Petrological and Os Isotopic Characteristics of Zedong Peridotites in the Eastern Yarlung–Zangbo Suture in Tibet

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Abstract: The Zedong ophiolites in the eastern Yarlung–Zangbo suture zone of Tibet represent a mantle slice of more than 45 km². This massif consists mainly of mantle peridotites, with lesser gabbros, diabases and volcanic rocks. The mantle peridotites are mostly harzburgite, thersolite; a few dike-like bodies of dunite are also present. Mineral structures show that the peridotites experienced plastic deformation and partial melting. Olivine (Fo89.7–91.2), orthopyroxene (En88–92), clinopyroxene (En45–49Wo47–51Fs2–4) and spinel ([Mg#]<sup>*</sup>=100×Mg/(Mg+Fe)=49.1–70.7; [Cr#]=(100×Cr/(Cr+Al))=18.8–76.5) are the major minerals. The degree of partial melting of mantle peridotites is 10%–40%, indicating that the Zedong mantle peridotites may experience a multi-stage process. The peridotites are characterized by depleted major element compositions and low REE content (0.08–0.62 ppm). Their “spoon-shaped” primitive-mantle normalized REE patterns with (La/Sm)N being 0.50–6.00 indicate that the Zedong ultramafic rocks belong to depleted residual mantle rocks. The PGE content of Zedong peridotites (18.19–50.74 ppb) is similar with primary mantle with Pd/Ir being 0.54–0.60 and Pt/Pd being 1.09–1.66. The Zedong peridotites have variable, unradiogenic Os isotopic compositions with 187Os/188Os=0.1228 to 0.1282. A corollary to this interpretation is that the convecting upper mantle is heterogeneous in Os isotopes. All data of the Zedong peridotites suggest that they formed originally at a mid-ocean ridge (MOR) and were later modified in supra-subduction zone (SSZ) environment.

Key words: Os isotopes, Zedong peridotites, Yarlung-Zangbo suture zone, mid-ocean ridge (MOR), supra-subduction zone (SSZ)

1 Introduction

Generally, mantle peridotites within a suture zone may have formed in mid-ocean ridges, island arcs, back-arc basins or marginal basins, and they have been interpreted as an important role in deciphering evolution of their tectonic setting. Some mantle peridotites from suture zone may even play a critical role in studying subcontinental lithospheric mantle (Miller et al., 2003). Recent reports of ultra–high pressure (UHP) minerals (e.g., diamond, coesite, kyanite) in mantle peridotites provide new insights and new challenges on the study of the ophiolites (Yang et al., 2014; Robinson et al., 2015).

The Yarlung–Zangbo Suture Zone (YZSZ) in southern Tibet separates the Indian plate to the south from the Eurasian plate to the north (Nicolas et al., 1981; Tapponnier et al., 1981; Allègre et al., 1984). Along the YZSZ, remnants of Neotethyan oceanic lithosphere have been preserved as ophiolites during the Mesozoic–Cenozoic collision between the Indian plate and the Lasha Block which is part of the Eurasian plate (Aitchison et al., 2000; Hébert et al., 2000, 2001, 2003, 2012; Huot et al., 2002; Dubois–Côté et al., 2005; Dupuis et al., 2005a, b, 2006; Guilmette et al., 2005, 2007, 2009; Bédard et al., 2009). Detailed geochronology, petrography, mineral chemistry, major and trace element geochemistry data

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have been presented by previous papers since the 1980s in order to determine the origin, the tectonic setting and the evolution of these ophiolites. Based on previous work, it becomes a consensus that YZSZ ophiolites have experienced complicated evolutionary processes in various tectonic settings and different ophiolites can be juxtaposed in one ophiolite during emplacement (Zhou et al., 1996, 2005; Huot et al., 2002; Hébert et al., 2003; Malpas et al., 2003; Dubois–Côté et al., 2005; Dupuis et al., 2005a,b; Bédard et al., 2009; Liu et al., 2010, 2012; Bezard et al., 2011; Xu et al., 2011; Xu Xiangzhen et al., 2016; Feng Guangying et al., 2017; Xiong Fahui et al., 2017).

The Zedong peridotite massif crops out at the eastern part of the YZSZ, which is a mantle slice covering an area of 45 km², tectonically overlying a late Cretaceous tectonic mélangé. In a previous study, Guo Guolin et al., (2015) has discovered diamond, moissanite and more than 30 other mineral species from 526 kg Zedong peridotites. Lai Shengmin et al., (2015) has reported some data and given a preliminary conclusion on formation process of the Zedong peridotites. During our second detailed field work, we found fresh dunites for the first time, which provided a better opportunity to study the Zedong ophiolites and to determine the evolution of mantle lithosphere under Neotethys.

We carried out a new analysis of the fresh Zedong dunites and obtain the Re–Os isotopic information of lherzolites, harzburgites and dunites in Zedong for the first time, which can bring us a better chance to determine the nature of them. We also process the published geochemical data of lherzolites and harzburgites again to improve the accuracy by increasing the number of valid digits and at last, we followed the former mineral analysis of these rocks (Lai Shengmin et al., 2015). In summary, the data in this paper can reflect the forming and evolutionary process of Zedong peridotites more systematically and accurately.

### 2 Geological Settings

As the youngest and the southernmost suture of the Tibetan plateau, the Yarlung–Zangbo Suture Zone is located between the Indian plate to the south and Lhasa block to the north, which represents a complex collage of relics of Neotethyan oceanic lithosphere (Hébert et al., 2012). The closure of the Neotethyan Ocean during the Mesozoic–Cenozoic was caused by the drift of Indian plate and the subsequent continual subduction between Asia and Greater India. The Zedong peridotites are located at the southeastern part of the YZSZ (Xiong Fahui et al., 2017).

The Zedong ophiolites lie about 180 km east of Lhasa and are about 45 km² in area, which consist of the Zedong arc complex, the peridotite massif and the Triassic Langjiexue flysch from north to south. The Zedong peridotite massif includes lherzolites, harzburgites and dunites, and harzburgites are the main rock type according to the aeromagnetic data. The massif is in thrust contact with the Zedong arc complex and the Triassic Langjiexue flysch which comprises silty slates and clastic rocks (Fig. 1). The gabbros and dolerites crop out at the southern margin of mantle peridotites, and yield a U–Pb age of 130±1 Ma (Xiong et al., 2016), which is consistent with the ages of Dongbo (128±1 Ma; Xiong Fahui et al., 2011), Dangxiong (126.7±0.4–123.4±0.8; Chan et al., 2007), Xiugugabu (122–126 Ma; Wei et al., 2006; Xu xiangzhen et al., 2008), Xigaze (110–132 Ma; Zyabrev et al., 1999; Chan et al., 2007) and Luobusa ophiolites (131.0±1.2 Ma; Zhang et al., 2015).

### 3 Petrographic Descriptions

Our sampling of the Zedong peridotites covers lherzolites (~40%), harzburgites (~50%) and dunites (~10%) (Fig. 2). The fresh lherzolites with equigranular textures contain medium–grained olivine (45%), orthopyroxene (40%), clinopyroxene (10%) and fine–grained spinel (5%) (Fig. 3a, b). Olivine grains in lherzolites are subhedral to euhedral and range from 50 μm to 5 mm in size; small olivine grains are locally embedded in the relatively large orthopyroxene grains. Orthopyroxenes are 100 μm–4 mm in size and show embayments generally filled by olivine neoblasts or, less commonly, by clinopyroxene. Clinopyroxene occurs as anhedral grains (0.5–3 mm) between olivine and orthopyroxene.

The harzburgites with porphyroclastic textures, which also consist of medium–grained olivine (70%), orthopyroxene (20–25%), minor clinopyroxene and spinel (5–10%), are fresh to lightly serpentinitized. Some olivines in these harzburgites are recrystallized to relatively fine–grained aggregates. Large orthopyroxene porphyroclasts are commonly surrounded by small grains of olivine, orthopyroxene and clinopyroxene. Olivine, clinopyroxene and spinel locally occur as round inclusions in larger orthopyroxene grains (Fig. 3d, e). This primary mantle fabric may have resulted from partial melting of the upper mantle (Mercier and Nicolas, 1975). Compared to the lherzolites, the harzburgites have fewer clinopyroxenes and show high–temperature deformation.

The Zedong dunites crop out in two separate places. One of these dunites is located in the Zedong harzburgites as a dyke, which are completely serpentinitized (Fig. 3c), whereas the other one is fresh to lightly serpentinitized,
cropping out near the southern margin of the harzburgites. The mineral assemblage of the fresh dunites include medium- to coarse-grained olivine (90–95%), which range from 500μm to 8mm, and fine to medium grained spinel (~10%). The small amounts of clinopyroxenes and much more spinel distinguish them from the harzburgites and the lherzolites.

4 Samples and Methods

Fresh samples are selected for mineral analysis and whole-rock geochemical analysis. Each sample was carefully cleaned, crushed, and then ground in an agate mortar to pass a 200-mesh screen. Petrographic examination of 74 thin sections provided detailed textural and mineralogical data.
4.1 Mineral analysis

Major elements of representative minerals were measured on JXA–8100 electron microprobe at the State Key Laboratory of Continental Tectonics and Dynamics, Institute of Geology, Chinese Academy of Geological Sciences, using an accelerating voltage of 15 kV, beam current of $1 \times 10^{-8}$ A and spot diameter of 1 μm.

4.2 Whole-rock major elements

The major element mass fraction expressed as oxides was measured by XRF using fused glass disks at the National Research Center for Geoanalysis, Chinese Academy of Geological Sciences, with measurement precision of <1% for SiO$_2$ and <2% for other major oxides.

Fig. 3. Microphotographs of different rock types of the Zedong mantle peridotites.
(a), coarse granular clinopyroxene, olivine and orthopyroxene in lherzolite; (b), vermiculate chromite spinel in lherzolite; (c), chromite spinel in dunite; (d), olivine in harzburgite, fine anhedral olivine distributed in coarse olivine; (e), coarse orthopyroxene in harzburgite; (f), chromite spinel and clinopyroxene under electric mirror.
4.3 Trace elements, rare earth elements and platinum group elements

Trace elements, including rare earth elements (REE), were determined by inductively coupled plasma–mass spectrometry (ICP–MS). Two national standard (GSR3 and GSR5), and three internal standards were measured simultaneously to ensure consistency of the analytical results. Analytical uncertainties are estimated to be 10% for trace elements with abundances <10 ppm, and around 5% for those with >10 ppm. Water and CO₂ were determined by gravimetric techniques in which the sample is heated in a closed container and the water vapor collected in a separate tube, condensed and then weighed. The detection limit for H₂O and CO₂ is 0.01 wt%. Because ultramafic rocks have very low concentrations of REE, prec–concentration of these elements was carried out using Fe (OH)₃ and Mg(OH)₂ co–precipitation. After separation of the major elements, the solutions were diluted approximately 60 times, compared with a dilution factor of 1000 in a normal acid digestion, and were then analyzed for Y and REE using a VG Elemental Plasma–Quad Excell inductively coupled plasma mass spectrometer (ICP–MS) at the Chinese Geological Experiment and Testing Center.

The PGE contents of the peridotites were determined in the National Research Center of Geoanalysis, Chinese Academy of Geological Sciences using NiS fusion pre–concentration followed by ICP–MS measurement. The CAS uses a modified NiS–fire assay method (Sun and Sun, 2005; Zhou et al., 2005) in which the samples are mixed with sodium carbonate, sodium borate, borax, glass powder, nickel powder, iron powder, and sulfur. The mixtures are transferred into fire – clay crucibles, with an appropriate amount of ¹⁹⁸Os spike solution and covered with a thin layer of Na₂B₂O₅. After fusing at 1150 °C for ~1 h and drying under an infrared lamp, the crucibles are cooled and the Ni–Fe buttons are removed. The buttons are then placed in a glass beaker containing 60 mL H₂O for a minimum of 10 h. To better dissolve the button, about 30 mL HCl are added and the heater is heated at ~110°C for ~30 min, until the solution becomes clear and little residue remains. The solution is then filtered using a millipore filter membrane (diameter 25 mm, 0.45 mm), and then the residue is collected and washed 5 times with ~15 mL water. The residue, together with the membrane, is transferred into a 7 mL Teflon beaker, sealed together with 1 mL HCl + 1 mL H₂O₂, and heated at ~110°C for 1.5 h. After cooling to room temperature, the beaker is opened and the solution transferred and diluted with H₂O to a total volume of 10 mL in preparation for ICP–MS analysis (Sun et al., 1998a, b; Sun and Sun, 2005). The precision of the analyses is better than 5% for Rh, Pd, and Ir, and 10% for the other elements. The detection limit is 0.2 ng/g for Pt and Pd, 0.001 ng/g for Ir, Rh, and Os, and 0.1 ng/g for Ru.

4.4 ¹⁸⁷Os/¹⁸⁸Os ratios

Re–Os isotopic measurements were carried out at the Guangzhou Institute of Geochemistry, Chinese Academy of Sciences. One to 0.6–0.7 g of sample powder were spiked with enriched ¹⁹⁰Os and ¹⁸⁵Re solutions. The powder samples were digested using ca. 10 mL of inverse aqua regia (HNO₃:HCl = 3:1) in Carius tubes (Shirley and Walker, 1995) and heated at 230 °C for 24 h. Osmium was extracted from the aqua regia fraction by carbon tetrachloride solvent extraction (Cohen and Waters, 1996; Pearson and Woodland, 2000) and then back–extracted into concentrated HBr. Further purification was performed by micro–distillation using chromic acid. Rhenium was separated and purified from the remaining aqueous solution by anion exchange chromatography using AG1-X8 resin (100 – 200 mesh). Isotopic ratios were measured by negative thermal ionization mass spectrometry (NT–TIMS) on a Thermo-Finnigan TRITON, where Os was measured as OsO₄⁻ and Re as ReO₄⁻ (Creaser et al., 1991; Völken ing et al., 1991). Osmium was loaded onto a high–purity Pt filament (99.999%, 1 × 0.025 mm, H. Cross Co. Ltd) that had already been heated in air for >3 min. The Re and Os isotope compositions were measured using a static multiple Faraday collector and a pulse counting electron multiplier, respectively. Os isotopic ratios were normalized to ¹⁹²Os/¹⁸⁸Os=3.08271 (Nier, 1937) and corrected using ¹⁷O/¹⁶O=0.00307 and ¹⁸O/¹⁶O=0.002047 (Nier, 1950). Rhenium isotope compositions were determined by the total evaporation technique (Suzuki et al., 2004). This method eliminates the instrumental mass fractionation effect, and obtains higher accuracy and precision. Duplicate measurements of the same whole–rock powder were undertaken. More detailed descriptions of the analytical procedures are given by Suzuki and Honda (2003), Kato et al. (2005) and Li et al. (2010a, b).

5 Results

5.1 Mineralogy

The mineralogical data of dunites is new and the information of lherzolites and harzburgites is from Lai Shengmin et al. (2015). The average value of major element data of olivine and spinel from the Zedong peridotites are presented in Table 1, and of orthopyroxene and clinopyroxene in Table 2 and n represents the number of analyses in one sample.

Olivines from the Zedong peridotites exhibit a uniform composition. The Fo [100× molar Mg/(Mg + Fe)] values
of these olivines range from 89.7 to 91.2. Compared with olivines elsewhere in the Yarlung–Zangbo Suture Zone ophiolites, these olivine compositions fall into the similar range for mantle peridotites (Dupuis et al., 2005a).

The grain size of spinels from the Zedong peridotites ranges from 0.1 to 1 mm, showing a wide range of variation for mantle peridotites (Dupuis et al., 2005a).

The 447 whole-rock geochemical data of the Zedong peridotites is presented in Table 3. The loss-on-ignition (LOI) values for dunites, which indicate that the lherzolites and harzburgites have relatively high Mg# (64.8 –70.7) and low Cr# (18.8–34.0). The black euhedral spinels occur in dunites have the highest Cr# (73.6–76.4) and lowest Mg# (49.1–51.5) of all the spinels from all three–type rocks. It is believed that the Cr# and Mg# of spinels and Mg# of olivines can reflect different degrees of partial melting and melt–rock reaction in the host peridotites (e.g., Dick and Bullen, 1984; Miller et al., 2003; Dubois–Côté et al., 2005; Dupuis et al., 2005a; Bezard et al., 2011). The relationships between Fo of olivines and Cr# of spinels are given in Fig. 4a, Mg# and Cr# of spinels in Fig. 4b. As shown in Fig. 4, the degree of partial melting of the Zedong peridotites ranges from 10–15% of lherzolites and harzburgites, to about 40% of dunites.

Orthopyroxenes from the Zedong peridotites have a composition of En49.9–70.7 and Cr# 18.8–34.0. The Mg# of these clinopyroxenes ranges from 91.7 to 95.6, MgO from 15.67 to 17.87 wt% and FeO from 1.44 to 2.75 wt%. The Al2O3 contents of clinopyroxene exsolution lamellae fall into similar range with those of the interstitial neoblasts and porphyrocrysts. The compositions of clinopyroxene exsolution lamellae fall into similar range with those of the interstitial neoblasts and porphyrocrysts.

5.2 Whole–rock geochemistry

Whole-rock geochemical data of the Zedong peridotites are presented in Table 3. The loss-on-ignition (LOI) values of these peridotite samples vary between 0.23–1.87 wt% for lherzolites and harzburgites and 2.64–2.73 wt% for dunites, which indicate that the lherzolites and harzburgites are relatively fresh, whereas the dunites are

| Table 1 Microprobe analyses of olivine and spinel from the Zedong ultramafic massif (wt%) |
|----------------------------------------|---------------------------------------------------|---------------------------------------------------|---------------------------------------------------|
| **Olivine** | 14Y-10-P1 | 14Y-10-P2 | 14Y-10-P3 | 14Y-11 | 14Y-12 | 14Y-13 | 14Y-14 | 14Y-15 | 14Y-16 |
| n | 10 | 8 | 12 | 11 | 10 | 9 | 9 | 10 | 10 |
| MgO | 49.52 | 49.34 | 50.08 | 49.59 | 49.02 | 48.87 | 48.14 | 50.46 | 49.01 |
| MnO | 0.35 | 0.40 | 0.36 | 0.13 | 0.14 | 0.17 | 0.15 | 0.21 | 0.17 |
| Cr2O3 | 0.01 | 0.02 | 0.01 | 0.13 | 0.01 | 0.03 | 0.01 | 0.01 | 0.01 |
| NiO | 0.03 | 0.03 | 0.04 | 0.06 | 0.07 | 0.06 | 0.05 | 0.01 | 0.01 |
| TiO2 | 0.14 | 0.14 | 0.09 | 0.03 | 0.02 | 0.05 | 0.03 | 0.21 | 0.17 |
| Na2O | 0.02 | 0.01 | 0.01 | 0.03 | 0.02 | 0.03 | 0.02 | 0.43 | 0.03 |
| K2O | 0.01 | 0.01 | <0.01 | 0.01 | 0.01 | <0.01 | <0.01 | 0.02 | 0.02 |
| Total | 99.28 | 99.53 | 100.11 | 99.65 | 99.96 | 100.06 | 99.73 | 99.51 | 99.93 |

- Note: *Mg#=Mg2+×100/(Mg2++Fe2+); **Cr#=Cr×100/(Cr+Al).
Fig. 4. (a), Plot of spinel Cr# vs. olivine Fo of the Zedong peridotites; (b), Plot of spinel Cr# vs. spinel Mg# of the Zedong peridotites.


Cr# = 100 × molar Cr/(Cr + Al), Mg# = 100 × molar Mg/(Mg + Fe).

Table 2 Microprobe analyses of orthopyroxene and clinopyroxene from the Zedong ultramafic massif (wt%)

<table>
<thead>
<tr>
<th></th>
<th>Dunite</th>
<th>Harzburgite</th>
<th>Lherzolite</th>
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</thead>
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<tr>
<td></td>
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<td>14Y-10-P2</td>
<td>14Y-10-P3</td>
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<tr>
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<td>89</td>
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<tr>
<td><strong>Fs</strong></td>
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<td>11</td>
</tr>
<tr>
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<td>1</td>
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<tr>
<td><strong>Mg#</strong></td>
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<td>92.3</td>
<td>89.4</td>
</tr>
</tbody>
</table>

|          | 7                       | 6                       | 5                       |
| **SiO2** | 54.62                   | 54.32                   | 52.55                   |
| **Al2O3**| 0.34                    | 0.40                    | 3.58                    |
| **TiO2** | 0.01                    | 0.01                    | 0.12                    |
| **Cr2O3**| 0.27                    | 0.39                    | 0.29                    |
| **FeO**  | 1.44                    | 2.03                    | 2.29                    |
| **MnO**  | 0.05                    | 0.07                    | 0.08                    |
| **MgO**  | 17.66                   | 17.87                   | 17.94                   |
| **CaO**  | 25.67                   | 24.56                   | 22.82                   |
| **Na2O** | 0.07                    | 0.08                    | 0.07                    |
| **K2O**  | 0.06                    | 0.09                    | 0.08                    |
| **Total**| 100.13                  | 99.83                   | 99.39                   |
| **En**   | 48                      | 49                      | 49                      |
| **Fs**   | 2                       | 3                       | 4                       |
| **Wo**   | 50                      | 48                      | 47                      |
| **Mg#**  | 95.6                    | 94.0                    | 92.9                    |

Note: Mg# = Mg2+ × 100/(Mg2+ + Fe2+).
partly serpentinized. After recalculated the data on LOI free basis, Zedong peridotites have MgO=42.70–50.58 wt %, Fe2O3=0.28–2.00 wt %, Al2O3=0.22–1.93 wt %, CaO=0.25–2.05 wt %, Na2O=0.05–0.10 wt % and TiO2=0.01–0.03 wt %. All peridotites show relatively linear increases in CaO, Al2O3 with decreasing MgO (Fig. 7).

Primitive mantle–normalized REE patterns of the peridotites are given in Fig. 8. The total REE contents range from 0.08 to 0.62 ppm, which are much lower than those of N–MORB–like mantle (Salters and Stracke, 2004) and chondrites (Boynton, 1984), but are higher than those of peridotites from the Izu-Bonin forearc (Parkinson and Pearce, 1998). The dunites have the highest (La/Yb)n = 0.75–1.80 and (La/Sm)n=3.25–6.00. The (La/Yb)n (0.25–0.82) and (La/Sm)n (1.08–5.00) of harzburgites are relatively low, whereas the lherzolites have the lowest (La/Yb)n (0.06–0.22) and (La/Sm)n (0.50–1.25). The REE patterns of the harzburgites are characteristic of U–shaped, which show a progressive depletion from La to Nd and a slight enrichment from Nd to Lu.

All Zedong peridotites have similar primitive mantle–normalized trace element patterns. These peridotites are characterized by moderately negative anomalies in Th and Nd. There is selective enrichment in highly incompatible elements (Rb to Ta) relative to LREE. The Zedong peridotites are strongly enriched in Ta (Fig. 9). Generally, the spider diagrams show that the Zedong peridotites are similar to abyssal peridotites (Goddard et al., 2000).

The lherzolites and harzburgites have nearly identical chondrite–normalized PGE patterns, which show slight enrichment in Pd and depletion in Ir (Fig. 10). The patterns of the dunites show enrichment in Ru and depletion in Ir (Fig. 10). The patterns of the dunites show enrichment in Pt and Pd with negative Ir and Pt. The total PGE contents of the Zedong peridotites mostly fall into an overall range of 21.15 to 32.59 ppb, except 14Y–10–P3 (18.19 ppb) and 13Y–6 (50.74 ppb). The dunites have the lowest Pd/Ir (0.54 to 0.60) and highest Pt/Pd (1.09 to 1.66). The Pd/Ir (1.49 to

Fig. 5. Compositional variations of orthopyroxenes from the Zedong peridotites. (a), Al2O3 vs. Mg#; (b), Cr2O3 vs. Mg#. Fields outlining Opx compositions in abyssal peridotites, forearc peridotites and peridotites from the YZSZ ophiolites are from Dupuis et al. (2005a) and references therein.

Fig. 6. Compositional variations of clinopyroxenes from the Zedong peridotites. (a), Al2O3 vs. Mg#; (b), Cr2O3 vs. Mg#. Fields outlining Opx compositions in abyssal peridotites, forearc peridotites and peridotites from the YZSZ ophiolites are from Dupuis et al. (2005a) and references therein.

Fig. 7. Compositional variations of orthopyroxenes from the Zedong peridotites. (a), Al2O3 vs. Mg#; (b), Cr2O3 vs. Mg#. Fields outlining Opx compositions in abyssal peridotites, forearc peridotites and peridotites from the YZSZ ophiolites are from Dupuis et al. (2005a) and references therein.
4.90) of the harzburgites increase with decreasing Pt/Pd (1.24 to 1.59), whereas the lherzolites have the highest Pd/Ir (2.30 to 3.94) and lowest Pt/Pd (1.09 to 1.43) (Fig. 11).

We analyzed three dunites, two harzburgites and three lherzolites for their Re, Os and Os–isotopic compositions. The Os isotope data of the Zedong peridotites are presented in Table 4. Given the chalcophile and siderophile geochemical behavior, both Re and Os have a strong affinity to trace phases (e.g., sulfides and alloys) and, thus, their budgets in these rocks are controlled mainly by these phases. The contribution of unequal distribution of these discrete trace phases on poor reproducibility of both Re and Os concentrations in applications of the isotopic system has been well documented in the past two decades, known as the nugget effect (e.g., Reisberg and Meisel, 2002; Meisel and Moser, 2004a, b; Li et al, 2015). In light of the nugget effect for both Re and Os concentrations, it is possible that the Os isotopic compositions of individual hand–specimen samples were not totally homogenized. It’s also important to note that in most cases only one analysis was conducted on 1–2 g of random selected aliquot of powdered whole samples. This implies that any of the individual analyzed values cannot perfectly represent the initial Os isotope composition of whole–rock (their source composition). Therefore, the nugget effect may bias the timing of formation events and the tracing of mantle sources. On the other hand, in comparison with low–Mg^# basalts, high–Mg^# peridotites are the residues of mantle and formed...
from higher degrees of mantle melting at higher temperatures, and they contain significantly more Os bearing sulfides and higher Os concentrations. At such higher temperatures, even though the nugget effect exists, the heterogeneity of the initial Os isotopic composition could be limited (Burton et al., 1999) and the results of Re and Os in this paper can still be used to discuss the origin of the Zedong peridotites to a certain extent.
The unradiogenic, variable Os isotopic compositions are between 2.41 and 8.61, with $^{187}\text{Os} / ^{188}\text{Os}$ ratios ranging from 0.1228 to 0.1282 (Fig. 12). The $^{187}\text{Os} / ^{188}\text{Os}$ ratios of Yungbawa peridotites are 0.1223–0.1313 (Miller et al., 2003; Liu et al., 2012) and the Troodos Peridotites are 0.1291 – 0.1390 (Büchl et al., 2002).

The $^{187}\text{Re} / ^{188}\text{Os}$ ratios of the Zedong peridotites range from 0.036 to 0.462, and it is believed that the age correction for isotopic growth since the time of formation of these peridotites is negligible. Because the Os contents of these peridotites are much higher than those of any metasomatic agents (0.100 ppb; Chesley et al., 2002, 2004; Dale et al., 2007), the Re–Os system of the Zedong peridotites was not disturbed after their formation. Thus, these Os isotope data can reflect the primary Os compositions of the Zedong peridotites.

The model ages for the Zedong mantle peridotites are 0.43–1.04 Ga, which are significantly older than those for the gabbros from YZSZ (~ 120–130 Ma) (Xiong et al., 2016), indicating that the Re–Os isotopic characteristics are very complex.

6 Discussions

6.1 Origin of the Zedong peridotites

Peridotitic tectonites in ophiolites are generally considered to be residues of the primary mantle after extraction of basaltic magma (Moore and Vine, 1971; Moores and Jackson, 1974; Coleman, 1977; Ringwood et al., 1981; Wang and Bao, 1987; Hawkins, 2003). The lherzolitic peridotites probably represent the residue after mid-ocean ridge basalt (MORB) extraction, which are structurally lower in the mantle sequence (Dilek and Furnes, 2009; Dilek and Morishita, 2009). The petrography, mineral compositions and whole-rock geochemistry results of our study propose a multi-stage model for the formation of Zedong peridotites.

One explanation for the porphyroclastic textures in Zedong peridotites is that these peridotites may originate from mantle rocks and then underwent high-temperature
deformation, which happened at an oceanic spreading center (Vernon, 2004; Dupuis et al., 2005a). The similar compositions and Mg# between olivines and orthopyroxenes are consistent with the minerals from residual mantle peridotites after variable degrees of partial melting (Dick, 1977; Komor et al., 1990). Compared with primitive mantle (MgO = 38.5 wt%, Al2O3 = 3.97 wt%, and CaO = 3.50 wt%, Jagoutz et al., 1979), the Zedong peridotites have higher MgO (40.66–47.33 wt%), lower Al2O3 (0.22–1.90 wt%) and CaO (0.25–2.05 wt%) contents, respectively also indicating these rocks have experienced degrees of partial melting process.

In the olivine–chromium spinel mantle array diagram, the lherzolites plot entirely within the area defined by abyssal peridotites, with approximately 8–10% partial melting (Fig. 4a). As shown in Fig. 8, the rare earth elements patterns of the lherzolites, coupled with the low Cr#s of these rocks (Fig. 4), suggest their formation in a MOR environment. At the same time, the week enriched LREE and PPGE also indicate that Zedong lherzolites

### Table 4 Re-Os isotopic data for peridotites of the Zedong ultramafic massif

<table>
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<tr>
<th></th>
<th>Dunite</th>
<th>Harzburgite</th>
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<th>Harzburgite</th>
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<td>145.96</td>
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<td>−62.45</td>
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<td>0.12672</td>
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<td>0.71</td>
<td>1.04</td>
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<td>0.84</td>
<td>0.43</td>
<td>0.54</td>
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</table>

Fig. 11. PGE diagram of the Zedong ophiolite.
Chondritic ratio and mantle values are from Chou et al. (1983). MORB and low–Ti lava fields are from Hamlyn et al. (1985).
harzburgites, such as Coleman (1977). However, this interpretation does not account for the occurrence of all the harzburgites, which indicates that the later modification on these lherzolites is lowest in the Zedong peridotites, which could be moderately to strongly modified.

Harzburgites have traditionally been viewed as depleted, refractory residues produced by partial melting of lherzolites and clinopyroxene–bearing harzburgites (Coleman, 1977). However, this interpretation does not account for the occurrence of all the harzburgites, such as those in the Zedong ophiolite, that have well-developed, U-shaped REE patterns, indicating significant LREE enrichment (Fig. 8). Such patterns are now believed to reflect partial melting coupled with melt–peridotite interaction (Edwards, 1990; Bodinier et al., 1991; Kelemen et al., 1992; Suhr et al., 2003). The U-shaped primitive mantle–normalized REE patterns of the harzburgites provide good evidence that the original MORB-type mantle was a consequence of secondary processes such as serpentinization, oceanic alteration or interaction with later melts/fluids (Miller et al., 2003).

Early studies, such as those by Coleman (1977), Greenbaum (1977) and Malpas (1978), suggested that the dunites are cumulate in origin and that they define a petrologic Moho within the transition zone. Later studies have suggested that dunites may also be formed by high degrees of partial melting and/or by extensive melt–rock reaction. In Zedong, all of the dunites have highly refractory olivine (Fo 90.7–91.2) with well-developed kink–banding and both contain minor orthopyroxene and interstitial clinopyroxene. They also have euhedral chromite grains with similar compositions that are relatively enriched in TiO₂. The low Al₂O₃ contents and the typically high Cr²⁺ in spinels are consistent with their being melt residues, rather than cumulates (Shi et al., 2012). The dunites in Zedong all have well-developed, U-shaped, chondrite–normalized REE patterns and in fact, the REE patterns of these dunites are indistinguishable from those of the harzburgites. Zedong dunites also have small Eu anomalies identical to some of the harzburgites indicating that these rocks may have a similar formation process with Zedong harzburgites. At the same time, in mantle peridotites, PGE of the Ir–subgroup occur both as alloys (Os–Ir–Ru) and sulphides, whereas Pd and Pt are mainly associated with interstitial sulphide in the fertile mantle (lherzolite) (Mitchell and Keays, 1981). Reaction of mantle peridotites with melts in a SSZ environment would have refertilized the Zedong peridotites by generating secondary sulphides and resulted in fractionation of Pt and Pd. Pd would concentrate preferentially into the liquid, whereas Pt would form an alloy with iron (Fe–Pt), Pt/Pd ratios would decrease as melt–rock interaction progressed as seen in Zedong dunites. As discussed above, the mantle peridotites in Zedong may have a MOR origin and then modified by later – stage melts and fluids in a SSZ setting. Furthermore, the extent of LREE and PGE enrichment of lherzolites is lowest in the Zedong peridotites, which indicates that the later modification on these lherzolites is relatively minor, whereas the harzburgites and dunites could be moderately to strongly modified.

6.2 Tectonic setting

Lherzolites have olivine, spinel, orthopyroxene and clinopyroxene compositions similar to those from the abyssal environment and dunites fall into the composition range of forearc environment, while harzburgites show transitional characteristics between them (Dick and Bullen, 1984; Bridges et al., 1995; Pearce et al., 2000; Dupuis et al., 2005a and references therein; Figs. 4–6), which indicates that the formation of the Zedong peridotites may be controlled by processes in mid–ocean ridge and forearc settings. These characteristics are consistent with most of the Yarlung–Zangbo peridotite massifs (Hébert et al., 2003; Dupuis et al., 2005a,b; Bédard et al., 2009; Bezard et al., 2011).

Although the Zedong peridotites have more enriched LREE compared to distinct U-shaped REE patterns of pridotites which formed in forearc environments, the degrees of LREE enrichment were not so extensive (Dupuis et al., 2005a). The whole rock compositions also...
suggest that the Zedong peridotites are less depleted than forearc peridotites. A similar interpretation of refertilized abyssal peridotites was made for the Luobusa ophiolite, located in the eastern part of the Indus–Yarlung Zangbo suture zone (Xu et al., 2011; Xiong Fahui et al., 2013). Hence, the Zedong peridotites appear to first form in a MOR environment and were then modified by later–stage melts/fluids in a SSZ setting during intra–oceanic subduction (Malpas et al., 2003). Similar conclusions have been reached in studies of other ophiolites that crop out along the Indus–Yarlung Zangbo suture zone, e.g., Luobusa, Xigaze, Saga, Purang and Sangsang (Zhou et al., 1996, 2005; Hébert et al., 2003; Malpas et al., 2003; Dubois–Côté et al., 2005; Bédard et al., 2009; Liu et al., 2010; Dai et al., 2011; Xu et al., 2011; Xiong Fahui et al., 2013).

Mineralogy, petrology and geochemistry compositions data show that the Zedong peridotites were originally residues of mantle rocks after variable degrees of partial melting at a mid–ocean–ridge environment, and that they were then involved in a subduction zone where they were modified by percolating subduction related melts/fluids.

6.3 The provenance of the Zedong peridotites

The concentrations of compatible elements are much higher in mantle peridotites than in the percolating melts/fluids, so these elements are less likely to be disturbed during later metasomatic processes compared to the incompatible elements (e.g., Sr, Nd, Pb and Hf). As a highly compatible element, Os preferentially remains in the residual mantle, whereas moderately incompatible Re enters into the melt (Walker et al., 1989; Reisberg and Lorand, 1995; Shirey and Walker, 1998). Therefore, the Re/Os ratios of the residual mantle tend to be low and unradiogenic Os isotopic composition will develop (e.g., Walker and Morgan, 1989; Walker et al., 1989; Reisberg and Lorand, 1995; Shirey and Walker, 1998; Meisel et al., 2001; Feng Guangying et al., 2017). Mantle peridotites contain Os two orders of magnitude higher than the basaltic melts, which makes their Os isotopic composition stable in late–stage metasomatism (Walker et al., 1989; Chesley et al., 2004; Harvey et al., 2006). With these reasons, the Re–Os system is particularly suitable for determining the provenance of mantle peridotites and for dating melting events of the peridotites (e.g., Hassler and Shimizu, 1998; Liu et al., 2012).

The LOI of the Zedong peridotites ranges from 0.23 to 2.73 wt%, reflecting that these peridotites are relatively fresh. As serpentinization is a common process under subduction conditions in which water is added to olivine and pyroxene, and the isochemical features will change (Paulick et al., 2006). It is important to note that less than 30% of the whole–rock highly–siderophile elements are retained in olivine, spinel orthopyroxene and clinopyroxene. In contrast, Ru–Os ± Ir sulfides and Pt–Ir ± Os alloys, the micron– to submicron– sized platinum group minerals, account for 70–100% of the HSE budget in these rocks. Slight to moderate serpentinization is expected to have negligible effect on the base metal sulfides (Paulick et al., 2006). Previous studies have also found no correlation between the degree of serpentinization in peridotites and their Re, Os contents and ratios (Burnham et al., 1998; Büchl et al., 2002; Harvey et al., 2006; Van Acken et al., 2010).

As shown in Fig. 13, no particularly regular correlation has been detected between 187Os/188Os and whole–rock Al2O3 contents or 187Re/188Os ratios. All the Os isotopic compositions of Zedong peridotites fall into the range of abyssal peridotites, indicating that Zedong peridotites may have originated in a MORB setting consistent with the characteristics of minerals and REEs. In a Re–Os system, TRD ages (Re–depletion–age) are the minimum age for Re depletion and thus melt extraction, assuming that a Re – depletion event previously removed all Re from the samples (Shirey and Walker, 1998). The Zedong peridotites have variable TRD ages ranging from 0.23 to
1.04 Ga. One explanation for the variation in Os isotopic compositions and $T_RD$ ages of the Zedong peridotites is that the Neotethyan mantle may be heterogeneous in Os isotopes, which are consistent with the opinions that the convecting upper mantle is heterogeneous in Os isotopes (Walker et al., 1989; Snow and Dick, 1995; Parkinson et al., 1998; Brandon et al., 2000; Meibom and Frei, 2002; Standish et al., 2002; Chesley et al., 2004; Walker et al., 2005; Frei et al., 2006; Harvey et al., 2006; Liu et al., 2008; Schulte et al., 2009).

The lherzolites in Zedong have a Re–Os isochron age of 520±60 Ma, with initial $^{187}Os/^{188}Os$ being 0.12371±0.00027, whereas the Re–Os data of harzburgites and dunites fails to give a suitable age because of data distribution and insufficient samples. The isochron ages of the lherzolites are significantly older than the U–Pb age of the gabbros and dolerites (~120–130 Ma) (Xiong et al., 2016), which may indicate that the formation of these lherzolites are much earlier than the intrusion of Zedong mafic dykes and the beginning of subduction. These results are different from the evolutionary models proposed by Xiong et al., (2016) and the main difference between them is the original source of lherzolites, harzburgites and dunites. On the basis of our results, all of Zedong peridotites fall into the abyssal aera or MORB fields in the source area discrimination diagrams (Figs. 12, 13a) and the geochemical patterns indicate that Zedong peridotites possibly have a origin in MOR environment. In addition, the occurrence of UHP and highly reduced minerals in Zedong peridotites suggest that these mantle peridotites may have experienced a deep process and surged upward to shallow crust by mantle plume or mantle convection in a spreading mid–ocean ridge setting (Guo Guolin et al., 2015).

It is still important to be noticed that the later melt–rock reaction in SSZ settings can affect both lithophile elements and siderophile elements and the heterogeneity of Os isotopic compositions in Neotethyan mantle may have an influence on the dating of peridotites (Snow and Dick, 1995; Parkinson et al., 1998; Brandon et al., 2000; Meibom and Frei, 2002; Standish et al., 2002; Walker et al., 2005; Frei et al., 2006; Harvey et al., 2006; Liu et al., 2008; Schulte et al., 2009; Liu et al., 2012). To figure out the protoliths and detailed evolution processes of these peridotites, more detailed field work and geological data are still needed.

In summary, based on the information above, we suggest an alternative multi–stage model for Zedong peridotites and our preferred explanation is that Zedong mantle peridotites may firstly originate in a MOR environment and were then modified by later–stage melts and fluids in a SSZ setting during intra–oceanic subduction (Malpas et al., 2003).

7 Conclusions

The Zedong peridotites along the eastern segment of the YZSZ formed from multi–stage processes. They are residues of mantle rocks after variable degrees of basaltic magma extraction at a mid–ocean ridge environment, and then were modified in a supra–subduction setting. Os–isotope results show that the age of lherzolites is significantly older than gabbros in Zedong and Neotethyan mantle may be heterogeneous in Os isotopes.

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References


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