.04  | 0.13291 ± 0.00229 | 0.01891 ± 0.00015 | 120.75 ± 0.94        |
| 12YL54-9-9 | 123.71   | 68.85    | 1.80  | 0.13369 ± 0.00302 | 0.01920 ± 0.00019 | 122.59 ± 1.20        |
| 12YL54-9-10| 130.67   | 73.54    | 1.78  | 0.13339 ± 0.00164 | 0.01924 ± 0.00017 | 122.87 ± 1.10        |
| 12YL54-9-11| 308.46   | 161.23   | 1.91  | 0.12581 ± 0.00165 | 0.01903 ± 0.00014 | 121.52 ± 0.90        |
| 12YL54-9-12| 111.06   | 57.18    | 1.94  | 0.13461 ± 0.00225 | 0.01911 ± 0.00014 | 122.02 ± 0.91        |
| 12YL54-9-13| 84.44    | 112.66   | 1.75  | 0.12785 ± 0.00209 | 0.01922 ± 0.00016 | 122.71 ± 1.02        |
| 12YL54-9-14| 158.24   | 96.90    | 1.63  | 0.13100 ± 0.00177 | 0.01923 ± 0.00016 | 122.77 ± 1.02        |
| 12YL54-9-15| 132.79   | 117.37   | 1.13  | 0.13364 ± 0.00201 | 0.01933 ± 0.00022 | 123.45 ± 1.42        |
| 12YL54-9-16| 160.70   | 93.99    | 1.71  | 0.13778 ± 0.00286 | 0.01954 ± 0.00029 | 124.72 ± 1.84        |
| 12YL54-9-17| 198.93   | 126.62   | 1.57  | 0.13566 ± 0.00216 | 0.01935 ± 0.00024 | 123.54 ± 1.52        |
| 12YL54-9-18| 91.35    | 60.36    | 1.51  | 0.13595 ± 0.00294 | 0.01928 ± 0.00027 | 123.11 ± 1.68        |
| 12YL54-9-19| 87.41    | 104.21   | 0.84  | 0.14022 ± 0.00255 | 0.01987 ± 0.00027 | 126.81 ± 1.73        |
| 12YL54-9-20| 128.38   | 75.64    | 1.70  | 0.13024 ± 0.00219 | 0.01898 ± 0.00018 | 121.22 ± 1.15        |
| 12YL54-9-21| 86.85    | 64.97    | 1.34  | 0.13143 ± 0.00239 | 0.01894 ± 0.00017 | 120.95 ± 1.07        |
| 12YL54-9-22| 72.01    | 71.16    | 1.01  | 0.13684 ± 0.00218 | 0.01940 ± 0.00017 | 123.87 ± 1.05        |
| 12YL54-9-23| 120.60   | 60.84    | 1.81  | 0.13093 ± 0.00253 | 0.01921 ± 0.00022 | 122.68 ± 1.38        |
| 12YL54-9-24| 99.03    | 63.63    | 1.56  | 0.12815 ± 0.00267 | 0.01896 ± 0.00024 | 121.10 ± 1.52        |
| 12YL54-9-25| 83.30    | 48.29    | 1.72  | 0.13784 ± 0.00673 | 0.01954 ± 0.00054 | 124.73 ± 3.41        |
| 12YL54-9-26| 183.65   | 181.39   | 1.01  | 0.12765 ± 0.00164 | 0.01904 ± 0.00021 | 121.59 ± 1.32        |
| 12YL54-9-27| 94.77    | 86.90    | 1.09  | 0.13019 ± 0.00302 | 0.01921 ± 0.00028 | 122.68 ± 1.76        |

**TABLE 1. LASER ABLATION–INDUCTIVELY COUPLED PLASMA–MASS SPECTROMETRY ZIRCON U–Pb DATING**

FOR DOLERITE DIES FROM THE SOUTH YARLINGBO SULFIDES (12YL54–9) AND NORTH BAER (12YL54–9) SUBMASSS, AND FOR A MICROGABBRO DIE (13YL30–30) FROM THE CUOBZHUA MASSIF IN THE NORTHERN BELT OF THE WESTERN YARLINGBO SULFURE ZONE
| Samples        | South Baer | North Baer |
|----------------|------------|------------|
|                |            |            |
|                |            |            |
| SiO₂           | 48.65      | 45.99      |
| Al₂O₃          | 14.98      | 14.92      |
| Fe₂O₃          | 1.56       | 1.82       |
| FeO            | 8.17       | 7.90       |
| MnO            | 0.17       | 0.17       |
| MgO            | 6.30       | 6.37       |
| CaO            | 12.57      | 16.63      |
| Na₂O           | 2.40       | 1.00       |
| K₂O            | 0.37       | 0.14       |
| LOI            | 2.31       | 2.84       |
| Total          | 98.90      | 99.16      |
| LOI            | 2.31       | 2.84       |
| SiO₂           | 48.65      | 45.99      |
| Al₂O₃          | 14.98      | 14.92      |
| Fe₂O₃          | 1.56       | 1.82       |
| FeO            | 8.17       | 7.90       |
| MnO            | 0.17       | 0.17       |
| MgO            | 6.30       | 6.37       |
| CaO            | 12.57      | 16.63      |
| Na₂O           | 2.40       | 1.00       |
| K₂O            | 0.37       | 0.14       |
| LOI            | 2.31       | 2.84       |
| Total          | 98.90      | 99.16      |
| LOI            | 2.31       | 2.84       |

**Note:** Major elements are in weight percent; trace elements are in parts per million. Mg# = 100 Mg/(Mg + Fe); M = 100 Mg/(Mg + Fe²⁺).
and M values \([M = 100 \text{Mg}/(\text{Mg} + \text{Fe}^++)]\) for the North Baer samples range from 68.06 to 75.95 (72.41 on average) and 72.14 to 79.50 (76.09 on average), and for the South Baer samples range from 54.28 to 78.23 (61.30 on average) and 58.12 to 82.22 (65.99 on average), respectively (Table 2). The \(\text{SiO}_2\), \(\text{TiO}_2\), and \(\text{FeO}\) total values (Fig. 6).

These features are comparable to those of mafic dike rocks documented from dolerite dikes in the Purang ophiolite exposed along the southern belt of the western YZSZ (Fig. 7).

In the Nb/Y-Zr/TiO\(_2\) diagram, all analyzed dike samples plot within the basalt field (Fig. 7A). In a Co-Th diagram the analyzed samples plot in the basalt and basaltic andesite–andesite fields of the island arc tholeiite (IAT) series (Fig. 7B). These geochemical features are similar to those of microgabbro and dolerite dike rocks from the North Baer Massif (2015b; Zheng et al., 2017) and Cuobuzha massif (Liu et al., 2015c) in the NB of the western YZSZ (Fig. 7).

Chondrite-normalized REE patterns of the South Baer dolerite dike (12YL 54) and the North Baer dolerite dike samples (12YL 61) display typical N-MORB–like affinities, with a light (L) REE-depleted pattern in comparison to N-MORB values (0.96; Sun and McDonough, 1989). However, the North Baer dolerite dike samples have (0.51291–0.51295 and +8.58 to +9.28) (Table 3). These isotope ratios and values we have obtained from the Cuobuzha microgabbro dikes. How- ever, the North Baer microgabbro dike samples (12YL60) exhibit slightly lower age-corrected \(^{143}\text{Nd}/^{144}\text{Nd}\) \(t\) ratios of 0.51290–0.51294 in comparison to the age-corrected \(^{87}\text{Sr}/^{86}\text{Sr}\) ratios of 0.70428–0.70437 in comparison to the age-corrected \(^{5}$$\text{Sr}/^{86}\text{Sr}\) ratios (0.70443–0.70449) obtained from the Cuobuzha microgabbro dikes. However, the North Baer microgabbro dikes have relatively high \((^{143}\text{Nd}/^{144}\text{Nd})\) \(t\) ratios of 0.51290–0.51294 and \(\epsilon_{\text{Nd}}(t)\) values of +8.39 to +9.13, just as the Cuobuzha dolerite dike samples have (0.51291–0.51295 and +8.58 to +9.28) (Table 3). These isotope ratios and values we have obtained from the North Baer and Cuobuzha dike intrusions are slightly higher than those documented from dolerite dikes in the Purang ophiolite exposed along the SB of the western YZSZ, showing \((^{87}\text{Sr}/^{86}\text{Sr})\) ratios of 0.70489–0.705310, \((^{143}\text{Nd}/^{144}\text{Nd})\) ratios of 0.51290–0.51291, and \(\epsilon_{\text{Nd}}(t)\) values of +8.6 to +8.8 (Miller et al., 2003; Liu et al., 2015c).

The North Baer microgabbro dike rocks have initial ratios of \(^{206}\text{Pb}/^{208}\text{Pb} = 17.546–17.679, ^{207}\text{Pb}/^{206}\text{Pb} = 15.432–15.581, \) and \(^{208}\text{Pb}/^{206}\text{Pb} = 37.724–37.845, \) which are slightly lower than those of the Cuobuzha microgabbro dikes (17.752–17.984, 15.667–15.783, and 37.851–38.952, respectively). All these dike plots within the Indian Ocean N-MORB field with those displayed by many other mafic dike rocks documented from the NB of the western YZSZ (Figs. 7C, 8D).

**Sr-Nd-Pb Isotopes**

We have calculated the initial Sr, Nd, and Pb isotope ratios of our dike samples at 128 Ma, which represents the crystallization ages of a microgabbro dike from the North Baer submassif (128.1 ± 2.1 Ma, sample 12YL60; Liu et al., 2015b), and microgabbro and dolerite dikes from the Cuobuzha massif (128.5 ± 1.6 Ma, 13YL30–30, and 128.2 ± 1.4 Ma, sample 12YL74; Liu et al., 2015c). The North Baer microgabbro dike samples (12YL60) exhibit slightly lower age-corrected \(^{87}\text{Sr}/^{86}\text{Sr}\) ratios, \(^{143}\text{Nd}/^{144}\text{Nd}\) ratios of 0.70428–0.70437 in comparison to the age-corrected \(^{5}$$\text{Sr}/^{86}\text{Sr}\) ratios (0.70443–0.70449) obtained from the Cuobuzha microgabbro dikes. However, the North Baer microgabbro dikes have relatively high \((^{143}\text{Nd}/^{144}\text{Nd})\) \(t\) ratios of 0.51290–0.51294 and \(\epsilon_{\text{Nd}}(t)\) values of +8.39 to +9.13, just as the Cuobuzha dolerite dike samples have (0.51291–0.51295 and +8.58 to +9.28) (Table 3). These isotope ratios and values we have obtained from the North Baer and Cuobuzha dike intrusions are slightly higher than those documented from dolerite dikes in the Purang ophiolite exposed along the SB of the western YZSZ, showing \((^{87}\text{Sr}/^{86}\text{Sr})\) ratios of 0.70489–0.705310, \((^{143}\text{Nd}/^{144}\text{Nd})\) ratios of 0.51290–0.51291, and \(\epsilon_{\text{Nd}}(t)\) values of +8.6 to +8.8 (Miller et al., 2003; Liu et al., 2013).
Figure 4. Cathodoluminescence images of representative zircons. (A) From a dolerite dike (sample 12YL54–9) in South Baer. (B) From a microgabbro dike (sample 13YL30–30) in the Cuobuzha massif. (C) From a dolerite dike (sample 12YL61–9) in the North Baer ophiolite in the northern belt. The circles show spots of laser ablation–inductively coupled plasma–mass spectroscopy dating; spot numbers and U-Pb ages are listed near the individual zircon grain.
Figure 5. Zircon U-Pb concordia diagrams. (A, B) Dolerite from South Baer. MSWD—mean square of weighted deviates. (C, D) Microgabbro from the Cuobuzha massif. (E, F) Dolerite from the North Baer ophiolite in the western Yarlung Zangbo suture zone, southern Tibet.
Figure 6. Plots of major elements and Ni against MgO for the mafic dike samples in the northern belt.
Mantle Melt Source

The Mg#s of the analyzed mafic dike rocks (average 61.47, 72.26 for the South and North Baer, respectively, and 64.56 for the Cuobuzha massifs; Liu et al., 2015c) are slightly higher than those of primitive MORBs, with average Mg#s of 52.8–59.7, from the Atlantic, Pacific, and Indian ocean spreading centers (Wilkinson, 1982). However, the observed negative correlations of the SiO$_2$, TiO$_2$, and FeO$_{tot}$ contents and the positive correlations of the Al$_2$O$_3$ and Ni values against the MgO contents in the dike rocks (Fig. 6) are comparable to the worldwide modern MORB patterns, which show decreasing Ti, Mn, Na, P, and increasing Al, Ca, Ni, Cr values with increasing Mg#s (Wilkinson, 1982). N-MORB extrusive rocks in the External Liguride ophiolites in the Apennines (Italy) (Montanini et al., 2008) and in the Alpine ophiolites in Corsica (France) display similar correlations similar to those of our dike samples from the South and North Baer and Cuobuzha massifs. The External Liguride and Corsican ophiolites represent a mid-ocean ridge–generated Jurassic oceanic lithosphere (Saccani et al., 2008; Dilek and Furnes, 2011, 2014). Our samples and these modern and ancient N-MORB upper crustal rocks are interpreted to have formed by various degrees of partial melting of depleted and heterogeneous mantle sources (Wilkinson, 1982, and references therein).

In chondrite-normalized REE diagrams, magmas generated from partial melting of a garnet-lherzolite mantle source generally exhibit relatively high fractionation of HREEs due to the presence of residual garnet. Magmas originated from partial melting of a spinel lherzolite source display flat REE patterns (Aldanmaz et al., 2000; Workman and Hart, 2005). All our analyzed dike samples display flat N-MORB–type REE patterns in the chondrite-normalized diagrams, indicating a depleted mantle origin (Figs. 8A, 8B). However, they also show a conspicuous HREE fractionation pattern in comparison to middle REEs. We interpret this geochemical feature as a garnet signature with high (Sm/Yb)$_N$ ratios, as documented from basaltic lavas of the Alpine Corsica ophiolites (1.1–2.6, most >1.5; Saccani et al., 2008), and from aphyric basaltic lavas of the Mid-Atlantic Ridge (0.98–1.72; Niu et al., 2001). These signatures may be a manifestation of either the initiation of partial melting in the garnet-peridotite stability field deep in the mantle, or partial melting of a lithospheric mantle source that contains networks of garnet-pyroxenite veins (Saccani et al., 2008). The average (Sm/Yb)$_N$ ratio is 1.23 and 1.20 for the mafic dike rocks from the South and North Baer submassifs, respectively. We have also calculated the mean ratio for the Cuobuzha microgabbro dikes (1.25; Liu et al., 2015c) and for the dolerite dikes from the North Baer submassif (1.20; Liu et al., 2015b). These (Sm/Yb)$_N$ ratios are markedly lower than those of the gabbro intrusions in the Corsica ophiolites. Therefore, this comparative analysis and evaluation of the (Sm/Yb)$_N$ ratios indicate that primitive magmas of the mafic dike intrusions in the NB reflect very little contribution from partial melting of garnet peridotites. The main mantle source for their magmas therefore appears to be composed mainly of spinel lherzolite.

The Sm/Yb ratios would not be changed during partial melting of a lherzolitic mantle source because both Sm and Yb have similar partition coefficients, but La/Sm ratios and Sm contents of melts produced from such a lherzolitic mantle source may decrease (Aldanmaz et al., 2000; Pearce, 2008). In the Sm/Yb versus La/Sm diagram, all the mafic dike rocks from the Cuobuzha and South and North Baer massifs along the NB of the western YZSZ plot slightly above the spinel lherzolite melting curve and close to N-MORB, indicating that their magmas may have been produced by ~7%–15% partial melting of a spinel lherzolite source with an N-MORB affinity (Fig. 9). We thus infer that mafic dike intrusions within the peridotite massifs in the NB were originated from magmas, derived predominantly from partial melting of a depleted N-MORB spinel lherzolite mantle source with minor garnet-bearing relics.
Figure 8. Chondrite-normalized rare earth element patterns and normal mid-oceanic ridge basalt (N-MORB; Sun and McDonough, 1989) normalized rare element diagrams for mafic dikes from the northern belt in the western Yarlung Zangbo suture zone, Tibet; backarc basalts (BAB; Gale et al., 2013), forearc diabases, and boninites from the Mariana arc (Reagan et al., 2010); Lau island arc tholeiite (IAT) (Hergt and Woodhead, 2007). FAB-D—forearc basalt-diabase; MB—Mariana boninite.
Modeling of Non-Modal Batch and Fractional Partial Melting

Scientists have applied non-modal batch melting equations to evaluate and to model variations in REE concentrations during partial melting of depleted MORB mantle, primitive enriched mantle sources (Aldanmaz et al., 2000; Stracke et al., 2003; Liang and Liu, 2016). The upper mantle peridotites in the Cuobuzha massif are composed mainly of depleted harzburgite, clinopyroxene harzburgite, and minor dunite, the first two of which are intruded by microgabbro and dolerite dikes (Liu et al., 2015c; Feng et al., 2015, 2017). Harzburgites appear to have undergone various degrees of partial melting, melt-rock interactions, or fractionation (Feng et al., 2017). However, the nature and origin of the inferred melts or melts and their association with the generation of mafic dike magmas are unclear. To approach this problem, we have modeled and compared the REE contents of partial melts with Cuobuzha mafic dikes and residual harzburgites. Our results are shown in Tables 5 and 6 and Figure 10. We also calculated the REE contents of melts created by non-modal instantaneous fractional melting (equation after Shaw, 1970) from a depleted MORB mantle source (see GSA Data Repository Item 1).

\[
C_{L}/C_{O} = 1/([D_{O} + F(1-P)]).
\]

\[
C_{S}/C_{O} = [(D_{O} - PF)/(1-F)]\times[1/(D_{O} + F(1-P))].
\]

\[
C_{L}/C_{O} = 1/F\times[(1-(1-PF/D_{O}))^{3}P].
\]

\[
C_{S}/C_{O} = 1/(1-F)/(1-PF/D_{O})^{3P}.
\]

\[
D_{O} = x_{1}kd_{1} + x_{2}kd_{2} + x_{3}kd_{3} + \ldots
\]

\[
P = y_{1}kd_{1} + y_{2}kd_{2} + y_{3}kd_{3} + \ldots
\]

\[
C_{L}, C_{O}, \text{and } C_{S} \text{ are trace element concentrations in the melt, in the original mantle rock, and in the residue mantle rock, respectively. } D_{O} \text{ represents the bulk distribution coefficient, and is calculated by using Equation 5. The term } x_{i} \text{ represents a starting mode, the weighted mean of the solid partition coefficient of mineral } i. \text{ and } y_{i} \text{ means the proportion of phase 1 in melt; } kd_{i} \text{ represents the Nernst partition coefficient of mineral } i.
\]

| TABLE 4. MINERAL/MELT PARTITION COEFFICIENTS USED FOR PARTIAL MELTING MODELS |
|-------------------|-----------------|-----------------|-----------------|-----------------|
|                  | DMM             | Di (partition coefficients) |
|                  | Olivine         | Orthopyroxene    | Clinopyroxene   | Spinel          |
| La                | 0.206           | 0.0002           | 0.0031          | 0.0800          | 0.0006          |
| Ce                | 0.722           | 0.00007          | 0.0031          | 0.1500          | 0.0006          |
| Nd                | 0.815           | 0.00042          | 0.00052         | 0.2600          | 0.0006          |
| Sm                | 0.299           | 0.0011           | 0.0016          | 0.4900          | 0.0010          |
| Eu                | 0.115           | 0.0005           | 0.0090          | 0.5500          | 0.0009          |
| Gd                | 0.419           | 0.0011           | 0.0065          | 0.6000          | 0.0006          |
| Dy                | 0.525           | 0.0017           | 0.0110          | 0.6500          | 0.0015          |
| Er                | 0.347           | 0.00109          | 0.0210          | 0.7200          | 0.0030          |
| Yb                | 0.347           | 0.0240           | 0.0380          | 0.7100          | 0.0045          |
| Lu                | 0.054           | 0.0200           | 0.0400          | 0.7200          | 0.0045          |

Note: DMM—depleted mid-oceanic ridge basalt mantle after Ewart et al. (1994); partition coefficients after Stracke et al. (2003).
TABLE 5. MODELING RESULTS OF THE REE CONTENTS OF MELTS CREATED BY NON-MODAL BATCH AND AGGREGATED FRACTIONATION PARTIAL
MELTING FROM A DEPLETED MORB MANTLE SOURCE

| REE | 12Y | 12YL | DM |
|-----|-----|------|----|
| La  | 1.89 | 2.45 | 0.206 |
| Ce  | 5.47 | 7.16 | 0.722 |
| Nd  | 5.19 | 6.87 | 0.815 |
| Sm  | 1.88 | 2.45 | 0.299 |
| Eu  | 0.72 | 0.96 | 0.115 |
| Gd  | 2.64 | 3.32 | 0.419 |
| Dy  | 3.10 | 3.87 | 0.525 |
| Er  | 2.00 | 2.47 | 0.347 |
| Yb  | 1.76 | 2.17 | 0.347 |
| Lu  | 0.27 | 0.33 | 0.054 |

Residues created by non-modal batch partial melting with various degrees (F)

| CH | DH | DM |
|----|----|----|
| La | 0.03 | 0.02 | 0.206 |
| Ce | 0.07 | 0.05 | 0.722 |
| Nd | 0.07 | 0.04 | 0.815 |
| Sm | 0.06 | 0.03 | 0.299 |
| Eu | 0.03 | 0.01 | 0.115 |
| Gd | 0.18 | 0.07 | 0.419 |
| Dy | 0.26 | 0.09 | 0.525 |
| Er | 0.24 | 0.07 | 0.347 |
| Yb | 0.04 | 0.01 | 0.054 |

Note: REE (rare earth elements) are in parts per million. MORB—mid-oceanic ridge basalt. DM—depleted mantle (after Ewart et al., 1994). 12YL74 and 12YL78 represent the mean compositions of Cuobuzha microgabbro dike samples (n = 7) and dolerite dike samples (n = 7), respectively (after Liu et al., 2015c). CH and DH represent the mean compositions of Cuobuzha clinopyroxene harzburgites (n = 8) and depleted harzburgites (n = 5), respectively (after Feng et al., 2017).

TABLE 6. MODELING RESULTS OF THE REE CONTENTS OF MELTS AND MANTLE RESIDUES CREATED BY AGGREGATED FRACTIONATION PARTIAL
MELTING FROM A DEPLETED MORB MANTLE SOURCE

| REE | 12Y | 12YL | DM |
|-----|-----|------|----|
| La  | 1.89 | 2.45 | 0.206 |
| Ce  | 5.47 | 7.16 | 0.722 |
| Nd  | 5.19 | 6.87 | 0.815 |
| Sm  | 1.88 | 2.45 | 0.299 |
| Eu  | 0.72 | 0.96 | 0.115 |
| Gd  | 2.64 | 3.32 | 0.419 |
| Dy  | 3.10 | 3.87 | 0.525 |
| Er  | 2.00 | 2.47 | 0.347 |
| Yb  | 1.76 | 2.17 | 0.347 |
| Lu  | 0.27 | 0.33 | 0.054 |

Residues created by non-modal aggregated fractionation partial melting with various degrees (F)

| CH | DH | DM |
|----|----|----|
| La | 0.03 | 0.02 | 0.206 |
| Ce | 0.07 | 0.05 | 0.722 |
| Nd | 0.07 | 0.04 | 0.815 |
| Sm | 0.06 | 0.03 | 0.299 |
| Eu | 0.03 | 0.01 | 0.115 |
| Gd | 0.18 | 0.07 | 0.419 |
| Dy | 0.26 | 0.09 | 0.525 |
| Er | 0.24 | 0.07 | 0.347 |
| Yb | 0.04 | 0.01 | 0.054 |

Note: REE (rare earth elements) are in parts per million. MORB—mid-oceanic ridge basalt. DM—depleted mantle (after Ewart et al., 1994). 12YL74 and 12YL78 represent the mean compositions of Cuobuzha microgabbro dike samples (n = 7) and dolerite dike samples (n = 7), respectively (after Liu et al., 2015c). CH and DH represent the mean compositions of Cuobuzha clinopyroxene harzburgites (n = 8) and depleted harzburgites (n = 5), respectively (after Feng et al., 2017).
element 1 between mineral 1 and the melt. F shows the degree of partial melting, and P represents the bulk distribution coefficient for the melt assemblage of minerals weighted by the proportion that each mineral contributes to the melt, and is calculated by Equation 6.

The modeling results, especially the HREE contents, of non-modal batch partial melting show that magmas of the Cuobuzha microgabbro dike rocks were produced from ~12%–14% degree of partial melting of a spinel lherzolite mantle source (Fig. 10A), and are nearly consistent with our observations (~9%–12%) in the La/Sm versus Sm/Yb diagram (Fig. 9), which is slightly lower than 10%–13% degree created by modeling of aggregated fractional melting (Fig. 10B). Cuobuzha dolerite dike rocks reflect ~7%–8% degree of non-modal batch partial melting (Fig. 10A), compatible with ~7%–12% degree partial melting as also observed in the La/Sm versus Sm/Yb diagram (Fig. 9). The Cuobuzha depleted harzburgites are compositionally similar to residual mantle rocks after 17%–20% degree calculated by non-modal batch partial melting of a depleted spinel lherzolite source (Fig. 10C), which is basically consistent with 10%–17% degree partial melting of the Cuobuzha depleted harzburgites as proposed by Feng et al. (2017). This result, however, is obviously higher than those of modeling melts created by non-modal batch partial melting of a depleted spinel lherzolite source (Fig. 10C).
with 11%–13% degree of aggregated fractional melting (Fig. 10D). The Cuobuzha clinopyroxene harzburgites represent the residues after 5%–8% degree modeled by non-modal batch partial melting (Fig. 10C), which is similar to the modeling results of 5%–9% degree created by aggregated fractional melting (Fig. 10D), and consistent with the results of 5%–8% degree modeled by the spinel and olivine compositions (Feng et al., 2017). Our partial melting modeling results confirm that Cuobuzha clinopyroxene harzburgites represent residues after a low degree (5%–8%) of non-modal batch partial melting from a spinel lherzolite source; this process mainly dominated the primitive magma formation of Cuobuzha dolerite dikes. Depleted harzburgites extracted ~17%–20% degree melts from the same mantle source. The Cuobuzha microgabbrro magmas formation may not pertain to the simple end-member melting models, and likely derived from the hybrid mantle sources of spinel lherzolite and remelting clinopyroxene harzburgite.

Isotopic Fingerprinting of Mafic Dike Magmas

The North Baer and Cuobuzha microgabbrro dikes have $\varepsilon_{\text{Nd}}(t)$ values of +8.39 to +9.28 and (87Sr/86Sr)$_t$ ratios of 0.70433–0.70489 that are comparable to those of dolerite dikes ($\varepsilon_{\text{Nd}}(t)$ values of +8.6 to +8.8 and (87Sr/86Sr)$_t$ ratios of 0.70300–0.70531) in the Purang ophiolite in the SB (Fig. 11A; Miller et al., 2003; Liu et al., 2013). The $\varepsilon_{\text{Nd}}(t)$ values of mafic extrusive rocks and dolerite dikes from the Angren, Deji, Jiding, and Pengcang massifs in the central YZSZ range from +8.3 to +9.9, and the (87Sr/86Sr)$_t$ ratios range from 0.70304 to 0.70484 (Niu et al., 2006; L.L. Zhang et al., 2016). The $\varepsilon_{\text{Nd}}(t)$ values of the Luobusa basalts and dolerite dikes from the eastern YZSZ range from +5.0 to +10.5 and the (87Sr/86Sr)$_t$ ratios range from 0.70349 to 0.70672 (Fig. 11A; Zhong et al., 2006; C. Zhang et al., 2016). In the (206Pb/204Pb)$_t$ versus (208Pb/204Pb)$_t$ diagram, the Northern Baer microgabbrro and the Cuobuzha microgabbrro dike rocks, Deji and Angren basalts and dolerite dikes in the central YZSZ (Niu et al., 2006), and the basaltic lavas in the eastern YZSZ (Zhong et al., 2006) all plot in the field of the Indian Ocean MORB (Fig. 11B). However, the Pb and Nd isotopic values of the analyzed mafic dikes from the NB and of similar dikes and basalts from the rest of the YZSZ deviate significantly from the trends of subducted sediments (Fig. 11). The positive $\varepsilon_{\text{Nd}}(t)$ values and Pb isotopes showing Indian Ocean MORB-type isotopic signatures indicate that the Baer and Cuobuzha mafic dikes originated from a depleted mantle source. However, their slightly high (87Sr/86Sr)$_t$ ratios and enrichment of fluid-mobile elements suggest that this inferred mantle source was modified by hydrous fluids derived from subducted-altered oceanic crust (Fig. 11A; Escrig et al., 2009).

Subduction Influence in Melt Evolution

Arc magmas mostly originate from the subarc mantle wedge, which is commonly modified by fluids and melts from subducted oceanic crust and overlying pelagic sediments (Münker et al., 2004). HFSEs such as Nb, Ta, Zr, Hf, and Ti relative to LILEs such as Rb, Sr, Ba, Pb, Th, and LREEs are not commonly transported into aqueous fluids (Pearce and Norry, 1979), so they exhibit conservative behavior during elements transfer.

Figure 11. Age (128 Ma) corrected Sr-Nd and Pb isotopic data for mafic dikes intruding peridotites in the northern belt (NB), Tibet. SB—one southern belt. Mafic rocks are from Semail in Oman (Godard et al., 2006). Indian mid-ocean ridge basalt (MORB) values are after X. Liu et al. (2014); Lau Basin basalts are after Escrig et al. (2009); subducted sediments are after Plank and Langmuir (1998) and X. Liu et al. (2014). NHRL—Northern Hemisphere reference line.
at the slab–mantle wedge interface, and the abundances of HFSE in arc rocks reflect those in the mantle wedge. In contrast, LILEs and LREEs have nonconservative properties in subduction zones due to their higher mobility in subducted fluids (Keppler, 1996). When the subduction-related fluids metasomatise the mantle wedge, island arc basalts would inherit the properties of being depleted in HFSEs and enriched in LILEs with regard to MORB.

HFSE and HREE patterns, with the exceptions of mobile elements such as Rb, Ba, Cs, U, K, Sr, P and Pb, of mafic dike rocks can be used effectively to decipher possible subduction influence in their melt evolution (Pearce and Cann, 1973; Dilek and Furnes, 2011, 2014; Pearce, 2014). In Figures 8E and 8F, we have placed HFSEs and HREEs in an order by their incompatibility during mantle melting. All the microgabbro and dolerite dike samples from the NB display negative Nb, Ti, and slightly negative Hf anomalies, which resemble those of subduction zone-related basalts in suprasubduction zone settings (Figs. 8E, 8F).

In order to evaluate the nature and the specific setting of subduction influence in the magmatic evolution of the dike rocks, we have plotted the multielement diagrams (Fig. 8) of the general trends and fields of backarc basin basalts (BAB), Lau Basin IATs, Mariana forearc basalt-diabase, and Mariana boninites. The BAB trend in these plots represents an average composition of backarc basin basalts recovered from the Lau, Manus, Mariana, Scotia, and Woodlark basins (Gale et al., 2013). BABs are generally characterized by slightly high SiO₂ and Al₂O₃ and low FeO and TiO₂ contents. Their TiO₂ contents decrease and Al₂O₃ values increase with increasing MgO contents as a result of their moderately high magmatic water contents, which lead to suppression of plagioclase crystallization relative to olivine and clinopyroxene (Langmuir et al., 2006; Eason and Dunn, 2015). The investigated mafic dikes in the NB of the western YZSZ and those geochemical features are significantly different from those of BAB and their magmatic derivatives. The FeO contents of the mafic dike rocks are much higher than FeO contents; their LREE, Th, and Nb contents are remarkably lower than those of BAB (Figs. 8A, 8C). The differences are further substantiated by the former showing negative Nb and Ti anomalies in the REE patterns (Fig. 8E) and suggest that the mafic dikes did not form in a backarc basin environment.

The REE and trace element abundances and patterns of the investigated mafic dikes are similar, however, to those of IAT lavas from the Lau island arc (Figs. 8B, 8C, 8E; Hergt and Woodhead, 2007), but different from those of diabase, basalt, and boninite rocks recovered from the Izu-Bonin-Mariana (IBM) forearc setting (Reagan et al., 2010). Extrusive rocks recovered from the IBM forearc environment are enriched in fluid-mobile elements and LILEs, are distinctly depleted in HFSEs and HREEs, and show stronger negative Nb anomalies in comparison to Th (Figs. 8D, 8F) on N-MORB–normalized multielement diagrams. Boninitic lavas or dikes, which represent the latest phase of subduction initiation magmatism in the IBM forearc setting and in many Tethyan ophiolites (Dilek et al., 2008; Dilek and Thy, 2009; Dilek and Furnes, 2014; Pearce, 2014; Saccani et al., 2017), have not been observed in the western part of the YZSZ. These signatures together with the various Sr, Nd, and Pb isotopes suggest that magmas of the mafic dikes intruding the Cuobuzha and Baer peridotites were influenced by island arc–type fluids. This interpretation is consistent with the geochemical and Re-Os isotopic data of peridotites from the Cuobuzha, Dongbo, and Purang massifs, suggesting that their upper mantle peridotites had interacted with arc-related fluids and melts (Xu et al., 2011; Niu et al., 2015; Su et al., 2015; Feng et al., 2017).

Enrichment in fluid-mobile elements commonly results in high Ba/Nb ratios in melt compositions, whereas enrichment in melt-mobile elements is characterized by high La/Sm values (Pearce and Stern, 2006; Escrig et al., 2009). The majority of the mafic dike samples from both the SB and NB plot in the field of BAB-like Lau Basin basalts in the La/Sm versus Ba/Nb diagram (Fig. 12). They display depletion in incompatible elements, indicated by their low La/Sm ratios, but exhibit enrichment in the fluid-mobile elements, indicated by their high ratios of Ba/Nb (Escrig et al., 2009). Thus, these geochemical signatures indicate that magmas of the analyzed mafic dikes in the NB peridotite massifs were influenced by subduction-derived fluids.

### Tectonic Setting of Magmatism

HFSE and HREE values of mafic rocks in ophiolites are helpful to discriminate possible tectonic settings of their melt and magmatic evolution, because they are relatively immobile during medium to high degrees of mantle melting, low- to high-grade metamorphism, and moderate hydrothermal alteration (Pearce, 2008, 2014; Dilek and Furnes, 2009, 2011, 2014). We have made several tectonic discrimination diagrams based on the HFSE concentrations of the analyzed mafic dike rocks and similar dike intrusions in the NB as reported by other researchers (Fig. 13). In a Ti-Zr-Y diagram, almost all dike samples plot in the field of ocean-floor basalts (Fig. 13A), suggesting that they represent typical ocean tholeiitic basalt. However, when plotted on a Zr/Zr/Y proxy diagram, the same samples are between the overlapping fields of island arc basalts and MORBs (Fig. 13B). Fluids or melts derived from a subducted slab and its thin sediment veneer are commonly enriched in Th, leading to high Th/Yb ratios in produced magmas (Pearce, 2014). In a Th/Yb versus Nb/Nb diagram (Fig. 13C), the investigated mafic dike rocks scatter above the MORB-OIB mantle array and plot close to the oceanic arc field. This inference is further supported by the V/Ti ratios between 20 and 30 (Fig. 13D), typical of mixed MORB and IAT melts. Based on all these geochemical and isotopic features of the analyzed mafic dikes and their host peridotites, we infer that magmas of these dikes evolved from partial melting of a spinel lherzolite mantle source that produced tholeiitic basaltic melts beneath an embryonic island arc–forearc spreading center.

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**Figure 12.** La/Sm versus Ba/Nb diagram modified from Escrig et al. (2009) for mafic dikes in the northern belt and southern belt, Tibet. Mafic dikes are from Purang (Liu et al., 2011; Liu et al., 2013) and Xiugugabu (Bezard et al., 2011).
Subduction-derived fluids facilitated the partial melting of this relatively fertile mantle source and caused fluid-mobile element enrichment of the produced basaltic melts.

**TECTONIC MODEL**

In Figure 14 we present a geodynamic model depicting the tectonomagmatic evolution of the western YZSZ with an emphasis on the development of the NB to the west of longitude 82°E. In the late Jurassic, the Neotethys Ocean basin to the south of Eurasia included two subbasins separated by the Zhongba terrane, a ribbon continent with a likely origin from the northern edge of East Gondwana (Fig. 14A). The ocean floor of the northern subbasin was strewn with seamounts and was subducting northward beneath the Lhasa block along the southern edge of Eurasia.

The Gangdese magmatic arc started developing along this active margin during the late Triassic–early Jurassic and included both plutonic and volcanic suites in an ~1000-km-long, east-west-trending belt (Zhang et al., 2007; Kang et al., 2014). The accretionary prism developed at this continental margin contained detrital material largely derived from the Gangdese magmatic arc and the Lhasa continental block, as well as slivers of seamounts scraped from the downgoing Neotethys slab. Such seamount fragments and thrust sheets exist within the accretionary prism complex bounding the Cuobuzha peridotite massif in the study area.

We infer that rapid rollback of the subducting Neotethys slab in the Early Cretaceous caused upper plate extension at the leading edge of the Lhasa block and exhumation of the continental lithospheric mantle to shallow depths. This process set up asthenospheric convection beneath and partial melting of the upper mantle rocks of the southward-migrated,
extended arc-forearc front (Fig. 14B). Asthenospheric upwelling and injection of high-temperature asthenospheric material may have fertilized the mantle wedge peridotites, as widely documented from the active continental margins of the western Pacific Ocean, where lherzolitic peridotites predominate in mantle wedges (Arai et al., 2007; Ishikawa et al., 2007). In the Timor-Tanimbar arc-trench system in the Melanesia region the slab rollback and the associated arc-forearc spreading took place ca. 8–5 Ma, nearly coeval with the arrival of the Australian continental margin at the trench (Berry and McDougall, 1986). Some researchers have proposed that encroachment of the Australian continental margin on the subduction zone likely induced an asthenospheric mantle flow and asthenospheric melt injection into the mantle wedge in the upper plate (Ishikawa et al., 2007). This scenario is similar to the arrival of the Zhongba terrane at the Gangdese subduction zone in the early Cretaceous (ca. 130 Ma; Fig. 14B).

Our partial melting models and geochemical investigations of the Cuobuzha peridotites in the NB ophiolites have demonstrated that clinopyroxene harzburgites were the residues of ~5%–8% partial melting of an N-MORB spinel lherzolite with minor networks of garnet-bearing veins. Slab rollback-induced extension in the arc-trench system led to partial melting of these peridotites and produced an oceanic crust, complete with lower and upper crustal components. With continued subduction and rollback, downdropping and altered Neotethys oceanic crust became dehydrated, and released fluids percolated through the overlying mantle wedge, triggering further partial melting. Basaltic melts were then enriched in fluid-mobile elements, producing magmas with arc-like signatures, and they were injected into the residual peridotites to form 122.1 ± 0.5 Ma South Baer doleritic dike, 124.8 ± 1.4 Ma North Baer doleritic dike, and 128.5 ± 1.6 Ma Cuobuzha microgabbro dike intrusions during their ascent (Fig. 14B). The oceanic slab subduction process lasted for at least 7 m.y., and occurred before 129 Ma. These multiple partial melting events left depleted harzburgite and clinopyroxene harzburgite with minor dunite in the mantle wedge (Feng et al., 2017; this study).

The collision of the Zhongba terrane with the trench ca. 115 Ma and its underplating beneath the accretionary prism and the active margin of the Lhasa block during the late Mesozoic. See text for discussion. AP—accretionary prism; NB—northern belt; SB—southern belt; SCLM—subcontinental lithospheric mantle; TH—Tethyan Himalaya; ZT—Zhongba terrane.
architecture of the NB in the western YSZSZ by the latest Cretaceous. The oblique collision of greater India with Eurasia starting in the early Paleogene superimposed further shortening and strike-slip deformation in and across the Zhongba terrane, NB, and the Gangdese magmatic arc–Lhasa block. Development of the dextral Karakorum fault zone along the collision interface between India and the Gangdese magmatic arc throughout the Paleogene–Neogene resulted in significant along-strike attrition and deformation across the NB and the Zhongba terrane.

CONCLUSIONS

1. Peridotite masses and their mafic dike intrusions in the NB of the western YSZSZ provide significant geochemical and time constraints for the evolution of the Tethyan mantle lithosphere north of East Gondwana during the late Mesozoic. Spatial and temporal relationships of these ultra-mafic-mafic rock assemblages with the late Mesozoic tectonic units of the active continental margin of Eurasia indicate that the magmatic evolution of these oceanic rocks within the Neotethyan realm took place in close proximity to this tectonic setting.

2. Harzburgite, clinopyroxene harzburgite, and minor lherzolite peridotites exposed in the NB ophiolites represent the lherzolitic mantle of the Eurasian continental margin that was situated in the mantle wedge above a north-dipping Neotethyan slab in the late Mesozoic. Rapid rollback of this slab caused upper plate extension, asthenospheric upwelling, and fertilization of these peridotites beneath the forearc setting. Impingement of the approaching Zhongba terrane at the trench may have also induced asthenospheric flow and melt injection into the mantle wedge in the upper plate. The NB peridotites and their melt products are compositionally different from their counterparts in the SB of the western YSZSZ. Predominantly harzburgitic and Iherzolitic peridotites in the SB are the partial melting products of spinel garnet Iherzolites of a lherzolitic mantle below the Zhongba terrane or beneath the northern edge of the Indian continent.

3. Basaltic to basaltic andesite–andesite dike swarms in the NB peridotites have a tight age range of 128–122 Ma (zircon U-Pb dates) indicating a significant episode of subduction-influenced magmatic flow through an N-MORB mantle, as evidenced by their negative Nb, Ta, and Ti anomalies and isotopic characteristics. These dike rocks represent IAT melt products, produced by ~7%–12% partial melting of a predominantly spinel lherzolite, as documented in their counterparts in the SB of the western YSZSZ. A significant episode of subduction-influenced magmatic flow through an N-MORB mantle, as evidenced by their negative Nb, Ta, and Ti anomalies and isotopic characteristics. These dike rocks represent IAT melt products, produced by ~7%–12% partial melting of a predominantly spinel lherzolite, as documented in their counterparts in the SB of the western YSZSZ.

4. Collision of the ~1000-km-long Zhongba terrane with the arc-trench system of the Eurasian continental margin in the early–late Cretaceous played a major role in the emplacement and exhumation of the NB ophiolites and peridotite masses, long after the India–Asia continental collision during the Paleogene. These tectonic events marked the terminal closure of the northern branch of Neotethys to the west of longitude 82°E (in the present coordinate system). The results of our study in the NB suggest major variations in the nature and tectonic setting of oceanic lithosphere formation during the late Jurassic–Cretaceous, as well as in the modes and mechanisms of ophiolite emplacement along the >3000-km-long east-west span of Neotethys.

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