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Presence of Permian extension- and arc-type magmatism in southern Tibet: Paleogeographic implications

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ABSTRACT

The geographical location of the Lhasa terrane in the Permian remains a subject of debate. The recognition of the Permian basalts in the Tethyan Himalaya and the Permian volcanic rocks in the Lhasa terrane in southern Tibet together with the geochemistry of these rocks offer some new insights. The Permian basalts in the Tethyan Himalaya show a geochemical affinity with tholeiitic continental flood basalts, and are interpreted to have formed in an extensional setting. The new geochemical data and the geographical distribution of these basalts indicate that they probably represent the easternmost extent of the Panjal continental flood basin province. All of the Permian basalts in the Lhasa terrane show a calc-alkaline, high-alumina basalt affinity, with significant negative Nb-Ta-Ti anomalies. These geochemical features, combined with the recent documentation of the Permian Songdo eclogite and sedimentological observations, indicate the existence of a subduction system beneath the central Lhasa subterrane in the Permian. The presence of both extension- and arc-type magmatism of Permian age in present-day southern Tibet is inconsistent with the general view that the Lhasa terrane did not rift away from the northern margin of the Greater India until the Late Permian or Triassic. Instead, we suggest that the central Lhasa subterrane may have been a microcontinent isolated in the Paleo-Tethyan Ocean basin, at least during the Carboniferous–Middle Permian.

INTRODUCTION

The Paleo-Tethyan Ocean occupied a large area around the equator from the Devonian to the Triassic (cf. Stampfl i and Borel, 2002; Metcalfe, 2006; Ferrari et al., 2008; Har a et al., 2009). It opened in the Late Ordovician–Devonian in response to the separation of the Hun superterrane, Tarim, North and South China, and Indochina from Gondwana as a result of the subduction of a former peri–Gondwana Ocean seafloor (e.g., Stöcklin, 1974; Şengör, 1979, 1987; von Raumer et al., 2002; Stampfli and Borel, 2002; Metcalfe, 2006; Ferrari et al., 2008; Har a et al., 2009). The subsequent subduction of this ocean seafloor led to the separation of the Cimmerian microcontinents (including parts of present-day Anatolia, Iran, Afghanistan, Tibet, and Malaya regions) (Şengör, 1987) and to the opening of the Neo-Tethyan Ocean as a backarc basin (e.g., Şengör, 1979; Yin and Harrison, 2000; Stampfli and Borel, 2002; Metcalfe, 2006; Ferrari et al., 2008). Although this conceptual framework is straightforward, its validity needs testing. For example, the closure of the Paleo-Tethyan Ocean and the opening of the Neo-Tethyan Ocean have been generally thought to have taken place in the late Paleozoic (Yin and Harrison, 2000; Metcalfe, 2002; Stampfli and Borel, 2002). However, the actual timing of the two major events remains hotly debated (e.g., Bhat et al., 1981; Scotes e et al., 1999; Golonka and Ford, 2000; Metcalfe, 2002; Stampfli and Borel, 2002; Angiolini et al., 2003; Golonka, 2007, and references therein). Studies undertaken in Oman have suggested that the opening of the Neo-Tethyan Ocean could have happened in the Triassic (Robertson and Searle, 1990). Middle Permian (Stampfl i et al., 1991; Stampfli and Borel, 2002) or Early Permian (Saidi et al., 1997; Angiolini et al., 2003).

Similar discrepancies have emerged from studies in southern Tibet. Garzanti and Sciu nach (1997) and Garzanti et al. (1999) proposed that the Neo-Tethyan Ocean opened synchronously over the region extending from India to Nepal and Tibet during the Early Permian, whereas Stampfli and Borel (2002), working mainly in the western Tethys, suggested that the opening was diachronous from east of Australia (Late Carboniferous–Early Permian) to the Indian and Arabian plates (Middle-Late Permian). Golonka (2007) argued that the Neo-Tethyan Ocean between the Lhasa terrane and Greater India opened during the Early Jurassic. These varying estimates on the timing have resulted in highly variable paleogeographic reconstructions of the Lhasa terrane during the late Paleozoic. For example, some studies have proposed that the Lhasa terrane was positioned adjacent to Greater India until the Late Permian (Golonka and Ford, 2000; Golonka, 2000, 2007; Metcalfe, 2002; Scotes e, 2004), whereas others concluded that the Lhasa terrane was isolated within the Tethyan Ocean basin during the Late Permian (Enkin et al., 1992; Ziegler et al., 1997; Scotes e et al., 1999; Stampfli and Borel, 2002). A likely reason for these contrasting views is the lack of sufficient observations pertaining to the issue from southern Tibet.

The geodynamic reorganization of the Tethyan realm that occurred during the late Paleozoic and early Mesozoic was accompanied by magmatic activity along the northern margin of Gondwana, from the eastern Himalaya to Tibet and Oman (Bhat and Zaimuddin, 1978; Bhat et al., 1981; Spring et al., 1993; Vannay and Spring, 1993; Garzanti et al., 1999; Noble...
et al., 2001; Maury et al., 2003; Lapierre et al., 2004; Chauvet et al., 2008). Recent studies have also documented Permian magmatic rocks in the Selong area of the Tethyan Himalaya (Zhu et al., 2002, 2004), and in the Pikang (Zhu et al., 2009a), Songdo (Yang et al., 2009), Linzhou (Pan et al., 2006), Coqen, and Ranwu areas in the Lhasa terrane (Fig. 1A). However, the significance of these Permian magmatic rocks in reconstructing the location of the Lhasa terrane remains poorly known because few geochemical data are available for the Permian volcanic rocks in the Lhasa terrane and the Tethyan Himalaya. In this study, we present geochemical and Sr-Nd isotopic data on the Permian volcanic rocks from both the Tethyan Himalaya (Selong area) and Lhasa terrane (Jiangrang, Nixiong, Leiqingla, and Ranwu areas), whose ages are

Figure 1. (A) Sketch map of tectonic outline (Zhu et al., 2008a) showing the localities of Permian volcanic rock (red stars) (this study), Permian granites (black stars) (Spring et al., 1993; Noble et al., 2001; Zhu et al., 2009a), Permian eclogite (yellow star) (Yang et al., 2009), and Panjal Traps (Garzanti et al., 1999) in the southern Qinghai-Tibetan Plateau, Emeishan basalts in southwest Sichuan (Shellnutt et al., 2008). (B) Geologic map of Selong area of the Tethyan Himalaya (modified from Pan and Ding, 2004). (C) Geologic map of Zedala and Nixiong areas of the central Lhasa subterrane. Abbreviations: Fm.—Formation; Gr.—Group.
well constrained by the paleontology (Fig. 1A). These geochemical data, together with the stratigraphic and petrographic evidence, are used to (1) determine the tectonic setting of the Permian volcanic rocks, and (2) explore the geographic location of the Lhasa terrane in the Permain, which combined provide new perspectives on important aspects of the tectonic evolution of the Tethyan system. Our studies emphasize the importance of effective use of tectonomagmatic data in paleogeographic reconstruction, in particular contemporaneous magmatic events reflecting different tectonic settings in different terranes (e.g., Tethyan Himalaya, Lhasa, and Qiangtang in southern Tibet).

**GEOLOGICAL BACKGROUND**

Geologically, southern Tibet consists of two large, E-W-trending tectonic units, India and Asia, separated by the Indus–Yarlung Zangbo Suture Zone. The Himalayan Belt is further divided into three subbelts, from south to north: the Lesser Himalaya, High Himalaya, and Tethyan Himalaya (Fig. 1A). The Tethyan Himalaya, which exposes Permian basalts described in this paper, is located immediately south of the Indus–Yarlung Zangbo Suture Zone. It is dominated by post-Paleozoic marine sedimentary sequences, and is generally considered to represent a passive continental margin sequence deposited on Greater India from the Late Triassic to the Early Cretaceous (Yu and Wang, 1990). The Tethyan Himalaya has also been interpreted by others as having developed in an extensional setting from mid-late Paleozoic to Early Cretaceous (Garzanti et al., 1999; Wang et al., 2000).

The Indus–Yarlung Zangbo Suture Zone is the locus where the Neo-Tethyan Ocean seafloor was consumed by northward subduction beneath the Lhasa terrane from Early Jurassic to Late Cretaceous or later (Marcoux et al., 1982; Xu et al., 1985; Bureau of Geology and Mineral Resources of Xizang Autonomous Region, 1993; Chu et al., 2006; Zhang et al., 2007; Zhu et al., 2008a, 2009b). Along the Indus–Yarlung Zangbo Suture Zone are abundant exposures of Jurassic–Cretaceous ophiolites and minor Late Triassic–Middle Jurassic ophiolites (e.g., Ziaibev et al., 2003; Zhou et al., 2004; Zhu et al., 2005; Zhang et al., 2005; Pan et al., 2006). A detailed account of the geology of the Lesser and High Himalayas can be found in Yin (2006).

The Lhasa terrane is bounded by the Bangong Tso–Nuijiang Suture Zone (BNSZ) to the north and the Indus–Yarlung Zangbo Suture Zone (IYZSZ) to the south (Fig. 1A). It is widely accepted that the Lhasa terrane is not only an archetype of a collisional orogen, related to the Cenozoic India-Asia collision but also an Andean-type convergent margin marked by northward subduction of the Neo-Tethyan Ocean seafloor prior to the collision (Xu et al., 1985; Yin and Harrison, 2000; Chu et al., 2006; Zhang et al., 2007; Mo et al., 2008; Zhi et al., 2008a, 2009b). The Lhasa terrane can be divided further (from north to south) into the northern, central, and southern three subterranes, separated by the Shiquanhe–Nam Tso Mélangé Zone (SNMZ) and Luobadui-Milashan Fault (LMF), respectively (Fig. 1A). The northern Lhasa subterranee is inferred to be underlain by Precambrian crystalline basement, which has only been recognized from the Amdo area (Amdo orthogneiss; Fig. 1A) (Xu et al., 1985; Dewey et al., 1988; Guynn et al., 2006). The main rock units exposed in this subterranee are Jurassic–Cretaceous sedimentary and igneous rocks (Leeder et al., 1988; Yin et al., 1988; Pan and Ding, 2004; Zhang et al., 2004; Leider et al., 2007, 2008; Zhu et al., 2008b). The central Lhasa subterranee is dominated by a Carboniferous–Permian metasedimentary sequence (metasandstone, slate, and phyllite) and a Late Jurassic–Early Cretaceous volcanic–sedimentary sequence, with minor Ordivician, Silurian, and Triassic limestone (Leeder et al., 1988; Yin et al., 1988; Pan and Ding, 2004; Kapp et al., 2005; Ji et al., 2007; Leider et al., 2007; Zhu et al., 2008b) and rare Precambrian strata (Hu et al., 2005). The Permian volcanic rocks investigated here are scattered along the southern margin of the central Lhasa subterranee from western Coqen County to central Linzhou County and eastern Ranwu Town (Fig. 1A). The southern Lhasa subterranee is dominated by the Late Triassic to early Tertiary Gangeside batholith and Linzinzong volcanic succession, with minor Triassic–Cretaceous volcanic–sedimentary rocks (Leeder et al., 1988; Pearce and Mei, 1988; Pan and Ding, 2004; He et al., 2007; Leider et al., 2007; Mo et al., 2008; Wen et al., 2008; Zhu et al., 2008a, 2009b; Ji et al., 2009).

The Lhasa terrane is traditionally thought to have rifted from Gondwana and then drifted northward before being finally amalgamated with the Qiangtang terrane during the Early Cretaceous (see Şengör, 1987; Yin and Harisson, 2000; Kapp et al., 2005; Leider et al., 2007). However, the recent recognition of the Songdo eclogite and Pikang granite of Permain age in the central Lhasa subterranee (Fig. 1A) (Yang et al., 2009; Zhu et al., 2009a) has raised questions regarding its tectonic reconstruction in the late Paleozoic. The crust of the northern Lhasa subterranee was shortened by >50% largely by southward thrusting during the Late Cretaceous to Paleocene (Kapp et al., 2003; Guynn et al., 2006; Volkmer et al., 2007). The central Lhasa subterranee must have been a microcontinental block, as indicated by zircon U-Pb age dates and Lu-Hf isotopic data (Zhu et al., 2009c).

The Carboniferous–Permian metasedimentary sequence of this subterranee was thrust southward over the southern Lhasa subterranee along the Luobadui-Milashan Fault during or prior to the India-Asia collision (Pan and Ding, 2004; He et al., 2007). The southern Lhasa subterranee experienced major upper-crustal shortening during the Late Cretaceous–earliest Tertiary, as indicated by the widespread presence of strongly shortened (>40%) pre-Cenozoic rocks unconformably overlain by the relatively undeformed Linzinzong volcanic succession (Mo et al., 2003, 2007; He et al., 2007, and references therein).

**FIELD OCCURRENCE OF PERMIAN VOLCANIC ROCKS**

This paper focuses on Permian volcanic rocks from one locality in the Tethyan Himalaya and five localities in the central Lhasa subterranee (Fig. 1A). The lithostratigraphic positions are shown in Figure 2 and briefly described below. Details of the stratigraphy and petrography for each locality are given as an electronic supplement (see GSA Data Repository1).

**Jilong Formation Basalts**

Basalts of the Jilong Formation, with a total thickness of ~130 m, occur south of Selong village (Fig. 1B) in the Tethyan Himalaya (Fig. 1A). The rocks are interbedded with sandstones of the Lower Permian Jilong Formation. The timing of volcanic activity is inferred to be Sakmarian–Artinskian age (Appendix A [see footnote 1]), coeval with the Bhole Kosi basalts south of Gyriong County (Garzanti et al., 1999), the Panjal Traps in NW India (Gaetani and Garzanti, 1991; Garzanti et al., 1999), and the Permian Yunam granites (281 ± 1 Ma) in the SE Zanskar area of the High Himalaya (Spring et al., 1993) (Fig. 1A).

**Selong Group Basalts**

The Selong Group basalts, with a total thickness of ~55 m, are exposed to the southeast of Selong village (Fig. 1B) in the Tethyan
The rocks are interbedded with sandstones of the Middle-Upper Selong Group (Fig. 2A). Abundant brachiopods within slate overlying the basalts (Fig. 2A) indicate a Capitanian–Lopingian age (Appendix A [see footnote 1]), slightly postdating the Permian granites in the Parkatchic (ca. 270 Ma) and Sankoo (268 ± 5 Ma) areas in the western Zanskar region of the High Himalaya (Noble et al., 2001) (Fig. 1A).

### Jiangrang Basalts

The Jiangrang basalts crop out ~60 km south of Coqen County in the central Lhasa subterrane (Fig. 1A). The basalts vary in thickness from several meters to ~20 m, and occur in slates of the Lower Permian Laga Formation (Fig. 2B) as massive sheet flows with filled vesicles. Brachiopods within the slate suggest a Sakmarian–Artinskian age for the Jiangrang magmatism (Appendix A [see footnote 1]), coeval with the Jilong Formation basalts and the Bhote Kosi basalts (Garzanti et al., 1999) in the Tethyan Himalaya.

### Zedala Basalts

The Zedala basalts are exposed in two localities ~14 km northwest of Nixiong village in the central Lhasa subterrane (Fig. 1C). The two basaltic occurrences have a combined thickness of...
Permian volcanic rocks in southern Tibet

~80 m in the Laga Formation (Fig. 2C). Brachiopod and crinoid fossils in the Laga Formation near Nixiong indicate an Early Permian age for the Zedala basalts (Appendix A [see footnote 1]).

Nixiong Volcanic Rocks

The Nixiong volcanic rocks occur within the Upper Permian Dibucuo Formation (Fig. 1C) that is in fault contact with the Middle Permian Xiai Formation in the central Lhasa subterrane (Fig. 1B). The volcanic rocks with a total thickness of ~130 m consist of basalt and basaltic andesite (Fig. 2C). Plant fossils within the Dibucuo Formation in Nixiong area (Fig. 2C) suggest a Late Permian age (Appendix A [see footnote 1]), probably coeval with the Selong Group basalts of the Tethyan Himalaya.

Leiqingla Volcanic Rocks

The Leiqingla volcanic rocks with a total thickness of ~200 m are found in the Middle Permian Luobadui Formation, ~35 km northwest of Linzhou County in the central Lhasa subterrane (Fig. 1A). The main rock types are andesite, basaltic andesite, and basaltic breccias, lavas, and tuffs. Corals and fusulinids within bioclastic limestone overlying the volcanic rocks (Fig. 2D) suggest that the Leiqingla volcanism occurred during the Middle Permian (Wordian–Capitanian) (Appendix A [see footnote 1]), which is supported by a volcanic breccia within the Leiqingla volcanic sequence (Xiang-Hui Li, 2009, personal communication). The volcanism slightly predates the Pikang granite (263 Ma; Zhu et al., 2009a) and the high-pressure metamorphism recorded in the Songdo eclogite (262 Ma; Yang et al., 2009) in the same tectonic location (Fig. 1A).

Ranwu Volcanic Rocks

The Ranwu basaltic andesites and andesites occur as ~2-m-thick layers intercalated with metasedimentary rocks of the Lower Permian Luobadui Formation along the eastern shore of Ranwu Lake of the central Lhasa subterrane (Fig. 1A). Brachiopods in the Leiqingla Formation from the Linzhou and Ranwu areas of the central Lhasa subterrane suggest a Sakmarian–Artinskian age for the volcanism (Appendix A [see footnote 1]), coeval with the Jilong Formation basalts and Bhote Kosi basalts (Garzanti et al., 1999) of the Tethyan Himalaya.

In summary, the lithostratigraphic records, paleontological criteria, and available U-Pb isotopic age dates indicate three episodes of volcanism, distinguished as temporally discrete events in southern Tibet (Fig. 1A): (1) a synchronous Early Permian (Sakmarian–Artinskian) volcanic activity in both the Tethyan Himalaya (Selong) and central Lhasa subterrane (Jiangrang, Zedala, and Ranwu); (2) Middle Permian volcanism (Wordian–Capitanian) in the central Lhasa subterrane (Leiqingla); and (3) Late Permian magmatism (Capitanian–Lopingian) recorded in both the Tethyan Himalaya (Selong) and central Lhasa subterrane (Nixiong).

GEOCHEMICAL CHARACTERISTICS OF THE PERMIAN VOLCANIC ROCKS

On the basis of detailed petrography, the least altered samples were crushed and powdered in an agate mill for chemical analysis. The analytical procedures and geochemical data are given in Table DR1 (see footnote 1). For the following discussion, major element data are normalized on an anhydrous basis, and samples are plotted on the Nb/Y versus Zr/TiO2 classification diagram (Winchester and Floyd, 1977) (Fig. 3A) that uses alteration-resistant elements.

Jilong Formation and Selong Group Basalts

The Jilong Formation basalts are characterized by moderate TiO2 (1.8–2.0 wt%), high MgO (9.8–10.6 wt%), and Mg# (60.3–61.8). The Selong Group basalts have similar compositions (e.g., 1.8–1.9 wt% TiO2, 10.0–11.5 wt% MgO, and Mg# of 60.8–63.0; see Table DR1 [see footnote 1]). The Jilong Formation and Selong Group basalts plot in the subalkalic basalt field on the Zr/TiO2 versus Nb/Y diagram (Fig. 3A), and are similar in composition to high-MgO and Mg# basalt (Fig. 1A). These basalts have low TiO2 (0.89–1.88 wt%), and low MgO (~3.7 wt%), Mg# (~40), Cr (~165 ppm), and Ni (~63 ppm), resembling high-alumina basalt (HAB) that is defined as having SiO2 ≤54 wt%, MgO ≤7 wt%, and Al2O3 ≥16.5 wt% (Crawford et al., 1987; Kersting and Arculus, 1994) (Fig. 3B).

The sample exhibits light REE enrichment ([La/Yb]N = 3.4), with no Eu anomaly (Fig. 4C), a moderately negative Nb-Ta anomaly ([Nb/La]PM = 0.51), and an obvious negative Ti anomaly (Figs. 3C and 4D). The sample has a positive εNd(t) value (+1.2, corrected to 280 Ma) and a high initial Sr isotopic ratio (~0.7122) (Table DR1 [see footnote 1]).

Jiangrang Basalts

Only one sample (plus one duplicate analysis) of the Jiangrang basalts was analyzed. The sample is characterized by high Al2O3 (~18.8 wt%), and low MgO (~3.7 wt%), Mg# (~40), Cr (~165 ppm), and Ni (~63 ppm), resembling high-alumina basalt (HAB) that is defined as having SiO2 ≤54 wt%, MgO ≤7 wt%, and Al2O3 ≥16.5 wt% (Crawford et al., 1987; Kersting and Arculus, 1994) (Fig. 3B).

The Zedala basalts have a narrow range of SiO2 (49–50 wt%), and plots in the subalkalic basalt field on the Zr/TiO2 versus Nb/Y diagram (Fig. 3A). These basalts have low TiO2 (0.89–0.96 wt%), and high Al2O3 (16.61–17.43 wt%), MgO (6.46–7.50 wt%), and Mg# (56.2–59.4), corresponding to a HAB composition (Fig. 3B). The basalts contain low Cr (127–194 ppm) and Ni (32.3–41.2 ppm).

The Zedala basalts are moderately enriched in light REEs ([La/Yb]N = 3.8–3.9), show a weak negative Eu anomaly (Eu/Eu* = 0.88–0.91; Fig. 4C), and are significantly depleted in high field strength elements (HFSs such as Nb, Ta, Zr, Hf, and Ti) relative to Th, U, and REEs (Fig. 4F). The Zedala basalts ([Nb/La]PM = 0.29–0.30) are similar to typical arc basalts (e.g., Andean...
The samples have high Al₂O₃ (17.68–18.14 wt%), and low MgO (3.89–5.60 wt%) and Mg# (45.6–52.8), resembling HAB (Fig. 3B). The samples have variably low Cr (72.8–212.1 ppm) and Ni (25.5–70.2 ppm) (Table DR1 [see footnote 1]).

The Nixiong samples are enriched in light REEs (i.e., [La/Yb]ₚ = 5.0–6.8) with or without a weak Eu anomaly ([Eu/Eu*] = 0.71–1.06; Fig. 4G). Primitive mantle-normalized incompatible element patterns show strong enrichment in Th and U, and significant negative Ti and variably negative Nb and Ta anomalies ([Nb/La]ₚₚ = 0.35–0.54) without obvious Zr and Hf anomalies (Figs. 3C and 4H). The samples yield high initial Sr isotopic ratios of 0.7102–0.7141 (corrected to 260 Ma) and negative εNd(t) values of −5.4 to −3.1 (Table DR1 [see footnote 1]).

### Leiqingla Volcanic Rocks

The Leiqingla samples are basaltic in composition with varying SiO₂ (49.91–54.00 wt%) except for sample LQ-11, which is andesitic (SiO₂ = 59.23 wt%). The key characteristics of these samples are low TiO₂ (0.91–1.13 wt%), high Al₂O₃ (16.82–21.78 wt%), low MgO (2.69–5.28 wt%), and low Mg# (32.8–47.4), corresponding to HAB (Fig. 3B). The Leiqingla andesite has high Al₂O₃ (18.59 wt%), very low MgO (1.97 wt%), and Mg# of 24.7. The Leiqingla volcanic rocks contain very low Cr and Ni in both the basalt (8.14–36.8 ppm Cr and 6.82–23.5 ppm Ni) and andesite (30 ppm Cr and 14.1 ppm Ni) (Table DR1 [see footnote 1]).

The Leiqingla basalts are enriched in light REEs (e.g., [La/Yb]ₚ = 3.36–7.00) with or without a weak Eu anomaly ([Eu/Eu*] = 0.94–1.20; Fig. 4I). The primitive mantle-normalized multi-element patterns (Fig. 4J) are characterized by significant negative Nb, Ta, Ti, Zr, and Hf anomalies, in particular very low [Nb/La]ₚₚ ratios that resemble typical arc basalts (Fig. 3C; Hawkesworth et al., 1991; http://georoc.mpch-mainz.gwdg.de/georoc/Entry.html). The Leiqingla basalts exhibit a limited range of initial Sr isotopic ratios (0.7052–0.7063, corrected to 280 Ma) and relatively high initial Sr isotopic ratios (0.7093–0.7110) (Table DR1 [see footnote 1]).

### Nixiong Volcanic Rocks

The Nixiong samples have varying SiO₂ (50.1–55.1 wt%), and plot in the basalt/andesitic andesite fields on the Zr/TiO₂ versus Nb/Y diagram (Winchester and Floyd, 1977) (Fig. 3A).

### Ranwu Volcanic Rocks

The Ranwu samples have a limited range of SiO₂ (57.65–58.42 wt%), and plot in the andesite field on the Zr/TiO₂ versus Nb/Y diagram (Fig. 3B).
Figure 4. Chondrite-normalized, rare-earth element (REE) patterns and primitive mantle–normalized trace element spectra for the Permian volcanic rocks in southern Tibet. Normalizing values and plotting order are from Sun and McDonough (1989). Quaternary backarc basin basalts (BABB) from the Middle Okinawa Trough (Shinjo et al., 1999), and Emeishan low-Ti basalts (Xiao et al., 2004) are shown for comparison. Abbreviations: Fm.—Formation; Gr.—Group.
The samples show a small range in initial $^{143}$Nd/$^{144}$Nd (0.7101–0.7107) and negative $\varepsilon_{\text{Nd}}(t)$ (−3.2) at 280 Ma (Table DR1 [see footnote 1]). It is therefore important to evaluate the chemical effects of alteration and metamorphism before interpreting their tectonic settings using the geochemistry.

Some major elements (e.g., Na, K, and Ca) and trace elements (e.g., Cs, Rb, Ba, and Sr) are readily mobilized by late- and post-magmatic fluids and during metamorphism. In contrast, HFSEs (e.g., Ti, Zr, Y, Nb, P, and Th), most REEs, and transitional elements (e.g., Ni, Cr, V, and Sc) within basaltic and more highly evolved rocks are considered to be relatively immobile during alteration and low-grade metamorphism (Bienvenu et al., 1990; Staudigel et al., 1996). Although light REEs are susceptible to hydrothermal alteration and low-grade metamorphism (Whitford et al., 1988), the coherent data (see Fig. 4) indicate that light REEs were essentially unaffected by the metamorphism. The absence of any correlation between LOI and SiO$_2$, TiO$_2$, Al$_2$O$_3$, or MgO in samples from individual outcrops in southern Tibet (Figs. DR2A–DR2D [see footnote 1]) suggest that these oxides were not significantly modified during alteration and/or metamorphism (Whitford et al., 1988; Dampare et al., 2008). Likewise, plots of LOI versus [Nb/La]$_{PS}O_3$ or [Th/La]$_{PS}O_3$ (Figs. DR2E–DR2F [see footnote 1]) suggest that Th-Nb-REE concentrations in samples from southern Tibet are essentially undisturbed by weathering, alteration, or greenschist facies metamorphism (Dampare et al., 2008).

For mantle-derived mafic rocks, a shift in Sr concentration caused by alteration is typically observed as elevated ($^{87}$Sr/$^{86}$Sr) values at a constant $\varepsilon_{\text{Sr}}(t)$ value. However, seawater has always possessed Sr isotopic ratios lower than 0.710 (Korte et al., 2003), implying that rocks with high initial Sr isotopic ratios above 0.710 cannot be interpreted solely in terms of seawater alteration, and other processes must have contributed to the observed values. In such cases, the elevated Sr isotopic compositions of the Permian basalts in the Selong area of the Tethyan Himalaya (Fig. 5A) could be due to seawater alteration, mantle metasomatism, and modification in the crust, and the negative correlation between Sr isotopic composition and $\varepsilon_{\text{Sr}}(t)$ values (Fig. 5A) of Permian volcanic rocks in the central Lhasa subterrane suggests a crustal Sr modification (see below).

In summary, in our attempts to fingerprint the tectonic setting, geochemical affinities, and origin of the Permian volcanic rocks in southern Tibet (see below), we focus on relatively immobile elements (e.g., HFSEs, REEs), transitional elements, and aspects of Sr-Nd isotopic systematics.

**DISCUSSION**

**Effects of Alteration and Low-Grade Metamorphism on Elemental Mobility**

Petrographic observations show that the studied samples have experienced various degrees of alteration and metamorphism, as indicated by the presence of chlorite, epidote, variable amounts of calcite, and variably high loss-on-ignition (LOI) values (2–11 wt%, Table DR1 [see footnote 1]). It is therefore important to evaluate the chemical effects of alteration and low-grade metamorphism before interpreting their tectonic settings using the geochemistry.

Some major elements (e.g., Na, K, and Ca) and trace elements (e.g., Cs, Rb, Ba, and Sr) are readily mobilized by late- and post-magmatic fluids and during metamorphism. In contrast, HFSEs (e.g., Ti, Zr, Y, Nb, P, and Th), most REEs, and transitional elements (e.g., Ni, Cr, V, and Sc) within basaltic and more highly evolved rocks are considered to be relatively immobile during alteration and low-grade metamorphism (Bienvenu et al., 1990; Staudigel et al., 1996). Although light REEs are susceptible to hydrothermal alteration and low-grade metamorphism (Whitford et al., 1988), the coherent data (see Fig. 4) indicate that light REEs were essentially unaffected by the metamorphism. The absence of any correlation between LOI and SiO$_2$, TiO$_2$, Al$_2$O$_3$, or MgO in samples from individual outcrops in southern Tibet (Figs. DR2A–DR2D [see footnote 1]) suggest that these oxides were not significantly modified during alteration and/or metamorphism (Whitford et al., 1988; Dampare et al., 2008). Likewise, plots of LOI versus [Nb/La]$_{PS}O_3$ or [Th/La]$_{PS}O_3$ (Figs. DR2E–DR2F [see footnote 1]) suggest that Th-Nb-REE concentrations in samples from southern Tibet are essentially undisturbed by weathering, alteration, or greenschist facies metamorphism (Dampare et al., 2008).

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In summary, in our attempts to fingerprint the tectonic setting, geochemical affinities, and origin of the Permian volcanic rocks in southern Tibet (see below), we focus on relatively immobile elements (e.g., HFSEs, REEs), transitional elements, and aspects of Sr-Nd isotopic systematics.

**Perman Continental Margin Arc System in the Central Lhasa Subterrane**

Previously, the Dagze calc-alkaline volcanic rocks of the Lhasa terrane were inferred to have been emplaced during the late Carboniferous–early Permian or Triassic (Smith and Xu, 1988) and are thought to have developed within an extensional setting related to separation of the Lhasa terrane from Gondwana (Leeder et al., 1988; Yin and Harrison, 2000; Booth et al., 2004). However, recent studies have shown that these volcanic rocks are actually Early Jurassic based on U-Pb zircon dating (Zhu et al., 2008a) and exhibit geological and geochemical characteristics of an arc volcano built upon transitional crust (Pearce and Mei, 1988) or juvenile crust (Chu et al., 2006; Zhu et al., 2008a).

As stated above, the Permian basalts from various sites in the central Lhasa subterrane are HAB (Fig. 3B), which is suggestive of a subduction zone setting, although its origin remains controversial (Crawford et al., 1987; Kersting and Arculus, 1994; Winter, 2001). These major element features, together with the characteristic negative Nb, Ta, and Ti anomalies, indicate that the Permian basalts in the central Lhasa subterrane are genetically associated with subduction-zone magmatism or of magmatic arc origin. This interpretation is consistent with their characteristics in Nb/Y versus Ti/Y (Fig. 6A) and Ta/Yb–Th/Yb (Fig. 6B) diagrams. With the exception of Leiqingla basalts, which have low Ta/Yb values
Figure 6. Selected plots for testing the nature of the Permian volcanic rocks in southern Tibet. (A) Ti/Y versus Nb/Y (Pearce, 1982) plot showing the Permian basalts in the central Lhasa subterrane have volcanic-arc basalt affinity and the Tethyan Himalayan basalts have within-plate tholeiitic basalt affinity; (B) Th/Yb versus Ta/Yb (Pearce, 1983) plot showing clear subduction zone affinities for the Permian basalts in the central Lhasa subterrane. Vectors indicate the influence of subduction components (S), crustal contamination (C), within-plate enrichment (W), and fractional crystallization (F). Data of ocean-island basalt (OIB), enriched mid-ocean ridge basalt (E-MORB), and normal mid-ocean ridge basalt (N-MORB) (Sun and McDonough, 1989). Abbreviations: Fm.—Formation; Gr.—Group.

The Jilong Formation and Selong Group basalts reported here have high MgO and low Al₂O₃, resembling those of HMB (Fig. 3B; Crawford et al., 1987; Kersting and Arculus, 1994) with no Ti anomalies but moderate Nb-Ta anomalies (Figs. 3C and 4B), which contrasts the contemporaneous volcanic rocks in the central Lhasa subterrane and typical arc basalts (Hawkesworth et al., 1991). These basalts are characterized by moderately fractionated HFSE and REE patterns, and are different from the Quaternary backarc basin basalts (BABB) from the Middle Okinawa Trough that developed on a continental basement (e.g., Shinjo et al., 1999) in having relatively flat HFSE and heavy
Formation and Selong Group basalts with Geochemical Comparison of the Jilong

the northern Indian margin was under tectonic

Chauvet et al., 2008, and references therein). All

to be associated with an extensional tectonic

Yunam around the Zanskar region of the High

Permian granites from Parkatchic, Sankoo, and

Nepal (Nar-Tsum spilites; Garzanti et al., 1999),

basalts in

Selong Group basalts and Bhote Kosi basalts in

within the Neo-Tethyan Ocean (Maury et al.,

consistent with formation in a within-plate set-

setting (Gorton and Schandl, 2000). Therefore, our

data favor a Permian extensional tectonic setting

for the generation of the Jilong Formation and

Selong Group basalts and Bhote Kosi basalts in

the Tethyan Himalaya (Garzanti et al., 1999). In

addition, the widespread Panjal Traps and the

Permian granites from Parchatkich, Sankoo, and

Yunam around the Zanskar region of the High

Himalaya (Fig. 1A) have all been interpreted to

be associated with an extensional tectonic setting

(Spring et al., 1993; Noble et al., 2001; Chauvet et al., 2008, and references therein). All these observations and inferences indicate that the northern Indian margin was under tectonic extension at the time of Permian Andean-type magmatism in the central Lhasa subterrane.

Geochronological Comparison of the Jilong Formation and Selong Group Basalts with Basalts of Similar Ages Emplaced along the Southern Margin of the Tethyan Ocean

Permian magmatism along the northern rifted margin of the Indian and Arabian shields and neighboring basins has been reported in the south of Gyirong County in southern Tibet (Bhote Kosi basalts; Garzanti et al., 1999), in northern Nepal (Nar-Tsum spilites; Garzanti et al., 1999), Kashmir and Zanskar (Panjal Traps; Bhat and Zainuddin, 1978; Bhat et al., 1981; Vannay and Spring, 1993; Chauvet et al., 2008), Arunachal Pradesh (Abor volcanic rocks; Bhat, 1984; Bhat and Ahmad, 1990) (Fig. 1A), and Oman (Maury et al., 2003; Lapiere et al., 2004).

The Panjal Traps consist of a thick sequence dominated by tholeiitic lavas of Lower Permian age intercalated within Tethyan sedimentary rocks (Bhat and Zainuddin, 1978; Dézes, 1999; Chauvet et al., 2008) (Fig. 1A). The Panjal Traps show a gradual eastward thinning from Kashmir (2500 m thick) to Upper Lahul (Dézes, 1999; Garzanti et al., 1999; Chauvet et al., 2008), and are thought to represent a major magmatic episode comparable in magnitude to that of tholeiitic continental flood basalts (CFB) related to continental breakup (Vannay and Spring, 1993; Garzanti et al., 1999). The contemporaneous Bhote Kosi basalts were first reported by Garzanti et al. (1999) from the Bhote Kosi valley in southern Tibet (Fig. 1A), and are tholeiitic in composition. The coeval Abor volcanic rocks in Arunachal Pradesh (Fig. 1A) are a 1500-m-thick sequence of tholeiitic to alkaline basalts (Bhat, 1984; Bhat and Ahmad, 1990). In Oman, the Middle Permian (based on biostratigraphy) volcanic rocks are compositionally diverse, consisting of tholeiitic and alkaline basalts. The origin of these rocks has been ascribed to a mantle plume—the “Tethyan plume”—that ascended beneath the Arabian passive margin following the initiation of seafloor spreading within the Neo-Tethyan Ocean (Maury et al., 2003; Lapiere et al., 2004).

The trace element patterns in Figure 7A (normalized to primitive mantle) show that the Jilong Formation and Selong Group basalts are similar to the adjacent Bhote Kosi basalts to the south of Gyirong County; they also overlap with basalts of the Panjal Traps. Moreover, the εNd(t) values (+0.7 to +1.2) of the Jilong Formation and Selong Group basalts are comparable with those of the Panjal Traps (Chauvet et al., 2008). However, both the Jilong Formation and Selong Group basalts and the Panjal Traps are markedly different from the Permian basalts of Oman in terms of abundances and patterns of trace elements (Fig. 7B). They also differ from the Abor volcanic rocks in having a weaker light REE enrichment and in the presence of a negative Nb anomaly (Fig. 7C). The differences among the Oman low-Ti basalts (Group 1 in Fig. 7D), the Oman tholeiitic and alkaline basalts (Group 3 in Fig. 7D), and the Jilong Formation and Selong Group basalts are particularly obvious in a Zr/Nb versus εNd(t) diagram (Fig. 7D). These differences indicate that (1) the basalts in Selong area may share a similar origin with the Panjal Traps; (2) compositionally uniform magmatism probably extended from Kashmir to the Selong area of southern Tibet (~1000 km), rather than ~2000 km from Kashmir to the Bhote Kosi valley and Abor along the northern margin of the Indian plate; and (3) the Oman basalts show a weak geochemical correlation with the Panjal Traps.

Previously, the linear geographical array of volcanic rocks that extends from the Oman basalts through the Panjal Traps to the Nar-Tsum spilites, Bhote Kosi basalts, Jilong Formation and Selong Group basalts, and Abor volcanic rocks was interpreted as reflecting continental rifting or breakup at the Gondwana margin (Garzanti et al., 1999). However, if we consider the geographical distribution of the cogenetic Nar-Tsum spilites of northern Nepal (Garzanti et al., 1999) and the absence of contemporaneous magmatism from Selong to Abor (Zhu et al., 2004) (Fig. 1A), the broad geochemical similarities observed between the Jilong Formation and Selong Group basalts and the Panjal Traps (Figs. 7A and 7B), and the geochemical differences identified between the Panjal Traps and Oman basalts and Abor volcanic rocks (Figs. 7C and 7D) lead us to suggest that the Jilong Formation and Selong Group basalts in the Selong area represent the easternmost extent of the Panjal continental flood basalts province.

Petrogenesis of Permian Volcanic Rocks in Southern Tibet

The Permian Jilong Formation and Selong Group basalts of the Tethyan Himalaya are interpreted here to have been erupted in an extensional continental setting, within which basaltic magmas were probably modified by crustal contamination. Such contamination is indicated by (1) the trend of crustal contamination apparent in the Ta/Yb–Th/Yb diagram (Fig. 6B), and (2) the high initial Sr isotopic ratios (0.7160–0.7185) of the Jilong Formation and Selong Group basalts, which require input of an enriched component with high Sr isotopic ratios (e.g., continental crust). Another process for such high initial Sr isotopic ratios involves mantle metasomatism, as indicated by the absence of any correlation between crustal geochemical components (e.g., Th, Th/Nb) and initial Sr isotopic ratios (not shown). Therefore, we interpret the high initial Sr isotopic ratios and the positive εNd(t) values (+0.7 to +1.2) (Table DR1 [see footnote 1]) of the Jilong Formation and Selong Group basalts as genetically associated with a depleted mantle source that was metasomatized by the fluids and/or melts derived from rising mantle plume material and contaminated subsequently by the continental crust through which they ascended.

The Leiqingba basalt has low Th abundances (3.4–4.9 ppm) relative to the middle and upper crust (typical values for them are 6.5 and 10.5 ppm, respectively; Rudnick and Gao, 2003), which, together with their positive εNd(t) values (+1.1 to +2.6), indicate minimal crustal assimilation during ascent. The low εNd(t) values of the Leiqingba basalts can be interpreted as having resulted from modification of the mantle wedge peridotite by subducted sediments rather than fluid metasomatism that does not alter the Nd isotopic composition of the mantle wedge source overlying the subducting slab (e.g., Gertisser and Keller, 2003; Peng et al., 2008). The input of subducted sediment in generating the Leiqingba high-Al basalts is further supported by (1) the high Th/ Ce (0.09–0.14) and Th/Nb (0.83–1.43) ratios that are consistent with the involvement of subducted sediments in the magma genesis (e.g., Stolz et al., 1990; Plank and Langmuir, 1998; Peng et al., 2008), and (2) the two-component mixing relationships in terms of Sr and Nd isotopes (Fig. 5A and also
Permian volcanic rocks in southern Tibet

For the Zedala and Nixiong basalts, which have negative $\varepsilon_{\text{Nd}}(t)$ values (–5.4 to –1.2), the absence of negative Ce anomalies (0.98–1.04) indicates insignificant sediment input in their petrogenesis. In contrast, the $^{148}\text{Sm}/^{144}\text{Nd}$ versus $^{143}\text{Nd}/^{144}\text{Nd}$ plot shown in Figure 5B suggests significant crustal contamination. To test this, a simple mixing model was done by assuming that the depleted component resembles the Leiqingla high-Al basalts (Table DR2 [see footnote 1]). The model results (Fig. 5A) suggest that the petrogenesis of the Zedala and Nixiong basalts is inconsistent with the mixing between the Leiqingla basalts and the assumed upper crustal melts (line 3 in Fig. 5A), but consistent with mixing with the Amdo orthogneiss (line 4 in Fig. 5A). These results indicate that a significant crustal component, isotopically similar to the Amdo orthogneiss, was incorporated into the Zedala and Nixiong basaltic magmas in a continental arc setting.

Paleogeographic Implications of the Permian Volcanic Rocks of Southern Tibet

It is widely accepted that extensional events that affected the northern Indian margin began in the Early Carboniferous and continued until the Early Cretaceous (Gaetani and Garzanti, 1991; Garzanti et al., 1999; Wang et al., 2000). Permian basalts of the Qiangtang terrane were also erupted in an extensional setting (Pearce and Mei, 1988; Yin et al., 1988; Deng et al., 1996; Yin and Harrison, 2000). For the Lhasa terrane, an understanding of the emplacement mechanism of the Songdo eclogite is crucial for tectonic reconstructions. It should be noted that eclogitized oceanic crust becomes negatively buoyant compared to both near-surface oceanic basalt and garnet lherzolite, and would continue to sink (Ernst, 2009). Thus, eclogite that can be exhumed to the surface approximates the last bit of subducting and/or subducted oceanic lithosphere before collision and exhumation, which means that the metamorphic age of the eclogite represents onset of the collision. Although the tectonic significance of the Songdo eclogite requires further investigation, we argue that it marks a collision suture zone between the central Lhasa terrane and the northern margin of the Indian-Arabian shields or in the neighboring basins. Normalizing values and plotting order are from Sun and McDonough (1989). (A) The basalts in Selong area compare closely with the Bhote Kosi basalts from the Bhote Kosi valley, south Gyirong County in southern Tibet (Garzanti et al., 1999), and the Panjal Traps in Kashmir and Zanskar (Vannay and Spring, 1993; Chauvet et al., 2008). (B) The basalts in Selong area differ significantly from the Group 1 and Group 3 basalts in Oman (Lapierre et al., 2004). (C) The basalts in Selong area differ geochemically from the Abor volcanic rocks in Arunachal Pradesh (Bhat and Ahmad, 1990). (D) Zr/Nb versus $\varepsilon_{\text{Nd}}(t)$ diagram shows that the basalts in Selong area are different from the Group 1 and Group 3 basalts in Oman (Lapierre et al., 2004).

Table DR2 [see footnote 1]). Figure 5A shows that the source of the Leiqingla basalts can be explained by mixing with a significant amount of subducted sediments (line 1 in Fig. 5A), but not by mixing with the middle crustal material represented by the Amdo orthogneiss (Xu et al., 1985) of the Lhasa terrane (line 2 in Fig. 5A). Accordingly, we propose that the Leiqingla basalts of the central Lhasa subterrane originated from partial melting of Paleo-Tethyan mantle wedge peridotite with a contribution from subducted sediments, most likely in a continental arc setting.

For the Zedala and Nixiong basalts, which have negative $\varepsilon_{\text{Nd}}(t)$ values (–5.4 to –1.2), the absence of negative Ce anomalies (0.98–1.04) indicates insignificant sediment input in their petrogenesis. In contrast, the $^{148}\text{Sm}/^{144}\text{Nd}$ versus $^{143}\text{Nd}/^{144}\text{Nd}$ plot shown in Figure 5B suggests significant crustal contamination. To test this, a simple mixing model was done by assuming that the depleted component resembles the Leiqingla high-Al basalts (Table DR2 [see footnote 1]). The model results (Fig. 5A) suggest that the petrogenesis of the Zedala and Nixiong basalts is inconsistent with the mixing between the Leiqingla basalts and the assumed upper crustal melts (line 3 in Fig. 5A), but consistent with mixing with the Amdo orthogneiss (line 4 in Fig. 5A). These results indicate that a significant crustal component, isotopically similar to the Amdo orthogneiss, was incorporated into the Zedala and Nixiong basaltic magmas in a continental arc setting.

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Australia (Zhu et al., 2009a). The nature of the Permian volcanic rocks and the Songdo eclogite suggests that the extension-related magmatism in the Qiangtang and Tethyan Himalayan terranes, and continental arc-related magmatism in the Lhasa terrane, occurred synchronously during the Permian in what is now present-day southern Tibet. These observations do not support the popular Paleozoic reconstructions depicting a vast shallow marine sea from the Qiangtang terrane via the Lhasa terrane to Greater India and the Himalaya (Dewey et al., 1988; Leeder et al., 1988; Golonka and Ford, 2000; Jin, 2002; Metcalfe, 2002), but offer some new perspectives on the Permian paleogeography of the Lhasa terrane.

Previous studies have proposed three representative palinspastic reconstructions to explain the location of the Lhasa terrane during the late Paleozoic. The first tectonic scenario argues that the Lhasa terrane did not rift away from the northern margin of the Greater India until the Late Permian or even the Late Triassic (e.g., Golonka, 2000, 2007; Metcalfe, 2002; Scotese, 2004). If this were the case, the Early Permian continental arc-type magmatism recorded in the central Lhasa subterrane could only be attributed to southward subduction of the Paleo-Tethyan Ocean seafloor (Fig. 8A). However, such a scenario fails to account for (1) the extension-related magmatism recorded in the Tethyan Himalaya, where the coeval basalts in Bhote Kosi and Selong areas exhibit geochemical signatures of tholeiitic continental flood basalts (CFB) (Garzanti et al., 1999; this study), rather than the signatures of backarc basin basalts that would be expected in such a regime; and (2) the presence of the Songdo eclogite that is exposed in the southern margin of the central Lhasa subterrane (Fig. 1B), which was probably exhumed to the surface in a continent-continent collision belt (Zhu et al., 2009a). Similar problems are encountered in the reconstruction by Stampfl i and Borel (2002), who argued that the Neo-Tethyan Ocean between the Lhasa terrane and Greater India did not open until the Early Permian, probably by unzipping from east to west during the Middle to Late Permian.

The second model, recently proposed by Ferrari et al. (2008), places the Lhasa terrane adjacent to the northern margin of Australia, while placing the Qiangtang terrane close to the northern margin of the Indian plate. Although no evidence is provided for the proposed affinity between the Qiangtang and Himalayan terranes by these authors, we tentatively argue for this possibility because the two terranes contain comparable Late Carboniferous–Early Permian glaciomarine sediments (Leeder et al., 1988; Pan and Ding, 2004), similar U-Pb detrital zircon age-probability plots (Kapp et al., 2003; Leier et al., 2007), and contemporaneous extension-related magmatism (Pearce and Mei, 1988; Yin et al., 1988; Gaetani and Garzanti, 1991; Deng et al., 1996; Garzanti et al., 1999; Yin and Harrison, 2000). In the model of Ferrari et al. (2008), the so-called Dugze Late Carboniferous–Early Permian arc magmatism, which was reinterpreted from the data reported by Pearce and Mei (1988), is attributed to southward subduction of the Paleo-Tethyan Ocean seafloor and consequent backarc opening of the Neo-Tethyan Ocean (Ferrari et al., 2008). However, this model cannot explain the Songdo eclogite exposed in the southern margin of the central Lhasa subterrane (Fig. 1A), which was considered to have resulted from northward seafloor subduction of the Carboniferous–Permian ocean south of the Lhasa terrane (Li et al., 2009; Yang et al., 2009).

Figure 8. (A) Tectonic reconstruction of Golonka (2000) shows the Lhasa terrane was adjacent to the Greater India during the Early-Middle Permian. Note that new observations documented in Yang et al. (2009), Zhu et al. (2009a), and this study cannot be effectively explained by this model. (B and C) An updated tectonic reconstruction of Ziegler et al. (1997) and Ferrari et al. (2008) illustrates the Lhasa terrane was isolated in the Paleo-Tethyan Ocean and was subjected to the northward subduction of the Paleo-Tethyan oceanic seafloor along its southern margin during the Early-Middle Permian. The red line with triangles shows the locality of inferred subduction zone. The red stars illustrate the estimated localities of the Permian volcanic rocks in southern Tibet, NW India, and in Oman during the Early-Middle Permian. Note that the Qiangtang terrane was placed adjacent to the northern margin of the Indian plate in this updated model.
The third tectonic reconstruction locates the Lhasa terrane outboard of Greater India and within the Paleo-Tethyan Ocean as early as the Early Permian (Enkin et al., 1992; Ziegler et al., 1997; Scotese et al., 1999). Although the location of the Lhasa terrane in the Permian is still speculative in this scenario, we tentatively argue for this possibility because the Songdo eclogite of seafloor protolith in the central Lhasa terrane (Fig. 1A) suggests the presence of the Paleo-Tethyan Ocean south of this subterrane during the Late Paleozoic (Li et al., 2009; Yang et al., 2009). This indicates in turn that the Lhasa terrane was isolated in the Paleo-Tethyan Ocean basin at that time. It is difficult to accurately reconstruct the locality of the Permian Songdo eclogite relative to the locations of Early-Middle Permian volcanic arc rocks during the Permian because of the overprinting effects of Cenozoic tectonic deformation and shortening. If the present-day Songdo eclogite is in situ (Yang et al., 2009) and is assumed to be located south of the Early Permian volcanic arc rocks (e.g., Jiangrang and Zedala basalts) (Fig. 1A), the Permian volcanic arc rocks identified in the central Lhasa subterrane may have been genetically associated with the northward subduction of the Paleo-Tethyan Ocean seafloor, as represented by the Songdo eclogite.

Considering the discussions presented above, we tentatively adopt an updated tectonic model (Figs. 8B and 8C) based on existing works (e.g., Enkin et al., 1992; Ziegler et al., 1997; Scotese et al., 1999; Ferrari et al., 2008) to depict the Permian paleogeographic location of southern Tibet. In this updated model, the Lhasa terrane was originally isolated in the Paleo-Tethyan Ocean basin, at least during the Carboniferous–Middle Permian (Fig. 8B). The Paleo-Tethyan Ocean seafloor was subducted northward beneath the Lhasa terrane during the Early-Middle Permian (Fig. 8C), during which time subducted sediments and/or sediment-derived fluids modified the overlying mantle wedge. Melting of the metasomatized wedge led to the production of the Early-Middle Permian arc-like volcanic rocks. The Panjal plume was active at this time, leading to the separation of the Qiangtang terrane from India.

There appears to be a consensus that the North China, South China, Tarim, and Indo-China blocks were distributed throughout the Paleo-Tethyan oceanic realm during the Early-Middle Permian (Enkin et al., 1992; Ziegler et al., 1997; Scotese et al., 1999; Golonka and Ford, 2000; Metcalfe, 2002; Scotese, 2004; Golonka, 2007). Our new data obtained from Permian continental arc-related rocks, combined with recognition of the Permian Songdo eclogite (Yang et al., 2009) in the central Lhasa subterrane, allow us to suggest that the Lhasa terrane may also have been an intra–Paleo-Tethyan ocean block during the Early-Middle Permian. This favored model implies the presence of the Paleo-Tethyan Ocean rather than Neo-Tethyan Ocean south of the Lhasa terrane during the Early-Middle Permian. Although it remains unknown when the Neo-Tethyan Ocean south of the Lhasa terrane opened, it must have occurred much later than the Middle Permian, probably in the Late Permian or Early Triassic, postdating the Permian collisional event (at ca. 263 Ma) between the central Lhasa subterrane and the northern margin of Australia (Zhu et al., 2009a) that led to the closure of the Paleo-Tethyan Ocean south of the Lhasa terrane (Yang et al., 2009).

Obviously, the new observations require revision of popular thinking about the paleogeography of the Lhasa terrane during the late Paleozoic. Our favored model takes into account the latest data on the volcanism (this study), the very high-pressure metamorphism (Yang et al., 2009), and the Permian collisional orogeny (Zhu et al., 2009a) in the Lhasa terrane. Nevertheless, it should be pointed out that although our new model is effective, further revision and improvement is needed to explain the contemporaneous Permo–Carboniferous glaciation-related deposits observed in the vast area from the Himalayan to the Lhasa, and to the southern Qiangtang terranes in Tibet (Jin, 2002). It is our hope that this new model will provide a stimulus in this continued effort.

CONCLUSIONS

(1) Combined lithostratigraphic and paleontological data indicate that (a) Early Permian (Sakmarian–Artinskian) volcanism occurred contemporaneously in both the Tethyan Himalaya (Selong) and the central Lhasa subterrane (Jiangrang, Zedala, and Ranwu), and (b) Middle Permian volcanism (Wordian–Capitanian) of the central Lhasa subterrane (Leiqingla) and Late Permian magmatism (Capitanian–Lopingian) took place both in the Tethyan Himalaya (Selong) and the central Lhasa subterrane (Nixiong).

(2) Both the Early Permian Jilong Formation and Mid-Late Permian Selong Group basalts in the Tethyan Himalaya show affinities with tholeiitic continental flood basalts and probably formed in an extensional setting; these rocks may represent the easternmost extent of the Panjal continental flood basalt province.

(3) All the Permian basalts in the Lhasa terrane show a calc-alkaline, high-alumina basalt (HAB) affinity, with significant negative Nb-Ta-Ti anomalies, indicating the existence of a Permian active continental margin arc system in the central Lhasa subterrane.

(4) Our new data from the Permian volcanic arc rocks, together with the recognition of the Permian Songdo eclogite, allow us to suggest that the central Lhasa subterrane may have been a microcontinent isolated in the Paleo-Tethyan Ocean Basin, at least during the Carboniferous–Middle Permian.

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Permain volcanic rocks in southern Tibet


