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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 basalt 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 time.

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INTRODUCTION

The Paleo-Tethyan Ocean occupied a large area around the equator from the Devonian to the Triassic (cf. Stampfli and Borel, 2002; Metcalfe, 2006; Ferrari et al., 2008; Hara 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; Hara 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; Scotese 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 (Stampfli 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 Sciunnach (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; Scotese, 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; Scotese 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 Zainuddin, 1978; Bhat et al., 1981; Spring et al., 1993; Vannay and Spring, 1993; Garzanti et al., 1999; Noble

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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

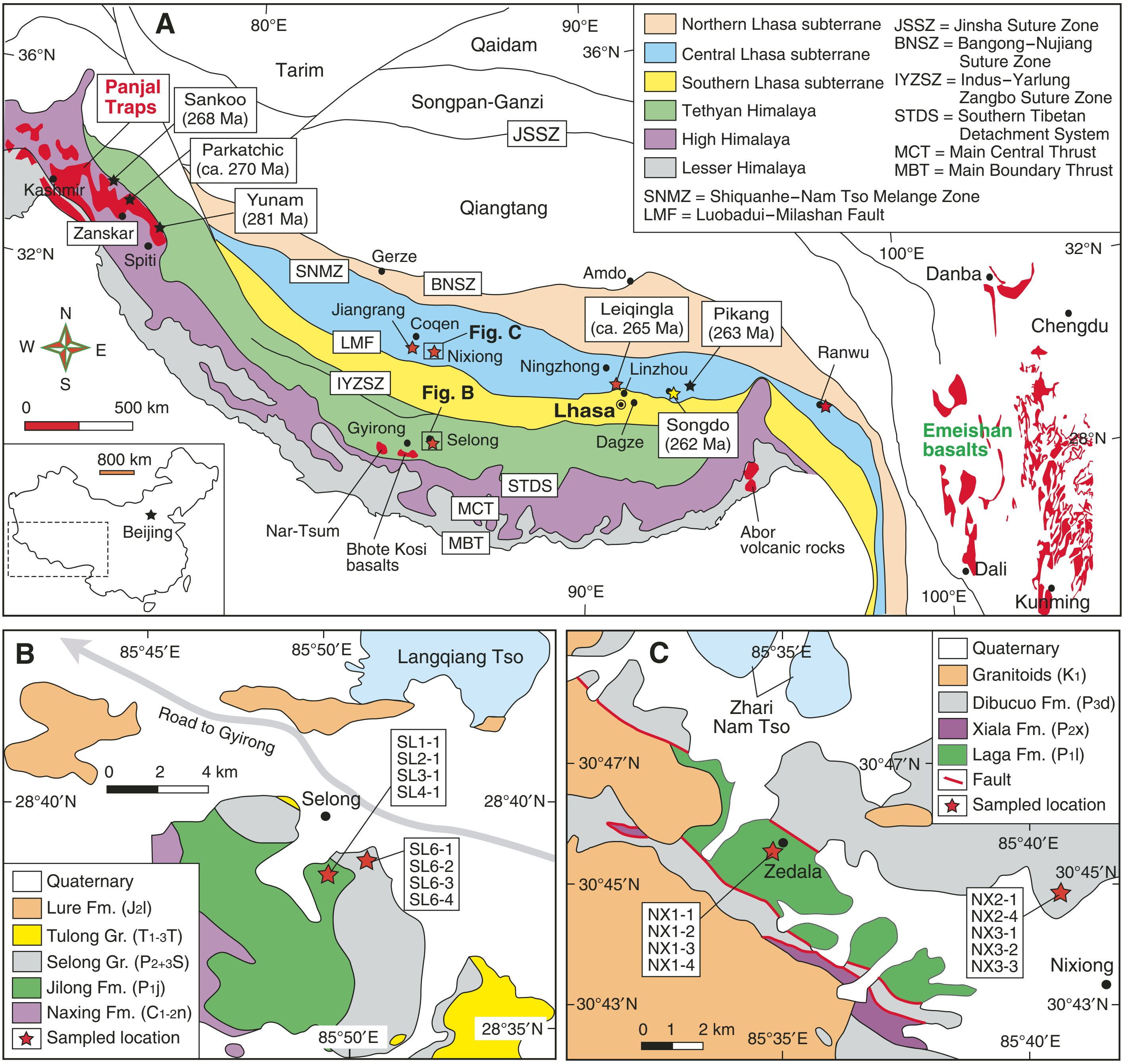

Figure 1. (A) Sketch map of tectonic outline (Zhu et al., 2008a) showing the localities of Permian volcanic rock (red stars) (this study), Permian granites (black stars) (Spring et al., 1993; Noble et al., 2001; Zhu et al., 2009a), Permian eclogite (yellow star) (Yang et al., 2009), and Panjal Traps (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 Permian, 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., Ziabrev 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–Nujiang 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; Zhu 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 Mélange Zone (SNMZ) and Luobadui-Milashan Fault (LMF), respectively (Fig. 1A). The northern Lhasa subterrane 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 subterrane are Jurassic–Cretaceous sedimentary and igneous rocks (Leeder et al., 1988; Yin et al., 1988; Pan and Ding, 2004; Zhang et al., 2004; Leier et al., 2007; Zhu et al., 2008b). The central Lhasa subterrane is dominated by a Carboniferous–Permian metasedimentary sequence (metasandstone, slate, and phyllite) and a Late Jurassic–Early Cretaceous volcano-sedimentary sequence, with minor Ordovician, Silurian, and Triassic limestone (Leeder et al., 1988; Yin et al., 1988; Pan and Ding, 2004; Kapp et al., 2005; Ji et al., 2007; Leier 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 subterrane from western Coqen County to central Linzhou County and eastern Ranwu Town (Fig. 1A). The southern Lhasa subterrane is dominated by the Late Triassic to early Tertiary Gangdese batholith and Linzizong volcanic succession, with minor Triassic–Cretaceous volcano-sedimentary rocks (Leeder et al., 1988; Pearce and Mei, 1988; Pan and Ding, 2004; He et al., 2007; Leier 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 Harrison, 2000; Kapp et al., 2005; Leier et al., 2007). However, the recent recognition of the Songdo eclogite and Pikang granite of Permian age in the central Lhasa subterrane (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 subterrane 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 subterrane 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 subterrane was thrust southward over the southern Lhasa subterrane along the Luobadui-Milashan Fault during or prior to the India-Asia collision (Pan and Ding, 2004; He et al., 2007). The southern Lhasa subterrane 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 Linzizong 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 subterrane (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 Repository[1]).

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 Bhote Kosi basalts south of Gyirong 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

[1]GSA Data Repository item 2010048, details of field occurrence and petrography of Permian volcanic rocks in southern Tibet (Appendix A), whole-rock geochemical data and analytical procedures (Table DR1), assumed end-members and modeling assumptions (Table DR2), photomicrographs of the representative rocks (Fig. DR1), and selected major and trace elements variations with respect to LOI (loss on ignition) (Fig. DR2), is available at http://www.geosociety.org/pubs/ft2009.htm or by request to editing@geosociety.org.

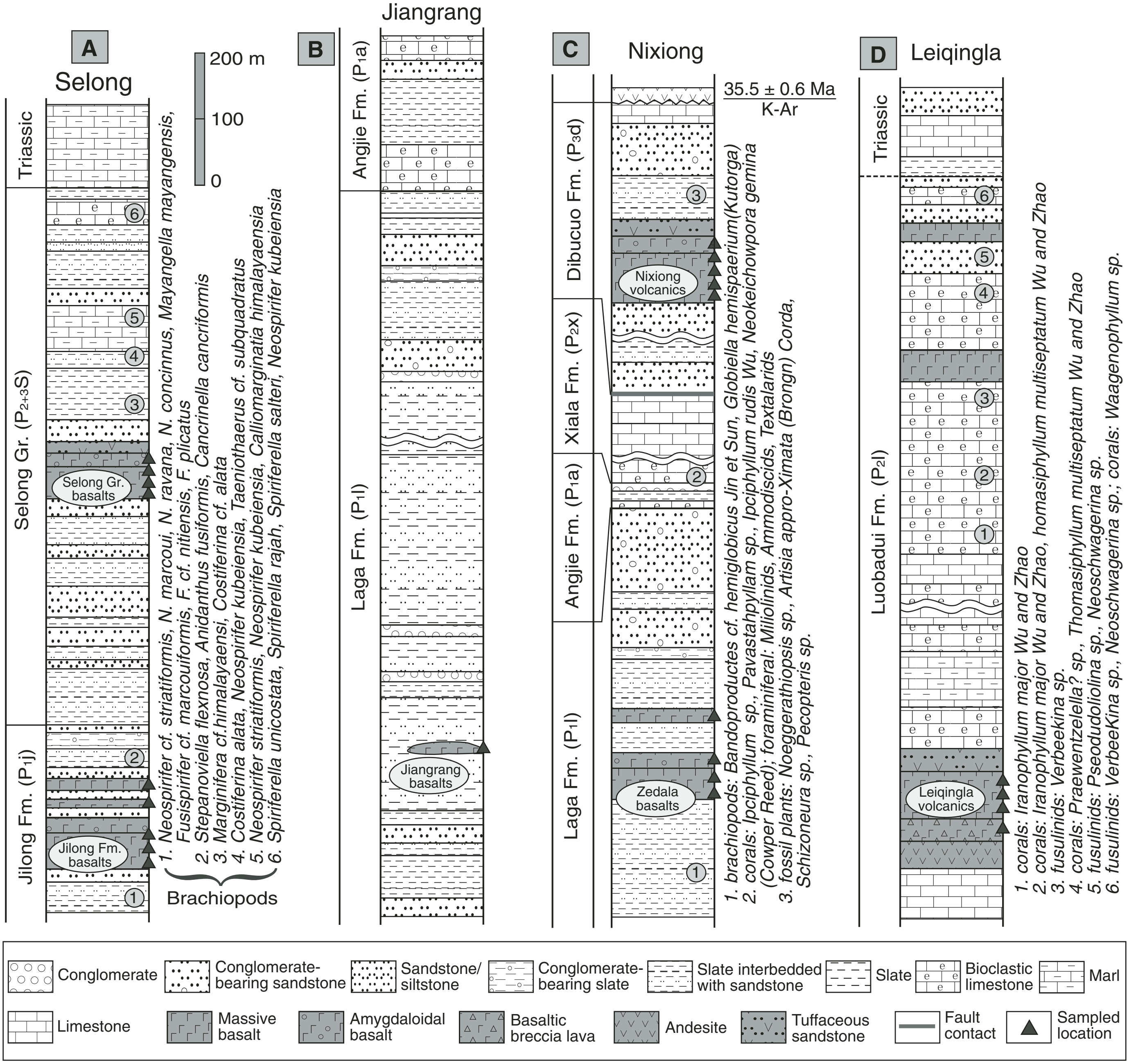

Figure 2. Lithostratigraphic positions of the studied Permian volcanic rocks. (A) Selong area in the Tethyan Himalaya (modified from Zhu et al., 2002); (B–D) Jiangrang area, Nixiong area, and Leiqingla area in the central Lhasa subterrane. Abbreviations: Fm.—Formation; Gr.—Group.

Himalaya (Fig. 1A). 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

~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 Xiala 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 slate of 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 recent zircon U-Pb isotopic age (ca. 265 Ma) for a volcanic breccia within the Leiqingla volcanic sequence (Xiang-Hui Li, 2009, personal commun.). 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 Laigu Formation along the eastern shore of Ranwu Lake of the central Lhasa subterrane (Fig. 1A). Brachiopods in the Laigu 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/TiO_2 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 TiO_2 (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% TiO_2, 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/TiO_2 versus Nb/Y diagram (Fig. 3A), and are similar in composition to high-MgO basalt (HMB), which is defined as having SiO_2 ≤54 wt%, MgO ≥7 wt%, and Al_2O_3 <16.5 wt% (Crawford et al., 1987; Kersting and Arculus, 1994) (Fig. 3B).

The basalts are enriched in Cr and Ni, e.g., 408–464 ppm Cr and 233–262 ppm Ni in the Jilong Formation basalts and 438–470 ppm Cr and 256–286 ppm Ni in the Selong Group basalts. These features, together with the high $Mg^{\#}$, suggest the rocks are relatively primitive without significant fractionation of olivine, Cr-spinel, and pyroxene.

The chondrite-normalized, rare-earth element (REE) patterns of the Jilong Formation and Selong Group basalts are relatively uniform, characterized by light REE enrichment with $[La/Yb]_N$ = 3.8–4.1 (where N denotes normalized to chondrite values of Sun and McDonough [1989] with or without a weak Eu anomaly [Fig. 4A]). The Jilong Formation and Selong Group basalts show similar patterns on primitive mantle-normalized (Sun and McDonough, 1989) multi-element diagrams (Fig. 4B), characterized by moderately negative Nb-Ta anomalies ($[Nb/La]_{PM}$ = 0.53–0.60, where PM denotes normalized to the primitive mantle composition), significant negative P anomalies, and the absence of Ti anomalies. The Jilong Formation and Selong Group basalts are distinct from arc basalts (e.g., Andean arc basalts; http://georoc.mpch-mainz.gwdg.de/georoc/Entry.html) in terms of $[Nb/La]_{PM}$ values and Ti anomalies (Fig. 3C); typical arc basalts show a marked depletion in Nb ($[Nb/La]_{PM}$ = 0.27) and Ti (Hawkesworth et al., 1991).

On the basis of paleontological constraints presented above, initial isotopic ratios were corrected to 280 Ma for the Jilong Formation basalts and 260 Ma for the Selong Group basalts. The initial Sr isotopic ratios of these basalts are very high, ranging from 0.7160 to 0.7185 at relatively constant $\varepsilon_{Nd}(t)$ values (+0.7 to +1.2) (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 Al_2O_3 (~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 SiO_2 ≤54 wt%, MgO ≤7wt%, and Al_2O_3 ≥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 $\varepsilon_{Nd}(t)$ value (+1.2, corrected to 280 Ma) and a high initial Sr isotopic ratio (~0.7122) (Table DR1 [see footnote 1]).

Zedala Basalts

The Zedala basalts have a narrow range of SiO_2 (49–50 wt%), and plot in the subalkalic basalt field on the Zr/TiO_2 versus Nb/Y diagram (Fig. 3A). These basalts have low TiO_2 (0.89–0.96 wt%), and high Al_2O_3 (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 (HFSEs 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

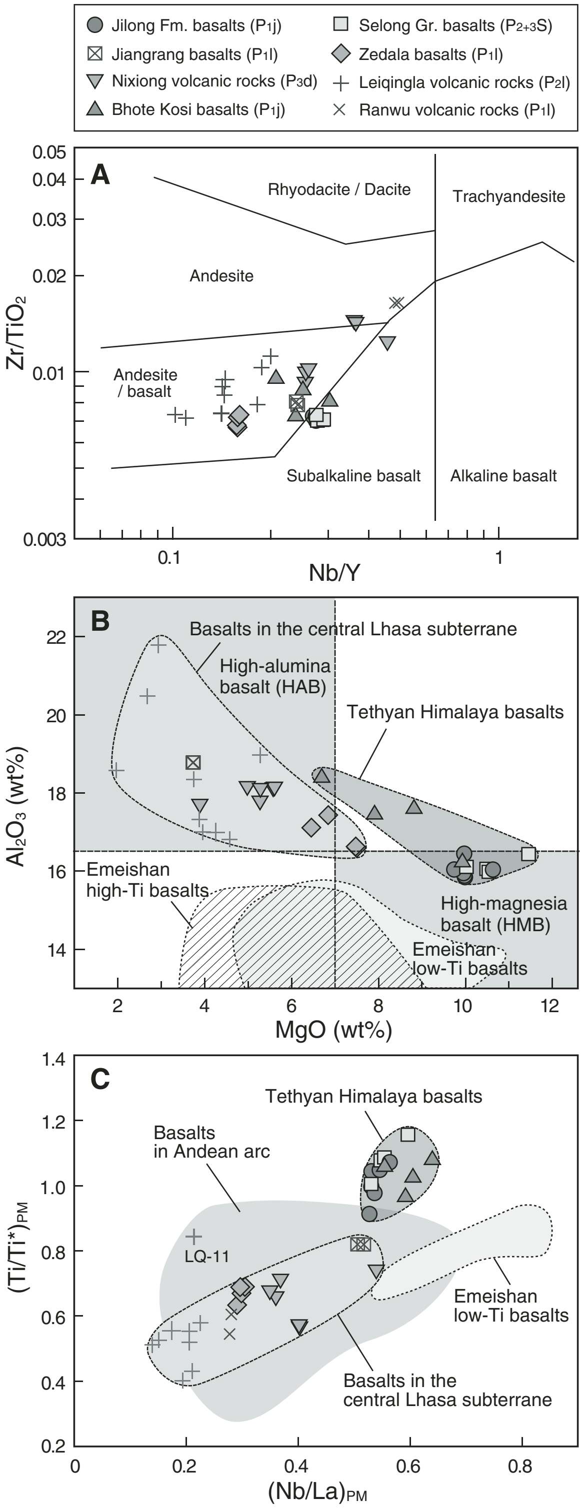

Figure 3. Geochemical classification for the Permian volcanic rocks in southern Tibet. (A) Zr/TiO_2 versus Nb/Y diagram of Winchester and Floyd (1977); (B) Al_2O_3 (wt%) versus MgO (wt%); (C) $(Ti/Ti^*)_{PM}$ versus $(Nb/La)_{PM}$. The domains of high-magnesia basalt (HMB) and high-alumina basalt (HAB) (Crawford et al., 1987; Kersting and Arculus, 1994), Emeishan high-Ti and low-Ti basalts (Xiao et al., 2004), and basalts in Andean arc (http://georoc.mpch-mainz.gwdg.de/georoc/Entry.html) are shown for comparison. $(Ti/Ti^*)_{PM} = Ti_{PM}/(Eu_{PM} \times Gd_{PM})^{1/2}$, where PM denotes normalized to primitive mantle of Sun and McDonough (1989). Note that almost all the Permian basalts in the central Lhasa subterrane have affinities with high-alumina basalt, while the Permian basalts in Selong area of the Tethyan Himalaya present high-magnesia basalt features. Abbreviations: Fm.—Formation; Gr.—Group.

arc basalts; http://georoc.mpch-mainz.gwdg.de/georoc/Entry.html) (Fig. 3C; Hawkesworth et al., 1991). The basalts show negative $\varepsilon_{Nd}(t)$ values of –1.4 to –1.2 (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 SiO_2 (50.1–55.1 wt%), and plot in the basalt/basaltic andesite fields on the Zr/TiO_2 versus Nb/Y diagram (Winchester and Floyd, 1977) (Fig. 3A). The samples have high Al_2O_3 (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., $[La/Yb]_N$ = 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 ($[Nb/La]_{PM}$ = 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 $\varepsilon_{Nd}(t)$ values of –5.4 to –3.1 (Table DR1 [see footnote 1]).

Leiqingla Volcanic Rocks

The Leiqingla samples are basaltic in composition with varying SiO_2 (49.91–54.00 wt%) except for sample LQ-11, which is andesitic (SiO_2 = 59.23 wt%). The key characteristics of these samples are low TiO_2 (0.91–1.13 wt%), high Al_2O_3 (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 Al_2O_3 (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., $[La/Yb]_N$ = 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 $[Nb/La]_{PM}$ 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 265 Ma), with $\varepsilon_{Nd}(t)$ values of +1.1 to +2.6. Although the Leiqingla andesite has relatively low REE abundances compared with the basalts (Figs. 4I and 4J), the initial Sr isotopic composition (0.7063) and $\varepsilon_{Nd}(t)$ value (+2.6) (Table DR1 [see footnote 1]) of the andesite indicate that the two rock types are genetically related.

Ranwu Volcanic Rocks

The Ranwu samples have a limited range of SiO_2 (57.65–58.42 wt%), and plot in the andesite field on the Zr/TiO_2 versus Nb/Y diagram

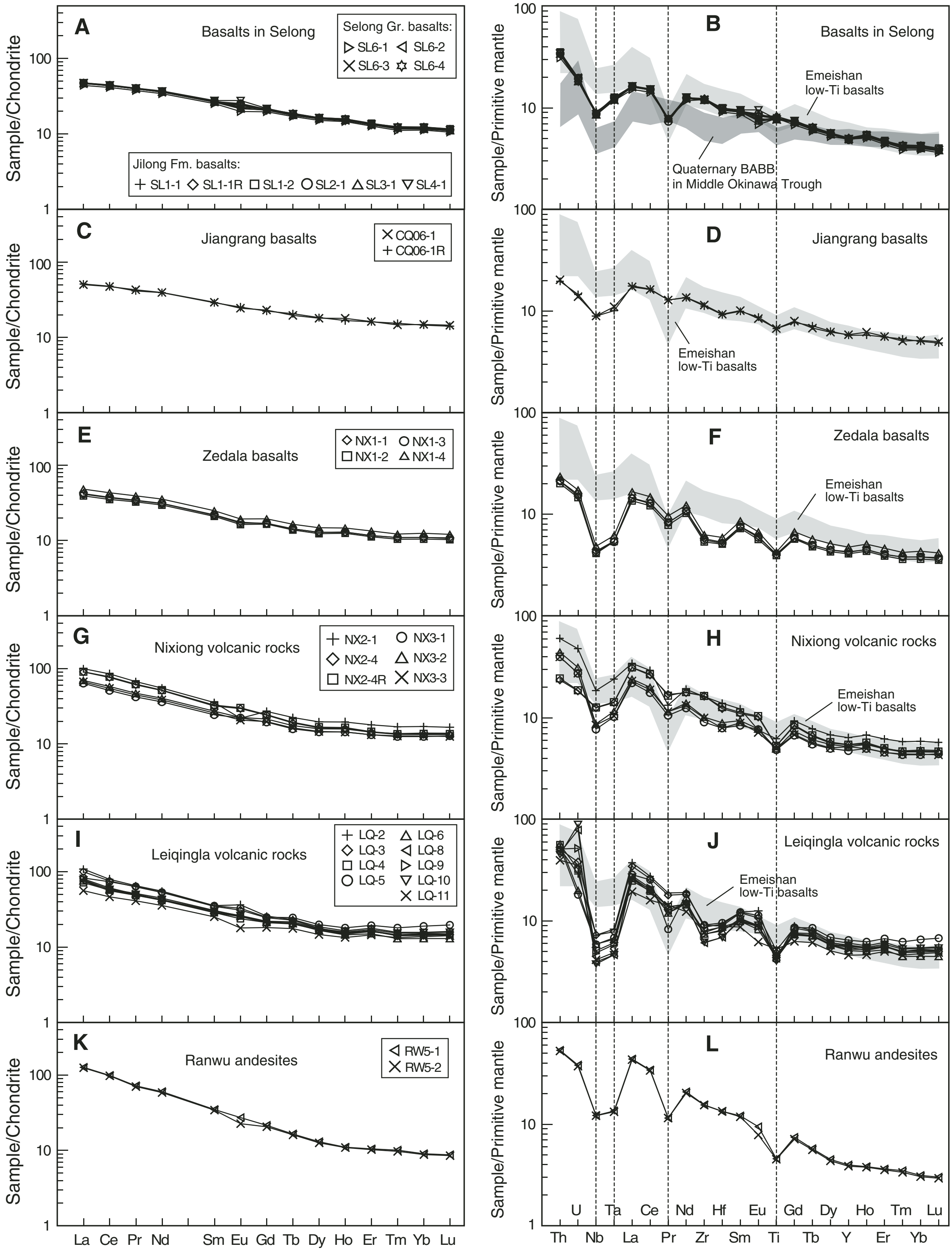

Figure 4. Chondrite-normalized, rare-earth element (REE) patterns and primitive mantle–normalized trace element spectra for the Permian volcanic rocks in southern Tibet. Normalizing values and plotting order are from Sun and McDonough (1989). Quaternary backarc basin basalts (BABB) from the Middle Okinawa Trough (Shinjo et al., 1999), and Emeishan low-Ti basalts (Xiao et al., 2004) are shown for comparison. Abbreviations: Fm.—Formation; Gr.—Group.

(Winchester and Floyd, 1977) (Fig. 3A). The samples are highly enriched in light REEs (e.g., $[La/Yb]_N$ = 14.02–14.21) and typically lack an obvious Eu anomaly (Eu/Eu* = 0.85–1.00) (Fig. 4K). The samples are also enriched in Th and U as well as light REEs. Negative Nb, Ta, P, and Ti anomalies are pronounced (Fig. 4L). The samples show a small range in initial $^{87}Sr/^{86}Sr$ (0.7101–0.7107) and negative $\varepsilon_{Nd}(t)$ (–3.2) at 280 Ma (Table DR1 [see footnote 1]).

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_2O_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 $[Nb/La]_{PM}$ or $[Th/La]_{PM}$ (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 $(^{87}Sr/^{86}Sr)_t$ values at a constant $\varepsilon_{Nd}(t)$ 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 $\varepsilon_{Nd}(t)$ 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.

Permian 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

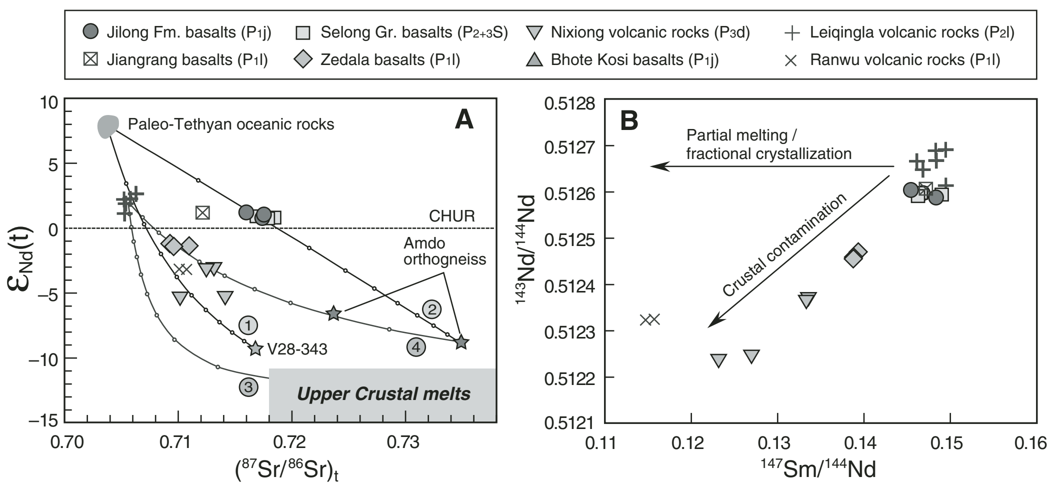

Figure 5. $\varepsilon_{Nd}(t)$ versus $(^{87}Sr/^{86}Sr)_t$ and $^{143}Nd/^{144}Nd$ versus $^{147}Sm/^{144}Nd$ plots for the Permian volcanic rocks in southern Tibet. The assumed end-members and modeling parameters are given in Table DR2 [see footnote 1].

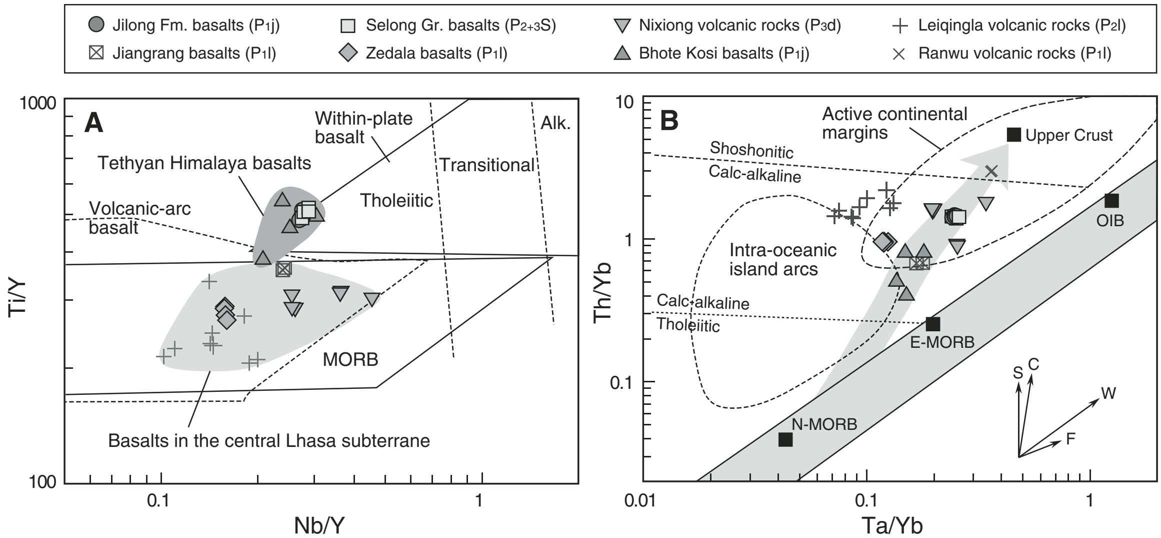

Figure 6. Selected plots for testing the nature of the Permian volcanic rocks in southern Tibet. (A) Ti/Y versus Nb/Y (Pearce, 1982) plot showing the Permian basalts in the central Lhasa subterrane have volcanic-arc basalt affinity and the Tethyan Himalayan basalts have within-plate tholeiitic basalt 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.

and therefore plot toward the field of intraoceanic island arc (Fig. 6B), the Permian basalt samples all plot in the field defined by active continental margin rocks. Their elevated Th/Ta values (13–21) are indicative of basalts formed in an active continental margin (Gorton and Schandl, 2000). Figure 6B shows that the Permian volcanic rocks of the central Lhasa subterrane are dominantly calc-alkaline in composition.

Collectively, the geochemical criteria strongly suggest an active continental arc setting for the central Lhasa subterrane during the Permian. This is consistent with the microcontinent nature of this subterrane (Zhu et al., 2009c). Such an arc setting is further supported by the occurrence of the Songdo eclogite (Yang et al., 2009) on the southern margin of the central Lhasa subterrane (Fig. 1A). Zircon U-Pb dating indicates that the very high-pressure metamorphism documented by the Songdo eclogite (ca. 262 Ma) (Yang et al., 2009) is effectively synchronous with the emplacement of the syncollisional Pikang peraluminous granite (ca. 263 Ma) and the development of a regional angular unconformity in the same geotectonic location (Zhu et al., 2009a). These events postdate the Early Permian continental arc volcanism documented in the Jiangrang, Zedala, and Ranwu areas of the central Lhasa subterrane. Such observations are inconsistent with the model that interprets the eclogite as intra-arc material, emplaced by diapiric flow during (not after) regional arc magmatism (Yin et al., 2007). Therefore, we favor the continent-continent collision model that predicts high-pressure metamorphism to postdate arc magmatism to explain the occurrence of the Songdo eclogite. In such a case, both the Songdo eclogite and the Permian volcanic rocks of this study indicate the presence of an active continental arc system in the central Lhasa subterrane during the Permian. In addition, sedimentary facies analysis indicates that the Lower to Middle Permian was dominated by an open-marine platform facies, whereas the Upper Permian is characterized by transitional facies ranging from shallow marine to nonmarine (Geng, 2007). Although such facies trends could be present in forearc basins, we tentatively interpret the facies changes as reflecting tectono-eustatic changes in response to the development of the Permian arc in the Lhasa terrane.

The active continental arc-related Permian volcanism of the central Lhasa subterrane was contemporaneous with large-scale upwelling of mantle plumes, as represented by the Siberian Traps in Russia, Emeishan flood basalts in SW China, and Panjal Traps in NW India (Fig. 1A) (Garzanti et al., 1999; Xiao et al., 2004; Saunders et al., 2007; Shellnutt et al., 2008). Previous studies have reported that basalts with arc signatures (e.g., negative Nb, Ta, and Ti anomalies) possibly form above an upwelling mantle plume, such as the case at Emeishan (Xiao et al., 2004). A plume-related origin may also apply to the Permian volcanic rocks of the central Lhasa subterrane. However, we consider this unlikely because (1) these rocks are geochemically different from the Emeishan low-Ti basalts (Xiao et al., 2004) in terms of Al_2O_3 contents (Fig. 3B), $[Nb/La]_{PM}$ values (Fig. 3C), and trace element patterns (Figs. 4D, 4F, 4H, and 4J); and (2) the Permian basalts of the central Lhasa subterrane are geochemically similar to arc basalts from Andean-type active continental margins (Fig. 3C).

Permian Extension-Type Magmatism in the Tethyan Himalaya

The Jilong Formation and Selong Group basalts reported here have high MgO and low Al_2O_3, 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

REE patterns on primitive mantle-normalized, multi-element diagrams (Fig. 4B). A previous study suggested that the Permian Bhote Kosi basalts of the Tethyan Himalaya were erupted in an extensional tectonic setting (Garzanti et al., 1999). The Jilong Formation and Selong Group basalts show relatively high Ti/Y values and plot mostly in the within-plate tholeiitic basalt field on the Ti/Y versus Nb/Y diagram (Fig. 6A). Their low Th/Ta values (5.4–5.9) are consistent with formation in a within-plate 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 Parkatchic, 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.

Geochemical 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; Lapierre 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; Dèzes, 1999; Chauvet et al., 2008) (Fig. 1A). The Panjal Traps show a gradual eastward thinning from Kashmir (2500 m thick) to Upper Lahul (Dèzes, 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 alkalic basalts (Bhat, 1984; Bhat and Ahmad, 1990). In Oman, the Middle Permian (based on biostratigraphy) volcanic rocks are compositionally diverse, consisting of tholeiitic and alkali 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; Lapierre 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 $\varepsilon_{Nd}(t)$ 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 alkali basalts (Group 3 in Fig. 7D), and the Jilong Formation and Selong Group basalts are particularly obvious in a Zr/Nb versus $\varepsilon_{Nd}(t)$ 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 basalt 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 $\varepsilon_{Nd}(t)$ 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 Leiqingla basalts have 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 $\varepsilon_{Nd}(t)$ values (+1.1 to +2.6), indicate minimal crustal assimilation during ascent. The low $\varepsilon_{Nd}(t)$ values of the Leiqingla 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 Leiqingla 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

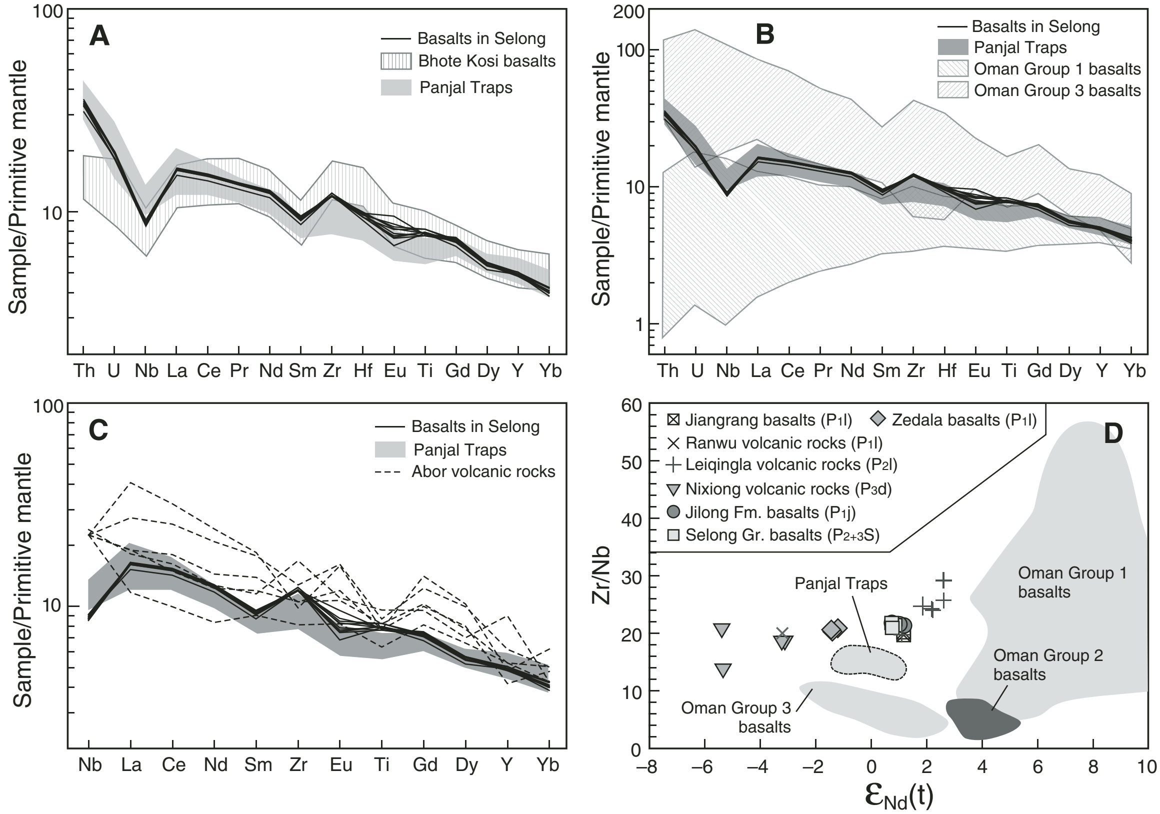

Figure 7. Primitive mantle–normalized trace element patterns for the Permian volcanic rocks along the northern rifted margin of the Indian-Arabian shields or in the neighboring basins. Normalizing values and plotting order are from Sun and McDonough (1989). (A) The basalts in Selong area compare closely 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 ε_{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 ε_{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 $^{147}Sm/^{144}Nd$ versus $^{143}Nd/^{144}Nd$ 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

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 Stampfli 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 Dagze 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).

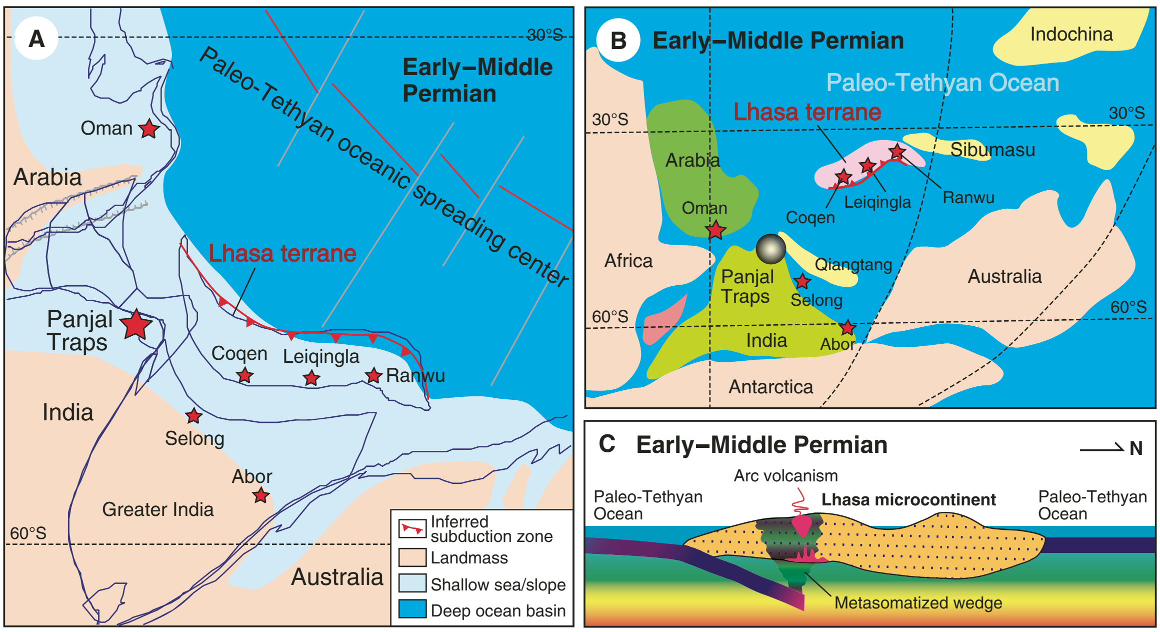

Figure 8. (A) Tectonic reconstruction of Golonka (2000) shows the Lhasa terrane was adjacent to the Greater India during the Early-Middle Permian. Note that new observations documented in Yang et al. (2009), Zhu et al. (2009a), and this study cannot be effectively explained by this model. (B and C) An 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 subterrane (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 Indochina 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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REFERENCES CITED

Angiolini, L., Balini, M., Garzanti, E., Nicora, A., and Tintori, A., 2003, Gondwanan deglaciation and opening of Neotethys: The Al Khlata and Saiwan Formations of Interior Oman: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 196, p. 99–123, doi: 10.1016/S0031-0182(03)00315-8.

Bhat, M.I., 1984, Abor volcanics: further evidence for the birth of the Tethys Ocean in the Himalayan segment: Journal of the Geological Society, v. 141, p. 763–775, doi: 10.1144/gsjgs.141.4.0763.

Bhat, M.I., and Ahmad, T., 1990, Petrogenesis and mantle source characteristics of the Abor Volcanic rocks, Eastern Himalayas: Journal of the Geological Society of India, v. 36, p. 227–246.

Bhat, M.I., and Zainuddin, S.M., 1978, Geochemistry of the Panjal Traps of Mount Kayol, Lidderwat, Pahalgam, Kashmir: Journal of the Geological Society of India, v. 19, p. 403–410.

Bhat, M.I., Zainuddin, S.M., and Rais, A., 1981, Panjal Trap chemistry and the birth of Tethys: Geological Magazine, v. 118, p. 367–375, doi: 10.1017/S0016756800032234.

Bienvenu, P., Bougault, H., Joron, M., and Dmitriev, L., 1990, MORB alteration: Rare-earth element/non-rare earth hygromagmaphile element fractionation: Chemical Geology, v. 82, p. 1–14, doi: 10.1016/0009-2541(90)90070-N.

Booth, A.L., Zeitler, P.K., Kidd, W.S.F., Wooden, J., Liu, Y.P., Idleman, B., Hren, M., and Chamberlain, C.P., 2004, U-Pb zircon constraints on the tectonic evolution of southeastern Tibet, Namche Barwa area: American Journal of Science, v. 304, p. 889–929, doi: 10.2475/ajs.304.10.889.

Bureau of Geology and Mineral Resources of Xizang Autonomous Region, 1993, Regional Geology of Xizang (Tibet) Autonomous Region: Beijing, Geological Publishing House, p. 449–450 (in Chinese with English abstract).

Chauvet, F., Lapierre, H., Bosch, D., Guillot, S., Mascle, G., Vannay, J.C., Cotten, J., Brunet, P., and Keller, F., 2008, Geochemistry of the Panjal Traps basalts (NW Himalaya): Records of the Pangea Permian break-up: Bulletin de la Société Géologique de France, v. 179, p. 383–395, doi: 10.2113/gssgfbull.179.4.383.

Chu, M.F., Chung, S.L., Song, B., Liu, D.Y., O'Reilly, S.Y., Pearson, N.J., Ji, J.Q., and Wen, D.J., 2006, Zircon U-Pb and Hf isotope constraints on the Mesozoic tectonics and crustal evolution of southern Tibet: Geology, v. 34, p. 745–748, doi: 10.1130/G22725.1.

Crawford, A.J., Falloon, T.J., and Eggins, S., 1987, The origin of island arc high-alumina basalts: Contributions to Mineralogy and Petrology, v. 97, p. 417–430, doi: 10.1007/BF00372004.

Dampare, S.B., Shibata, T., Asiedu, D.K., Osae, S., and Banoeng-Yakubo, B., 2008, Geochemistry of Paleoproterozoic metavolcanic rocks from the southern Ashanti volcanic belt, Ghana: Petrogenetic and tectonic setting implications: Precambrian Research, v. 162, p. 403–423, doi: 10.1016/j.precamres.2007.10.001.

Deng, W.M., Yin, J.X., and Wo, Z.P., 1996, Basic-ultrabasic and volcanic rocks in Chagbu-Shuanghu area of northern Xizang (Tibet), China: Science in China, v. 39, p. 359–368.

Dewey, J.F., Shackleton, R.M., Chang, C.F., and Sun, Y.Y., 1988, The Tectonic Evolution of the Tibetan Plateau: Philosophical Transactions of the Royal Society of London (Series A): Mathematical and Physical Sciences, v. 327, p. 379–413.

Dèzes, P., 1999, Tectonic and metamorphic evolution of the central Himalayan domain in southeast Zanskar (Kashmir, India), *in* Guex, J., ed.: Lausanne, Institut de Géologie et Paléontologie, Université de Lausanne, Mémoires de Géologie, v. 32, 149 p.

Enkin, R.J., Yang, Z.Y., Chen, Y., and Courtillot, V., 1992, Paleomagnetic constraints on the geodynamic history of the major blocks of China from the Permian to the present: Journal of Geophysical Research, v. 97, p. 13953–13989, doi: 10.1029/92JB00648.

Ernst, W.G., 2009, Subduction-zone metamorphism, calc-alkaline magmatism, and convergent-margin crustal evolution: Gondwana Research, doi: 10.1016/j.gr.2009.05.010.

Ferrari, O.M., Hochard, C., and Stampfli, G.M., 2008, An alternative plate tectonic model for the Palaeozoic–Early Mesozoic Palaeotethyan evolution of Southeast Asia (Northern Thailand–Burma): Tectonophysics, v. 451, p. 346–365, doi: 10.1016/j.tecto.2007.11.065.

Gaetani, M., and Garzanti, E., 1991, Multicyclic history of the northern India continental margin (northwestern Himalaya): American Association of Petroleum Geologists Bulletin, v. 75, p. 1427–1446.

Garzanti, E., and Sciunnach, D., 1997, Early Carboniferous onset of Gondwanian glaciation and Neo-Tethyan rifting in Southern Tibet: Earth and Planetary Science Letters, v. 148, p. 359–365, doi: 10.1016/S0012-821X(97)00028-9.

Garzanti, E., Le Fort, P., and Sciunnach, D., 1999, First report of Lower Permian basalts in South Tibet: Tholeiitic magmatism during break-up and incipient opening of Neotethys: Journal of Asian Earth Sciences, v. 17, p. 533–546, doi: 10.1016/S1367-9120(99)00008-5.

Geng, Q.R., 2007, The Late Paleozoic volcanic rocks in the Gangdese zone in Tibet: petrology, geochemistry and tectonic implications [Ph.D. thesis]: Wuhan, China University of Geosciences, p. 1–143.

Gertisser, R., and Keller, J., 2003, Trace element and Sr, Nd, Pb and O isotope variations in medium-K and high-K volcanic rocks from Merapi volcano, central Java, Indonesia: Evidence for the involvement of subducted sediments in Sunda arc magma genesis: Journal of Petrology, v. 44, p. 457–489, doi: 10.1093/petrology/44.3.457.

Golonka, J., 2000, Cambrian-Neogene plate tectonic maps: Kraków, Wydawnictwa Uniwersytetu Jagiellońskiego, p. 1–195 (with 32 maps).

Golonka, J., 2007, Late Triassic and Early Jurassic palaeogeography of the world: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 244, p. 297–307, doi: 10.1016/j.palaeo.2006.06.041.

Golonka, J., and Ford, D., 2000, Pangean (Late Carboniferous–Middle Jurassic) paleoenvironment and lithofacies: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 161, p. 1–34, doi: 10.1016/S0031-0182(00)00115-2.

Gorton, M.P., and Schandl, E.S., 2000, From continents to island arcs: A geochemical index of tectonic setting for arc-related and within-plate felsic to intermediate volcanic rocks: Canadian Mineralogist, v. 38, p. 1065–1073, doi: 10.2113/gscanmin.38.5.1065.

Guynn, J.H., Kapp, P., Pullen, A., Gehrels, G., Heizler, M., and Ding, L., 2006, Tibetan basement rocks near Amdo reveal "missing" Mesozoic tectonism along the Bangong suture, central Tibet: Geology, v. 34, p. 505–508, doi: 10.1130/G22453.1.

Hara, H., Wakita, K., Ueno, K., Kamata, Y., Hisada, K., Charusiri, P., Charoentitirat, T., and Chaodumrong, P., 2009, Nature of accretion related to Paleo-Tethys subduction recorded in northern Thailand: Constraints from mélange kinematics and illite crystallinity: Gondwana Research, doi: 10.1016/j.Group2009.01.006.

Hawkesworth, C.J., Hergt, J.M., Ellam, R.M., and McDermott, F., 1991, Element fluxes associated with subduction related magmatism: Philosophical Transactions of the Royal Society of London. Series A: Mathematical and Physical Sciences, v. 335, p. 393–405, doi: 10.1098/rsta.1991.0054.

He, S.D., Kapp, P., DeCelles, P.G., Gehrels, G.E., and Heizler, M., 2007, Cretaceous–Tertiary geology of the Gangdese Arc in the Linzhou area, southern Tibet: Tectonophysics, v. 433, p. 15–37, doi: 10.1016/j.tecto.2007.01.005.

Hu, D.G., Wu, Z.H., Jiang, W., Shi, Y.R., Ye, P.S., and Liu, Q.S., 2005, SHRIMP zircon U-Pb age and Nd isotopic study on the Nyainqêntanglha Group in Tibet: Science in China, v. 48, p. 1377–1386.

Ji, Z.S., Yao, J.X., and Wu, G.C., 2007, Stratigraphic division of the marine Triassic in the Coqen area, western Gangdese, Tibet, China: Geological Bulletin of China, v. 26, p. 947–952.

Ji, W.Q., Wu, F.Y., Chung, S.L., Li, J.X., and Liu, C.Z., 2009, Zircon U-Pb chronology and Hf isotopic constraints on the petrogenesis of Gangdese batholiths, southern Tibet: Chemical Geology, v. 262, p. 229–245, doi:10.1016/j.chemgeo.2009.01.020.

Jin, X., 2002, Permo-Carboniferous sequences of Gondwana affinity in southwest China and their paleogeographic implications: Journal of Asian Earth Sciences, v. 20, p. 633–646, doi: 10.1016/S1367-9120(01)00084-0.

Kapp, P., Murphy, M.A., Yin, A., Harrison, T.M., Ding, L., and Guo, J.R., 2003, Mesozoic and Cenozoic tectonic evolution of the Shiquanhe area of western Tibet: Tectonics, v. 22, p. 1029, doi: 10.1029/2001TC001332.

Kapp, P., Yin, A., Harrison, T.M., and Ding, L., 2005, Cretaceous–Tertiary shortening, basin development, and volcanism in central Tibet: Geological Society of America Bulletin, v. 117, p. 865–878, doi: 10.1130/B25595.1.

Kersting, A.B., and Arculus, R.J., 1994, Klyuchevskoy Volcano, Kamchatka, Russia: The role of high-flux recharged, tapped, and fractionated magma chamber(s) in the genesis of high-Al_2O_3 from high-MgO basalt: Journal of Petrology, v. 35, p. 1–41.

Korte, C., Kozur, H.W., and Bruckschen, P., 2003, Strontium isotope evolution of Late Permian and Triassic seawater: Geochimica et Cosmochimica Acta, v. 67, p. 47–62, doi: 10.1016/S0016-7037(02)01035-9.

Lapierre, H., Samper, A., Bosch, D., Maury, R.C., Bechennec, F., Cotton, J., Demant, A., Brunet, P., Keller, F., and Marcoux, J., 2004, The Tethyan plume: Geochemical diversity of Middle Permian basalts from the Oman rifted margin: Lithos, v. 74, p. 167–198, doi: 10.1016/j.lithos.2004.02.006.

Leeder, M.R., Smith, A.B., and Yin, J.X., 1988, Sedimentology, palaeoecology and palaeoenvironmental evolution of the 1985 Lhasa to Golmud Geotraverse: Philosophical Transactions of the Royal Society of London. Series A: Mathematical and Physical Sciences, v. 327, p. 107–143, doi: 10.1098/rsta.1988.0123.

Leier, A.L., Kapp, P., Gehrels, G.E., and DeCelles, P.G., 2007, Detrital zircon geochronology of Carboniferous-Cretaceous strata in the Lhasa terrane, southern Tibet: Basin Research, v. 19, p. 361–378, doi: 10.1111/j.1365-2117.2007.00330.x.

Li, Z.L., Yang, J.S., Xu, X.Z., Li, T.F., Xu, X.Z., Ren, Y.F., and Robinson, P.T., 2009, Geochemistry and Sm-Nd and Rb-Sr isotopic compositions of eclogite in the Lhasa terrane, Tibet, and its geological significance: Lithos, v. 109, p. 240–247, doi: 10.1016/j.lithos.2009.01.004.

Marcoux, J., De Wever, P., Nicolas, A., Girardeau, J., Xiao, X.C., Chang, C.F., Wang, N.W., Cao, Y.G., Bassoullet, J.P., Colchen, M., and Mascle, G., 1982, Preliminary report of depositional sediments on top of the volcanic member: Xigaze ophiolite (Yarlung Zangbo suture zone), South Xizang (Tibet): Ofioliti, v. 2, p. 395–396.

Maury, R.C., Béchennec, F., Cotton, J., Caroff, M., Cordey, F., and Marcoux, J., 2003, Middle Permian plume-related magmatism of the Hawasina Nappes and the Arabian Platform: Implications on the evolution of the Neotethyan margin in Oman: Tectonics, v. 22, doi: 10.1029/2002TC001483.

Metcalfe, I., 2002, Permian tectonic framework and palaeogeography of SE Asia: Journal of Asian Earth Sciences, v. 20, p. 551–566, doi: 10.1016/S1367-9120(02)00022-6.

Metcalfe, I., 2006, Palaeozoic and Mesozoic tectonic evolution and palaeogeography of East Asian crustal fragments: The Korean Peninsula in context: Gondwana Research, v. 9, p. 24–46, doi: 10.1016/j.Group2005.04.002.

Mo, X.X., Zhao, Z.D., Deng, J.F., Dong, G.C., Zhou, S., Guo, T.Y., Zhang, S.Q., and Wang, L.L., 2003, Response of volcanism to the India-Asia collision: Earth Science Frontiers, v. 10, p. 135–148.

Mo, X.X., Hou, Z.Q., Niu, Y.L., Dong, G.C., Qu, X.M., Zhao, Z.D., and Yang, Z.M., 2007, Mantle contributions to crustal thickening during continental collision: Evidence from Cenozoic igneous rocks in southern Tibet: Lithos, v. 96, p. 225–242, doi: 10.1016/j.lithos.2006.10.005.

Mo, X.X., Niu, Y.L., Dong, G.C., Zhao, Z.D., Hou, Z.Q., Zhou, S., and Ke, S., 2008, Contribution of syncollisional felsic magmatism to continental crust growth: A case study of the Paleocene Linzizong Volcanic Succession in southern Tibet: Chemical Geology, v. 250, p. 49–67, doi: 10.1016/j.chemgeo.2008.02.003.

Noble, S.R., Searle, M.P., and Walker, C.B., 2001, Age and tectonic significance of Permian granites in western Zanskar, High Himalaya: The Journal of Geology, v. 109, p. 127–135, doi: 10.1086/317966.

Pan, G.T., and Ding, J., 2004, Geological map (1:1,500,000) of Qinghai-Xizang (Tibetan) Plateau and adjacent areas: Chengdu: Chengdu Cartographic Publishing House.

Pan, G.T., Mo, X.X., Hou, Z.Q., Zhu, D.C., Wang, L.Q., Li, G.M., Zhao, Z.D., Geng, Q.R., and Liao, Z.L., 2006, Spatial-temporal framework of the Gangdese Orogenic Belt and its evolution: Acta Petrolei Sinica, v. 22, p. 521–533.

Pearce, J.A., 1982, Trace elements characteristic of lavas from destructive plate boundaries, *in* Thorpe, R.S., ed., Andesites: New York, Wiley, p. 525–548.

Pearce, J.A., 1983, Role of the sub-continental lithosphere in magma genesis at active continental margins, *in* Hawkesworth, C.J., and Norry, M.J., eds., Continental Basalts and Mantle Xenoliths: Nantwich, Shiva, p. 230–249.

Pearce, J.A., and Mei, H.J., 1988, Volcanic rocks of the 1985 Tibet Geotraverse: Lhasa to Golmud: Philosophical Transactions of the Royal Society of London. Series A: Mathematical and Physical Sciences, v. 327, p. 169–201, doi: 10.1098/rsta.1988.0125.

Peng, T.P., Wang, Y.J., Zhao, G.C., Fan, W.M., and Peng, B.X., 2008, Arc-like volcanic rocks from the southern Lancangjiang zone, SW China: Geochronological and geochemical constraints on their petrogenesis and tectonic implications: Lithos, v. 102, p. 358–373, doi: 10.1016/j.lithos.2007.08.012.

Plank, T., and Langmuir, C.H., 1998, The geochemical compositions of subducting sediment and its consequences for the crust and mantle: Chemical Geology, v. 145, p. 325–394, doi: 10.1016/S0009-2541(97)00150-2.

Robertson, A.H.F., and Searle, M., 1990, The northern Oman Tethyan Continental margin: Stratigraphy, Structure, Concepts and Controversies, *in* Robertson,

A.H., Searle, M.P., and Ries, A.C., eds., The Geology and Tectonics of the Oman Region: Geological Society of London, Special Publication, v. 49, p. 3–25.
Rudnick, R.L., and Gao, S., 2003, The Composition of the Continental Crust, *in* Holland, H.D., and Turekian, K.K., eds., Treatise on Geochemistry, The Crust: Oxford, Elsevier-Pergamon, p. 1–64.
Saidi, A., Brunnet, M.F., and Ricou, L.E., 1997, Continental accretion of the Iran Block to Eurasia as seen from Late Paleozoic to early Cretaceous subsidence curves: Geodinamica Acta, v. 10, p. 189–208.
Saunders, A.D., Jones, S.M., Morgan, L.A., Pierce, K.L., Widdowson, M., and Xu, Y.G., 2007, Regional uplift associated with continental large igneous provinces: The roles of mantle plumes and the lithosphere: Chemical Geology, v. 241, p. 282–318, doi: 10.1016/j.chemgeo.2007.01.017.
Scotese, C.R., 2004, A continental drift flipbook: The Journal of Geology, v. 112, p. 729–741, doi: 10.1086/424867.
Scotese, C.R., Boucot, A.J., and McKerrow, W.S., 1999, Gondwanan palaeogeography and palaeoclimatology: Journal of African Earth Sciences, v. 28, p. 99–114, doi: 10.1016/S0899-5362(98)00084-0.
Şengör, A.M.C., 1979, Mid-Mesozoic closure of Permo-Triassic Tethys and its implications: Nature, v. 279, p. 590–593, doi: 10.1038/279590a0.
Şengör, A.M.C., 1987, Tectonics of the Tethysides: Orogenic Collage Development in a Collisional Setting: Annual Review of Earth and Planetary Sciences, v. 15, p. 213–244, doi: 10.1146/annurev.ea.15.050187.001241.
Shellnutt, J.G., Zhou, M.F., Yan, D.P., and Wang, Y.B., 2008, Longevity of the Permian Emeishan mantle plume (SW China): 1 Ma, 8 Ma or 18 Ma?: Geological Magazine, v. 145, p. 373–388, doi: 10.1017/S0016756808004524.
Shinjo, R., Chung, S.L., Kato, Y., and Kimura, M., 1999, Geochemical and Sr-Nd isotopic characteristics of volcanic rocks from the Okinawa Trough and Ryukyu arc: Implications for the evolution of a young, intracontinental back arc basin: Journal of Geophysical Research, v. 104, p. 10,591–10,608, doi: 10.1029/1999JB900040.
Smith, A.B., and Xu, J.T., 1988, Palaeontology of the 1985 Tibet Geotraverse, Lhasa to Golmud: Philosophical Transactions of the Royal Society of London. Series A: Mathematical and Physical Sciences, v. 327, p. 53–105, doi: 10.1098/rsta.1988.0122.
Spring, L., Bussy, F., Vannay, J.C., Hunon, S., and Cosca, M.A., 1993, Early Permian granitic dykes of alkaline affinity in the Indian High Himalaya of upper Lahul and SE Zanskar: Geochemical characterization and geotectonic implications, *in* Treloar, P.J., and Searle, M., eds., Himalayan Tectonics: The Geological Society of London, Special Publication, v. 74, p. 251–264.
Stampfli, G., Marcoux, J., and Baud, A., 1991, Tethyan margins in space and time: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 87, p. 373–409, doi: 10.1016/0031-0182(91)90142-E.
Stampfli, G.M., and Borel, G.D., 2002, A plate tectonic model for the Paleozoic and Mesozoic constrained by dynamic plate boundaries and restored synthetic oceanic isochrones: Earth and Planetary Science Letters, v. 196, p. 17–33, doi: 10.1016/S0012-821X(01)00588-X.
Staudigel, H., Plank, T., White, B., and Schmincke, H.U., 1996, Geochemical fluxes during seafloor alteration of the basaltic upper oceanic crust: DSDP sites 417 and 418, *in* Bebout, G.E., Scholl, S.W., Kirby, S.H., and Platt, J.P., eds.: Washington, D.C., American Geophysical Union, p. 19–38.
Stöcklin, J., 1974, Possible ancient continental margin in Iran, *in* Burk, C.A., and Drake, C.A., eds., The geology of continental margins: Berlin, Springer-Verlag, p. 873–887.
Stolz, A.J., Vame, R., Davies, G.R., Wheller, G.E., and Foden, J.D., 1990, Magma source components in an arc-continent collision zone: The Flores-Lembata sector, Sunda Arc, Indonesia: Contributions to Mineralogy and Petrology, v. 105, p. 585–601, doi: 10.1007/BF00302497.
Sun, S.S., and McDonough, W.F., 1989, Chemical and isotope systematics of oceanic basalts: Implications for mantle composition and processes, *in* Saunders, A.D., and Norry, M.J., eds., Magmatism in the Ocean Basins: The Geological Society of London, Special Publication, v. 42, p. 313–345.
Vannay, J.C., and Spring, L., 1993, Geochemistry of the continental basalts within the Tethyan Himalaya of Lahul-Spiti and SE Zanskar (NW India), *in* Treloar, P.J., and Searle, M.P., eds., Himalayan Tectonics: The Geological Society of London, Special Publication, v. 74, p. 237–249.
Volkmer, J.E., Kapp, P., Guynn, J.H., and Lai, Q., 2007, Cretaceous-Tertiary structural evolution of the north central Lhasa terrane, Tibet: Tectonics, v. 26, TC6007, doi: 6010.1029/2005TC001832.
von Raumer, J., Stampfli, G., Borel, G., and Bussy, F., 2002, Organization of pre-Variscan basement areas at the north-Gondwanan margin: International Journal of Earth Sciences, v. 91, p. 35–52, doi: 10.1007/s005310100200.
Wang, G.H., Liang, D.Y., Liu, W.C., Dong, W.T., and Wang, S.H., 2000, Extensional movement and extending action in southern Tibet since Hercynian: Geoscience, v. 14, p. 133–139.
Wen, D.R., Liu, D.Y., Chung, S.L., Chu, M.F., Ji, J.Q., Zhang, Q., Song, B., Lee, T.Y., Yeh, M.W., and Lo, C.H., 2008, Zircon SHRIMP U-Pb ages of the Gangdese Batholith and implications for Neotethyan subduction in southern Tibet: Chemical Geology, v. 252, p. 191–201, doi: 10.1016/j.chemgeo.2008.03.003.
Whitford, D.J., Korsch, M.J., Porritt, P.M., and Craven, S.J., 1988, Rare-earth mobility around the volcanogenic polymetallic massive sulfide deposit at Que River, Tasmania, Australia: Chemical Geology, v. 68, p. 105–119, doi: 10.1016/0009-2541(88)90090-3.
Winchester, J.A., and Floyd, P.A., 1977, Geochemical discrimination of different magma series and their differentiation products using immobile elements: Chemical Geology, v. 20, p. 325–342, doi: 10.1016/0009-2541(77)90057-2.
Winter, J.D., 2001, An introduction to igneous and metamorphic petrology: Englewood Cliffs, New Jersey, Prentice Hall, p. 1–210.
Xiao, L., Xu, Y.G., Mei, H.J., Zheng, Y.F., He, B., and Pirajno, F., 2004, Distinct mantle sources of low-Ti and high-Ti basalts from the western Emeishan large igneous province, SW China: Implications for plume-lithosphere interaction: Earth and Planetary Science Letters, v. 228, p. 525–546, doi: 10.1016/j.epsl.2004.10.002.
Xu, R.H., Schärer, U., and Allègre, C.J., 1985, Magmatism and metamorphism in the Lhasa block (Tibet): A geochronological study: The Journal of Geology, v. 93, p. 41–57, doi: 10.1086/628918.
Yang, J.S., Xu, Z.Q., Li, Z.L., Xu, X.Z., Li, T.F., Ren, Y.F., Li, H.Q., Chen, S.Y., and Robinson, P.T., 2009, Discovery of an eclogite belt in the Lhasa block, Tibet: A new border for Paleo-Tethys?: Journal of Asian Earth Sciences, v. 34, p. 76–89, doi: 10.1016/j.jseaes.2008.04.001.
Yin, A., 2006, Cenozoic tectonic evolution of the Himalayan orogen as constrained by along-strike variation of structural geometry, exhumation history, and foreland sedimentation: Earth-Science Reviews, v. 76, p. 1–131, doi: 10.1016/j.earscirev.2005.05.004.
Yin, A., and Harrison, T.M., 2000, Geologic evolution of the Himalayan-Tibetan orogen: Annual Review of Earth and Planetary Sciences, v. 28, p. 211–280, doi: 10.1146/annurev.earth.28.1.211.
Yin, J.X., Xu, J.T., Liu, C.J., and Li, H., 1988, The Tibetan Plateau: Regional stratigraphic context and previous work: Philosophical Transactions of the Royal Society of London. Series A: Mathematical and Physical Sciences, v. 327, p. 5–52, doi: 10.1098/rsta.1988.0121.
Yin, A., Manning, C.E., Lovera, O., Menold, C.A., Chen, X.H., and Gehrels, G.E., 2007, Early Paleozoic tectonic and thermomechanical evolution of ultrahigh-pressure (UHP) metamorphic rocks in the northern Tibetan Plateau, northwest China: International Geology Review, v. 49, p. 681–716, doi: 10.2747/0020-6814.49.8.681.
Yu, G.M., and Wang, C.S., 1990, Sedimentary Geology of the Xizang (Tibet) Tethys: Beijing, Geological Publishing House, p. 10–49 (in Chinese with English abstract).
Zhang, H.F., Xu, W.C., Guo, J.Q., Zong, K.Q., Cai, H.M., and Yuan, H.L., 2007, Zircon U-Pb and Hf isotopic composition of deformed granite in the southern margin of the Gangdese belt, Tibet: Evidence for early Jurassic subduction of Neo-Tethyan oceanic slab: Acta Petrolei Sinica, v. 23, p. 1347–1353.
Zhang, K.J., Xia, B.D., Wang, G.M., Li, Y.T., and Ye, H.F., 2004, Early Cretaceous stratigraphy, depositional environments, sandstone provenance, and tectonic setting of central Tibet, western China: Geological Society of America Bulletin, v. 116, p. 1202–1222, doi: 10.1130/B25388.1.
Zhang, S.Q., Mahoney, J.J., Mo, X.X., Ghazi, A.M., Milani, L., Crawford, A.J., Guo, T.Y., and Zhao, Z.D., 2005, Evidence for a widespread Tethyan upper mantle with Indian-Ocean-type isotopic characteristics: Journal of Petrology, v. 46, p. 829–858, doi: 10.1093/petrology/egi002.
Zhou, S., Mo, X., Dong, G., Zhao, Z., Qiu, R., Guo, T., and Wang, L., 2004, ^{40}Ar-^{39}Ar geochronology of Cenozoic Linzizong volcanic rocks from Linzhou Basin, Tibet, China and their geological implications: Chinese Science Bulletin, v. 49, p. 1970–1979, doi: 10.1360/03wd0511.
Zhu, D.C., Pan, G.T., Mo, X.X., Liao, Z.L., Jiang, X.S., and Wang, L.Q., 2004, Permian to Cretaceous volcanic activities in the central segment of the Tethyan Himalayas (I): Distribution characteristics and significance: Geological Bulletin of China, v. 23, p. 645–654.
Zhu, D.C., Pan, G.T., Chung, S.L., Mo, X.X., Zhao, Z.D., Liao, Z.L., Wang, L.Q., Li, G.M., and Dong, G.C., 2008a, SHRIMP zircon age and geochemical constraints on the origin of Early Jurassic volcanic rocks from the Yeba Formation, southern Gangdese in south Tibet: International Geology Review, v. 50, p. 442–471, doi: 10.2747/0020-6814.50.5.442.
Zhu, D.C., Pan, G.T., Wang, L.Q., Mo, X.X., Zhao, Z.D., Zhou, C.Y., Liao, Z.L., Dong, G.C., and Yuan, S.H., 2008b, Tempo-spatial variations of Mesozoic magmatic rocks in the Gangdese belt, Tibet, China, with a discussion of geodynamic setting-related issues: Geological Bulletin of China, v. 27, p. 1535–1550.
Zhu, D.C., Mo, X.X., Niu, Y.L., Zhao, Z.D., Yang, Y.H., and Wang, L.Q., 2009a, Zircon U-Pb dating and in-situ Hf isotopic analysis of Permian peraluminous granite in the Lhasa terrane, southern Tibet: Implications for Permian collisional orogeny and paleogeography: Tectonophysics, v. 469, p. 48–60, doi: 10.1016/j.tecto.2009.01.017.
Zhu, D.C., Pan, G.T., Zhao, Z.D., Lee, H.Y., Kang, Z.Q., Liao, Z.L., Wang, L.Q., Li, G.M., Dong, G.C., and Liu, B., 2009b, Early Cretaceous subduction-related adakite-like rocks in the Gangdese, south Tibet: Products of slab melting and subsequent melt-peridotite interaction?: Journal of Asian Earth Sciences, v. 34, p. 298–309, doi: 10.1016/j.jseaes.2008.05.003.
Zhu, D.C., Mo, X.X., Niu, Y., Zhao, Z.D., Wang, L.Q., Liu, Y.S., and Wu, F.Y., 2009c, Geochemical investigation of Early Cretaceous igneous rocks along an east-west traverse throughout the central Lhasa Terrane, Tibet: Chemical Geology, v. 268, p. 298–312, doi:10.1016/j.chemgeo.2009.09.008.
Zhu, J., Du, Y.S., Liu, Z.X., Feng, Q.L., Tian, W.X., Li, J.P., and Wand, C.P., 2005, Mesozoic radiolarian chert from the middle sector of the Yarlung Zangbo suture zone, Tibet and its tectonic implications: Science in China, v. 49, p. 348–357.
Zhu, T.X., Pan, G.T., Feng, X.T., Zou, G.F., and Li, J.Z., 2002, Discovery and tectonic significance of Permian basic volcanic rocks in the Selong area on the northern slope of the Himalayas, southern Tibet: Geological Bulletin of China, v. 21, p. 717–722.
Ziabrev, S.V., Aitchison, J.C., Abrajevitch, A., Badengzhu, Davis, A.M., and Luo, H., 2003, Precise radiolarian age constraints on the timing of ophiolite generation and sedimentation in the Dazhuqu terrane, Yarlung-Tsangpo suture zone, Tibet: Journal of the Geological Society, v. 160, p. 591–600, doi: 10.1144/0016-764902-107.
Ziegler, A.M., Hulver, M.L., and Roeley, D.B., 1997, Permian world topography and climate, *in* Martini, I.P., ed., Late glacial and postglacial environmental changes: Quaternary, carboniferous-Permian and Proterozoic: New York, Oxford University Press, p. 111–146.

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