Rapid forearc spreading between 130 and 120 Ma: Evidence from geochronology and geochemistry of the Xigaze ophiolite, southern Tibet

Jingen Dai a,⁎, Chengshan Wang a, Ali Polat b, M. Santosh c,d, Yalin Li a, Yukui Ge a

a State Key Laboratory of Biogeology and Environmental Geology, School of Earth Sciences and Resources, Research Center for Tibetan Plateau Geology, China University of Geosciences, Beijing 100083, China
b Department of Earth and Environmental Sciences, University of Windsor, Windsor, ON, N9B 3P4 Canada
c Division of Interdisciplinary Science, Faculty of Science, Kochi University, Akebono-cho, Kochi 780-8520, Japan
d School of Earth Science and Resources, China University of Geosciences, Beijing 100083, China

1. Introduction

Ophiolites are fragments of ancient oceanic lithosphere that are emplaced at convergent plate margins (e.g., Dewey and Bird, 1971; Dilek and Furnes, 2011). Although ophiolites can be generated in different tectonic settings (Dilek and Furnes, 2011), the vast majority forms in a supra-subduction-zone (SSZ) environment (e.g., Pearce, 2003; Pearce et al., 1984; Shervais, 2001; Whattam et al., 2011; Vellappa et al., 2012). The recognition of most ophiolites as of an SSZ origin is largely based on crustal rocks possessing geochemical characteristics of island arcs as well as the occasional occurrence of boninites (e.g., Crawford, 1989; Pearce et al., 1984; Xia et al., 2012), and depleted mantle rocks displaying typical U-shaped REE patterns (e.g., Dai et al., 2011b; Polat et al., 2006; Whattam et al., 2011; Zhou et al., 2005).

The oceanic crust in the SSZ type is generated in three specific tectonic settings: backarc, island arc, and forearc. The association of Mid-Ocean Ridge Basalt (MORB)-like and Island Arc Basalt (IAB)-type mafic rocks in most ophiolites (Colakoglu et al., 2012; Dai et al., 2012; Shervais et al., 2005; Whattam and Stern, 2011) has been interpreted to form in distinct tectonic settings (Bezard et al., 2011; Dilek, 2003; Dilek and Furnes, 2011) or in a complex backarc system (Dubois-Côté et al., 2005; Furnes et al., 2012; Hébert et al., 2012). Nonetheless, recent investigations indicate that all magmatic components (i.e., MORB-like and IAB) can be generated in the forearc extension setting resulting from slab rollback during subduction initiation (Dilek and Thy, 2009; Dilek et al., 2008; Shervais, 2001; Shervais and Choi, 2012; Stern and Bloomer, 1992; Whattam and Stern, 2011). The forearc remnants are often analogous to the modern intra-oceanic subduction systems such as that of Izu–Bonin–Mariana (Reagan et al., 2010), but most fossil forearc-type ophiolites lack an island arc which has been widely attributed to an infant arc. The Yarlung Zangbo Suture Zone (YZSZ), southern Tibet, consisting of the Gangdese arc, the Xigaze forearc basin, the Yarlung Zangbo ophiolite (YZO), and the accretionary prism, is an ideal association that also includes the Gangdese arc and the Xigaze forearc basin. This study reports new geochronological and geochemical data for this ophiolite to revisit its geodynamic and petrogenetic evolution. The Xigaze peridotites have low CaO and Al2O3 contents and U-shaped Rare Earth Element (REE) patterns, suggesting that they are residues after moderate to high degrees of partial melting and were modified by infiltration of Light Rare Earth Element (LREE)-enriched boninitic melts. The Xigaze crustal rocks belong to two groups: Mid-Ocean Ridge Basalt (MORB)-like rocks and boninitic rocks showing a uniform LREE depletion and flat to LREE enrichment on chondrite-normalized patterns, respectively. Geochemically, both groups show the influence of subducting oceanic slab-derived fluids. LA-ICPMS zircon U–Pb and Lu–Hf analyses from dolerite and quartz diorite dikes, which intruded into the mantle peridotite, and dolerite sheeted sills show that they were generated between 127 and 124 Ma. The zircons possess positive εHf(t) values ranging from +7.5 to +17.3. Taking into account the geological and geochronological characteristics of the central-western YZSZ, we propose that ophiolites in this region formed in a forearc spreading setting through rapid slab rollback during subduction initiation between 130 and 120 Ma. Following this stage of spreading, the forearc was stabilized and the zone of melting migrated beneath the Gangdese arc producing the voluminous Late Cretaceous granitoids displaying depleted mantle-type Hf isotopic compositions. Our model provides a new explanation for the generation and evolution of forearc-type ophiolites.

© 2013 Elsevier B.V. All rights reserved.
Fig. 1. (A) Schematic tectonic map of southern Tibet showing the ophiolitic massifs within the YZSZ (after Dai et al., 2012). Zircon U–Pb ages of the mafic rocks and hornblende ⁴⁰Ar/³⁹Ar ages of the amphibolites across the whole YZSZ are also presented. Major faults: GCT, Great Counter thrust; ZGT: Zhongba–Gyangze thrust; GT: Gangdese thrust. Inset is the simplified tectonic map of Tibetan Plateau showing major sutures (Chung et al., 2005). The major sutures are: AKSZ, A’nenmaqin–Kunlun suture zone; JSSZ, Jinshajiang suture zone; BNSZ, Bangong–Nujiang suture zone; YZSZ, Yarlung Zangbo Suture Zone. MO, Myitkyina ophiolite, Myanmar (Yang et al., 2012). (B) Geological map of the Xigaze area (modified from Wang et al., 1987) showing the locations of five dated samples.
between India and Eurasia following the late Cretaceous–Paleogene transition, the Yarlung Zangbo ophiolite belt are critical for testing the above models. In this study, we present new zircon U–Pb and Lu–Hf data, and whole-rock major and trace element data for the crustal rocks and mantle peridotites from the Xigaze ophiolite. The objectives of this study are as follows: 1) to elucidate the origin and the timing of the magmatism; 2) to determine the tectonic setting of the Xigaze ophiolite; 3) to compare their ages and tectonic setting with those of other ophiolitic massifs of the central-western YZSZ; and 4) to discuss the geodynamic evolution within the framework of the regional tectonics of the YZSZ. Our new tectonic model indicates that the central-western part of the Yarlung-Zangbo ophiolite belt might have formed rapidly in a forearc setting along the southern margin of the Gangdese arc during subduction initiation at 130–120 Ma. This rapid crustal accretion sheds new light on the timing and development of other SSZ ophiolites around the world.

2. Regional geology

The Tibetan Plateau is an amalgamation of several blocks separated by major suture zones, such as A'neiqian–Kunlun, Jinchajiang, Bangong–Nujiang, and Yarlung Zangbo sutures (Fig. 1A inset; Chung

### Table 1
Summary of ages and tectonic settings of the Yarlung Zangbo Ophiolite and Myanmar ophiolite.

<table>
<thead>
<tr>
<th>Locality, Rock type</th>
<th>Method</th>
<th>Age (Ma)</th>
<th>Tectonic setting</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Myitkyina ophiolite,</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Myanmar</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eastern segment</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Central segment</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dazhuo</td>
<td>Dolerite dike</td>
<td>Zircon U–Pb</td>
<td>126 ± 1.3</td>
<td>Forearc (SSZ)</td>
</tr>
<tr>
<td></td>
<td>Radiolarian fauna</td>
<td>Radiolarian</td>
<td>-130 to -112</td>
<td>SSZ</td>
</tr>
<tr>
<td></td>
<td>Quartz diorite</td>
<td>Zircon U–Pb</td>
<td>126 ± 1.5</td>
<td>SSZ</td>
</tr>
<tr>
<td><strong>Bainang</strong></td>
<td>Amphibolite</td>
<td>Hornblende 40Ar–39Ar</td>
<td>127 ± 2.3</td>
<td>SSZ</td>
</tr>
<tr>
<td></td>
<td>Quartz diorite</td>
<td>Zircon U–Pb</td>
<td>123 ± 1.5</td>
<td>SSZ</td>
</tr>
<tr>
<td><strong>Deji</strong></td>
<td>Dolerite dike</td>
<td>Zircon U–Pb</td>
<td>124 ± 1.1</td>
<td>Forearc (SSZ)</td>
</tr>
<tr>
<td></td>
<td>Dolerite sheeted dike</td>
<td>Zircon U–Pb</td>
<td>126 ± 4.7</td>
<td>SSZ</td>
</tr>
<tr>
<td><strong>Qunrang</strong></td>
<td>Gabbro</td>
<td>Zircon U–Pb</td>
<td>126 ± 0.8</td>
<td>SSZ</td>
</tr>
<tr>
<td></td>
<td>Gabbro dikes</td>
<td>Zircon U–Pb</td>
<td>127 ± 1.5</td>
<td>Forearc (SSZ)</td>
</tr>
<tr>
<td></td>
<td>Gabbro</td>
<td>Zircon U–Pb</td>
<td>128 ± 2</td>
<td>SSZ</td>
</tr>
<tr>
<td></td>
<td>Amphibolite</td>
<td>Hornblende 40Ar–39Ar</td>
<td>127 ± 2.2</td>
<td>SSZ</td>
</tr>
<tr>
<td><strong>Nangming</strong></td>
<td>Dolerite</td>
<td>Zircon U–Pb</td>
<td>125 ± 3.4</td>
<td>SSZ</td>
</tr>
<tr>
<td><strong>Sangiang</strong></td>
<td>Amphibolite</td>
<td>Hornblende 40Ar–39Ar</td>
<td>128 ± 2.6</td>
<td>SSZ</td>
</tr>
<tr>
<td></td>
<td>Dolerite</td>
<td>Zircon U–Pb</td>
<td>128 ± 2.6</td>
<td>SSZ</td>
</tr>
<tr>
<td><strong>Saga</strong></td>
<td>Amphibolite</td>
<td>Hornblende 40Ar–39Ar</td>
<td>128 ± 2.5</td>
<td>SSZ</td>
</tr>
</tbody>
</table>

**Western segment**

| Zhongba                  | Dolerite      | Zircon U–Pb               | 125 ± 0.9                      | Forearc (SSZ)            | Dai et al. (2011b, 2012)      |
|                         | Dolerite      | Zircon U–Pb               | 122 ± 2.4                      | SSZ                      | Bezard et al. (2011), Xia et al. (2011) |
| **Yungbwa**             | Tholeiitic basalt | Whole-rock Sm–Nd   | 147 ± 25                       | Originally mid-ocean-ridge subsequently SSZ | Li et al. (2008), Liu et al. (2010, 2011), Miller et al. (2003), Xia et al. (2011) |
|                         | Tholeiitic dikes | Hornblende 40Ar–39Ar  | 152 ± 33                       | SSZ                      | Guilmette et al. (2009)       |
|                         | Dolerite      | Zircon U–Pb               | 120 ± 2.3                      | SSZ                      | Li et al. (2008), Liu et al. (2010, 2011), Miller et al. (2003), Xia et al. (2011) |
|                         | Dolerite      | Zircon U–Pb               | 118 ± 1.8                      | SSZ                      | Li et al. (2008), Liu et al. (2010, 2011), Miller et al. (2003), Xia et al. (2011) |
| Dongbo                  | Gabbro        | Zircon U–Pb               | 130 ± 3.0                      | SSZ                      | Xiong et al. (2011)          |
|                         | Pyroxenite dikes | Zircon U–Pb               | 130 ± 0.5                      | SSZ                      | Xiong et al. (2011)          |
|                         | Gabbro dikes   | Zircon U–Pb               | 128 ± 1.1                      | SSZ                      | Xiong et al. (2011)          |

and references therein) predict that the magmatism would have lasted for more than 40 Ma. Therefore, systematic geochronologic and detailed geochemical investigations in different domains of the Yarlung-Zangbo ophiolite belt are critical for testing the above models. In this study, we present new zircon U–Pb and Lu–Hf data, and whole-rock major and trace element data for the crustal rocks and mantle peridotites from the Xigaze ophiolite. The objectives of this study are as follows: 1) to elucidate the origin and the timing of the Xigaze ophiolite; 2) to determine the tectonic setting of the Xigaze ophiolite; 3) to compare their ages and tectonic setting with those of other ophiolitic massifs of the central-western YZSZ; and 4) to discuss the geodynamic evolution within the framework of the regional tectonics of the YZSZ. Our new tectonic model indicates that the central-western part of the Yarlung-Zangbo ophiolite might have formed rapidly in a forearc setting along the southern margin of the Gangdese arc during subduction initiation at 130–120 Ma. This rapid crustal accretion sheds new light on the timing and development of other SSZ ophiolites around the world.

2. Regional geology

The Tibetan Plateau is an amalgamation of several blocks separated by major suture zones, such as A’neiqian–Kunlun, Jinchajiang, Bangong–Nujiang, and Yarlung Zangbo sutures (Fig. 1A inset; Chung
The southernmost Yarlung Zangbo Suture Zone (YZSZ) has been widely considered as the youngest suture that represents the remnants of the Neo-Tethyan oceanic lithosphere accreted to Eurasia (Allègre et al., 1984; Hébert et al., 2012). The YZSZ includes four basic lithotectonic units and from north to south these are: 1) the Gangdese arc, 2) the Xigaze forearc basin, 3) the Yarlung Zangbo ophiolite, and 4) the accretionary prism (Fig. 1A).

The Gangdese arc, located in the southern part of the Lhasa block, is composed of the latest Triassic to Eocene granitoids (Chu et al., 2006, 2011; Ji et al., 2009; Wen et al., 2008; Zhang et al., 2010b; Zhu et al., 2009a) and Cretaceous to Tertiary terrestrial volcanic rocks of the Linzizong Group (Lee et al., 2009; Mo et al., 2008). Geochronological studies suggest that the plutonic rocks of the Gangdese arc formed in discrete magmatic events at ~205–152, ~109–80, ~65–41 and ~33–13 Ma (Ji et al., 2009). The Xigaze forearc basin is located at the southern part of the Gangdese arc in an east–west oriented belt, and extends over 500 km in length from Renbu in the east and Zhongba in the west. The width of the Xigaze forearc basin ranges from 22 km to 50 km (Fig. 1A; Wang et al., 2012). It is composed of late Aptian to Coniacian flysch-dominated Xigaze Group and Santonian to early Ypresian shallow marine Cuojiangding Group (Dürr, 1996; Wan et al., 1998; Wang et al., 2012; Wu et al., 2010). The accretionary prism is a narrow elongate belt up to 1000 km long and 10–50 km wide (Fig. 1A), and consists of rocks derived from the ophiolitic complex represented by highly deformed and schistose serpentinitized pyroxene peridotite together with a tectonic mélange of Triassic to Eocene sediments (Wang et al., 2012). In the eastern part, the late Triassic Langjixue Group of turbidite sequence contains mudstone, siltstone, and sandstone. It has whole-rock Sm–Nd (Dai et al., 2008) and zircon U–Pb–Hf isotopic compositions (Li et al., 2010) similar to those of the Lhasa block.

The Yarlung Zangbo ophiolite (YZO) comprises well preserved to disrupted ophiolitic massifs. The YZO is divided into three segments: the eastern, the central and the western segments. The eastern segment includes the Luobusa and the Zedang massifs. The central segment contains at least twelve massifs varying from the Renbu to the Saga. The western segment consists of seven massifs ranging from the Zhongba to the Dajiwen (Table 1; Fig. 1A).

Fig. 2. Field photographs of the Xigaze ophiolite. (A) Harzburgite outcrop; (B) dolerite dike cutting mantle peridotite; (C) quartz diorite–granite dike invaded into the mantle peridotite; (D) dolerite dike within isotropic gabbro; (E) sheeted dike or silt; (F) pillow lava.
3. Field occurrence and petrography

The Xigaze ophiolite belongs to the central segment, extending continuously from the Renbu to the Ngamring massifs (Fig. 1A). Our field investigations and sample collection in this study were focused around the Dazhuqu, Deji, Qunrang, Luqu, and Jiding massifs (Fig. 1B). In the early 1980s, several investigations on petrology, metamorphic conditions and structural history were carried out in this area by Chinese and French geologists (e.g., Burg et al., 1987; Girardeau and Mercier, 1988; Girardeau et al., 1985a, 1985b, 1985c; Göpel et al., 1984; Nicolas et al., 1981; Pozzi et al., 1984; Wang et al., 1987).

The Xigaze ophiolite displays well preserved sections from mantle to crustal rocks, together with the overlying sedimentary strata. The abyssal sediments consist of mudstone, chert, felsic tuffs and fine-grained volcaniclastic deposits. They are termed locally as the Chongdoi Formation of the Xigaze Group (Cao, 1981), and are exposed along the northern margin of the Xigaze ophiolite (Fig. 1B) with the best outcrops at Qunrang. The planktonic foraminifera from the limestone at the top of the Chongdoi Formation (Wu, 1984) indicates depositional age of no later than Cenomanian, whereas the radiolarian ages assign a relatively short (<10 Ma) interval from late Barremian to late Aptian (Ziabrev et al., 2003).

The Xigaze ophiolite is dominated by mantle peridotites (Fig. 1B), and are mainly composed of variably serpentinized harzburgites (Fig. 2A), associated with dunite and lherzolite (Hébert et al., 2003; Nicolas et al., 1981). These rocks are abundantly intruded by mafic dikes (Fig. 2B), and by quartz diorite–granitoid dikes sporadically in the Dazhuqu and Deji massifs (Fig. 2C; Malpas et al., 2003; Wang et al., 1987). A few fresh harzburgite outcrops show mainly porphyroclastic texture, characterized by millimeter-sized porphyroclasts of olivine and orthopyroxene. Orthopyroxene contains exsolution lamellae of clinopyroxene and occurs in close spatial association with spinel, and shows replacement by olivine (Fig. 3A). The spinel usually appears as brown to dark red vermicular crystals.

The mafic sequence of the Xigaze ophiolite is particularly thin (about 2 km) (Girardeau et al., 1985a) probably resulting from the strong post-tectonic attenuation (Burg et al., 1987). Only a few cumulate gabbro layers were found in the Dazhuqu, Bainang and Jiding massifs (Fig. 1B; Wang et al., 1987). The isotropic gabbros exhibit typical gabbroic texture (Fig. 3B), altered to varying degrees, and are cut by late dolerite dikes (Fig. 2D). The dolerite presents a complex of dikes or sills (Fig. 2E; Wang et al., 1987). Under thin sections, the rocks show typical ophitic texture (Fig. 3C). Opaque minerals (Fe–Ti oxides) are also common in the dolerite samples (Fig. 3C). Both pillowed and massive basalts are observed in the field (Fig. 2F), with secondary veins and amygdules of carbonate, quartz, and chlorite. Quartz diorite–granitoid dikes intruded into sheeted sills and mantle peridotite (Fig. 2C). One quartz diorite sample (DJ11-22) was collected from the Deji massif for zircon U–Pb and whole-rock geochemical analyses. The rock is composed of plagioclase, quartz, hornblende, and biotite (Fig. 3D).

4. Analytical methods

The least-altered samples were powdered to less than 200 mesh for whole-rock analyses. Fifteen ultramafic, sixteen mafic and one quartz diorite samples were analyzed. Major element analyses were performed on a Rigaku RIX 2000 spectrometer by X-ray fluorescence
Whole-rock trace element compositions were determined by an Agilent-7500a inductively coupled plasma mass spectrometry (ICP-MS) at State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Beijing. The samples (50 mg powder of each sample) were dissolved by a mixture of HF and HNO₃ in Teflon digesting vessels on a hot-plate for 24 h. This procedure was repeated using smaller amounts of acids for 12 h. After digestion, samples were dried, refluxed with 6 N HNO₃, and heated again to incipient dryness. The USGS reference materials (W-2, AGV-2) were used to monitor the analytical accuracy. These results indicate that the accuracy is better than 10% for most elements, with many elements agreeing to within 2% of the recommended values (Tables S1 and S2; only presenting the results of W-2). Analytical details are reported in Song et al. (2010). The whole-rock major- and trace-element data from mantle rocks and crustal rocks are given in Supplementary Tables S1 and S2, respectively.

U–Pb zircon dating was performed on five representative samples (DJ11-22, JD07, DZQ11-03, DJ11-14 and DJ11-01). Zircon concentrates were separated from samples using standard density and magnetic separation techniques. Individual crystals were handpicked and were mounted in epoxy resin along with standard zircon. Zircon U–Pb dating was carried out by LA-ICP-MS at the Key Laboratory of Continental Collision and Plateau Uplift, Institute of Tibetan Plateau Research, Chinese Academy of Sciences. Laser analyses were performed using a NewWave and ATL 193 nm ArF excimer laser ablation system (UP193FX). During our analyses, the laser-ablation spot diameter was 35 μm. Element and isotope ion-signal intensities were acquired by Agilent 7500a ICP-MS instrument. Plesovice natural zircon references (Sláma et al., 2008) were used as external standard for the matrix-matched calibration of U–Pb dating. NIST SRM 612 reference glasses were analyzed as external standard for the trace element content calibration. Off-line isotope ratios and trace element concentrations were calculated by GLITTER_Ver4.0. Common Pb correction and ages of the samples were calibrated and calculated using ComPbCorr#3.15 (Andersen, 2002). U–Pb concordia diagrams, weighted mean calculations and probability density plots of U–Pb ages were made using Isoplot 3.7 (Ludwig, 2008). Zircon U–Pb ages are given in Supplementary Table S3.

In situ zircon Lu–Hf isotopic measurements (DJ11-22, JD07, and DZQ11-03) were carried out on a Neptune multi-collector ICP-MS equipped with a GeoLas-193 laser-ablation system with laser pulse frequency of 8 Hz at the Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing. These analyses were performed on the dated spots of each zircon grain. The diameters of laser ablated pits were 40 μm for samples DZQ11-03 and JD07, and 60 μm for sample DJ11-22, which were larger than that of preexisting pits (35 μm) produced by the U–Pb dating. Instrumental conditions and data acquisition were similar to those described by Wu et al. (2006) and Xie et al. (2008). Measured 176Hf/177Hf ratios were normalized to 176Hf/177Hf = 0.7219. The εHf(t) values and TDM were calculated following Griffin et al. (2000) using the 176Lu decay constant given by Blichert-Toft and Albarède (1997). The zircon Hf isotope data are listed in Supplementary Table S4.

5. Results

5.1. Major and trace elements

The majority of the Xigaze peridotite samples analyzed in this study have undergone intense serpentinization as inferred from their high loss-on-ignition (LOI) values (LOI = 9.0–15.5 wt.%), and also petrographic observations. Sample LQ05 is relatively fresh with low LOI (Table S1). Major elements of both the peridotite and the crustal rock are normalized to 100% on an anhydrous basis for the following discussion. The rocks are depleted in Al₂O₃ and CaO contents. Mg-numbers [Mg/(Mg + Fe) × 100] vary from 90.9 to 92.8 (Table S1).

Samples QR07, QR11-05, and DJ11-11 have relatively high total REE concentrations, especially for LREE (Fig. 5A). Their high LREE contents might reflect late stage contamination in the crust rather than mantle processes and thus they are excluded from the following discussion. All other samples show very low REE concentrations (Table S1). On chondrite-normalized diagrams, they exhibit typically U-shaped REE patterns, characterized by a highly fractionated HREE to MREE segment and significant enrichment of LREE relative to MREE (except for samples LQ05 and DJ11-13) (Fig. 5A).
All the crustal rocks from the Xigaze ophiolite are relatively fresh, with LOI values varying from 1.4 to 4.3 wt.%. Generally, dikes and isotropic gabbros, dolerites, and pillow lavas have broadly similar whole-rock major element compositions (Table S2). Four samples (DJ11-01, DJ11-06, DJ11-09 and JD07) of the dikes have high MgO contents (8.6–15.6 wt.%) and low TiO₂ contents (0.2–0.5 wt.%), and plot within or near the boninitic field (Fig. 4B; Le Bas, 2000). These samples also have low contents of Zr and Y (Table S2), resembling
Thus, the geochemistry of these four samples indicates a boninite affinity. Sample DJ11-22 (quartz diorite) has low MgO (3.7 wt.%) and low TiO₂ contents (0.4 wt.%), but with high SiO₂ contents (61.9 wt.%) (Fig. 4A; Table S2). This diorite sample is excluded from the discussion of petrogenesis. The MORB-like rocks have SiO₂ contents ranging from 47.2 to 57.4 wt.%, TiO₂ from 0.6 to 2.5 wt.% and MgO from 4.8 to 11.8 wt.% (Table S2).

Total REE contents of the boninitic rocks are lower than those of MORB-like rocks (Table S2). The boninitic rocks and a quartz diorite (DJ11-22) show relatively flat to LREE enriched chondrite-normalized patterns (Fig. 5C), whereas the MORB-like rocks display slight to significant LREE depletion, similar with N-MORB (Fig. 5B). Except for samples DJ11-22 and DJ11-01 with obvious Eu anomalies (Eu/Eu* = 0.65 and 0.75, respectively), all the other samples show very slight to no Eu negative anomalies (Fig. 5B and C, and Table S2). On an MORB-normalized diagram, the MORB-like rocks generally display enrichment in LILE and Pb, and show negative Nb and Ta anomalies (Fig. 6A). Similarly, the boninitic dikes also show LILE enrichment, but larger negative Nb and Ta anomalies (Fig. 6B).

5.2. Zircon U–Pb ages

Among the five representative samples from different units of the Xigaze ophiolite selected for zircon U–Pb dating, sample DJ11-22 is a quartz diorite that intruded into the mantle peridotite of the Deji massif (Fig. 1B). Zircons from the quartz diorite predominantly show euhedral, long-prismatic shape and relatively large size with lengths of 120–250 μm and a width of 90–150 μm. In CL images, these zircons display broad magmatic oscillatory zoning to weak or no zoning (Fig. S1). Their Th/U ratios range from 0.14 to 0.51. The majority of analyzed twenty grains plot on or slightly below the concordia, and yield a weighted mean age of 123.3 ± 1.5 Ma (MSWD = 2.4; Fig. 7; Table S3).

Sample JD07 is a gabbroic dike that cuts through the mantle peridotite in the Jiding massif (Fig. 1B). Zircons from this sample are much smaller than those in sample DJ11-22, with length of 80–150 μm and width of 50–80 μm. The grains are euhedral with long-prismatic shape, and display broad magmatic oscillatory zoning to no or weak zoning (Fig. S1). Their Th/U ratios vary from 0.33 to 0.64 with one exception (Th/U = 1.28). Most of the twenty analyzed...
grains plot on the concordia, and yield a weighted mean age of 127.1 ± 3.5 Ma (MSWD = 3.3; Fig. 7; Table S3).

Samples DZQ11-03 and DJ11-01 are dolerite dikes that intruded the mantle section at the Dazhuqu and the Deji massifs, respectively (Fig. 1B). Zircons from sample DZQ11-03 show various sizes, with a length of 100–200 μm, and a width of 50–100 μm. They show sector and wide oscillatory zoning and euhedral, long-prismatic shape (Fig. S1). Their Th/U ratios are between 0.16 and 0.95. Twenty zircon grains in sample DZQ11-03 yield a weighted mean age of 126.1 ± 1.3 Ma (MSWD = 3.1; Fig. 7). However, we could not obtain sufficient number of good quality zircons from sample DJ11-01. Most of the analyzed zircons are fragments of euhedral, long-prismatic grains, but some of them show obvious old cores. The Th/U ratios of analyzed spots are between 0.19 and 1.16. Seven of eleven analyzed spots yield a weighted mean age of 124.9 ± 1.1 Ma (MSWD = 0.54; Fig. S2; Table S3) excluding the inherited zircons.

Sample DJ11-14 was collected from dolerite sheeted sill at the Deji massif (Fig. 1B). Like sample DJ11-01, sample DJ11-14 yields only eleven good grains showing euhedral, long-prismatic shape and weak zoning. The Th/U ratios of analyzed spots are between 0.12 and 0.87. Seven of the eleven analyzed spots yield a weighted mean age of 126.5 ± 4.7 Ma (MSWD = 10.6; Fig. S2; Table S3).

All the above ages are interpreted as the crystallization age of the rocks and represent the timing of magmatic activity. Within errors, all the samples display similar ages ranging from 124 to 127 Ma, indicating their relatively rapid formation.

5.3. Zircon Lu–Hf data

Zircons from samples DJ11-22, JD07 and DZQ11-03 were measured for Lu–Hf isotopes. Some of zircons have generated high errors of $^{176}$Hf/$^{177}$Hf (2σ is larger than 0.000050), and thus are excluded

![Fig. 7. Concordia plots and weighted average of $^{206}$Pb/$^{238}$U ages for three representative samples (DJ11-22, JD07 and DZQ11-03). Gray bar in the weighted average plot represents the mean age.](image-url)
from the following discussions (Table S4). Sixteen grains from sample DJ11-22 exhibit a range of initial $^{176}\text{Hf}/^{177}\text{Hf}$ ratios from 0.282993 to 0.283192, and high positive $\epsilon_{\text{Hf}}(t)$ values of +9.8 to +17.3 (Fig. S1 and Table S4). Their Hf TDM model ages vary from 185 to 458 Ma (except for two zircons of 89, 119 Ma, which are younger than their corresponding zircon U–Pb ages). Sample JD07 yields fourteen reliable Lu–Hf data with initial $^{176}\text{Hf}/^{177}\text{Hf}$ ratios ranging from 0.283038 to 0.283174. They also show positive $\epsilon_{\text{Hf}}(t)$ values of +11.8 to +16.9 and young Hf TDM model ages of 148–232 Ma (except for two zircons of 111, 116 Ma). Nine zircons from sample DZQ11-03 yield initial $^{176}\text{Hf}/^{177}\text{Hf}$ ratios of 0.282923–0.283151, positive $\epsilon_{\text{Hf}}(t)$ values of +7.5 to +16.0 and young Hf TDM model ages of 148–376 Ma with one old age of 561 Ma (Table S4). In general, the Lu–Hf isotopic compositions of zircons from our samples are broadly similar (Fig. 8).

### 6. Discussion

#### 6.1. Effects of alteration

The Xigaze mantle peridotites have experienced significant alteration as shown by high LOI values and strong serpentinization. The Xigaze crustal rocks (lavas and plutonic rocks) have relatively low LOI values, indicating that they have undergone various degrees of alteration after their emplacement. The concentration of some mobile trace elements could have been modified under conditions of low-temperature alteration. Before discussing petrogenesis, we will evaluate the effects of alteration on the geochemistry of the Xigaze ophiolite.

Zirconium is widely used as an alteration-independent index of geochemical compositions because it is one of the least mobile elements during low-temperature alteration (Polat and Hofmann, 2003; Polat et al., 2002; Tang et al., 2012). For peridotites, the abundances of element U, Rb, Cs, and Sr do not correlate with Zr abundances (Fig. S3), suggesting that they were mobile during post-magmatic processes. Conversely, the HREE (such as Gd, Lu, Yb), Hf, and Th contents show good correlation with Zr (Fig. S3), suggesting that they were immobile during metamorphism and alteration. Except for three samples with higher LREE concentration (DJ11-11, QR11-05 and QR07), the other samples show good correlations between concentrations of LREE (such as La, Sm) and Zr (Fig. S3), implying that the effects of alteration on these elements are minor. These observations are consistent with the parallel REE patterns (Fig. 5A). Similarly, for crustal rocks, abundances of most LILE such as K, Rb, Ba, Cs, Sr, and U show large variations and do not correlate well with Zr contents (Fig. S4), indicating that they were probably affected by alteration processes.

The high field strength elements (Hf, Ti, Nb, Ta), REE (e.g. La, Yb), transition metal elements (such as Cr, Ni), as well as Y, Pb, MgO, and CaO display coherent trends with Zr (Fig. S4), suggesting that these elements were relatively immobile. Contents of U and Th also show a good linear relationship (Fig. S4). The above interpretations are in good agreement with previous studies on the mobility of trace elements during low-grade alteration (Bienvenu et al., 1990; Pearce and Cann, 1973). Therefore, REE for mantle peridotites and HFSE, REE, Yi, Cr, Th, Pb, and MgO for crustal rocks are used for petrogenesis and geodynamic interpretation.

#### 6.2. Partial melting process of mantle peridotites

The whole-rock compositions of the Xigaze peridotites indicate their highly refractory nature. The low Al$_2$O$_3$ and CaO abundances, combined with the moderately incompatible trace element concentrations below primitive mantle values suggest that these peridotites are mantle residues (Fig. S5; Table S1). Given that HREE are the most immobile elements during metasomatic processes, thus they can be used to model degree of partial melting of mantle peridotites. On a chondrite-normalized REE diagram, the Xigaze peridotites plot on the curves between 15% and 24% partial melting, which were calculated from spinel facies melting of N-MORB mantle (Fig. S6; Piccardo et al., 2007). The moderate to high degrees of partial melting resemble those of the Zhongba harzburgites (Fig. S6; Dai et al., 2011b).

However, the partial melting model cannot explain the significant enrichment of LREE (Fig. 5A). In general, the U-shaped REE patterns of peridotites from ophiolites worldwide have been attributed to partial melting coupled with fluid/melt–rock interaction (Caran et al., 2010; Dai et al., 2011b; Polat et al., 2006; Song et al., 2009; Zhou et al., 2005). Melt–rock interactions are also supported by mineralogical and textural characteristics such as: 1) olivine embayments partly corroding the orthopyroxene porphyroclast (Fig. 3A), suggesting
that the orthopyroxene was replaced by olivine, which required
the involvement of percolating melt; and 2) orthopyroxene and
spinel symplectite (Fig. 3A). The melt that reacted with the Xigaze
peridotites to generate the U-shaped REE patterns is unlikely to be
MORB type, because such magmas have LREE depleted patterns.
However, boninites commonly possess LREE enriched patterns (Fig. 5A;
Crawford, 1989; Hickey and Frey, 1982; Varfalvy et al., 1997), suggesting
boninitic melts as potential candidates which reacted with the
harzburgites and produced the U-shaped REE patterns observed in
this study. The presence of boninitic dikes from the Xigaze ophiolite is
consistent with this interpretation (Fig. 5C).

6.3. Fractionation and mantle source of crustal rocks

The SiO2, and TiO2 contents of the crustal rocks slightly increase
with decreasing MgO, comparable to those of dikes and lavas in the
Izu–Bonin–Mariana forearc and other massifs in the Xigaze (Fig. 4),
suggesting significant crystal fractionation. This interpretation is also
supported by large variations in Mg-numbers (43.4–80.5), compatible
elements such as Cr (38.4–736.2 ppm) and Ni (22.8–272.2 ppm), and
strong linear relationship between Cr and Ni, suggesting significant
fractionation of olivine. The Al2O3 and MgO contents do not show any
correlation, indicating that plagioclase was not significantly fractionated,
which is consistent with the absence of Eu anomaly in REE patterns
for most samples.

Trace element concentrations, especially the REE, can be used to
identify magma groups and the nature of their mantle source. The MORB-like rocks show a uniform slight LREE depletion (Fig. 5B). On
multi-element diagram, these samples show generally negative Nb
and Ta anomalies (Fig. 6A), indicating the influence of subducting
oceanic slab-derived fluids. Even though the LILE were probably
altered during post-magmatic process, the majority of MORB-like
rocks display strong enrichments in LILE and Pb, implying that they
were probably modified by fluids or melts from subducting oceanic slab
(Fig. 6A). Therefore, the MORB-like rocks are inferred to have been generated from partial melting of an MORB residual mantle
source, with contribution from subduction-related components. The
boninitic rocks (especially samples JD07 and DJ11-01) and sample
DJ11-22 display LREE enrichment, but their REE are relatively low
compared to N-MORB, resembling those of the Izu–Bonin–Mariana
forearc boninites (Fig. 5C). Such REE patterns of boninites have been
explained by melts derived from a depleted mantle source and subse-
quently enriched by small amount slab-derived fluids (Dilek and Thy,
2009). Zircons from both groups have high positive δ18O values and
wide ranges from +7.5 to +17.3 (Fig. 8), and relatively young model
ages (Table S4), indicating the addition of enriched material into their
mantle source.

6.4. Tectonic setting of the Xigaze ophiolite

Most of the Xigaze peridotites have low CaO and Al2O3 contents
and U-shaped REE patterns similar to the features of modern South
Sandwich forearc peridotites (Pearce et al., 2000), peridotites from
Dazhuqu and Baining (Dubois-Côté et al., 2005), harzburgites from
Zhongba (Dai et al., 2011b), and boninites (Hickey and Frey, 1982),
respectively (Fig. 5A). Their trace element patterns are very similar to
those of the modern depleted forearc peridotites from Izu–Bonin–
Mariana arc (Parkinson and Pearce, 1998), the fossil forearc peridotites
from Yushigou, north Qilian (Song et al., 2009) and those from the
Zhongba massif (Fig. 5S; Dai et al., 2011b). Thus, the Xigaze peridotites
might have formed in the mantle wedge beneath a forearc region in
a supra-subduction zone during the initiation of subduction, where
these peridotites were modified by infiltration of LREE-enriched
boninitic melt.

We use a series of immobile trace element discrimination diagrams
to assess the tectonic setting of the Xigaze crustal rocks. On the Ti–V
plot, the MORB-like rocks have high Ti/V ratios (30>Ti/V>20) and fall
in the mixed MORB and arc field (Fig. 9A; Shervais, 1982); whereas
the boninites and sample DJ11-22 have low Ti/V ratios (Ti/V<20) and
plot in the volcanic arc basalt field (Fig. 9A). On the Y–Cr diagram, all
the MORB rocks and boninites plot within the Island Arc Basalt field
(Fig. 9B; Pearce et al., 1984). On Th/Yb versus Nb/Yb diagram, except
for one sample plotting close to N-MORB, the majority of samples fall
at the boundary between volcanic arc and MORB-OIB array, strikingly
similar to those of the Izu–Bonin–Mariana forearc basalt and dolerite
dikes (Pearce, 2008), the boninitic rocks and sample DJ11-22 are
displaced from the mantle array owing to their higher concentrations
of Th content as a subduction-related element. The trace element patterns of the MORB-like rocks are comparable to those of the
Izu–Bonin–Mariana forearc basalt and dolerite dikes (Reagan et al., 2010), and those of mafic rocks from the Xigaze ophiolite
(Shervais, 1982; Chen and Xia, 2008; Chen et al., 2003; Dubois-Côté et al.,
2005; Li et al., 2012; Malpas et al., 2003; Niu et al., 2006). Similarly, the trace element patterns of the boninitic dikes resemble those of the

---

Fig. 9. (A) Ti–V diagram of Shervais (1982). (B) Y–Cr plot of Pearce et al. (1984). Compared data sources are the same as for Fig. 4.
Izu–Bonin–Mariana forearc boninitic rocks (Fig. 6B; Reagan et al., 2010) and those of the Xigaze boninitic rocks (Chen et al., 2003; Dubois-Côté et al., 2005; Malpas et al., 2003). Given that modern boninites are mainly restricted to forearc environments such as those of the Izu–Bonin–Mariana forearc, these trace element characteristics suggest that these rocks were generated in a forearc setting.

The MORB-like rocks formed first when Neo-Tethyan oceanic plate began to sink beneath the Eurasian plate (Pozzi et al., 1984). At this stage, seafloor spreading occurred because of decompression in the extensional setting above the upper plate through rapid rollback of the subducting slab (Fig. 11A). Much of the layered architecture of the Xigaze ophiolite, including mantle peridotite, layered and isotropic gabbro, sheeted sills (dikes), some diorites, and pillow to massive lavas was generated at this seafloor spreading stage. The depleted, harzburgitic residues formed under continued melting, and they were progressively metamorphosed by fluids/melts from the sinking slab (Fig. 11A). Subsequent partial melting of these residues yielded more depleted boninitic lavas and dikes. These boninitic melts, in turn, interacted with the residues which lead to the enrichment of LREE. The latest stage of magmas was produced by melting of subducting slab and yielded late-stage crosscutting quartz diorite (sample DJ11-22) and plagiogranite dikes (Fig. 11A; Rollinson, 2009). Alternatively, the MORB-like rocks might also form in normal mid-ocean ridge and then they would be trapped in the subduction zone and partly be modified by later slab-derived melts. This model would require that some older crustal rocks (>130 Ma) are included in the YZSZ. However, older crustal rocks have not been reported so far, precluding the possibility of the above model.

6.5. Stages of magmatic activities and rapid forearc spreading in the central-western YZSZ

A rapidly growing number of geochronological studies are being carried out in the YZSZ. We summarize the ages and tectonic settings of different ophiolitic massifs from the eastern to the west segment and those of the Myitkyina ophiolite in Myanmar (Table 1 and Fig. 1A). Reliable ages from zircon U–Pb and hornblende 40Ar/39Ar methods record two distinct stages of magmatic activities in the YZSZ. The ages of the eastern segment (Luobusa and Zedang massifs) are in the range of 160–150 Ma, whereas the high precision ages of central and western segments are clustered at 130–120 Ma (Table 1 and Fig. 1A).

The distinct difference in ages suggests that the eastern segment and central-western segment are not coeval. We assume that they formed in different locations within the Neo-Tethyan ocean. The eastern segment might have formed in an intra-oceanic forearc setting during Mid- to Late Jurassic (McDermid et al., 2002; Zhong et al., 2006; Zhou et al., 2005), spatially and temporally associated with the eastern Jurassic Myanmar ophiolite (Table 1; Fig. 1A inset; Yang et al., 2012). Alternatively, the eastern segment might represent pre-existing Indian Ocean lithosphere (e.g., Malpas et al., 2003). In the central-western segment, the ages from gabbro/dolerite dike, pyroxenite dike, and quartz diorite dike that intruded into mantle peridotite of the ophiolitic massifs, and amphibolite of the metamorphic sole, overlap with the ages from sheeted dike and gabbro/dolerite, suggesting that any age differences between these magmatic series and metamorphic sole are smaller than the analytical uncertainties or intra-sample variability. Most of the dated crustal rocks show an SSZ tectonic setting (Table 1). The hornblende 40Ar/39Ar ages from the metamorphic sole at Bainang, Ngamring and Saga massifs are interpreted to represent the time of the inception of a subduction (Fig. 1A; Guilmette et al., 2009, 2012). A simple explanation is that the central-western YZSZ ophiolites formed at a fast spreading ridge rapidly between 130 and 120 Ma (Fig. 11A).

6.6. Implication for geodynamical evolution of the YZSZ

Any geodynamical model of the YZO should take into account the following fundamental observations: (1) the geochemical and geochronological characteristics of different ophiolitic massifs; (2) the geochronological and geochemical data of the Gangdese arc; and (3) the biostratigraphic and geochronological ages of the Xigaze forearc basin sediments.

The Xigaze ophiolite was probably generated in the forearc setting. The transition from MORB-like rocks to boninites records the subduction initiation to later stage of slab rollback during a short time (124–127 Ma). This tectonic setting is not consistent with the previously proposed model of slow-spreading ridge and complex backarc basin settings, which imply that the crustal accretion should have been longer than 10 m.y. (Girardeau et al., 1985b; Hébert et al., 2012). For the central-western YZO, many studies proposed that these rocks formed at intra-oceanic backarc basin–arc and could be analogous with the Lau basin, Philippine Sea and Mariana arc (Aitchison et al., 2000; Bédard et al., 2009; Bezard et al., 2011; Dubois-Côté et al., 2005;
Hébert et al., 2012; Malpas et al., 2003). However, the Lau basin and Philippine Sea have undergone long and complex seafloor spreading for at least 40 m.y. (Hall et al., 1995; Hergt and Woodhead, 2007). Thus, the duration of magmatic activities in the backarc basin contradicts the geochronological data with ages between 130 and 120 Ma (Fig. 1A). We infer that other coeval ophiolitic massifs from central-western massifs had similar geodynamic evolution to that of the Xigaze ophiolite on the basis of the following observations: (1) the majority of mantle peridotites show typical U-shaped REE patterns (Bezard et al., 2011; Dai et al., 2011b; Dubois-Côté et al., 2005; Xia et al., 2003); (2) most of the crustal rocks display significant Nb-Ta negative anomalies (Bédard et al., 2009; Bezard et al., 2011; Chen and Xia, 2008; Chen et al., 2003; Dubois-Côté et al., 2005; Hébert et al., 2012); and (3) the mafic or felsic dikes intruded into the mantle peridotites (Bédard et al., 2009; Hébert et al., 2003; Liu et al., 2011; Xia et al., 2011; Xiong et al., 2011).

This scenario is mostly similar to the model proposed from the Eocene Izu–Bonin–Mariana forearc oceanic crust (Reagan et al., 2010), where formation via seafloor spreading during the initiation of subduction with a lava stratigraphy from early erupted MORB-like to late-stage boninitic lavas is envisaged (Reagan et al., 2010). If the central-western YZO formed rapidly during the subduction initiation, what’s the mechanism that caused this stage of subduction?

Recent zircon U–Pb and Lu–Hf studies reveal that the Jurassic/Cretaceous Gangdese granitoids possess high positive $\varepsilon_{Hf}(t)$ values, indistinguishable from those of the zircons of the intra-oceanic Ladakh–Kohistan batholiths (Fig. 8; Chu et al., 2011). Thus, Chu et al. (2011) proposed that the Mesozoic Gangdese arc might have formed in an intra-oceanic arc and it was subsequently assembled with the Lhasa block. However, Zhu et al. (2011) argued that Jurassic magmatism of the Gangdese might have resulted from southward Bangong–Nujiang Tethyan subduction beneath the Lhasa block based on comprehensive zircon U–Pb and Hf isotopic data, and whole-rock geochemistry of Mesozoic–Early Tertiary magmatic rocks across south Tibet. Both the above models need to be tested with more detailed geological data. Here we suggest that the Jurassic granitoids formed by southward subduction of Bangong–Nujiang Tethyan ocean. Alternatively, they might have formed by an intra-oceanic subduction within the Yarlung Zangbo Tethyan ocean and were then accreted to the Lhasa block at the end of Jurassic because the zircon U–Pb and Hf isotopic data from Xigaze ophiolite are plotted in the field between Jurassic and latest Early Cretaceous–Late Cretaceous granitoids (Fig. 8; Chu et al., 2006, 2011; Ji...

![Fig. 11. Schematic model for genesis of the western-central Yarlung Zangbo ophiolite and geodynamical evolution of the southern Tibet. Please see text for more details.](image-url)
et al., 2009). Therefore, collision between Jiangtang and Lhasa during early Cretaceous or the accretion of a Jurassic intra-oceanic arc to the Lhasa block might have induced this stage of subduction. We should point out that the identified Comet large igneous province (ca. 132 Ma) in the eastern Tethyan Himalaya (Fig. 1A; Zhu et al., 2008b, 2009b) may also be one of the possible factors for inducing this stage of subduction.

After this stage of rapid slab rollback at the initiation of subduction (~130–120 Ma), the subducting slab became stabilized owing to slow rollback, and the forearc was frozen (cf., Whattam and Stern, 2011). The zone of melting migrated into the Gangdese arc, producing the Cretaceous granitoids (Fig. 11B; Ji et al., 2009). This migration of the subduction system might be attributed to its close location to the Gangdese arc. At about 116–113 Ma, the Xigaze forearc basin began to develop and to receive sediments derived from the Gangdese arc as shown by the Chongdoi Formation of the Xigaze Group (Fig. 11B; Wang et al., 2012; Wu et al., 2010).

7. Conclusion

The Xigaze ophiolite is dominated by mantle peridotites with low CaO and Al2O3 contents, and U-shaped REE patterns. Their petrological and geochemical characteristics indicate that these rocks represent residues after moderate to high degrees of partial melting (~15–24%) and were metasomatized by LREE-enriched boninitic melts in a mantle wedge of a forearc setting.

The mafic rocks of the Xigaze ophiolite are particularly thin and can be divided into two groups based on their whole-rock compositions: (1) MORB-like rocks, and (2) boninitic rocks. Both groups display geochemical evidence of metasomatism of their mantle source by slab-derived fluids.

LA-ICPMS zircon U–Pb data from five representative samples indicate formation ages of 124–127 Ma. The zircons are also characterized by positive εHf(t) values varying from +7.5 to +17.3.

These observations, combined with the geological and geochronological characteristics of the central-western Yarlung Zangbo ophiolites, the Gangdese arc and the Xigaze forearc basin, suggest that the central-western YZO might have formed in a forearc setting where rapid crustal accretion was caused by slab rollback during subduction initiation at 130–120 Ma. Subsequently, the rollback of the subducting slab slowed down and stabilized, and the zone of melting migrated to below the Gangdese arc producing voluminous Late Cretaceous granitoids with depleted mantle-type Hf isotopic characteristics.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.lithos.2013.03.011.

Acknowledgments

We thank Editor Dr. Andrew Kerr, referee Dr. Paul Robinson and another anonymous referee for their helpful comments and suggestions. Juan He and Baosen Zhang are gratefully acknowledged for their assistance in the whole-rock major and trace element analyses. Another anonymous referee for their helpful comments and suggestions.

References


Dilek, Y., Furnes, H., Shallo, M., 2008. Geochemistry of the Jurassic Mirdita Ophiolite (Albania) and the MORB to SSZ evolution of a marginal basin oceanic crust. Lithos 100, 174–209.


