1 Southward trench migration at ~130-120 Ma caused accretion
2 of the Neo-Tethyan forearc lithosphere in Tibetan ophiolites
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17 **Abstract**

18 The preservation of ultrahigh-pressure and super-reduced phases (diamond, moissanite,
19 etc.) in the harzburgites and chromitites of the Yarlung Zangbo ophiolites (South Tibet, China)
20 has major implications for mantle recycling and lithosphere evolution in the tectonic system
21 related to the closing of the Neo-Tethyan Ocean. However, important aspects of the genesis of
22 these enigmatic ophiolites and the related geodynamic evolution are still unclear. In the

Zedang ophiolite of the eastern Yarlung Zangbo Suture, detailed mineral chemical data reveal that the harzburgite domain in the east [spinel Cr# (mole $\text{Cr}^{3+}/(\text{Cr}^{3+}+\text{Al}^{3+}) = 0.62-0.33$] is more depleted than the lherzolite domain in the west (spinel Cr# = 0.30-0.17) and shows much lower equilibration temperatures (by $\sim 250-150$ °C) than the lherzolites. Clinopyroxene trace-element compositions indicate that the harzburgites underwent pervasive metasomatism after melt extraction, while the lherzolites did not. New zircon U-Pb ages show that the harzburgites were intruded by dolerite dykes with chilled margins at $\sim 130-128$ Ma, consistent with the widespread mafic magmatism at $\sim 130-120$ Ma in the Yarlung Zangbo ophiolites. Nd-Hf isotopic data indicate that the Zedang lherzolites subcreted the pre-emplaced harzburgites concurrently with the intrusion of the dolerite dykes into the harzburgites, and that the lherzolites and dolerites both were derived from upwelling asthenosphere with minor slab input. Available zircon geochronology and Hf-isotope data show that juvenile magmatism in the adjacent Gangdese Arc was almost completely interrupted from $\sim 130-120$ Ma.

We suggest that the extension of the overlying harzburgitic lithosphere, subcretion of lherzolites, intrusion of mafic dykes, and the waning of Gangdese-Arc magmatism all reflect a southward trench migration in the Neo-Tethyan subduction system from the Gangdese Arc to the oceanic forearc lithosphere. This magmatic relocation and tectonic linkage are inferred to be the far-field effects of plate reorganization related to the Lhasa-Qiangtang collision and the breakup of Gondwanaland in the early Cretaceous. This model provides a solution for the global “ophiolite conundrum”: supra-subduction-zone type ophiolites with mid-ocean-ridge features.

Key words: Yarlung Zangbo ophiolites; South Tibet; Neo-Tethyan forearc accretion;
southward trench migration; ophiolite conundrum

1. Introduction

Ophiolites record shallow crust-mantle processes in oceanic basins, arcs and ocean-continent transitions on Earth, and play a critical role in deciphering ancient plate tectonics (e.g., [Dilek and Furnes, 2011](#)). The documentation of ultrahigh-pressure (UHP) and super-reduced (SuR) phases (e.g., diamond, moissanite) from the Yarlung Zangbo ophiolites (South Tibet, China) has provided new insights into the deep convective mantle, and even the Mantle Transition Zone (e.g., [Yang et al., 2007, 2014](#); [McGowan et al., 2015](#); [Satsukawa et al., 2015](#); [Griffin et al., 2016](#)). These important findings require a more detailed examination of the formation and evolution of the Yarlung Zangbo ophiolites, and the related geodynamic processes during the closing of the Neo-Tethyan Ocean, arc evolution and continental assembly.

However, the global “ophiolite conundrum” [supra-subduction-zone (SSZ) type ophiolites with mid-ocean-ridge (MOR) features (e.g., [Moore et al., 2000](#))] has also been recognized during the investigations of the Yarlung Zangbo ophiolites, as two contrasting models have been proposed for the Tibetan ophiolites: (1) they were generated at slow-spreading mid-ocean ridges, based on the paucity of crustal mafic magmatism and structural similarities to the present-day South-West Indian Ridge (e.g., [Nicolas et al., 1981](#); [Girardeau and Mercier, 1988](#); [Liu et al., 2014](#); [Wu et al., 2014](#)); (2) they formed in supra-subduction-zone (SSZ) settings similar to those in the Izu-Bonin-Mariana arc system of

western Pacific, based on stratigraphic, petrological, geochemical and paleomagnetic evidence (e.g., [Aitchison et al., 2000](#); [Malpas et al., 2003](#); [Zhou et al., 2005](#); [Hébert et al., 2012](#); [Dai et al., 2013](#); [Huang et al., 2015](#); [Maffione et al., 2015](#)).

The key to reconciling the two contrasting sets of observations is to find the genetic link between the mantle rocks and the dominantly MORB-type magmas in the Yarlung Zangbo ophiolites. This requires systematic examination of the mantle sections and further understanding of the geodynamic processes that formed the enigmatic Tibetan ophiolites.

Here, we present detailed mineral chemical data on the basal lherzolites and overlying harzburgites, and Nd-Hf isotopic data on the lherzolites and the dolerite dykes that intrude the harzburgites, in the Zedang ophiolite from the Yarlung Zangbo Suture (South Tibet; [Fig. 1](#)); we also report new U-Pb and Hf-isotope data for zircon from the mafic dykes. These data reveal genetic links between the extension of the harzburgitic lithospheric mantle, intrusion of mafic dykes and the subcretion of the lherzolites, and link these processes to a period of magmatic waning in the Gangdese Arc, reflecting the migration of the Neo-Tethyan trench from the Gangdese Arc region to the oceanic forearc lithosphere. Our model provides a solution for the “ophiolite conundrum” observed globally.

2. Yarlung Zangbo ophiolites and sample descriptions

The Yarlung Zangbo ophiolites represent relics of the Neo-Tethyan oceanic lithosphere within the ~2000 km Yarlung Zangbo Suture (South Tibet, China), formed during the Mesozoic-Cenozoic closure of the Neo-Tethyan Ocean between Greater India and Asia (e.g., [Aitchison et al., 2000](#); [Hébert et al., 2012](#)). The rifting of Greater India from Eastern

Gondwanaland in the early Cretaceous and its subsequent northward drift caused continual subduction of the Neo-Tethyan Ocean beneath the southern margin of Asia (i.e., the Lhasa Block; [Fig. 1a](#)) and growth of the Gangdese magmatic arc on the Lhasa Block during Cretaceous to early Cenozoic time (e.g., [Yin and Harrison, 2000](#); [Ji et al., 2009](#); [Zhu et al., 2011](#)). Previous subduction of the Tethyan slab beneath the northward-drifting Lhasa Block generated the late Triassic to Jurassic Gangdese batholiths (e.g., [Ji et al., 2009](#); [Zhu et al., 2011](#)).

The Yarlung Zangbo ophiolites are sandwiched between the Tethyan Himalayan unit in the south and the Xigaze forearc basin and Luobusa conglomerate belt in the north ([Fig. 1b](#)). Two Cenozoic thrusts (the Renbu-Zedang and Gangdese thrusts) localize the Yarlung Zangbo suture zone between the northern margin of Greater India and the Gangdese Arc lying on the Lhasa Block (e.g., [Yin et al., 1999](#)). The ophiolites show several distinctive features. (1) They have very thin, if any, crust and abundant individual mafic dykes intrude the harzburgites and highly deformed serpentinites (~130-120 Ma; e.g., [Wu et al., 2014](#); [Zhang et al., 2015](#)). (2) The mélanges underlying the ophiolites enclose garnet-amphibolite blocks with ^{40}Ar - ^{39}Ar cooling ages of 132-127 Ma ([Guilmette et al., 2012](#)). (3) Some of the Yarlung Zangbo peridotites contain basal clinopyroxene-rich peridotites that underlie clinopyroxene-poor harzburgites (e.g., [Girardeau and Mercier, 1988](#); [Malpas et al., 2003](#)). (4) The ophiolites in the central-western segment contain internal detachment structures that developed during exhumation of the lithospheric mantle onto the ocean floor ([Liu et al., 2014](#); [Maffione et al., 2015](#)). (5) The harzburgites enclose SSZ-related dunites and chromitites (e.g., [Zhou et al., 2005](#); [Hébert et al., 2012](#)).

The Zedang ophiolitic assemblage includes, from south to north, four sub-units in thrust contact (a serpentinite layer, crustal mélanges, gabbro-dolerite associations and the peridotite massif) between the Triassic Langjiexue flysch in the south and the Jurassic Zedang arc complex in the north (Fig. 1b, 1c). The peridotite massif comprises lherzolites to the west and harzburgites to the east (Fig. 1b). Our comprehensive sampling of the Zedang ultramafic body covers five major sub-units, named from west to east, Guanjingtai (GJT), Jieni (JN), Jinlu (JL), Jiacun (JC) and Zantang (ZT). A diffuse boundary (~NE-SW) between the lherzolites and the harzburgites can be roughly defined around the Jinlu sub-unit, based on our petrographic examination [details shown by Xiong et al. (2015, submitted)]. This type of lithological zoning (basal lherzolite and upper harzburgite) has also been observed in the Xigaze ophiolite (e.g., Girardeau and Mercier, 1988; Malpas et al., 2003) and revealed by the study of the Luobusa ophiolite (Huang et al., 2014) in South Tibet, as well as found in other SSZ-type ophiolites (e.g., Bodinier and Godard, 2014).

The Zedang lherzolites consist of porphyroblastic olivine (Ol), orthopyroxene (Opx) and clinopyroxene (Cpx), in a medium-grained matrix of Ol + Opx + Cpx + spinel + sulfide ± serpentine ± magnetite. Crystal-preferred orientation of minerals, exsolution relationships and deformation-related microstructures (such as undulatory extinction and kink bands) are consistent with high-temperature plastic deformation (Fig. A1-a, -b). The lherzolite textures are different from those observed in refertilized lherzolites enclosed within harzburgites, but similar to the basal lherzolites found in other ophiolites (e.g., Bodinier and Godard, 2014). The harzburgites contain porphyroblasts of Ol and Opx set in a medium- to fine-grained matrix of Ol + Opx + Cpx + spinel ± sulfide ± serpentine ± magnetite (Fig. A1-c, -d). The

generally higher extent of serpentinization, much lower amounts of Cpx and sulfide, and fewer high-temperature deformation features in the harzburgites distinguish them from the lherzolites. The dolerite dykes intrude the upper harzburgites and serpentinites, and in some cases invade crustal gabbros that have been heavily altered by sea water (Fig. 1b). The mafic dykes have chilled margins and cut the shearing planes in the serpentinized harzburgites, indicating that the intrusion of dolerite dykes was later than the low-temperature alteration and deformation of the harzburgites.

Detailed descriptions of the sample preparation and analytical methods are presented in the **Supplementary Material**.

3. Results

3.1. Mineral major-element compositions and equilibration temperatures

Spinel grains in the Zedang lherzolites have higher contents of Al₂O₃ (50.4-42.0 wt%), NiO (0.34-0.21 wt%), MgO (18.9-16.8 wt%) and higher Mg# (0.76-0.70), and lower Cr₂O₃ (26.8-15.8 wt%), FeO (14.8-12.7 wt%), V₂O₃ (0.15-0.10 wt%) and Cr# (0.30-0.17), but similar contents of TiO₂ and ZnO, compared to spinel in the harzburgites (Table A1; Fig. 2).

Orthopyroxene porphyroblasts in the lherzolites have higher contents of Al₂O₃ (6.54-3.61 wt%), lower Cr# (0.12-0.08) and Mg# (0.91-0.90), and similar Cr₂O₃, TiO₂, MnO and CaO, compared to those of porphyroblastic Opx in the harzburgites (Table A2). Exsolved Opx within the Cpx porphyroblasts has higher Al₂O₃ and Cr₂O₃ contents, but lower Mg# than Opx porphyroblasts.

The Al-Cr exchange thermometer applied to orthopyroxene porphyroblasts (T_{WS91} ; Witt-Eickschen and Seck, 1991) gives equilibration temperatures for the lherzolites (~1260-1050 °C) generally ~250-150 °C higher than those of harzburgites (~1060-910 °C; Fig. 2; Table 1). The Ca-in-Opx thermometer (T_{BKCa90}) and Fe-Mg exchange thermometers between Opx and Cpx (T_{BK90} and T_{W77}) also show that the lherzolites have been hotter than the harzburgites (Table 1).

3.2. Trace-element compositions of peridotitic clinopyroxene and dolerite

Clinopyroxenes from the Zedang lherzolites show consistent REE patterns similar to those of clinopyroxenes in abyssal peridotites (Johnson et al., 1990), with a slow decrease in HREE-MREE from Yb to Eu and rapid decrease in LREE from Sm to Ce (Fig. 3a). Two analyses give measureable La contents, which are similar (in chondrite-normalized terms) to those of Ce, suggesting rare later metasomatic enrichment of La relative to simple decompression-melting residues. Clinopyroxenes from the representative harzburgites (Table A3) show “spoon-shaped” REE patterns, with lower contents of MREE-HREE but higher LREE than those of lherzolitc clinopyroxenes.

Extended trace-element patterns (Fig. 3b) show that the Cpx grains in lherzolites have extremely low concentrations of the more incompatible lithophile elements (Table A3), and negative anomalies in Sr and Zr relative to neighboring REE. On the other hand, Cpx grains in harzburgites show generally lower contents of MREE-HREE and Ti, and obvious enrichment in fluid-mobile elements (e.g., U, Pb, Sr), LREE and Zr, relative to those in lherzolitc clinopyroxenes.

In the chondrite-normalized REE plot (Fig. 3a), the Zedang dolerites show generally flat to LREE-depleted patterns, mostly similar to those of gabbros and dolerites close to the Moho in the Izu-Bonin-Mariana forearc lithosphere (Reagan et al., 2010, 2013). Minor Eu anomalies suggest different degrees of fractionation or accumulation of plagioclase. The extended trace-element diagram (Fig. 3b) is generally flat from Cs to Lu at the concentration levels of $\sim 10^{-1}$ times primitive mantle (Table A3), as seen in typical forearc basal gabbros and dolerites (Reagan et al., 2010, 2013). However, the relative enrichments in fluid-mobile elements (Cs, Ba, U, Pb and Sr) and minor negative anomalies in Nb, Ta, Zr and Ti, compared to neighboring elements and those forearc basal mafic rocks, may reflect some subduction-slab input to the generation of the Zedang dolerite dykes.

3.3. Nd-Hf isotopic compositions of lherzolitic clinopyroxene and dolerite

Sm-Nd and Lu-Hf isotopic compositions of clinopyroxenes from lherzolites and whole-rock dolerite samples are shown in Table 2. The clinopyroxenes have variable $^{147}\text{Sm}/^{144}\text{Nd}$ (2.17-1.30) and $^{143}\text{Nd}/^{144}\text{Nd}$ (0.51455-0.51414), which define a pseudo-isochron together with the depleted mantle (DM) at 119 ± 12 Ma (2σ ; Fig. 4a). The dolerites have Sm-Nd ratios similar to those of global mean MORB and DM (Fig. 4a). The initial $^{143}\text{Nd}/^{144}\text{Nd}$ ratios at 130 Ma of the lherzolitic clinopyroxenes, dolerites, mean MORB and DM are undistinguishable at the 2σ level (Fig. 4b).

The Lu-Hf systems of lherzolitic clinopyroxenes and DM define a pseudo-isochron with an age of 101 ± 15 Ma (2σ ; Fig. 4c). Dolerites have Lu-Hf ratios similar to those of DM, except for ZD11-60, which has higher $^{176}\text{Lu}/^{177}\text{Hf}$ and $^{176}\text{Hf}/^{177}\text{Hf}$ ratios but still lies on the

isochron. Initial $^{176}\text{Hf}/^{177}\text{Hf}$ ratios of the lherzolitic clinopyroxenes and dolerites are close to that of modeled DM at 130 Ma (Fig. 4d).

3.4. U-Pb ages, trace-element and Hf-isotope compositions of zircons from dolerite

U-Pb ages were obtained from 25 zircon grains from dolerite ZD11-69 and 24 grains from dolerite ZD11-70 (Table A4). All grains are euhedral prisms or subhedral fragments, with igneous oscillatory or sector zoning (Fig. A2). 25 analyses on 25 zircon grains from ZD11-69 are concordant (Fig. 5a, 5b) and give a weighted average $^{206}\text{Pb}/^{238}\text{U}$ age of 130 ± 1 Ma (2σ , MSWD=0.68); 24 concordant results on 24 grains from ZD11-70 (Fig. 5c, 5d) yield a weighted average $^{206}\text{Pb}/^{238}\text{U}$ age of 128 ± 2 Ma (2σ , MSWD=2.2). The REE patterns of these grains (Fig. A3; Table A5) are consistent with igneous zircons formed in a magma that crystallized plagioclase (Belousova et al., 2002). Th/U ratios (0.59-0.19) are similar to those of igneous zircons. U/Yb ratios and the contents of Hf and Y in these zircons show that they are similar mainly to those crystallized within igneous oceanic crust, although a few grains have very low U/Yb ratios, and thus resemble continental-crust zircons (Fig. A3-b, -c; Grimes et al., 2007).

Hf isotopes have been measured in twenty-three zircon grains from ZD11-69 and 20 grains from ZD11-70 (Table A6). All analyses show low $^{176}\text{Lu}/^{177}\text{Hf}$ ratios (<0.004685) and high $^{176}\text{Hf}/^{177}\text{Hf}$ ratios (0.28328-0.28300), giving positive $\epsilon_{\text{Hf}}(t)$ values close to those of DM (Fig. 6). The $^{176}\text{Hf}/^{177}\text{Hf}$ ratios of the zircons at 130 Ma are indistinguishable from those of the lherzolite clinopyroxenes and whole-rock dolerites at the 2σ level (Fig. 4d).

4. Discussion

4.1. Two distinctive lithospheric mantle domains

Our comprehensive sampling (Fig. 1b) and detailed petrographic examination (e.g., Fig. A1) show that the Zedang ultramafic massif is composed mainly of lherzolites in the west and harzburgites in the east. The lherzolites have: (1) >5% Cpx; (2) coarse-grained or porphyroblastic Cpx, with plastic deformation, bending and Opx exsolution lamellae; and (3) higher modes of sulfides than the harzburgites. In contrast, the harzburgites show less than ~3% modal Cpx, no porphyroblastic Cpx, few high-temperature deformation features, and almost no sulfides. The major-element compositions of spinel and orthopyroxene reflect a dichotomy between lherzolites and harzburgites (e.g., Sp_Cr# of 0.30-0.17 vs 0.62-0.33, Al₂O₃ contents in Opx porphyroblasts of 6.54-3.61 wt% vs 3.11-1.34 wt%; Tables A1, A2), indicating that the lherzolites are much more fertile than the harzburgites (Fig. 2). The REE (Fig. 3a) and extended trace-element (Fig. 3b) patterns also show that the harzburgites are more depleted than the lherzolites, in terms of MREE-HREE and Ti concentrations. However, the LREE, Zr and other fluid-mobile elements in the harzburgitic Cpx show relative enrichments, compared to the lherzolitic Cpx, implying that the Zedang harzburgites have experienced a more complex metasomatic history than the lherzolites. Detailed comparison of whole-rock and mineral elemental and isotopic geochemistry also reveals two distinctive layers of lithospheric mantle in the Zedang ophiolite (Xiong et al., 2015, submitted).

Equilibration temperatures (Fig. 2) estimated by the Cr-Al exchange thermometer in Opx show differences of ~250-150 °C between the Zedang lherzolites (~1260-1050 °C) and harzburgites (~1060-910 °C). Because these temperatures are calculated based on exchange of

Cr³⁺-Al³⁺, which have sluggish diffusion rates (e.g., Witt-Eickschen and Seck, 1991) and using compositions of Opx porphyroblastic cores and exsolved lamellae, they should give the most primary estimates of the temperature of the mantle protoliths. Thermometers based on the exchange of divalent cations give relatively lower temperatures, but still show that the lherzolites were hotter than the harzburgites (Table 1). Considering the thermal state of the global lithospheric mantle (e.g., McKenzie et al., 2005), the high-temperature lherzolite domain should in theory be located closer to the asthenosphere than the low-temperature harzburgite domain. The refractory nature and complex metasomatic signatures of the harzburgites also indicate that the Zedang harzburgite-lithosphere layer was probably formed earlier and located at shallower levels than the lherzolites, to be able to experience later enrichment. This inference is consistent with the field observation that the harzburgites are close to the ophiolitic crustal sections while the lherzolites are located in basal sections, similar to observations in the Xigaze ophiolite (Nicolas et al., 1981; Girardeau and Mercier, 1988).

4.2. Intrusion of mafic dykes into harzburgite and lherzolite accretion

The U-Pb ages of igneous zircons from the Zedang dolerite dykes indicate intrusion of the dykes into the harzburgites at ~130-128 Ma (Fig. 5). This mafic magmatism at ~130-120 Ma has been recognized as widespread in other Yarlung Zangbo ophiolites, and shows chemical features of MORB and forearc basalts (e.g., Malpas et al., 2003; Dai et al., 2013; Wu et al., 2014; Zhang et al., 2015). The intrusive relationships between the mafic dykes and the deformed/serpentinized harzburgites indicate that the mafic magmatism postdated the

low-temperature alteration and deformation of the harzburgites, which occurred close to the ocean floor, and suggest that the accretion and emplacement of harzburgitic lithosphere from the convective mantle was earlier than the intrusion of mafic dykes. The accretion for the harzburgites may have occurred at ~170-150 Ma, based on dating of concordant gabbro lenses within the neighboring Luobusa harzburgites and the western ophiolites in the Yarlung Zangbo Suture (e.g., [Zhong et al., 2006](#); [Hébert et al., 2012](#); [Chan et al., 2015](#)). The coeval growth of the Zedang arc complex (e.g., [McDermid et al., 2002](#)) and the generation of Late Triassic-Jurassic Gangdese Arc batholiths ([Fig. 6](#); e.g., [Ji et al., 2009](#); [Zhu et al., 2011](#)) can also provide indirect age constraints for the ophiolitic harzburgite generation, probably related to the operation of the Jurassic SSZ system ([Figs. 7, 8a](#)).

On the other hand, the Sm-Nd and Lu-Hf isotopic compositions of the Zedang lherzolites give pseudo-isochron ages that imply the lherzolites were emplaced concurrently with the intrusion of mafic dykes at ~130-120 Ma ([Fig. 4a, 4c](#)). The initial Nd-Hf isotopic compositions of the lherzolites are generally consistent with those of the Zedang dolerite dykes, and both are undistinguishable from those of the depleted mantle at 130 Ma ([Fig. 4b, 4d](#)). The zircon Hf-isotope data ([Figs. 4d, 6b](#)) show that the dolerite dykes were also derived from the depleted asthenosphere, and the trace-element compositions of the dykes suggest only minor slab input into this mantle source ([Fig. 3b](#)). Furthermore, the clinopyroxene trace-element patterns ([Fig. 3](#)) suggest that the Zedang lherzolites represent residues after moderate decompression melting of the asthenosphere, like the abyssal peridotites generated in oceanic spreading regimes (e.g., [Johnson et al., 1990](#)). The isotopic and chemical evidence indicates that the Zedang lherzolites and dolerite dykes came from the same source, i.e.,

asthenosphere with minor slab input, and represent the residue and magma products, respectively, generated during the upwelling and partial melting of the weakly-contaminated asthenosphere at ~130-120 Ma. Therefore, we can suggest that the subcretion of lherzolites beneath the Zedang harzburgites was linked with the upward migration and intrusion of mafic magmas into the overlying harzburgites at ~130-120 Ma.

Recent studies of the Yarlung Zangbo ophiolites suggest that they formed as forearc lithosphere in front of the Gangdese Arc and that internal detachment structures were generated during forearc hyperextension at ~130-120 Ma (An et al., 2014; Huang et al., 2015; Maffione et al., 2015), although these extensional structures have previously been regarded as formed in slow- to ultraslow-spreading mid-ocean ridges (e.g., Nicolas et al., 1981; Girardeau and Mercier, 1988; Wu et al., 2014; Liu et al., 2014). Our study provides robust evidence that the extension of the harzburgitic Tethyan lithosphere and coeval widespread mafic magmatism as dykes in the harzburgites were directly related to the upwelling of asthenosphere, which resulted in the subcretion of lherzolites and the doming of the overlying harzburgites at ~130-120 Ma (Figs. 7, 8b).

4.3. Neo-Tethyan trench migration and evolution of the Gangdese Arc

Studies of the Izu-Bonin-Mariana, Tonga and South Sandwich forearcs have identified a general sequence of the initiation and the evolution of slab subduction, starting with the early formation of less-depleted lherzolitic lithosphere and tholeiitic MORB-like magmas and evolving to a later generation of harzburgitic mantle with associated boninitic and calc-alkaline magmas (e.g., Stern et al., 2012). The sequence of the lherzolites and

harzburgites in the Zedang ophiolite is the opposite to those suggested by [Stern et al. \(2012\)](#), implying that they were not formed during the same subduction episode, if their geneses were related to SSZ processes.

The Zedang dolerite dykes show general similarities to gabbros and dolerites close to the Moho in the Izu-Bonin-Mariana forearc ([Fig. 3](#)), which formed during the subduction-initiation stages ([Reagan et al., 2010, 2013](#)). Spikes in fluid-mobile elements and depressions in HFSE imply minor contributions from the subducting Tethyan slab into the magma sources (i.e. asthenosphere weakly contaminated by slab fluids) of the Zedang mafic dykes. The lherzolite accretion and the generation of forearc mafic magmas in the Zedang ophiolite both reflect the onset of Neo-Tethyan subduction at ~130-120 Ma in a new cycle.

The growth of the Jurassic arc complexes in the Gangdese and Zedang areas indicates an earlier cycle of SSZ processes ([Figs. 6, 7](#)), possibly related to the generation of the Zedang harzburgitic lithosphere (cycle I; [Fig. 8a](#)). The internal weakness zones that formed during harzburgite emplacement, and the buoyancy contrast between harzburgite and the asthenosphere, can make the harzburgitic lithosphere become a favored site for the initiation of new slab subduction (cycle II; [Fig. 8b](#)) (e.g., [Niu et al., 2003](#); [Stern et al., 2012](#)). The collision of the northward-drifting Lhasa block with the Qiangtang block at ~140-120 Ma (e.g., [Kapp et al., 2007](#); [Zhu et al., 2011](#)) can provide a dynamic force to initiate a new Tethyan subduction cycle in front of the south Lhasa margin (e.g., underneath the Jurassic harzburgite lithosphere). Moreover, the rifting of East Gondwanaland to open the East Indian Ocean and the initial breakup of West Gondwanaland to open the South Atlantic Ocean, both probably were due to the plume activity at ~132 Ma (e.g., [Storey, 1995](#); [Zhu et al., 2009](#)). The

plate reorganization related to the Lhasa-Qiangtang collision and the Gondwana breakup in early Cretaceous probably provided the geodynamic impetus for initiation of the northward subduction of the Neo-Tethyan slab beneath the southern margin of Asia (e.g., the Gangdese Arc) in a new cycle (Figs. 7, 8b, 8c). This initiation of subduction has also been recorded by the coeval formation of garnet-amphibolite blocks in the subduction mélange (e.g., Guilmette et al., 2012) and by the onset of sedimentation within the Xigaze forearc basin (e.g., An et al., 2014; Huang et al., 2015). Therefore, all lines of evidence suggest that the accretion of lherzolites, the intrusion of dolerite dykes and the hyperextension of the older harzburgites were the consequences of the initiation of the Neo-Tethyan subduction beneath the pre-existing harzburgitic lithosphere at ~130-120 Ma.

Published U-Pb ages and Hf-isotope data (Fig. 6) for zircons from plutons in the Gangdese Arc indicate that juvenile arc magmatism from the subarc region was fluxed by fluids from the subducting Tethyan slab, from ~210-140 Ma (Fig. 8a) and from ~120-55 Ma (Fig. 8c; e.g., Ji et al., 2009; Zhu et al., 2011; and other references in Supplementary Material). However, the supply of juvenile magmas from the sub-arc convective mantle was almost completely interrupted from ~130-120 Ma; during this period the dominant magmatism in the broad subduction system was the MORB-like magmas intruded as dykes into the forearc ophiolitic peridotites (Figs. 7, 8b), with very rare magmatic activity in the Gangdese Arc (e.g., ~122 Ma high-Mg dioritic rocks; Wang et al., 2013). The waning of the Gangdese Arc magmatism suggests that the Neo-Tethyan slab was not subducting beneath the Gangdese arc system or at least was far removed from the arc-magma plumbing region at ~130-120 Ma. We suggest that this magmatic lull probably corresponds to the southward migration of

Neo-Tethyan subducting slab front (and trench) from the Gangdese subarc to the oceanic forearc in a new subduction cycle, and this tectonic process formed the newly accreted lherzolites beneath pre-existing harzburgites in the forearc lithosphere (Fig. 8b). The subsequent Neo-Tethyan subduction (Fig. 8c) reactivated the introduction of juvenile magmas from the subarc mantle into the Gangdese Arc crust (Fig. 6), and resulted in the ongoing development of the Xigaze forearc basin (Fig. 7) and later emplacement of the duplexed oceanic lithosphere as the Yarlung Zangbo ophiolites on the collisional margin (e.g., An et al., 2014; Huang et al., 2015; Maffione et al., 2015).

4.4. A solution for the global “ophiolite conundrum”

The observations in this study suggest that the depleted harzburgites were emplaced earlier in the oceanic lithosphere as a lid, and that the later upwelling of asthenosphere, induced by the southward migration of Neo-Tethyan slab front, has caused the subcretion of asthenosphere-derived lherzolites, doming and extension of the harzburgite lid, and coeval intrusion of mafic dykes (Figs. 7, 8b). These processes at ~130-120 Ma formed the MORB-type magmas and extensional structures like those usually observed in slow-spreading mid-ocean-ridges (e.g., Nicolas et al., 1981; Liu et al., 2014; Wu et al., 2014). However, these features could also be generated during subduction initiation in a forearc setting, consistent with the geochemical evidence for an SSZ-related origin (e.g., Zhou et al., 2005; Hébert et al., 2012; Dai et al., 2013; An et al., 2014). Our multi-stage model provides a solution to the global “ophiolite conundrum” that a SSZ-type ophiolite has MOR features.

5. Conclusions

The slab front of the subducting Neo-Tethyan lithosphere migrated southward from the Gangdese subarc region to the oceanic forearc at ~130-120 Ma, triggering upwelling of asthenosphere beneath the forearc harzburgitic lithosphere. These events caused subcretion of lherzolites and coeval intrusion of basaltic magmas as dolerite dykes within the Zedang harzburgites and other Yarlung Zangbo ophiolites (South Tibet, China). The coincidence between the relocation of the Neo-Tethyan trench and the waning of magmatism in the Gangdese Arc at ~130-120 Ma marks an unusual tectonic regime along the southern Asian convergent margin. This short-lived (~10 Ma) tectonic process may have been a far-field consequence of plate reorganization related to the Lhasa-Qiangtang collision and the breakup of Gondwanaland in the early Cretaceous. This study provides a multi-stage forearc accretion model, which can resolve the “ophiolite conundrum” observed globally.

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551

Figure captions

Fig. 1. Simplified tectonic map (a) showing the Tibetan-Himalayan orogenic system [modified after DeCelles et al. (2002)], geological sketch map (b) of the Zedang ophiolite and adjacent tectonic units [south Tibet; modified after McDermid et al. (2002)], and a simple cross section (c) of line A-A' in Fig. 1b illustrating the geological context of this ophiolite. The inset in the bottom left corner of Fig. 1a shows the major tectonic units in eastern Asia, and the red box indicates the area of Fig. 1a. Sampling localities for lherzolite, harzburgite and dolerite are shown in Fig. 1b, and samples for Nd-Hf isotopic analyses are marked by "I" in cycles. The dashed line with a question mark in Fig. 1c shows the proposed diffuse boundary between the lherzolite and harzburgite domains. Legends of Fig. 1b and 1c are given in the upper-right panel. Abbreviations: MBT, Main Boundary Thrust; MCT, Main Central Thrust; STDS, South Tibetan Detachment System; YZS, Yarlung Zangbo suture; BNS, Bangong-Nujiang suture; JS, Jinsha suture; AKMS, Anyimaqen-Kunlun-Muztagh suture; NQO, North Qaidam orogen; NQS, North Qilian suture; ATF, Altyn Tagh Fault; GT, Gangdese Thrust; RZT, Renbu-Zedang Thrust.

Fig. 2. Variations of spinel Cr# vs equilibration temperatures (°C) estimated using the Cr-Al exchange thermometer in orthopyroxene (T_{WS91} ; Witt-Eickschen and Seck, 1991) for the Zedang peridotites, South Tibet. Three lherzolites with tie lines between thick and thin black outlines connect the minerals in equilibration stages 0 (exsolved Opx laths in Cpx porphyroblasts) and I (Opx porphyroblasts). All other temperatures are calculated using the

compositions of the cores of Opx porphyroblasts. Abbreviations: GJT, Guanjingtai; JN, Jieni; JL, Jinlu; JC, Jiacun; ZT, Zantang.

Fig. 3. REE (a) and extended trace-element (b) patterns of peridotitic clinopyroxenes and dolerite dykes in the Zedang ophiolite (South Tibet), normalized to values of chondrite and primitive mantle, respectively (McDonough and Sun, 1995). Forearc basal gabbro and dolerite are from the lower crust close to the Moho in the Izu-Bonin-Mariana forearc (Reagan et al., 2010, 2013).

Fig. 4. Variations of $^{147}\text{Sm}/^{144}\text{Nd}$ (t=0 Ma) vs $^{143}\text{Nd}/^{144}\text{Nd}$ (t=0 Ma) (a), $^{147}\text{Sm}/^{144}\text{Nd}$ (t=0 Ma) vs $^{143}\text{Nd}/^{144}\text{Nd}$ (t=130 Ma) (b), $^{176}\text{Lu}/^{177}\text{Hf}$ (t=0 Ma) vs $^{176}\text{Hf}/^{177}\text{Hf}$ (t=0 Ma) (c), and $^{176}\text{Lu}/^{177}\text{Hf}$ (t=0 Ma) vs $^{176}\text{Hf}/^{177}\text{Hf}$ (t=130 Ma) (d) for lherzolitic clinopyroxenes and dolerites in the Zedang ophiolite (South Tibet). Gray rectangles in (b) and (d) represent the regions of initial Nd- and Hf-isotope ratios of dolerite whole rocks, respectively. The probability distribution of $^{176}\text{Hf}/^{177}\text{Hf}$ (t=130 Ma) in dolerite zircons is shown in Fig. 1d. All errors are at $\pm 1\sigma$ level, and those of dolerites are smaller than the symbols. Nd-Hf isotopic compositions of mean MORB are from Gale et al. (2013).

Fig. 5. Concordia plots of U-Pb isotopic data (a, c) and $^{206}\text{Pb}/^{238}\text{U}$ age distributions (b, d) for zircons from dolerites in the Zedang ophiolite (south Tibet). Error ellipses and bars are at 2σ level. Weighted averages of $^{206}\text{Pb}/^{238}\text{U}$ ages are given in the two insets in (a) and (c), and also shown by thick, gray vertical lines in (b) and (d).

Fig. 6. (a) Probability distribution diagram of U-Pb ages for zircons with $^{206}\text{Pb}/^{238}\text{U}$ ages >40 Ma from Gangdese Arc plutons. **(b)** Variations of U-Pb ages vs $\varepsilon_{\text{Hf}}(t)$ of zircons from the Zedang dolerite dykes, similar mafic dykes in the literature (Dai et al., 2013) and Gangdese Arc plutons, including mafic intrusions (green crosses) and intermediate-felsic granitoids (red crosses) (Data sources, see Supplementary Material). Gray column marks the time span of 130-120 Ma.

Fig. 7. Summary chart of the tectono-magmatic evolution related to the generation of the Zedang ophiolite, Yarlung Zangbo Suture (South Tibet). Detailed tectonic and magmatic processes are described in the main text. Abbreviations: YZO, Yarlung Zangbo ophiolites; T3-J, late Triassic-Jurassic; K-Pg, Cretaceous-Paleogene.

Fig. 8. Schematic cartoons (not to scale) illustrating the tectonic evolution of the Neo-Tethyan lithosphere in front of the Gangdese Arc from ~200 Ma to 55 Ma. **(a)** The Tethyan oceanic slab subduction (cycle I) during ~200-130 Ma caused the emplacement of depleted harzburgites through an upwelling asthenosphere channel into the forearc lithosphere, and led to the activation of Gangdese Arc magmatism. After emplacement, the harzburgites were cooled and serpentinized. **(b)** The southward migration of the Neo-Tethyan slab front from the Gangdese subarc region to the oceanic forearc at ~130-120 Ma resulted in waning of magmatism in the Gangdese Arc and triggered the upwelling of asthenosphere beneath the forearc lithosphere, which caused the subcretion of lherzolites, intrusion of dolerite dykes, doming and extension of overlying harzburgitic lithosphere and the formation of metamorphic

617 soles in the forearc. At this time, the broken-off Tethyan slab was far from the shallow
618 subduction system. (c) When the Neo-Tethyan slab gradually subducted beneath the
619 Gangdese Arc, the arc magmatism was reactivated from ~120-55 Ma; the forearc lithosphere
620 was emplaced as the Yarlung Zangbo ophiolites in the late Cretaceous time (e.g., [Malpas et](#)
621 [al., 2003](#); [An et al., 2014](#); [Huang et al., 2015](#)). Abbreviations: OLM, oceanic lithospheric
622 mantle; SCLM, subcontinental lithospheric mantle; YZ, Yarlung Zangbo.

Figure 1

Figure 2

Figure 3

Figure 4

$^{176}\text{Hf}/^{177}\text{Hf}_i$

Figure 5

Figure 6

Figure 7

Figure 8

Table 1
Summary of estimated temperatures (°C) of representative peridotites in the Zedang ophiolite, South Tibet

Lithology	T _{WS91}	T _{BKCa90}	T _{BK90}	T _{W77}
Lherzolite	1261~1045	1166~941	1053~753	1044~821
Harzburgite	1061~914	994~956	857~718	895~807

Detailed temperature estimation can be found in [Xiong et al. \(2015, submitted\)](#). All temperatures are estimated based on the compositions of porphyroblastic cores and exsolved phases in pyroxenes, at a set pressure of 1.5 GPa. Thermometers: T_{WS91}, Al-Cr exchange in Opx ([Witt-Eickschen and Seck, 1991](#)); T_{BKCa90}, Ca-in-Opx ([Brey and Kohler, 1990](#)); T_{BK90}, Fe-Mg exchange between Opx and Cpx ([Brey and Kohler, 1990](#)); T_{W77}, Fe-Mg exchange between Opx and Cpx ([Wells, 1977](#)).

Table 2

Table 2

Sm-Nd and Lu-Hf isotopic compositions of minerals and whole rocks of the Zedang ophiolite, South Tibet (China)

Sample ID	ZD11-60	ZD11-61	ZD11-69	ZD11-70	ZD11-71	ZD11-72	ZD11-74	ZD11-18	ZD11-64	10ZD-6-1
Lithology	Dolerite	Dolerite	Dolerite	Dolerite	Dolerite	Dolerite	Dolerite	Lherzolite	Lherzolite	Lherzolite
Locality	JL	JL	JL	JL	JL	JL	JL	GJT	JN	JL
Comments	WR	WR	WR	WR	WR	WR	WR	Cpx	Cpx	Cpx
$^{147}\text{Sm}/^{144}\text{Nd}$	0.258612	0.230048	0.233797	0.222230	0.281408	0.245270	0.238701	1.301653	1.776066	2.174394
1 σ	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	0.163357	0.089625	0.268429
$^{143}\text{Nd}/^{144}\text{Nd}$	0.513002	0.512975	0.513044	0.513004	0.513117	0.513003	0.513054	0.514142	0.514348	0.514545
1 σ	0.000014	0.000012	0.000004	0.000001	0.000003	0.000006	0.000002	0.000016	0.000028	0.000016
$^{143}\text{Nd}/^{144}\text{Nd}_i$	0.512782	0.512779	0.512846	0.512815	0.512878	0.512794	0.512851	0.513035	0.512837	0.512696
1 σ	0.000014	0.000012	0.000004	0.000001	0.000003	0.000006	0.000002	0.000140	0.000081	0.000229
$\epsilon_{\text{Nd}}(t)$	6.2	6.2	7.5	6.9	8.1	6.5	7.6	11.2	7.3	4.5
1 σ	0.3	0.2	0.1	0.0	0.1	0.1	0.0	2.7	1.6	4.5
$T_{\text{DM}}(\text{Ma})$	-502	-1634	-800	-2595	-73	-710	-586	139	117	109
1 σ	46	116	33	25	6	30	11	21	7	15
$^{176}\text{Lu}/^{177}\text{Hf}$	0.158685	0.060346	0.064787	0.048034	0.039160	0.043158	0.041721	0.394575	0.435707	N.A.
1 σ	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	0.030364	0.034412	N.A.
$^{176}\text{Hf}/^{177}\text{Hf}$	0.283501	0.283202	0.283200	0.283249	0.283247	0.283227	0.283200	0.283907	0.284015	N.A.
1 σ	0.000007	0.000007	0.000009	0.000003	0.000004	0.000004	0.000013	0.000046	0.000043	N.A.
$^{176}\text{Hf}/^{177}\text{Hf}_i$	0.283116	0.283055	0.283043	0.283133	0.283152	0.283122	0.283098	0.282949	0.282958	N.A.
1 σ	0.000007	0.000007	0.000009	0.000003	0.000004	0.000004	0.000013	0.000087	0.000094	N.A.
$\epsilon_{\text{Hf}}(t)$	14.6	12.4	12.0	15.2	15.9	14.8	14.0	8.7	9.0	N.A.
1 σ	0.2	0.2	0.3	0.1	0.1	0.2	0.4	3.1	3.3	N.A.
$T_{\text{DM}}(\text{Ma})$	111	-120	-104	-9	-312	-277	-836	99	103	N.A.
1 σ	3	16	18	15	300	50	207	11	11	N.A.

Abbreviations: JL, Jinlu; GJT, Guanjingtai; JN, Jieni; WR, whole rock; Cpx, clinopyroxene; N.A., not analyzed; DM, depleted mantle. Initial Nd-Hf isotopic compositions, $\epsilon_{\text{Nd}}(t)$ and $\epsilon_{\text{Hf}}(t)$ are calculated back to 130 Ma. Parameters using for calculation of initial Nd-Hf ratios and model ages have been described in the Methods of the [Supplementary Material](#).