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The origin and pre-Cenozoic evolution of the Tibetan Plateau

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ABSTRACT

Different hypotheses have been proposed for the origin and pre-Cenozoic evolution of the Tibetan Plateau as a result of several collision events between a series of Gondwana-derived terranes (e.g., Qiangtang, Lhasa and India) and Asian continent since the early Paleozoic. This paper reviews and reevaluates these hypotheses in light of new data from Tibet including (1) the distribution of major tectonic boundaries and suture zones, (2) basement rocks and their sedimentary covers, (3) magmatic suites, and (4) detrital zircon constraints from Paleozoic metasedimentary rocks. The Western Qiangtang, Amdo, and Tethyan Himalaya terranes have the Indian Gondwana origin, whereas the Lhasa Terrane shows an Australian Gondwana affinity. The Cambrian magmatic record in the Lhasa Terrane resulted from the subduction of the proto-Tethyan Ocean lithosphere beneath the Australian Gondwana. The newly identified late Devonian granitoids in the southern margin of the Lhasa Terrane may represent an extensional magmatic event associated with its rifting, which ultimately resulted in the opening of the Songdo Tethyan Ocean. The Lhasa—northern Australia collision at ~263 Ma was likely responsible for the initiation of a southward-dipping subduction of the Bangong-Nujiang Tethyan Oceanic lithosphere. The Yarlung-Zangbo Tethyan Ocean opened as a back-arc basin in the late Triassic, leading to the separation of the Lhasa Terrane from northern Australia. The subsequent northward subduction of the Yarlung-Zangbo Tethyan Ocean lithosphere beneath the Lhasa Terrane may have been triggered by the Qiangtang–Lhasa collision in the earliest Cretaceous. The mafic dike swarms (ca. 284 Ma) in the Western Qiangtang originated from the Panjal plume activity that resulted in continental rifting and its separation from the northern Indian continent. The subsequent collision of the Western Qiangtang with the Eastern Qiangtang in the middle Triassic was followed by slab breakoff that led to the exhumation of the Qiangtang metamorphic rocks. This collision may have caused the northward subduction initiation of the Bangong-Nujiang Ocean lithosphere beneath the Western Qiangtang. Collision-related coeval igneous rocks occurring on both sides of the suture zone and the within-plate basalt affinity of associated mafic lithologies suggest slab breakoff-induced magmatism in a continent—continent collision zone. This zone may be the site of net continental crust growth, as exemplified by the Tibetan Plateau.

Abbreviations: ACNK(aluminum saturation index), molecular Al_2O_3 $(CaO+Na_2O+K_2O)$]; BABB, Back-Arc Basin Basalt; BGMRXAR, Bureau of Geology and Mineral Resources of Xizang Autonomous Region; BNSZ, Bangong-Nujiang Suture Zone, represents the Bangong-Nujiang Tethyan Oceanic relics; E-MORB, Enriched Mid-Ocean Ridge Basalt; Greater Tibetan Plateau, Tibetan Plateau plus Himalayas; HREE, Heavy Rare Earth Element (i.e., Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu); IYZSZ, Indus-Yarlung Zangbo Suture Zone, represents the Indus—Yarlung Zangbo Tethyan Oceanic relics; JSSZ, Jinsha Suture Zone, represents the Jinsha Tethyan Oceanic relics; LA-ICP-MS, Laser Ablation Inductively-Coupled Plasma Mass Spectrometry; LIP, Large Igneous Province; LMF, Luobadui-Milashan Fault, may represent the Songdo Tethyan Oceanic relics; LSSZ, Longmu Tso-Shuanghu Suture Zone, represents the Longmu Tso-Shuanghu Tethyan Oceanic relics; MBT, Main Boundary Thrust; MCT, Main Central Thrust; MORB, Mid-Ocean Ridge Basalt; MREE, Middle Rare Earth Element (i.e., Sm, Eu, Gd, Tb, Dy, Ho); N-MORB, Normal Mid-Ocean Ridge Basalt; OIB, Ocean Island Basalt; REE, Rare Earth Element (i.e., La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu); SHRIMP, Sensitive High-Resolution Ion MicroProbe; SNMZ, Shiquan River-Nam Tso Mélange Zone, represents the site of the Shiquan River-Nam Tso back-arc basin closure; SSZ, Supra-Subduction Zone; STDS, South Tibetan Detachment System; Tibetan Plateau, Lhasa Terrane plus Qiangtang Terrane.

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1. Introduction

The theory of plate tectonics has advanced the century-old concept of continental drift. Studies of the Himalayan–Tibetan orogenic belt as a result of continental drift and the origin and evolution of the Tibetan Plateau have in turn enriched this theory (Dewey and Burke, 1973; Sengör, 1987; Royden et al., 2008). Much has been learned in the past three decades about the complexities of the styles of deformation and magmatism caused by the India–Asia continental collision (Xu et al., 1985; Sengör, 1987; Dewey et al., 1988; Pearce and Mei, 1988; Sengör et al., 1993; Yin and Harrison, 2000; Chung et al., 2005; Mo et al., 2008; Deng et al., 2011; Xu et al., 2012). However, further research must be undertaken regarding the precise timing and specific mechanisms of all magmatic, metamorphic, and tectonic processes in response to this collisional event. Such research, in turn, requires the knowledge of the nature and the pre-collisional geological history of the Tibetan Plateau lithosphere.

As the main tectonic components of the Greater Tibetan Plateau, the Qiangtang and Lhasa Terranes are generally thought to have rifted from Indian Gondwana in the late Paleozoic and to have drifted northward across the Tethyan Ocean basins before their sequential accretion to the Asian continent in the Mesozoic, before the India–Asia collision in the Cenozoic (cf. Allègre et al., 1984; Sengör, 1987; Yin and Harrison, 2000). The validity of this paleogeographic interpretation needs further evaluation using new data and observations, as many aspects of the related tectonic models were developed based on limited observations made during the Sino-French and Sino-British expeditions in the 1980s (Yin and Harrison, 2000 and references therein). These earlier reconnaissance efforts have been important, but featured neither adequate spatial coverage nor the necessary space–time resolution. The abundant new data that have been accumulated in the last two decades as a result of a systematical field mapping program and numerous geological expeditions supported by the Chinese government have increased substantially our understanding of the Tibetan geology.

This review focuses on the pre-Cenozoic geological evolution of the Greater Tibetan Plateau (including the Qiangtang, Lhasa, and Tethyan Himalayan terranes) and presents a synoptic overview based on both the extant literature and new data showing the distributions of the major tectonic boundaries, magmatic suites, and basement rocks and their sedimentary cover, as well as new detrital zircon data obtained from the Paleozoic metasedimentary rocks in Tibet. We consider this overview as a working report on the current state of knowledge and ideas on the Tibetan geology to better understand the origin, geodynamic settings, and evolution of various terranes, which make up the Tibetan Plateau; we also attempt to offer new insights into the Tethyan evolution of the Tibetan–Himalayan orogenic system with a specific focus on the syncollisional magmatism and pre-Cenozoic continental growth in the southern margin of the Asian continent.

2. Major tectonic boundaries

2.1. Suture zones

The Indus-Yarlung Zangbo (IYZSZ) and Bangong-Nujiang (BNSZ) suture zones divide the Tibetan plateau from south to north into the Tethyan Himalaya, Lhasa, and Qiangtang terranes (Fig. 1a) (cf. Pan et al., 1983; Girardeau et al., 1985a; Pearce and Deng, 1988). Recently, the existence of the Longmu Tso-Shuanghu suture zone (LSSZ) within the Qiangtang Terrane has also been identified (cf. Li, 1987; Li et al., 1995; Zhang et al., 2006a, 2006b, 2011; Zhai et al., 2011a, 2011b).

2.1.1. Indus-Yarlung Zangbo suture zone

Extending for more than 2000 km from NW India via southern Tibet to NE India, the Indus-Yarlung Zangbo suture zone (IYZSZ) (Fig. 1a) is one of the most important tectonic boundaries in the Tibetan Plateau. It is bounded to the north by the Xigaze forearc basin sequence and the Gangdese batholith and to the south by a Triassic flysch. It marks the site where the Indus-Yarlung Zangbo Tethyan Ocean lithosphere was consumed at a subduction zone dipping northward beneath the Lhasa Terrane (Girardeau et al., 1985a; Pearce and Deng, 1988; Sengör et al., 1988; BGMRXAR, 1993; Yin and Harrison, 2000). Many of the ophiolite sequences in the IYZSZ are incomplete and tectonically disrupted, although nearly complete ophiolite sequences occur at Luobusa and Xigaze (Fig. 1a) (cf. BGMRXAR, 1993; Wang et al., 2000; Pan et al., 2006; Bédard et al., 2009).

The igneous age of the diabasic or gabbroic rocks from the ophiolite sequences along the IYZSZ has been estimated at 163–120 Ma by zircon SHRIMP U–Pb dating (Fig. 1a) (Wang et al., 2006; Wei et al., 2006; Zhong et al., 2006; Li et al., 2008a; Xia et al., 2008a). Radiolarian chert deposits associated with these ophiolites range in age from the Middle–Upper Triassic to late Lower Cretaceous (cf. Matsuoka et al., 2002; Zhu et al., 2006a). Recently, Dai et al. (2011) reported from the western IYZSZ in Najiu a Late Devonian alkaline gabbro (~364 Ma) with typical Ocean Island Basalt (OIB) characteristics (Fig. 1a), and interpreted it as a remnant of the Paleo-Tethyan seafloor. However, this interpretation may be questionable since the Najiu gabbro occurs as a tectonic block within a shaly matrix mélange of the IYZSZ (Dai et al., 2011).

The Middle–Upper Triassic and Upper Jurassic–Lower Cretaceous radiolarian cherts were deposited in a rifted marginal basin, unlike the Lower Cretaceous radiolarian cherts, which were deposited in a pelagic basin (Zhu et al., 2006a). This sedimentary record may suggest that the Neo-Tethyan Ocean might have been a large basin during the early Cretaceous, consistent with the paleomagnetic data indicating the presence of a wide Indus-Yarlung Zangbo Tethyan Ocean (>2000-km wide) at that time (Li et al., 2004). Previous studies have shown that the Xigaze ophiolite predominantly has an N-MORB affinity and a mid-ocean ridge origin (cf. Girardeau et al., 1985a; Pearce and Deng, 1988; Xu and Castillo, 2004; Zhang et al., 2005). Subsequent investigations have documented the occurrence of intrusive and volcanic rocks in the Xigaze ophiolite that display supra-subduction-zone (SSZ) geochemical signatures (Malpas et al., 2003). Such SSZ-related units have also been found in the early Cretaceous ophiolites elsewhere along the IYZSZ (cf. Qiu et al., 2007; Bédard et al., 2009; Guilmette et al., 2009).

2.1.2. Bangong-Nujiang suture zone

The Bangong-Nujiang suture zone (BNSZ), which extends for more than 2000 km across the central Tibetan Plateau (Fig. 1a), marks the site where the Bangong-Nujiang Tethyan Ocean lithosphere was subducted either northward under the Qiangtang Terrane during the Mesozoic (Coulon et al., 1986; Pearce and Deng, 1988; Yin and Harrison, 2000; Kapp et al., 2003, 2007; Guynn et al., 2006) or southward under the Lhasa Terrane during the Permian—Early Cretaceous (Hsü et al., 1995; Pan et al., 2006; Zhu et al., 2006b, 2009a, 2011a). The ophiolites at Yunzhug and western Nam Tso, which were previously considered as klippes rooted in the BNSZ, are most likely remnants from the Shiquan River-Nam Tso mélange zone (SNMZ) (see below). If so, the southern boundary of the BNSZ should be moved northward and located to the north of the Baingoin batholith, close to Baila and Nagqu (Fig. 1a). It is generally thought that the ophiolites from both to the north (e.g., Amdo ophiolites) and to the south (e.g., Baila, Yila, and Nagqu ophiolites) of the Amdo (Fig. 1a) represent oceanic remnants derived from the BNSZ (cf. Girardeau et al., 1985b; Xu et al., 1985; Pearce and Deng, 1988; Pan et al., 2006). If this is the case, the Amdo basement must have been isolated within the Bangong-Nujiang Tethyan Ocean during the formation of the ophiolites.

The magmatic age of the BNSZ ophiolites has generally been considered as the late Triassic to early Cretaceous based on SHRIMP U–Pb dating on zircons from ophiolitic cumulate gabbros (Fig. 1a) (Bao et al., 2007; Xia et al., 2008b; Qiangba et al., 2009) and based on the biostratigraphical dating of radiolaria in interbedded cherts (cf. Wang et al., 2002). Some researchers have proposed that the Bangong-Nujiang Tethyan Ocean may have developed in the Paleozoic, using the following constraints: (1) the identification of an angular unconformity between the Upper Triassic flysch (with a basal conglomerate that contains ophiolitic elements) and the underlying ophiolites in Baila (Chen et al., 2005; Pan et al., 2006) and (2) the possible existence of late Paleozoic ophiolites at Dolie, SW Nagqu (Fig. 1a), where the cumulate gabbros have been dated at 242 and 259 Ma (Nimaciren et al., 2005). This interpretation of a Paleozoic origin of the Bangong-Nujiang Tethyan Ocean needs to be further validated with additional age data.

Arc tholeiites, back-arc basin basalts, and boninites, which are indicative of formation or modification in supra-subduction zone environments (Dilek and Furnes, 2011), have been identified in the ophiolite sequences along the BNSZ (Girardeau et al., 1985b; Pearce and Deng, 1988; Liu et al., 2002; Qiu et al., 2007; Shi et al., 2008). Ophiolitic components with N-MORB, E-MORB, and OIB signatures have been also found along the BNSZ (cf. Bao et al., 2007; Shi et al., 2008). Different lithological and geochemical compositions documented from the ophiolite sequences along the BNSZ may indicate that these ophiolites may in fact represent the remnants of different types of oceanic lithosphere evolved in different tectonic settings (Dilek and Furnes, 2011).

2.1.3. Longmu Tso-Shuanghu suture zone

The Longmu Tso-Shuanghu suture zone (LSSZ) extends from northwest to southeast across the Qiangtang Terrane (Fig. 1a). It was originally proposed by Li (1987) as an in situ Triassic suture zone, but this interpretation has not been widely accepted by the scientific community because of the lack of data indicating the occurrence of a complete ophiolitic sequence (see Li et al., 2009a, 2009c; Pullen et al., 2011). The ophiolitic units (e.g., peridotites, cumulate gabbros, pillow basalts, and radiolarian cherts) occurring as blocks or slices in the LSSZ are in fault contact with the Upper Paleozoic metasedimentary rocks and are locally unconformably overlain by the Upper Triassic volcano-sedimentary strata (Zhai et al., 2007; Li et al., 2008b, 2009a). The cumulate gabbros in the Taoxing Lake and the Guoganjianian areas have recently been dated at ~467 Ma (Zhai et al., 2010) and at ~432 Ma (Li et al., 2008b) (Fig. 1a), respectively, using the zircon SHRIMP U–Pb method. The basalts and cumulate gabbros from Guoganjianian show N-MORB geochemical affinities (Zhai et al., 2007), whereas the Permian basalts interbedded with radiolarian cherts from Jiaomuri (Fig. 1a) are geochemically similar to the OIB basalts (Zhai et al., 2006). Both of these mafic sequences are interpreted to represent the remnants of a Paleo-Tethyan oceanic lithosphere (cf. Zhai et al., 2007, 2010, 2011b; Li et al., 2009a). These results, together with the data on the Upper Devonian and

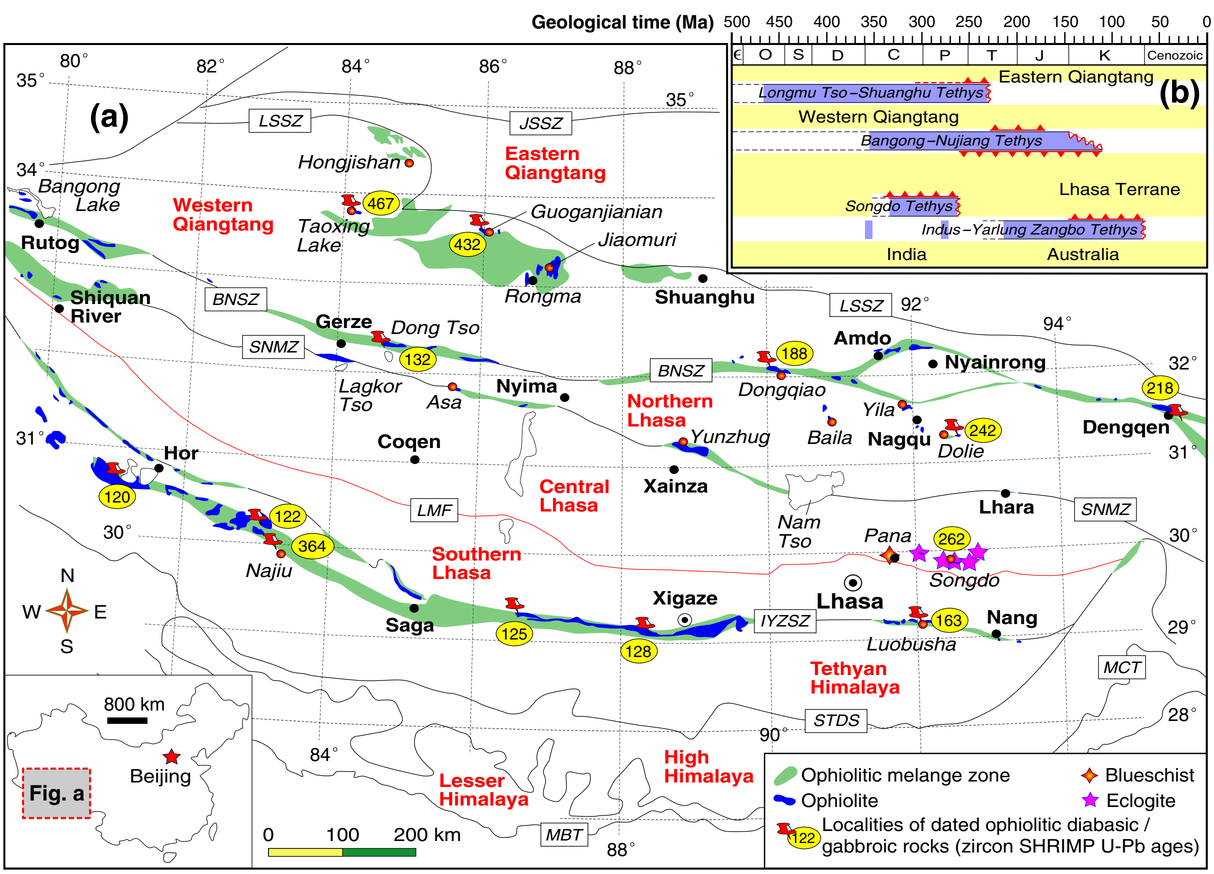

Fig. 1. (a) Tectonic framework of the Tibetan Plateau showing the major tectonic subdivisions, distribution of suture zones, and localities of dated ophiolitic diabasic/gabbroic rocks (ovals with numerals) by zircon SHRIMP U–Pb method. JSSZ = Jinsha Suture Zone; LSSZ = Longmu Tso-Shuanghu Suture Zone; BNSZ = Bangong-Nujiang Suture Zone; SNMZ = Shiquan River-Nam Tso Mélange Zone; LMF = Luobadui-Milashan Fault; IYZSZ = Indus-Yarlung Zangbo Suture Zone. Literature data: Nimaciren et al. (2005), Wang et al. (2006), Wei et al. (2006), Zhong et al. (2006), Bao et al. (2007), Li et al. (2008a, 2008b), Xia et al. (2008a, 2008b), Wang et al. (2008), Qiangba et al. (2009), Yang et al. (2009), Zhai et al. (2010), Dai et al.(2011). (b) Schematic diagram showing the timing of existence, subduction initiation, and subduction termination of the Tethys recovered from the ophiolites in the Tibetan Plateau. Light blue band = timing of existence of Tethyan ocean inferred from geological records; broken line = timing of existence of Tethyan ocean inferred from geodynamic perspective in a global context; heavy red line with triangles = subduction direction; red wave line = continental collision. See text for details.

Upper Permian radiolarian cherts east of Shuanghu (Zhu et al., 2006c), have been interpreted to suggest the presence of a Paleozoic ophiolite along the LSSZ (cf. Li et al., 2009a). Future studies focusing on more precise age dating and structural field studies to document the internal structure of these mafic sequences are needed.

The high-pressure metamorphic rocks spatially associated with the LSSZ ophiolites were discovered earlier (Kapp et al., 2000, 2003; Yin and Harrison, 2000; Li et al., 2006a, 2009a; Zhang et al., 2006b; Pullen et al., 2011; Zhai et al., 2011a). These metamorphic rocks consist mainly of blueschist and phengites-schist, metabasite with minor marble, and eclogite. They form a high-pressure metamorphic belt across the Qiangtang Terrane from Hongjishan in the northwest via Guoganjianian and Jiaomuri in the center to Shuanghu in the east (cf. Liu et al., 2006; Li et al., 2009a; Zhai et al., 2011a) (Fig. 1a). The high TiO_2 content (>2%) and light REE enrichment of the blueschists and eclogites without Nb–Ta anomalies suggest that their protoliths are basalts similar in composition to the OIB (Zhang et al., 2006a; Zhai et al., 2011b). The high SiO_2 and low Na_2O content of the metasedimentary rocks indicates that the source region was most likely a passive continental margin (Zhang et al., 2006a, 2011). The thermobarometric estimates for the metamorphic rocks are 1.0–1.5 GPa at 420 ± 50 °C for the blueschists (Kapp et al., 2003) and 2.0–2.5 GPa at 482–625 °C for the eclogites (Li et al., 2006a; Zhang et al., 2006b; Zhai et al., 2011a). The timing of this high-pressure, low-temperature metamorphism has been constrained as the Middle to early Late Triassic (i.e., 244–223 Ma) based on Lu–Hf isochron dating of the eclogites and blueschists (244–223 Ma; Pullen et al., 2008) and zircon SHRIMP U–Pb dating of the eclogites (237–230 Ma; Zhai et al., 2011a).

Currently, there exist two contrasting models for the formation of the Qiangtang metamorphic belt. The first model suggests that the metamorphic rocks are part of the Songpan-Ganzi accretionary mélange that was underthrust during the low-angle southward subduction of the Paleo-Tethyan oceanic lithosphere along the Jinsha suture (Kapp et al., 2000, 2003; Yin and Harrison, 2000; Pullen et al., 2008, 2011). In this model, the Qiangtang Terrane is inferred to have a Gondwana affinity and to consist mainly of material from the Triassic Songpan-Ganzi accretionary mélange. The high-pressure metamorphism along the LSSZ is attributed to the collision between the Qiangtang Terrane and an inferred intra-Paleo-Tethyan arc terrane during the Middle Triassic (Pullen et al., 2008). These high-P rocks were exhumed to shallow crustal levels as a result of a rollback of the Songpan-Ganzi oceanic lithosphere along the Jinsha suture during the Late Triassic (Kapp et al., 2000, 2003; Pullen et al., 2008, 2011). The second model suggests that the high-pressure metamorphic belt formed *in situ* along the LSSZ, which separates the Western Qiangtang with Gondwana affinity from the Eastern Qiangtang subterranes with Cathaysian affinity (e.g., Li, 1987; Li et al., 1995, 2009a; Zhang et al., 2006b). In this model, the LSSZ formed from the northward subduction of the Longmu Tso-Shuanghu Tethyan oceanic lithosphere (e.g., Li, 1987; Li et al., 1995, 2009a; Zhai et al., 2011a; Yang et al., 2011), and the metamorphic rocks were exhumed in response to the slab breakoff of the subducted Longmu Tso-Shuanghu Tethyan oceanic lithosphere beneath the Eastern Qiangtang subterrane (cf. Zhang et al., 2006a, 2011).

Several lines of evidence favor the *in situ* model explaining the origin of the Qiangtang metamorphic belt. First, the difference in provenance between the meta-siliciclastic rocks from the LSSZ (a passive continental margin source) and the Jinsha suture (an active continental margin source) indicates that the Jinsha suture zone is not the source of the Qiangtang metamorphic belt (Zhang et al., 2006a). Second, the Middle Triassic Nb-enriched basalt–magnesian andesite–adakite association documented from south of the Jinsha suture indicates a well-developed subduction-modified sub-arc mantle wedge (Wang et al., 2008); in contrast, a low-angle subduction regime would require a poorly developed sub-arc wedge (Gutscher et al., 2000) in the Eastern Qiangtang subterrane. Third, the high-pressure metamorphism that likely occurred at ~244 Ma (Pullen et al., 2008) predates the accumulation of the Songpan-Ganzi turbidites that began at ~230 Ma (Zhang et al., 2008a). This time difference indicates that the metamorphic rocks in the LSSZ most likely were not derived from the Songpan-Ganzi mélange along the Jinsha suture. Finally, the low-angle subduction model cannot account for the presence of the Paleozoic ophiolite or for the remnants of the Permian seamount sequence (e.g., basaltic breccia, OIB-type pillow basalt interbedded with bioclastic limestone, etc.) along the LSSZ. Both of these entities are only weakly metamorphosed (cf. Li et al., 1995, 2009a; Zhai et al., 2010).

2.2. Tectonic boundaries in the Lhasa Terrane

The Lhasa Terrane contains two major tectonic boundaries, the Luobadui-Milashan Fault (LMF) and the Shiquanhe-Nam Tso mélange zone (SNMZ) (Fig. 1a) (cf. Pan et al., 2004, 2006; Chen et al., 2009; Yang et al., 2009; Zhu et al., 2009b, 2010, 2011a).

2.2.1. Luobadui-Milashan Fault

The Luobadui-Milashan Fault (LMF) is a large thrust fault, extending for ~1500 km across the southern part of the Lhasa Terrane (Fig. 1a). The Permo-Carboniferous metasedimentary sequence was thrust southward over the Jurassic–Cenozoic volcano-sedimentary sequence along the Luobadui-Milashan Fault prior to or during the India–Asia collision (Pan et al., 2004; He et al., 2007). Recent studies indicate that the LMF may represent a Carboniferous–Permian suture zone based on the following observations and data:

(1) The Songdo eclogite belt indicates the existence of the subducted Songdo Tethyan Ocean seafloor during the Permian. Recent studies have reported a 500–1000-m-wide eclogite belt stretching for more than 100 km around Songdo, immediately north of the LMF (Fig. 1a) (cf. Chen et al., 2009; Yang et al., 2009). The Songdo eclogite forms tectonic slices in a garnet-bearing, mica-quartz schist and exhibits typical N-MORB geochemical signatures. Its protoliths, oceanic remnants of the Songdo Tethyan lithosphere (cf. Li et al., 2009b; Yang et al., 2009), have been dated at 306 ± 50 Ma (Sm–Nd isochron age).

(2) The peridotites present south of the Songdo eclogite belt may represent remnants of the Tethyan oceanic lithosphere. These harzburgitic rocks, whose existence was discovered ~20 years ago (BGMRXAR, 1993), are spatially associated with the Songdo eclogite belt (Chen et al., 2009) and are in fault contact with a micaschist to the north and with greenschist rocks to the south. The greenschists have been dated at ~305 Ma based on zircon SHRIMP U–Pb dating (Chen et al., 2009), making them coeval with the Songdo eclogite protoliths.

(3) The garnet glaucophane blueschists from Pana may represent the westward extension of the Songdo high-pressure metamorphic belt. Liu et al. (2009) reported the presence of garnet glaucophane blueschists in association with Permian limestone and quartzite from Pana, ~80 km west of Songdo, immediately north of the LMF (Fig. 1a). The P–T calculations indicate that the Pana blueschists experienced eclogite facies metamorphism at conditions similar to those of the Songdo eclogite during the late Permian (Liu et al., 2009; Yang et al., 2009). Thus, the Pana blueschists can be connected to the east with the Songdo eclogite. Both are products of high-pressure metamorphism in the same tectonic environment during the late Permian.

(4) The zircon Hf-isotope data from magmatic rocks support the westward extension of the Carboniferous–Permian suture zone along the LMF. A recent Hf-isotope analysis of zircons derived from the Mesozoic–early Tertiary magmatic rocks across

the Lhasa Terrane clearly indicates a significant decrease in the zircon $\varepsilon_{Hf}(t)$ values from the south to the north across the LMF (Zhu et al., 2011a). We interpret these data to indicate the presence of a microcontinent with an Archean basement north of the LMF, i.e., the central portion of the Lhasa Terrane (Zhu et al., 2009a, 2011a). If this is the case, the LMF represents a plate boundary, now represented by the Carboniferous–Permian suture zone recognized in the Songdo–Pana region and its westward extension along the LMF.

2.2.2. Shiquan River-Nam Tso mélange zone

The Shiquan River-Nam Tso mélange zone (SNMZ) extends SE–NW for ~2000 km across the northern part of the Lhasa Terrane (Fig. 1a). The ophiolite sequences in the SNMZ are well-preserved at Yunzhug and Lagkor Tso (Girardeau et al., 1985b; BGMRXAR, 1993; Pan et al., 2006; Baxter et al., 2009) and occur discontinuously at Shiquan River in the west, Asa and western Nam Tso in the center, and Lhara in the east (Fig. 1a) (cf. BGMRXAR, 1993; Pan et al., 2006).

The igneous age of the ophiolites in the SNMZ has been widely cited as ranging between 218 Ma and 118 Ma (cf. Pan et al., 2006; Zhang et al., 2007a). However, this is highly questionable because the existing radiometric age dates have not been ascertained using accurate techniques or suitable samples, as exemplified by the whole-rock Rb–Sr isochron dating of serpentinized harzburgite (~166 Ma) and metamorphosed gabbro (~173 Ma) samples in western Nam Tao (Ye et al., 2004), the whole-rock K–Ar dating of an altered diabase (~118 Ma) in Asa (Tang et al., 2004), and the SHRIMP U–Pb dating of zircons from serpentinized troctolite (~218 Ma) in Lhara (Fig. 1a). In the latter case, the dated zircons exhibit cathodoluminescence (He et al., 2006) similar to that of granitoids. In contrast, stratigraphical studies and radiolarian dating indicate that the deposition of the cherts associated with the ophiolites occurred almost synchronously along the SNMZ in the very Early Cretaceous (Girardeau et al., 1985b; Zhang et al., 2004; Zheng et al., 2004; Baxter et al., 2009).

Two contrasting hypotheses have been proposed for the origin of the SNMZ. The first suggests that the ophiolites preserved in Yunzhug and Lagkor Tso of the SNMZ actually represent northerly-derived klippes rooted in the Bangong-Nujiang mélange zone (Girardeau et al., 1985b; Kapp et al., 2003, 2007; Zhang et al., 2007a; Baxter et al., 2009). This suggestion was originally proposed based on the petrological and geochemical similarities of the ophiolites from Dongqiao in the BNSZ and Yunzhug in the SNMZ, both of which exhibit island arc geochemical affinities (cf. Girardeau et al., 1985b). However, this hypothesis may be too simplistic (Pearce and Deng, 1988; Schneider et al., 2003) and requires further testing because (1) the Yunzhug ophiolites resemble forearc lithosphere, whereas the Dongqiao ophiolites resemble back-arc lithosphere (Pearce and Deng, 1988), and (2) SSZ-type geochemical signatures are common in many Phanerozoic ophiolites from southern Tibet and elsewhere in the Tethyan system (cf. Qiu et al., 2007; Dilek and Furnes, 2009).

The second hypothesis argues that the ophiolites at Shiquan River, Lagkor Tso, Yunzhug, western Nam Tso, and Lhara in the SNMZ represent discrete remnants of a single, autochthonous mélange zone (i.e., the SNMZ) (Srimal, 1986; Hsü et al., 1995; Matte et al., 1996; Ye et al., 2004; He et al., 2006; Pan et al., 2006; Zhu et al., 2008a, 2009a, 2010, 2011a). This hypothesis is supported by a recent geochemical study indicating that the SNMZ is a tectonic boundary separating a piece of juvenile crust to the north from the Lhasa microcontinent to the south (Zhu et al., 2011a). The back-arc basin (BABB) characteristics of the basalts associated with the ophiolites in Lagkor Tso, western Nam Tso, and Lhara along the SNMZ (Girardeau et al., 1985b; Ye et al., 2004; He et al., 2006) may indicate that the SNMZ is a back-arc basin that developed in the early Cretaceous (Ye et al., 2004; Zhang et al., 2004; He et al., 2006; Pan et al., 2006; Zhu et al., 2008a, 2009a, 2011a). The ophiolites along the SNMZ may have been emplaced by the collision of Qiangtang with an arc-trench rollback system developed in the northern Lhasa subterrane (Zhu et al., 2011a) and by the collapse of such back-arc basin, analogous to the other Tethyan systems (cf. Dilek and Furnes, 2011).

In summary, the ophiolitic rocks preserved in the Tibetan Plateau are mainly SSZ-type ophiolites that are geochemically similar to many Phanerozoic ophiolites elsewhere in the global Tethyan system (Dilek and Furnes, 2009, 2011) that were formed in supra-subduction zone settings. This observation, together with the occurrence of seamount (or oceanic island) sequence remnants reported in suture zones in the Tibetan Plateau, may potentially reflect a bias in preservation. This is because normal oceanic lithosphere is too dense to obduct but is readily subducted, whereas the SSZ-type intraoceanic island arc (and seamount) system has the potential for accretion as a result of its buoyancy (cf. Niu et al., 2003; Cawood et al., 2009). The available geochronological and biostratigraphical data indicate that the Tethyan ocean remnants preserved in the ophiolites in southern Tibet should no longer be simply designated as relics of the Paleo- or Neo-Tethyan Ocean as was previously suggested (cf. Sengör, 1979, 1987; Metcalfe, 1996, 2009, 2011; Stampfli and Borel, 2002) because Paleo- and Neo-Tethyan remnants occur together along the same suture zone (Fig. 1b). Therefore, to avoid further confusion, the Tethyan ocean remnants should be designated according to their particular geographical location in the Tibetan Plateau (Fig. 1b).

3. Basement rock and sedimentary cover

Efforts to use stratigraphical, paleontological, and paleomagnetic data and the geology of basement rocks to trace the origins of (micro-) continents or terranes have a long history of success (cf. Metcalfe, 1996, 2009, 2011; Stampfli and Borel, 2002; Ferrari et al., 2008). The paleomagnetic data that have previously been obtained from the Tibetan Plateau are limited (see Li et al., 2004 for a review of these data). The most recent paleomagnetic data reported from the Lhasa and Tethyan Himalayan terranes are mainly for late Mesozoic to Cenozoic rocks. These data shed new light on the timing of the India–Asia collision (cf. Chen et al., 2010) but provide little to no help in indicating the origin of these terranes in Tibet (Wang et al., 2010a).

3.1. Tethyan Himalaya

The Tethyan Himalaya lies between the Indus-Yarlung Zangbo mélange zone (IYZSZ) and the South Tibetan Detachment System (STDS) (Fig. 1a). The Precambrian crystalline basement of the Tethyan Himalaya is composed of amphibolite facies metasedimentary rocks (e.g., gneiss and schist), migmatite, and gneiss of the Lhagoi Kangri Group in Meso- to Neo-Proterozoic age (Pan et al., 2004; Liao et al., 2008) (Fig. 2), along with Paleoproterozoic granitic gneiss (Liao et al., 2008) and possibly Cambrian augen orthogenesis (528–504 Ma) (Xu et al., 2005). The granitic gneiss from north of Dinggye that has been dated at 1812 ± 7 Ma (Liao et al., 2008) in the Tethyan Himalaya is coeval with the orthogneisses from south of Dinggye in the center (1812 ± 3 Ma, Liao et al., 2008; 1799 ± 9 Ma, Cottle et al., 2009) and from Arunachal Pradesh (1752 ± 12 Ma, Yin et al., 2010a) in the east of the High Himalaya (Fig. 2). This nearly synchronous timing of emplacement indicates that the Tethyan Himalaya may share a common Paleoproterozoic crystalline basement with the High Himalaya. It follows, therefore, that the Tethyan and High Himalayan terranes were most likely part of the same Indian continent in the Proterozoic, as also supported by paleomagnetic data (Torsvik et al., 2009).

A recent study indicates that the oldest sedimentary cover in the Tethyan Himalaya is early Cambrian in age (Myrow et al., 2010). The fossiliferous sedimentary cover of the Tethyan Himalaya is thick and nearly continuous from the Ordovician to early Tertiary (cf. Liu

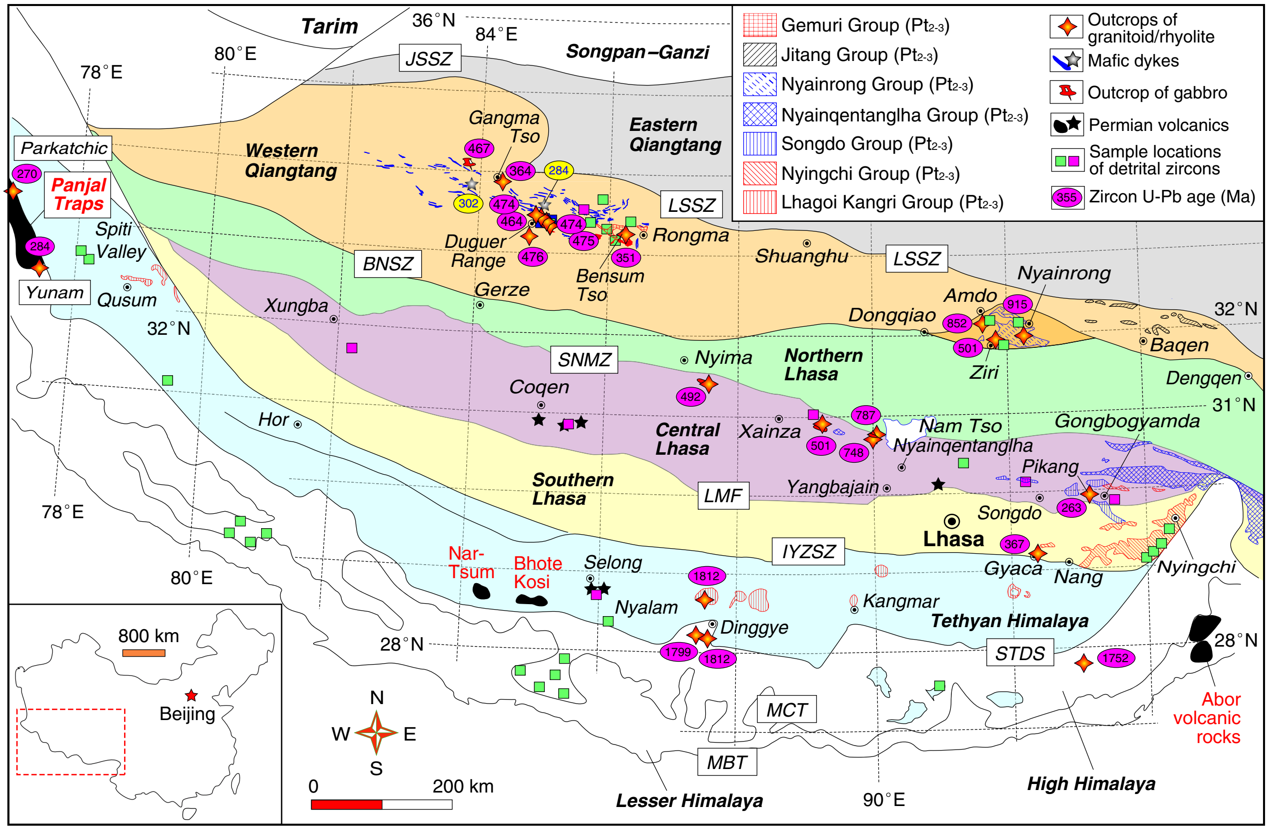

Fig. 2. Distributions of the basement rocks, pre-Mesozoic magmatic rocks, and sample localities of detrital zircons in the Tibetan Plateau. Literature data include Hu et al. (2005), Li et al. (2006b), Gehrels et al. (2006a, 2006b), Guynn et al. (2006, 2012), Liao et al. (2008), McQuarrie et al.(2008), Pullen et al. (2008, 2011), Cottle et al. (2009), Ji et al. (2009b), Zhai et al. (2009), Zhu et al. (2009a, 2009b, 2009c, 2009 d, 2010, 2011b), Myrow et al. (2009, 2010), Dong et al. (2010a, 2011a), Yin et al. (2010a), Guynn et al. (2012). Abbreviations are the same as in Fig. 1.

and Einsele, 1994; Pan et al., 2004), in which the Ordovician strata unconformably overlie the Cambrian strata and basement rocks (cf. Garzanti et al., 1986; Yin and Harrison, 2000; Pan et al., 2004; Myrow et al., 2006, 2010) (Fig. 3). The Permo-Carboniferous strata include glacial-marine diamictites and basalt interlayers in the Selong (Jin, 2002; Zhu et al., 2010) and Kangmar regions (Chen et al., 2002) (Fig. 2). The Lower Cretaceous sedimentary strata in the eastern Tethyan Himalaya contain abundant volcanic rocks (Zhu et al., 2007, 2008b) and significant mafic intrusions of the same or similar ages (ca. 132 Ma; Zhu et al., 2009c).

3.2. Southern Lhasa subterrane

The southern Lhasa subterrane is bounded to the south by the IYZSZ and to the north by the LMF (Fig. 1a). The Precambrian metamorphic basement of this subterrane was previously thought to have been represented by the Nyingchi Group (Fig. 2), which mainly includes gneiss, amphibolite, schist, and marble (Xu et al., 1985; Harris et al., 1988a; Pan et al., 2004). However, recent studies have determined the youngest detrital zircon ages of orthogneiss intrusive rock to be ~550 Ma and ~496 Ma (Dong et al., 2010a) and have thereby concluded that part of the Nyingchi Group must have been deposited between 550 and 496 Ma. The new zircon U–Pb chronological data have revealed that the Nyingchi Group was subjected to amphibolite facies and locally to granulite facies metamorphism during the late Mesozoic (~90 Ma; Wang et al., 2009; Zhang et al., 2010a) and the Cenozoic (~32 Ma; Dong et al., 2010a). All of these new observations indicate that part of the Nyingchi Group is not associated with the Precambrian metamorphic basement of the southern Lhasa subterrane (cf. Dong et al., 2010a) as previously thought. Although numerous radiogenic isotopic data for magmatic rocks suggest that the southern Lhasa subterrane is characterized by the presence of juvenile crust rather than ancient reworked crust (cf. Mo et al., 2008; Chung et al., 2009; Ji et al., 2009a; Zhu et al., 2011a; Guan et al., 2012), the emplacement of the early Paleozoic granite (ca. 496 Ma; Dong et al., 2010a) suggests that a Precambrian crystalline basement may be locally present in the southern Lhasa subterrane.

The sedimentary cover in the southern Lhasa subterrane is largely restricted to the eastern portion (cf. Pan et al., 2004). With the exception of the part of the Nyingchi Group that may represent the Paleozoic sedimentary cover for this subterrane (Dong et al., 2010a), the oldest cover unit consists mainly of clastic sedimentary rocks (e.g., slate, limestone, and sandstone) and abundant volcanic rocks (include mafic and silicic varieties) collectively known as the Yeba Formation (Fig. 3) (Pan et al., 2004; Zhu et al., 2008a). The Yeba Formation was previously identified as the late Carboniferous–early Permian or Triassic in age (Smith and Xu, 1988), but later bivalve fossils (Yin and Grant-Mackie, 2005) and zircon U–Pb chronological studies (cf. Zhu et al., 2008a) revealed it to be the late Triassic–early Jurassic. The younger sedimentary rocks in this subterrane include Upper Jurassic to Cretaceous volcano-sedimentary strata consisting mainly of sandstone, slate, limestone, and mudstone (Fig. 3) (Pan et al., 2004).

3.3. Central Lhasa subterrane

The central Lhasa subterrane lies between the SNMZ to the north and the LMF to the south (Fig. 1a). The existence of a Precambrian basement in this subterrane has been inferred based on inherited zircon ages of the Yangbajain gneiss (Allègre et al., 1984) (Fig. 2) and the whole-rock Nd isotope data from clastic sedimentary rocks (Zhang et al., 2007b). The Nyainqêntanglha Group (Fig. 2), which consists

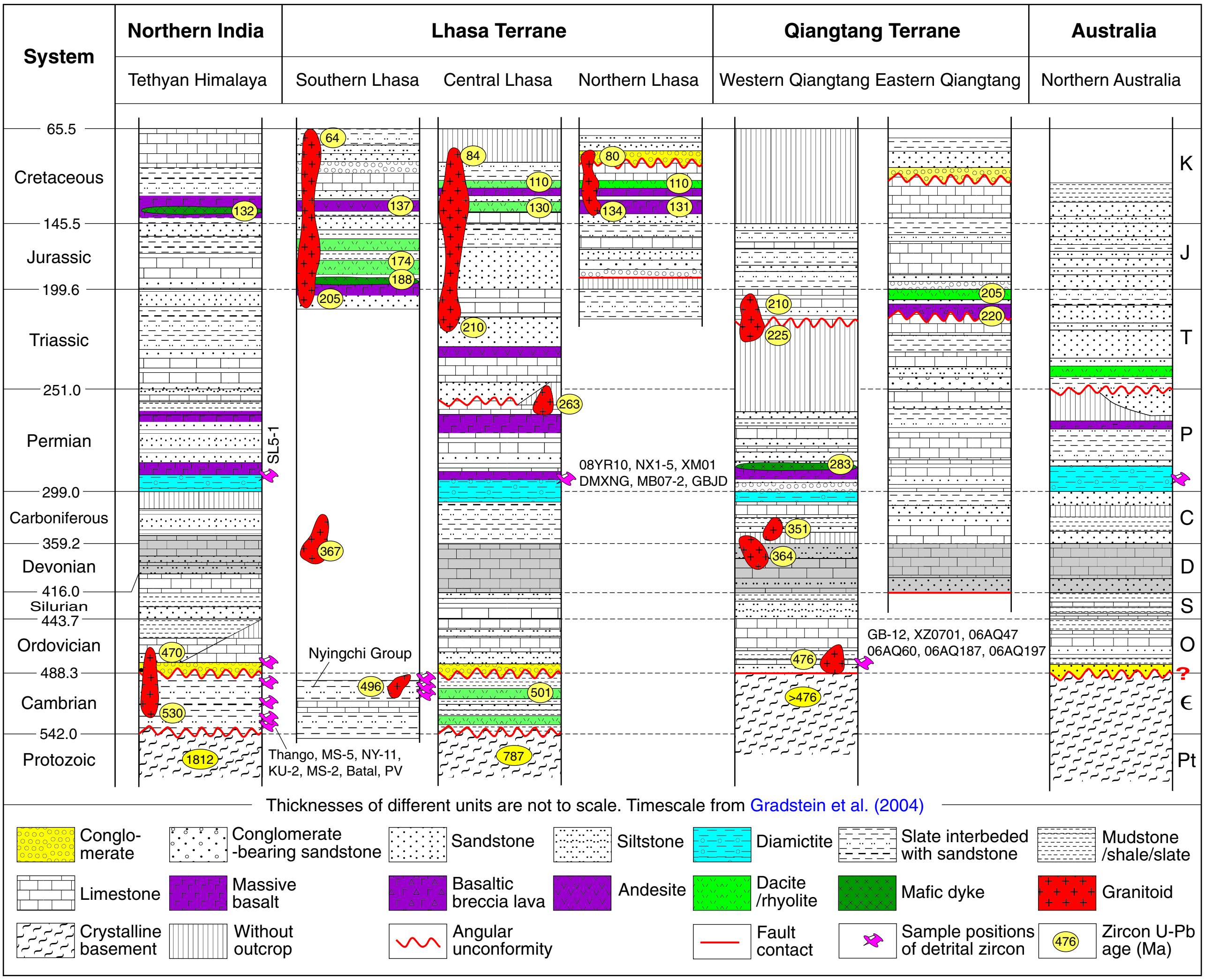

Fig. 3. Generalized space–time diagrams showing the basement rocks, sedimentary covers, tectonic, and magmatic history of different subterranes in the Tibetan Plateau. The geology of northern Australia (Görür and Sengör, 1992; Veevers and Tewari, 1995; Mory and Backhouse, 1997; Archbold, 1999; Crostella and Backhouse, 2000; Eyles and Eyles, 2000; Eyles et al., 2006; Haines and Wingate, 2007) is shown for comparison. The stratigraphical localities of detrital zircon samples are also indicated. See text for details.

mainly of amphibolite facies (and, locally, granulite facies) metamorphic rocks (e.g., orthogneiss, schist, amphibolite, and marble), has been interpreted as the surface record of the Precambrian basement of this subterrane (Li, 1955; Allègre et al., 1984; BGMRXAR, 1993; Pan et al., 2004). However, no direct geochronological data have been available that support this interpretation until recently. On the basis of zircon U–Pb dating for a trondhjemite mylonite rock (~787 Ma) intruded by mylonitized granite (~748 Ma), Hu et al. (2005) suggested that the protoliths of the Nyainqêntanglha Group west of Nam Tso (Fig. 2) must have formed between 787 and 748 Ma. Recent zircon LA-ICP-MS U–Pb dating for metamorphic rocks from west of Nam Tso revealed the dates of the metamorphism to be ~720 Ma (Zhang et al., 2010b) and ~690 Ma (Dong et al., 2011a). These new data also indicate the presence of a Precambrian metamorphic basement west of Nam Tso in the central Lhasa subterrane.

It is important to note that only part of the Nyainqêntanglha Group (west of Nam Tso) represents the Precambrian metamorphic basement of the central Lhasa subterrane. Some of the rocks (including amphibolite, schist, and orthogneiss) elsewhere in this group were metamorphosed during the late Triassic (e.g., 225–213 Ma; Dong et al., 2011b) or formed during the Cenozoic (Xu et al., 1985; Hu et al., 2003; Kapp et al., 2005a). Recently, Zhu et al. (2011a) investigated the spatial extent of the basement beneath the Lhasa Terrane using a combined method of *in situ* U–Pb dating and Hf-isotope analysis on zircons from Mesozoic–early Tertiary magmatic rocks, and concluded that the central Lhasa subterrane was once a microcontinent with Proterozoic and Archean basement rocks.

The Precambrian metamorphic basement of the central Lhasa subterrane is covered with widespread Permo-Carboniferous metasedimentary rocks that contain continental arc volcanic rocks (cf. Zhu et al., 2010) and abundant glacial-marine diamictites similar to those in the Tethyan Himalaya (Jin, 2002) and northern and western Australia (Eyles and Eyles, 2000; Eyles et al., 2006) (Fig. 3). Also included in the basement cover are Upper Jurassic–Lower Cretaceous sedimentary rocks, including abundant volcanic rocks (cf. Zhu et al., 2006b, 2009a, 2011a), small amounts of well-exposed Ordovician, Silurian, and Devonian strata in northeast Xainza, and Triassic limestone (cf. Pan et al., 2004). The Upper Permian is locally absent and generally rests unconformably on the Middle Permian (cf. Zhu et al., 2009b) (Fig. 3). Ji et al. (2009b) reported a Cambrian age of 501 ± 2 Ma for a metarhyolite from east of Xainza, which makes it coeval with metarhyolites (ca. 492 Ma) identified in southeast Nyima (Zhu et al., 2012) (Fig. 2). Most recently, Li et al. (2010a) confirmed the presence of Cambrian metarhyolites and identified an angular unconformity between the overlying Ordovician basal conglomerates and the underlying Cambrian metasandstones and metarhyolites (Fig. 3) east of Xainza. All of these new observations indicate that the

Cambrian sedimentary cover and the Cambro-Ordovician orogenic records that occurred in the northern margin of the Indian continent (cf. Garzanti et al., 1986; Myrow et al., 2006; Cawood et al., 2007) are also evident in the central Lhasa subterrane.

3.4. Northern Lhasa subterrane

The northern Lhasa subterrane is defined here as a geological entity bounded to the south by the SNMZ and to the north by the Bangong–Dongqiao–Yila–Dengqen–Nujiang ophiolitic mélange zone (Fig. 1a). Basement rocks in this subterrane have not been reported so far (Pan et al., 2004). These results are consistent with the findings of recent studies indicating the existence of juvenile crust rather than ancient reworked crust beneath this subterrane (Zhu et al., 2009a, 2011a). The oldest sedimentary cover currently identified in this subterrane is of Middle to Upper Triassic age, and consists mainly of slate, sandstone, and radiolarian chert found to the west of Nagqu (Pan et al., 2004, 2006; Nimaciren et al., 2005). This sequence is unconformably overlain by Middle Jurassic coarse-grained clastic rocks (include sandstone and conglomerate-bearing sandstone). The Upper Jurassic strata consist of fine-grained clastic rocks (e.g. shale, chert, and limestone) (Nimaciren et al., 2005). These Triassic–Jurassic strata are mostly restricted to the eastern part of the northern Lhasa subterrane, whereas the Lower Cretaceous strata occur extensively along strike of this subterrane (Pan et al., 2004; Zhu et al., 2006b, 2011a). The Lower Cretaceous sequence includes slate, siltstone, and limestone along with abundant volcanic rocks (131–110 Ma; Zhu et al., 2009a, 2011a) (Fig. 3); it is unconformably overlain by an Upper Cretaceous sequence characterized by a terrigenous molasse deposit (e.g., conglomerate, sandstone, and siltstone) (cf. Pan et al., 2004, 2006; Kapp et al., 2005b, 2007).

The Triassic flysch in the Nagqu basin has been interpreted as an accretionary complex related to the southward subduction of the Bangong-Nujiang Tethyan Ocean lithosphere (Pan et al., 2006). The nature of the Nagqu basin during the Jurassic remains unclear. Several alternative explanations exist for the origin of the Lower Cretaceous strata in the northern Lhasa subterrane. They may have formed in a peripheral foreland basin associated with the Lhasa–Qiangtang collision (Leeder et al., 1988; Kapp et al., 2003, 2005b; DeCelles et al., 2007; Leier et al., 2007a), or in an extensional back-arc basin related to the northward subduction of the Indus-Yarlung Zangbo Tethyan Ocean lithosphere (cf. Zhang et al., 2004). We suggest that this Lower Cretaceous sequence represents a magmatic arc (immediately south of the BNSZ) and a back-arc basin (further south of the BNSZ) that formed during the southward subduction of the Bangong-Nujiang Tethyan Ocean lithosphere (cf. Zhu et al., 2006b, 2009a, 2011a).

3.5. Amdo microcontinent

The Amdo microcontinent is an augen-shaped tectonic entity in central Tibet that is bounded to the south by the Yila and to the north by the Amdo ophiolites (Fig. 1a). The Nyainrong Group (Fig. 2), interpreted as the crustal basement of the Amdo microcontinent (Pan et al., 2004), includes strongly foliated orthogneiss, migmatite, gneiss, and amphibolite (cf. Pan et al., 2004; Guynn et al., 2006). The inherited Pb-components in zircons (Allègre et al., 1984), the upper intercept age (531 ± 14 Ma) of a discordant curve generated using zircon U–Pb dating (Xu et al., 1985), and the Nd isotopic model ages (Harris et al., 1988a) of Amdo gneisses have been used to argue for the existence of a Precambrian basement in the Amdo area (cf. Dewey et al., 1988; Yin and Harrison, 2000). Guynn et al. (2006, 2012) recently reported zircon crystallization ages of 915–840 Ma and 530–470 Ma for the Amdo orthogneisses, providing direct evidence for the presence of a Neoproterozoic—early Paleozoic basement in the Amdo region. The most recent zircon Hf-isotope data from undeformed granitoids (185–175 Ma) intruding the Amdo basement have revealed the presence of a Meso- to Paleo-Proterozoic basement at the subsurface (Zhu et al., 2011a).

The metasedimentary rocks consist of marble, schist, phyllite, and quartzite near Nyainrong in the north and Ziri (Fig. 2) in the south (Pan et al., 2004; Guynn et al., 2006, 2012). Devonian and Middle Permian marble have been found in the western region (Pan et al., 2004; Nimaciren et al., 2005). All of these metasedimentary rocks overlying the Amdo basement were likely deposited in a passive continental margin setting (Guynn et al., 2012). Geochronological data suggest that both the crustal basement and its sedimentary cover were subjected to amphibolite facies metamorphism at 185–170 Ma (Xu et al., 1985; Guynn et al., 2006) and granulite facies metamorphism at ~169 Ma (Zhang et al., 2010c). Such magmatism and metamorphism are most likely related to the accretion of the Amdo microcontinent into the Western Qiangtang subterrane (Guynn et al., 2006; Zhu et al., 2011a).

3.6. Western Qiangtang subterrane

The Western Qiangtang subterrane, also known as the South Qiangtang (cf. Pan et al., 2004; Li et al., 2009a), is bounded to the south by the BNSZ and to the north by the LSSZ (Fig. 1a). The Meso- to Neo-Proterozoic Gemuri Group west of Shuanghu and Jitang Group north of Baqen (Fig. 2) are interpreted as the metamorphic basement of this subterrane (Wang and Wang, 2001; Wang et al., 2004), although other researchers have questioned this explanation (Li et al., 2009a, and references therein). The likely metamorphic basement of the Western Qiangtang subterrane has been found in the Duguer Range (Kapp et al., 2000; Pullen et al., 2011) (Fig. 2), where the Gemuri Group includes strongly tectonized metasedimentary rocks (e.g., phyllite, quartzite, metasandstone, schist, and paragneiss) and orthogneisses. The Duguer Range orthogneisses that locally intruded the metasedimentary rocks have been dated at 476–471 Ma (Fig. 2), indicating the presence of an Ordovician and older crystalline basement beneath the Western Qiangtang subterrane (Pullen et al., 2011).

The Western Qiangtang basement is locally covered with an unfossiliferous Lower Ordovician sequence (siltstone and shale interbedded with limestone) and an overlying fossiliferous Middle Ordovician–Devonian sequence consisting mainly of marine carbonate rocks and including some siltstones (Fig. 3). These rocks are shallow marine sediments deposited on a stable carbonate platform in a continental margin (cf. Li et al., 2009a). The late Paleozoic strata are widespread and nearly continuous from the Upper Carboniferous to the Middle Permian (Fig. 3). The Upper Carboniferous strata contain abundant glacial-marine diamictites and basalt interlayers (cf. Li et al., 1995, 2009a) and are intruded by voluminous E–W mafic dikes that have been dated at 302 and 284 Ma (Zhai et al., 2009) (Fig. 2). The late Paleozoic strata are locally overlain unconformably by the Upper Triassic strata, which mainly include carbonate rocks but also include a small quantity of sandstones. The Jurassic strata, which consist of sandstone, mudstone, and limestone, may represent the youngest sedimentary cover in the Western Qiangtang subterrane (cf. Ding and Wang, 2008) (Fig. 3).

3.7. Eastern Qiangtang subterrane

The Eastern Qiangtang subterrane lies between the Jinsha suture zone (JSSZ) to the north and the LSSZ to the south (Fig. 1a). It is also known as the North Qiangtang (cf. Pan et al., 2004; Li et al., 2009a). The original crystalline basement of this subterrane might have been tectonically eroded and replaced by the central Qiangtang mélange underthrust southward along the Jinsha suture (Kapp et al., 2000, 2003; Pullen et al., 2008, 2011). However, it is unclear whether or not the basement exists beneath this subterrane because no direct records are currently available.

The oldest sedimentary cover in the Eastern Qiangtang subterrane is inferred to be late Neoproterozoic to Paleozoic in age based on the youngest age of the detrital zircons from a quartz schist from the Ningduo Group (He et al., 2011). The oldest known fossiliferous cover of this subterrane consists of Devonian bioclastic limestones with minor siltstones and sandstones (cf. Ding and Wang, 2008; Li et al., 2009a) (Fig. 3). The late Paleozoic strata are nearly continuous from the Lower Carboniferous to Upper Permian and consist mainly of limestones and sandstones without glacial-marine diamictites or basalt interlayers (cf. Li et al., 2006b, 2009a). The ages within the fossiliferous sequence that constitutes the Mesozoic cover of this subterrane range from early Triassic to early Cretaceous. An Upper Triassic unit rich in volcanic rocks (225–204 Ma) unconformably overlies the early Triassic rocks, indicating a short-lived hiatus in sedimentation (cf. Fu et al., 2010) (Fig. 3). The widespread Upper Triassic or Jurassic sedimentary strata are locally overlain unconformably by the Upper Cretaceous conglomerates and sandstones (Fig. 3).

In summary, the existing geochronological, geochemical, and geological data indicate that (1) a Proterozoic crystalline basement must exist beneath the Tethyan Himalaya, the central Lhasa subterranes, and the Amdo microcontinent, all of which experienced a Cambro-Ordovician magmatic event (530–490 Ma); (2) a crystalline basement older than 476 Ma likely exists in the Western Qiangtang subterrane, but more data are required to verify its presence; (3) it remains unknown whether or not a crystalline basement in the Eastern Qiangtang subterrane exists because of the absence of any direct geological evidence, but there exists a major difference of the sedimentary cover between the Eastern and Western Qiangtang subterranes (Fig. 3); (4) the geological features of the central Lhasa subterrane, the Tethyan Himalaya, and northern Australia are similar in that all of them have the same time-equivalent strata for glacial-marine diamictites and Paleozoic fine clastic sedimentary records (Fig. 3).

4. Detrital zircon

Detrital zircon isotope data have been widely used as geochronological (U–Pb dating) and geochemical fingerprints (Hf-isotope determination) for tracing sediment provenance and in the paleogeographic reconstruction of continents in Earth's history (cf. Veevers et al., 2005; Howard et al., 2009). Several studies have reported detrital zircon data from the Tibetan Plateau (Fig. 4), making it possible to characterize the detrital zircon signature and to trace the provenance of sediments from the Tibetan Plateau.

4.1. Detrital zircon signature

Gehrels et al. (2003) reported the results of 962 analyses of detrital zircons from Ordovician–Devonian sandstones in the Tethyan sequence. They pointed out that these detrital zircons were derived mainly from underlying metasedimentary rocks and Cambro-Ordovician granites and that they had similar age patterns, with a main population at ~1.0–1.3 Ga. This population has been widely used as a diagnostic age signature for Tethyan Himalaya-derived detrital zircons in tracing the provenance of sediments and in palaeogeographic reconstructions (e.g., Leier et al., 2007b; Dong et al., 2010a; Hu et al., 2010b; Li et al., 2010b; Pullen et al., 2011). However, this signature should be treated with caution because it was developed using $^{207}Pb/^{206}Pb$ ages of >800 Ma (Gehrels et al., 2003) rather than >1000 Ma as accepted in the more recent literature (e.g., Leier et al., 2007b; McQuarrie et al., 2008) for old zircons. This difference will discernibly influence the age distributions of the detrital zircons. For example, when using $^{207}Pb/^{206}Pb$ ages for >1000-Ma zircons, the first-order age signature of detrital zircons from the Neoproterozoic metasedimentary rocks in the High Himalaya (Fig. 2) has been redefined as 0.9–1.0 Ga (with a strong peak at ~960 Ma) (Fig. 4a), rather than ~1.0–1.3 Ga using $^{207}Pb/^{206}Pb$ ages for >800-Ma zircons (Gehrels et al., 2006a, 2006b), although the 1.0–1.25 Ga population still exists.

The Cambro-Ordovician sandstones from the Spiti Valley and Nyalam (Myrow et al., 2009, 2010), a Permian sandstone from the Selong area (Zhu et al., 2011b), and a Neoproterozoic quartzite from northern Bhutan (McQuarrie et al., 2008) (Fig. 2) in the Tethyan Himalaya contain detrital zircons with a prominent age peak at ~950 Ma and a rather weak age population at 1.0–1.25 Ga (Fig. 4b). These ages are consistent with the age distribution for detrital zircons from the High Himalaya (Gehrels et al., 2006a, 2006b) (Fig. 4a).

Dong et al. (2010a) recently reported the first dataset for detrital zircons from the Nyingchi Group in the southern Lhasa subterrane (Fig. 2) and suggested that the age distribution of these zircons was similar to those of the Neoproterozoic–Permian strata in the Tethyan Himalaya. Working with the same dataset, however, we show that with the exception of an ~550 Ma age peak, the detrital zircons from the Nyingchi Group defines a prominent age peak at ~1160 Ma (Fig. 4d); this is not the case for detrital zircons from the Tethyan Himalaya (Fig. 4b).

The age distributions of the detrital zircons from the Permo-Carboniferous sandstones (Leier et al., 2007b; Zhu et al., 2011b) (Fig. 4e) and those of the inherited zircons from the Mesozoic peraluminous granites (Zhu et al., 2009b, 2011a) in the central Lhasa subterrane (Fig. 2) are remarkably similar to those of the detrital zircons from the Nyingchi Group (Fig. 4f). They are all typically characterized by two main peaks, one at ~550 and one at ~1170 Ma. These ages are consistent with those of the detrital zircons in the Permian sandstones (Fig. 4c) from the Collie Basin north of the Albany–Fraser Belt, from the Perth Basin to the north in the Pinjarra Orogen in Western Australia (Cawood and Nemchin, 2000; Veevers et al., 2005), and in the Lower Ordovician sandstones from the Canning Basin in Northern Australia (Haines and Wingate, 2007).

As first noted by Guynn et al. (2012), the detrital zircons from the metamorphic rocks in the Amdo basement (Fig. 2) define two primary age populations at 580–480 Ma (with a peak at ~550 Ma) and 1000–850 Ma (with a peak at ~950 Ma) (Fig. 4g). This age distribution is very similar to that of the Neoproterozoic–Permian strata in the Tethyan Himalaya (Fig. 4b) but is quite different from those available for the southern and central Lhasa subterranes (Fig. 4d–f).

Kapp et al. (2003) first reported the presence of a large population of detrital zircons at ~950 Ma in the metasedimentary rocks in the Western Qiangtang subterrane. These results have been further corroborated by detrital zircon data recently reported (Fig. 2) (Pullen et al., 2008; Dong et al., 2011c; Zhu et al., 2011b). The combined detrital zircon data from the Western Qiangtang subterrane yield two main age peaks at ~550 and ~950 Ma (Fig. 4h), which are strikingly similar to detrital zircon age distributions from the Neoproterozoic–Permian strata in the Tethyan Himalaya (Fig. 4a) but distinct from those of the southern and central Lhasa subterranes (Fig. 4d–f).

In the Eastern Qiangtang subterrane, the detrital zircons from a late Neoproterozoic—early Paleozoic quartz schist in the Changdu Block (He et al., 2011) exhibit a prominent age peak at ~980 Ma, with two smaller populations at 1150—1050 Ma and 2550—2400 Ma (Fig. 4i). These data are consistent with the age distributions of the detrital zircons from the Ordovician sandstones from the Cathaysia continent (Yao et al., 2011) (Fig. 4j), but differ discernibly from the data for the Western Qiangtang subterrane because of the 1150—1050 Ma age population (Fig. 4h).

4.2. Detrital zircon provenance

The notable similarity of the age distributions documented by detrital zircons from the Western Qiangtang (Fig. 4h) (Kapp et al., 2003;

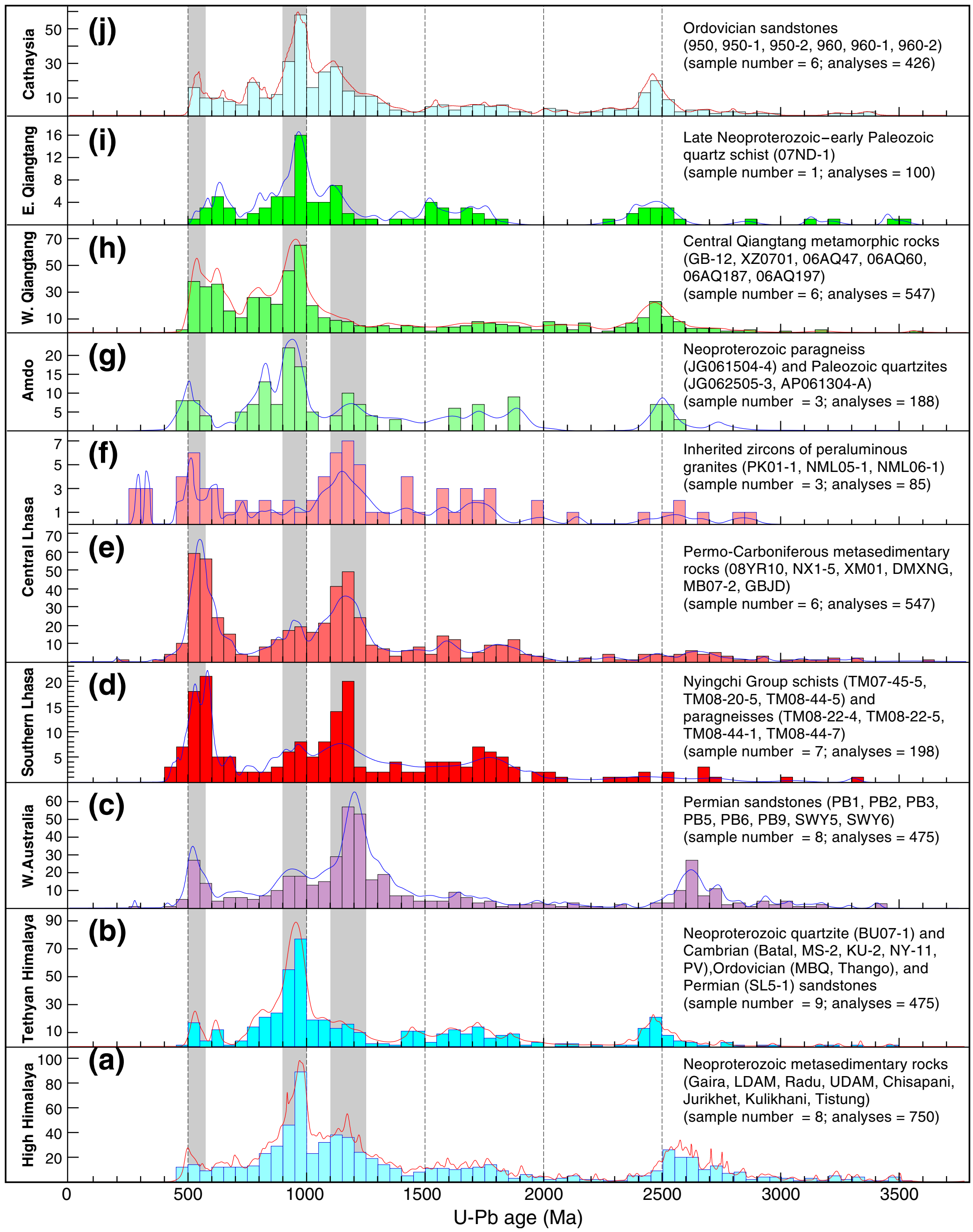

Fig. 4. Detrital zircon age distributions of the Tibetan Plateau. Important age peaks are shown in grey bands. The $^{207}Pb/^{206}Pb$ ages were used for >1000 Ma, and the $^{206}Pb/^{238}U$ ages for younger zircons. Results described in this study exclude analyses with >10% discordance. Data sources: Cathaysia (Yao et al., 2011); Eastern Qiangtang (He et al., 2011); Western Qiangtang (Pullen et al., 2008; Dong et al., 2011c; Zhu et al., 2011b); Amdo (Guynn et al., 2012); inherited zircons of peraluminous granites in the central Lhasa (Zhu et al., 2009b, 2011a); detrital zircons in the central Lhasa (Zhu et al., 2011b); southern Lhasa (Dong et al., 2010a); Western Australia (Cawood and Nemchin, 2000; Veevers et al., 2005); Tethyan Himalaya (McQuarrie et al., 2008; Myrow et al., 2009, 2010; Zhu et al., 2011b); High Himalaya (Gehrels et al., 2006a, 2006b).

Pullen et al., 2008; Dong et al., 2011c; Zhu et al., 2011b), Amdo (Fig. 4g) (Guynn et al., 2012) and Tethyan Himalaya (Fig. 4b) (DeCelles et al., 2000; McQuarrie et al., 2008; Myrow et al., 2009, 2010; Zhu et al., 2011b) indicates that the detrital zircons from these different terranes probably share a common provenance. This conclusion is further reinforced by the identical $\varepsilon_{Hf}(t)$ values of the ~950 Ma detrital zircons from the Western Qiangtang and Tethyan Himalaya (Zhu et al., 2011b). Furthermore, the notable age peak of ~950 Ma defined by the detrital zircons from the Western Qiangtang, Amdo, and Tethyan Himalaya is also visible in data for zircons from the Neoproterozoic metasedimentary rocks in the High Himalaya (DeCelles et al., 2000; Gehrels et al., 2003, 2006a, 2006b) (Fig. 4a). It follows that the detrital zircons from the Western Qiangtang, Amdo, and Tethyan Himalaya may have actually been derived from the High Himalaya during the Paleozoic.

The provenance of the detrital zircons from the High Himalaya is the subject of much debate. DeCelles et al. (2000) proposed that the detrital zircons from the High Himalayan rocks with age peaks at ~851 and ~954 Ma come from the Western Gondwana (Arabian–Nubian Shield and East Africa). However, later studies have shown that the most likely source of these zircons is Eastern Gondwana because of the predominance of ~900–1300 Ma zircons (cf. Yoshida and Upreti, 2006; Cawood et al., 2007). A comprehensive explanation for the provenance of detrital zircons from the High Himalaya, Tethyan Himalaya, Amdo, and Western Qiangtang should consistently take into account the presence of the prominent ~950 Ma detrital zircon signature, which requires the occurrence of extensive outcrops of ~950 Ma magmatic rocks in the source region. Existing geochronological data from Gondwanaland indicate that the 990–900 Ma granitoids are widespread only in the Eastern Ghats Province of the Indian Shield and the Rayner Province of East Antarctica (Fitzsimons, 2000, 2003; Dobmeier and Raith, 2003; Veevers, 2007). Therefore, we infer that the most likely source of the widespread ~950 Ma zircons in the High Himalaya, Tethyan Himalaya, Amdo, and Western Qiangtang rocks was the Eastern Ghats–Rayner Provinces, which were uplifted during the late Neoproterozoic. A similar conclusion was also reached by Yoshida and Upreti (2006) and Myrow et al. (2010), who suggested that the detrital zircons in the High and Tethyan Himalayan rocks most likely came from the Eastern Ghats–Rayner Provinces within the Circum–East Antarctic orogen.

There is a distinctive ~1170 Ma age population of zircons in the central (and southern) Lhasa subterrane (Zhu et al., 2011b) (Fig. 4d, e and f) that is absent in samples from the Western Qiangtang (Kapp et al., 2003; Pullen et al., 2008; Dong et al., 2011c; Zhu et al., 2011b), Amdo (Guynn et al., 2012), and Tethyan Himalaya terranes (McQuarrie et al., 2008; Myrow et al., 2009, 2010; Zhu et al., 2011b). Likewise, the distinctive ~950 Ma age peak common in detrital zircons from the Western Qiangtang, Amdo, and Tethyan Himalaya (Fig. 4b, g and h) is rather weak (Fig. 4d and e) or even essentially absent (Fig. 4f) in zircons from the southern and central Lhasa subterranes. These differences strongly suggest that the Proterozoic detrital zircons from the southern and central Lhasa subterranes were derived from a source different from the common source of Proterozoic zircons in the Western Qiangtang, Amdo, and Tethyan Himalaya terranes.

One possibility is that the abundant ~1170 Ma zircons from the Permo-Carboniferous metasedimentary rocks that are widespread in the central (plus southern) Lhasa subterrane (Pan et al., 2004) were sourced from the High Himalaya, which contains 1.00–1.25 Ga detrital zircons in its Neoproterozoic metasedimentary rocks (Fig. 4a) (Gehrels et al., 2003, 2006a, 2006b). However, existing geochronological data indicate that the ~1170 Ma magmatic rocks are not extensively exposed in the High Himalaya (Singh and Jain, 2003) and that ~950 Ma detrital zircons are rare to absent in the southern and central Lhasa subterranes. Using this information, Zhu et al. (2011b) have proposed that the High Himalaya cannot be considered a potential source of sediments for the southern and central Lhasa subterranes. In contrast, previous studies have shown the extensive existence of ~1170 Ma magmatic rocks in the Nornalup Complex, the Albany–Fraser Belt in Western and Southwestern Australia, and the Bunger Hills and Windmill Islands in East Antarctica (Clark et al., 2000; Fitzsimons, 2000, 2003; Veevers et al., 2005), whereas there are no 1000−900 Ma rocks. These 1170 Ma magmatic rocks provided sediments to the Collie and Perth Basins in the north during the Permian (Sircombe and Freeman, 1999; Cawood and Nemchin, 2000; Veevers et al., 2005). Considering the remarkable similarity of the age distributions of the detrital zircons from the southern and central Lhasa subterranes (Fig. 4d, e, and f), the Permian sandstones in Western Australia (Fig. 4c) (Cawood and Nemchin, 2000; Veevers et al., 2005), and the Lower Ordovician sandstones in Northern Australia (Haines and Wingate, 2007), we have concluded that the southern and central Lhasa subterranes in the Tibetan Plateau and the Collie and Perth Basins in Western Australia received sediments from the Albany–Fraser–Bunger–Windmill orogenic belt in Western Australia and East Antarctica when Gondwana was still intact in the earliest Paleozoic (Zhu et al., 2011b). The similar Hf isotopic composition of the ~1170 Ma detrital zircons from the central Lhasa subterrane and the Collie and Perth Basins in Western Australia provides strong additional support for this interpretation (Zhu et al., 2011b). Cawood et al. (2007) have also linked some of the High Himalayan zircons to an Australian source. These observations and data collectively suggest a Lhasa–Australia spatial link prior to the Paleozoic.

It is difficult to trace the provenance of the detrital zircons from the Changdu Block because of the scarcity of relevant data. However, if the presence of the 1150−1050 Ma age population (Fig. 4i) can be validated, then the striking similarity in the age distributions (Fig. 4i and j) recorded in the detrital zircons from both the Changdu Block of the Eastern Qiangtang subterrane (He et al., 2011) and the Cathaysia continent (cf. Yao et al., 2011) indicates that the zircons from these two blocks likely have a common provenance. This is also because the 1150−1050 Ma age population discernable in the Changdu Block is weak or even essentially absent (Fig. 4h) in zircons from the Western Qiangtang subterrane (cf. Gehrels et al., 2011; Zhu et al., 2011b).

The Tibetan Plateau microcontinents and/or subterranes all contain detrital zircons of 600–500 Ma (with a peak at ~550 Ma) (Fig. 4). It is likely that the exposed basement rocks within the Tibetan Plateau itself supplied sediments to the local Paleozoic basins. However, the available age data (530–490 Ma) for the basement rocks in the Tibetan Plateau lack the significant pre–550 Ma signatures required for the ~550 Ma detrital zircons. Therefore, although the exposed basement rocks within the Tibetan Plateau may have contributed some sediments, the main sources of the ~550 Ma detrital zircons were likely the granitoid intrusions that occur extensively in the Himalaya, Western Australia, and East Antarctica (Fitzsimons, 2000, 2003; Cawood et al., 2007).

5. Magmatism

Here, we only summarize the distributions and geochemical data for magmatic rocks associated with some of the main tectonic events of the Tibetan Plateau. More comprehensive summaries of magmatic data from the Tibetan Plateau (Fig. 5a) can be found in Chung et al. (2005); Wen et al. (2008a); Chiu et al. (2009); Ji et al. (2009a, 2009c); Lee et al. (2009); and Zhu et al. (2009a, 2009c, 2011a).

5.1. Cambro-Ordovician magmatic rocks (~530–470 Ma)

Cambro-Ordovician magmatic rocks have been documented by zircon U–Pb dating in the Tethyan Himalaya (~530–470 Ma; Cawood et al., 2007; Quigley et al., 2008), southern Lhasa (~496 Ma; Dong et al., 2010a), central Lhasa (~501 Ma, Ji et al., 2009b; ~492 Ma, Zhu et al., 2012), Amdo (~530–470 Ma; Guynn et al., 2012), and Western Qiangtang (476–471 Ma, Pullen et al., 2011) (Fig. 2). The geochemical data for these rocks are limited. The Duguer Range granitoids in the Western Qiangtang subterrane are characterized by a high aluminum saturation index (A/CNK = 1.11–1.34) (Fig. 6) and high normative corundum (1.68–4.10%) with no normative diopside. These geochemical features, together with the presence of muscovite (Mu et al., 2005), indicate that they are strongly peraluminous S-type granites with mature crustal protoliths.

5.2. Late Devonian–Early Carboniferous magmatic rocks (~370–350 Ma)

Late Devonian–Early Carboniferous granitoids occur in Gangma Tso (~364 Ma; Pullen et al., 2011), and Bensum Tso (~351 Ma; Li et al., 2006b) in the Western Qiangtang subterrane and in Gyaca (~367 Ma, Dong et al., 2010b) in the southern Lhasa subterrane (Fig. 2). The limited whole-rock data indicate that the older granitoids (367–364 Ma) from the Western Qiangtang and southern Lhasa subterranes are geochemically similar; they are both calc-alkaline and metaluminous (A/CNK = 0.96–1.00) (Fig. 6) in nature, with low normative corundum of 0.0−0.28% (Mu et al., 2005; Dong et al., 2010b). The younger granitoids (~351 Ma) from the Western Qiangtang are high-K (K_2O/Na_2O = 1.93) and weakly peraluminous (A/CNK = 1.02) (Fig. 6) with high normative corundum of 1.99% (Li et al., 2006b). These geochemical features are interpreted here as the consequences of varying degrees of mixing between melts largely

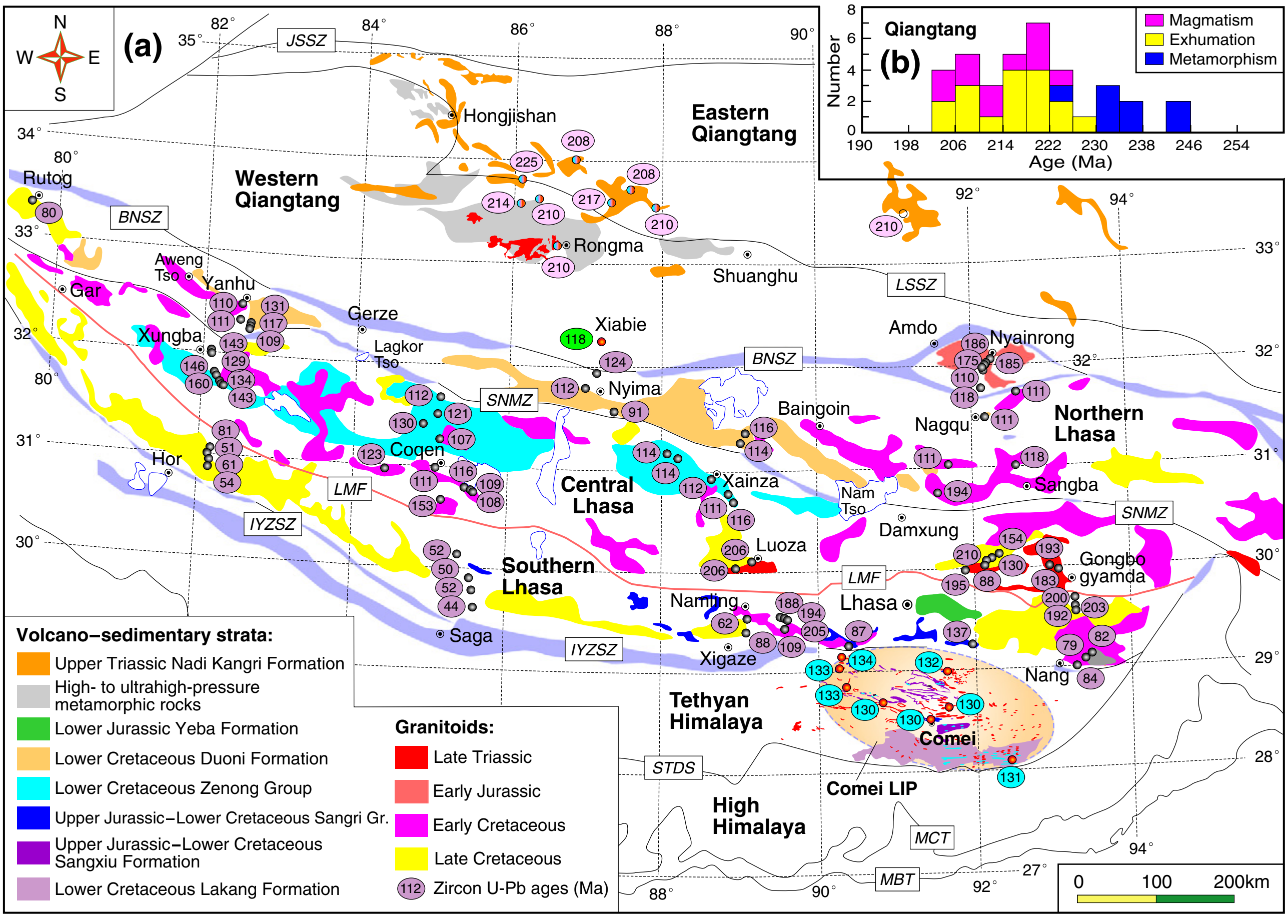

Fig. 5. (a) Distribution of the Mesozoic magmatic rocks in the Tibetan Plateau (modified from Zhu et al., 2009a, 2011a; Fu et al., 2010). (b) Histogram of age dates in the Qiangtang. Data sources: magmatism (234 − 202 Ma; Kapp et al., 2000, 2003; Huang et al., 2007; Zhai et al., 2007; Wang et al., 2008; Hu et al., 2010a; Fu et al., 2010; Zhang et al., 2011); exhumation (227 − 203 Ma; Kapp et al., 2000, 2003; Li et al., 2006a; Zhai et al., 2009, 2011a); metamorphism (244–223 Ma; Pullen et al., 2008; Zhai et al., 2011a). See text for details.

derived from the anatexis of mature continental crustal materials and minor basalt-derived melts.

5.3. Permo-Carboniferous magmatic rocks (~300–260 Ma)

Permo-Carboniferous magmatic rocks occur in the Western Qiangtang, central Lhasa, and Tethyan Himalaya (Fig. 2). Those in the Western Qiangtang subterrane include mafic dikes, sills, and basaltic lavas that intruded or interlayered with the Permo-Carboniferous strata (cf. Yin and Harrison, 2000; Zhai et al., 2009; Wang et al., 2010b). The dikes and sills, with widths varying from several meters to 2–3 km, generally extend from east to west direction up to ~800 km (Fig. 2). The mafic dike samples have been dated at 302 ± 4 Ma and 284 ± 3 Ma using zircon SHRIMP U–Pb method (Fig. 2) (Zhai et al., 2009), which makes them coeval with the basaltic lavas from the Bhote Kosi and Selong areas in the Tethyan Himalaya (Garzanti et al., 1999; Zhu et al., 2010), Panjal Traps in NW India (Gaetani and Garzanti, 1991) and the Permian Yunam granites (281 ± 1 Ma) in the High Himalaya (Spring et al., 1993) (Fig. 2). The mafic rocks in the Western Qiangtang subterrane display OIB-type geochemical affinities, e.g., high TiO_2 content (mostly > 2.0), the depletion of heavy rare earth elements (HREEs), and no discernible Nb–Ta negative anomalies. These features have been attributed to plume-derived magmas (Zhai et al., 2009; Wang et al., 2010b).

Zhu et al. (2010) summarized the paleontological and stratigraphical evidence in support of the presence of the Permo-Carboniferous volcanic rocks in the central Lhasa subterrane. These volcanic rocks are scattered within the time correlative strata (Fig. 2) and consist mainly of basalt with minor andesite, dacite, and rhyolite. All of the basalts in the central Lhasa subterrane show a calc-alkaline, high-alumina basalt affinity, with significant negative Nb–Ta–Ti anomalies (cf. Zhu et al., 2010). These geochemical features, combined with the presence of the Permian Songdo eclogite in this subterrane (Yang et al., 2009), strongly indicate an active continental arc setting for the central Lhasa subterrane during the Permo-Carboniferous (cf. Zhu et al., 2010). Approximately 90 km to the east of the Songdo eclogite near Pikang (Fig. 2), Booth et al. (2004) first reported the possible presence of Permian granite, which was subsequently verified (Zhu et al., 2009b). Zircon SHRIMP U–Pb and LA-ICP-MS U–Pb dating indicate that the Pikang granites were emplaced at ~263 Ma (Zhu et al., 2009b), coeval with the high-pressure metamorphism that occurred at ~262 Ma, as indicated by the Songdo eclogite (Yang et al., 2009). The high A/CNK (1.08–1.14) (Fig. 6), the high normative corundum (1.3–2.0%), the absence of normative diopside, and the predominantly negative zircon $\varepsilon_{Hf}(t)$ (−4.5 to +1.9%) together suggest that these rocks are peraluminous S-type granites generated by mixing between melts derived largely from ancient continental crustal materials and minor basalt-derived melts (Zhu et al., 2009b). The Pikang peraluminous granite magmatism and Songdo high-pressure metamorphism are coeval with the regional angular unconformity between the Middle and the Upper Permian, all of which have been linked to an orogeny referred to as the Permian Gangdese Orogeny (Zhu et al., 2009b).

The presence of the Permian volcanic rocks has been known for decades from Nar-Tsum, Bhote Kosi, and Selong in the Tethyan

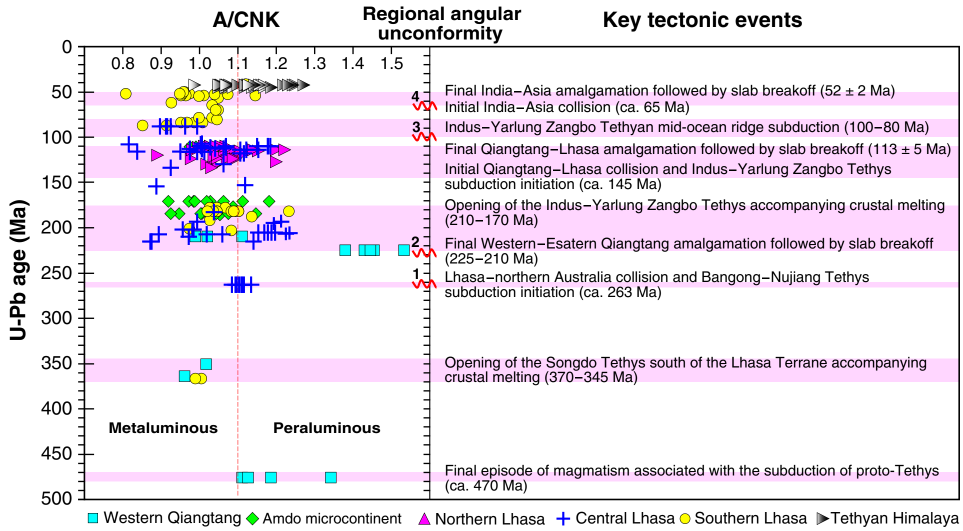

Fig. 6. Tectonomagmatic events through time in the Tibetan Plateau. A/CNK = molecular $Al_2O_3/(CaO + Na_2O + K_2O)$. Whole-rock data sources: Mu et al. (2005), Li et al. (2006b), Mo et al. (2007, 2008), Yang et al. (2008), Zhu et al. (2009a, 2011a, unpublished data), Dong et al. (2010b), Hu et al. (2010a), Zeng et al. (2011). Regional angular unconformity: 1 = Permian–Triassic unconformity in the central Lhasa subterrane and northern Australia; 2 = Upper Triassic-underlying strata unconformity in the Eastern Qiangtang subterrane; 3 = Upper Cretaceous-underlying strata unconformity in the Northern Lhasa subterrane; 4 = Upper Cretaceous–Early Tertiary unconformity in the Southern Lhasa subterrane. See text for details.

Himalaya (Fig. 2) (cf. Garzanti et al., 1999; Zhu et al., 2010, and references therein). The volcanic rocks from Bhote Kosi and Selong are interlayered with the Permian strata and consist of basalts. These rocks are characterized by high MgO and low Al_2O_3, resembling those of high-MgO basalt with no Ti but moderate Nb–Ta anomalies. The Permian basalts in the Tethyan Himalaya are suggested to have formed in an extensional setting (Garzanti et al., 1999; Zhu et al., 2010), consistent with the coeval Panjal Traps and Permian granites from Yunam and Parkatchic in the High Himalaya (Fig. 2), which have also been interpreted as associated with an extensional tectonic setting (Spring et al., 1993; Noble et al., 2001; Chauvet et al., 2008). All of these observations and interpretations indicate that the northern Indian margin was under tectonic extension at the time of Permian Andean-type magmatism in the central Lhasa subterrane.

5.4. Late Triassic–Early Jurassic magmatic rocks (~225–175 Ma)

Late Triassic–Early Jurassic magmatic rocks have been found in the Eastern and Western Qiangtang, Amdo, and central and southern Lhasa subterranes (Fig. 5a). The Upper Triassic volcanic rocks, which are mainly found in the Eastern Qiangtang, are interlayered with the Nadi Kangri strata, which extend ~1000 km from northwest to southeast (cf. Fu et al., 2010) (Fig. 5a). The volcanic rocks consist mainly of silicic rocks (dacite, rhyolite) with minor basalts and have been dated at ~220 Ma for mafic rocks (Zhai et al., 2007; Fu et al., 2010) and ~225–202 Ma for silicic rocks (cf. Fu et al., 2010; Zhang et al., 2011) using the zircon SHRIMP U–Pb method. The mafic rocks display high Nb/Zr and Zr/Y ratios with positive $\varepsilon_{Nd}(t)$ values (approximately +2.0). These values are distinct from those of arc basalts but similar to those of within-plate basalts (Fu et al., 2010; Zhang et al., 2011). The silicic rocks are characterized by strongly negative $\varepsilon_{Nd}(t)$ values (around −10.0) (Zhang et al., 2011) and can be interpreted to be derived from the anatexis of the ancient continental crust. The coeval intrusives of the Nadi Kangri Formation volcanic rocks are mainly found in the Western Qiangtang and occur as batholiths or apophyses intruding the Permo-Carboniferous strata (Fig. 5a). These plutonic rocks have been dated at 225–210 Ma using the zircon U–Pb method and 210–204 Ma using the biotite Ar–Ar method (Kapp et al., 2000, 2003; Huang et al., 2007; Hu et al., 2010). These rocks are characterized by high A/CNK (1.11–1.99) (Fig. 6), high normative corundum (2.34–9.78%), and the absence of normative diopside. These geochemical features, together with the presence of muscovite (Huang et al., 2007), indicate that these are peraluminous S-type granites derived from magmas that resulted from the anatexis of the ancient continental crust.

In the Amdo microcontinent, the basement rocks are intruded by undeformed granitoids that were previously thought to have been emplaced at ~140–120 Ma (Xu et al., 1985). However, recent zircon U–Pb dating has adjusted those figures to 185–170 Ma (Guynn et al., 2006; Liu et al., 2010; Zhu et al., 2011a). The Amdo granitoids include tonalite, granodiorite, monzogranite, syenogranite, and dioritic enclave. They exhibit varying A/CNK (0.92–1.18) (Fig. 6) and exclusively negative $\varepsilon_{Hf}(t)$ (−11.1 to −3.6) (Bai et al., 2005; Zhu et al., 2011a). We suggest that these granitoids formed from ancient continental crust-derived melts that were variably mixed with mafic magmas.

In the central Lhasa subterrane, the Late Triassic–Early Jurassic magmatic rocks are mainly confined to the Luoza–Damxung–Gongbo gyamda area along its southern margin (Fig. 5a). These intrusive rocks are composed of granodiorite, monzogranite, syenogranite, and two-mica granite and have been dated at 210–183 Ma (Chu et al., 2006; Zhang et al., 2007c; Zhu et al., 2011a). They are silicic, metaluminous to peraluminous (A/CNK = 0.87–1.23) (Fig. 6) with exclusively negative $\varepsilon_{Hf}(t)$ values (−17.3 to −2.5), suggesting that these rocks are derived from the anatexis of ancient continental crustal material with or without basalt-derived contributions (Zhang et al., 2007c; Zhu et al., 2011a).

In the southern Lhasa subterrane, the Late Triassic–Early Jurassic volcanic rocks include basalt and silicic rock, with minor amounts of andesite in the Yeba Formation (Fig. 5a). The mafic rocks are compositionally diverse and were likely produced by the partial melting of a heterogeneous mantle source. The silicic rocks are characterized by concave-upward MREE-depleted patterns with positive $\varepsilon_{Nd}(t)$ values; they have been interpreted as derived from the partial melting of juvenile lower crust caused by the underplating of mafic magmas (Zhu et al., 2008a). The plutonic rocks of this age occur as small relics of varying size within the Cretaceous–early Tertiary Gangdese Batholith and have been dated at 205–178 Ma (Chu et al., 2006; Zhang et al., 2007 d; Yang et al., 2008; Ji et al., 2009a; Zhu et al., 2011a). These rocks are silicic, metaluminous to peraluminous (A/CNK – 0.97–1.23) (Fig. 6), and display concave-upward MREE-depleted patterns (Yang et al., 2008; Zhu et al., 2011a) similar to those of the silicic rocks of the Yeba Formation. These results, along with a wide range of $\varepsilon_{Nd}(t)$

values (−5.0 to +16.7) (Chu et al., 2006; Zhang et al., 2007d; Ji et al., 2009a; Zhu et al., 2011a), indicate that the magma of these rocks mainly originated from the partial melting of juvenile lower crust, with varying contributions from ancient continental crustal material.

5.5. Early Cretaceous magmatic rocks (~130–110 Ma)

A limited occurrence of ~124–105 Ma magmatic rocks has been reported from the southern margin of the Western Qiangtang subterrane (Kapp et al., 2005b, 2007), but the nature and origin of these rocks remain unclear because of the absence of good quality whole-rock geochemical and zircon isotopic data.

Regarding the widespread Early Cretaceous magmatic rocks in the Lhasa Terrane, recent studies indicate that (1) a low-K to high-K calc–alkaline andesite–dacite–rhyolite suite of 131–110 Ma and granitoids of 134–125 Ma with positive zircon $\varepsilon_{Hf}(t)$ values are present in the northern Lhasa subterrane (Zhu et al., 2011a), (2) the mafic rocks of ~113 Ma in the central and northern Lhasa subterranes were emplaced in an extensional setting, as indicated by their high Zr/Y (4.40–8.25) ratios (Pearce and Norry, 1979), and (3) the Early Cretaceous magmatic rocks in the southern Lhasa subterrane are more widespread than previously thought (Coulon et al., 1986; Kapp et al., 2007), as indicated by the presence of adakite-like andesites of ~137 Ma (Zhu et al., 2009d), granitoids of 109–102 Ma (Wen et al., 2008a; Ji et al., 2009a), and the abundant 130–100 Ma detrital zircons with positive $\varepsilon_{Hf}(t)$ values from the Xigaze forearc basin strata sourced from the Gangdese arc (Wu et al., 2010).

The presence of the Cretaceous igneous rocks in the Tethyan Himalaya has been known for years (BGMRXAR, 1993). These rocks are mainly confined to the eastern Tethyan Himalaya around Comei (Fig. 5a) and include abundant volcanic rocks (mostly basalt with some silicic rock) (Zhu et al., 2007, 2008b), voluminous mafic intrusions (diabasic sill, dike, and gabbro), and minor ultramafic rocks (layered pyroxenite and picrite porphyrite) (Zhu et al., 2008b, 2009d). The silicic and mafic rocks and layered pyroxenites, which collectively cover an areal extent of ~40,000 km^2 (Fig. 5a), were emplaced at ~132 Ma (Zhu et al., 2009 d), coeval with the eruption of the Bunbury Basalts in SW Australia (~132 Ma; Frey et al., 1996; Coffin et al., 2002). Using this coeval emplacement age and the early Cretaceous tectonic reconstruction of eastern Gondwana at ~132 Ma, Zhu et al. (2009d) have suggested that the extensive Comei magmatic rocks in SE Tibet and the Bunbury Basalts in SW Australia may represent the erosional and/or deformational remnants of a large igneous province referred to as the Comei-Bunbury large igneous province (LIP). Geochemical studies indicate that the Comei-Bunbury LIP magmas and Kerguelen plume-derived lavas may have shared common source components (Frey et al., 1996; Ingle et al., 2004; Zhu et al., 2007, 2008b, 2008c).

5.6. Late Cretaceous magmatic rocks (~100–80 Ma)

Late Cretaceous magmatic rocks have been widely found in the Gangdese Batholith in the southern Lhasa subterrane (Fig. 5a), whereas the contemporaneous rocks in the central and northern Lhasa subterranes have been reported from only several locations (Zhao et al., 2008; Zhu et al., 2011a). The rocks in the southern Lhasa subterrane include a wide range of lithologies from gabbro, diorite, tonalite, granodiorite, monzogranite, and granite. Abundant zircon U–Pb geochronological data obtained mainly from the central to eastern segments of the Gangdese Batholith indicate that these rocks were emplaced at 95–80 Ma (Quidelleur et al., 1997; Wen et al., 2008a, 2008b; Ji et al., 2009a; Guan et al., 2010; Zhu et al., 2011a). Recently, Zhang et al. (2010a) reported the occurrence of coeval charnockites (90–86 Ma) that appear to have crystallized under high- to ultra-high-temperature conditions (950–900 °C) within the eastern Gangdese Batholith. All of the intermediate to silicic intrusive rocks of this age in the Gangdese Batholith display high Al_2O_3 and Sr, low Y and Yb, and low Cr and Ni abundances, with positive whole-rock $\varepsilon_{Nd}(t)$ or zircon $\varepsilon_{Hf}(t)$ values suggestive of adakite affinity (Wen et al., 2008b; Guan et al., 2010; Zhang et al., 2010a). These adakite-like rocks have been interpreted as derived from partial melting of a newly underplated, mafic lower crust during the low-angle northward subduction of the Indus-Yarlung Zangbo Tethyan ocean lithosphere (Wen et al., 2008a, 2008b) or from the partial melting of a subducted ocean lithosphere during the Indus-Yarlung Zangbo Tethyan mid-ocean ridge subduction (Guan et al., 2010; Zhang et al., 2010a).

5.7. Cretaceous–Early Tertiary magmatic rocks (~69–43 Ma)

The voluminous Linzizong volcanic successions and coeval plutonic rocks with abundant mafic enclaves within the Gangdese Batholith are largely confined to the southern Lhasa subterrane (Xu et al., 1985; Coulon et al., 1986; Harris et al., 1988a, 1988b; Pearce and Mei, 1988; Mo et al., 2003, 2007, 2008; Chung et al., 2005; Lee et al., 2009; Zhu et al., 2011a). The volcanic successions range from andesitic to rhyolitic in composition with minor basalts. The late phase of the Linzizong volcanism is dominated by ignimbrites dated at ~43 Ma (Mo et al., 2003, 2008). A rhyolite from the base of the Linzizong volcanic successions has been dated at ~69 Ma using the zircon U–Pb method (He et al., 2007), suggesting that the Linzizong volcanism was active during ~69–43 Ma (Mo et al., 2003, 2008; He et al., 2007; Lee et al., 2009). The coeval plutonic rocks consist mainly of mafic to felsic calc-alkaline rocks and have been dated at 65–41 Ma (cf. Ji et al., 2009a). New geochronological data indicate that the mafic enclaves and gabbros commonly developed in the Gangdese Batholith and mafic dikes that intruded the Linzizong volcanic successions were emplaced at ~53–47 Ma (Dong et al., 2005; Mo et al., 2005; Yue and Ding, 2006). This time interval coincides with an intense episode of magmatism (~52 Ma) throughout the entire southern Lhasa subterrane (cf. Mo et al., 2008; Wen et al., 2008; Ji et al., 2009a; Lee et al., 2009; Zhu et al., 2011a). Compositionally, both volcanic and plutonic rocks are quite diverse, ranging from calc-alkaline to shoshonitic series (Lee et al., 2009) and from metaluminous to peraluminous (A/CNK = 0.81–1.15) (Fig. 6) varieties. The basalts and associated mafic dikes (~52 Ma) display high Zr/Y (3.7–6.7) ratios similar to those of basalts formed in continental extensional settings rather than convergent margin settings (Pearce and Norry, 1979). These geochemical affinities and the intensified magmatism with compositional diversity at ~52 Ma have been attributed to the breakoff of the subducting Indus-Yarlung Zangbo Tethyan lithospheric slab (cf. Wen et al., 2008a; Chung et al., 2009; Ji et al., 2009a; Lee et al., 2009; Zhu et al., 2011a).

When the late Linzizong volcanic successions and coeval plutons were emplaced in the southern Lhasa subterrane, the Tethyan Himalaya was synchronously experiencing plutonism as documented by the Dala and Yardoi two-mica granites intruding the deformed Upper Triassic and Upper Paleozoic metasedimentary rocks. The Dala and Yardoi two-mica granites exposed ~70–100 km south of the IYZSZ have been dated at ~44–43 Ma using the zircon U–Pb method (Aikman et al., 2008; Qi et al., 2008; Zeng et al., 2011). Geochemical studies indicate that the Dala and Yardoi granites are Na-rich metaluminous to peraluminous (A/CNK = 0.99–1.28) (Fig. 6), and display low Y and high Sr/Y ratios (Xie et al., 2010; Zeng et al., 2011). These signatures, together with the negative $\varepsilon_{Nd}(t)$ values (−14.9 to −9.2), indicate that these granites are most likely derived from the partial melting of garnet amphibolites in the lower part (>50 km) of the thickened crust (Xie et al., 2010; Zeng et al., 2011). The presence of the Dala and Yardoi granites indicates that the Tethyan Himalayan crust was overthickened beyond 50 km prior to 44 Ma, reaffirming the results of structural geological studies undertaken in the Tethyan Himalaya (cf. Aikman et al., 2008; Zeng et al., 2011).

6. Discussion

6.1. Origin of the Tibetan Plateau

The comparable Pan-African crystalline basement and Paleozoic to Mesozoic sedimentary cover (Fig. 3), Late Paleozoic Gondwana affinity fauna and flora, and Permo-Carboniferous glacial-marine diamictite identified in the Tethyan Himalaya, Lhasa, and Qiangtang have been widely accepted to indicate a common origin of these terranes. One conventional interpretation suggests that all these terranes were part of the wide north-facing passive continental margin of the Indian plate during the Paleozoic (Chang et al., 1986; Leeder et al., 1988; Smith and Xu, 1988; Metcalfe, 1996, 2009, 2011; Yin and Harrison, 2000; Jin, 2002; Pan et al., 2004; Li et al., 2010a). However, this interpretation may be too simplistic because similar geological records, such as the Permian volcanic rocks and Permian–Triassic unconformity (Görür and Sengör, 1992; Veevers and Tewari, 1995; Mory and Backhouse, 1997; Archbold, 1999; Crostella and Backhouse, 2000), as well as the Permo-Carboniferous glacial-marine diamictites (Eyles and Eyles, 2000; Eyles et al., 2006), have also been reported from northern Australia (Fig. 3), which at the time constituted the northern margin of Gondwana. On the basis of several independent lines of geological evidence (e.g., the presence of late Paleozoic glacial deposits, the distribution of key land floras, tropical and subtropical marine faunas etc.), Audley-Charles (1983, 1984, 1988) suggested that the Lhasa Terrane might have rifted from northern Australia in the mid- to late Jurassic. Lawver et al. (2004) also speculated that the Lhasa Terrane may have separated from northern Australia in the late Jurassic. This suggested connection between Australia and the Lhasa Terrane has not been widely accepted by the scientific community because of the lack of supporting data in the previous models. However, several new lines of recently available geological evidence strongly support the paleogeographic connection between the Lhasa Terrane and northern Australia.

First, the age distributions of detrital zircons from the Amdo and Western Qiangtang rocks are remarkably similar to those of the Tethyan Himalaya (Fig. 4), all of which are sourced from the High Himalaya (Zhu et al., 2011b) and the Eastern Ghats–Rayner Provinces in the Circum–East Antarctic orogen. These zircon provenance data indicate that all of these terranes originate from Indian Gondwana. The fact that ~950 Ma zircons are lacking in the Lhasa Terrane but occur abundantly in the Western Qiangtang, Amdo, and Tethyan Himalayan terranes suggests a paleogeographic disconnection. This inference is strongly supported by the absence of ~1170 Ma zircons in the Western Qiangtang, Amdo, and Tethyan Himalaya (Fig. 4). All these findings indicate that during or prior to the Permo-Carboniferous, the Lhasa Terrane was not geographically in the vicinity of Western Qiangtang, Tethyan Himalaya, and India, but was instead adjacent to northwest Australia (Zhu et al., 2011b).

Second, as stated earlier, the basement rocks in the central Lhasa subterrane underwent amphibolite facies metamorphism during the Cryogenian (~720 Ma, Zhang et al., 2010b; ~690 Ma, Dong et al., 2011a). Existing studies indicate that the geological record of such a tectonothermal event is lacking in the Tethyan Himalaya, High Himalaya, and interior Indian continent (Xu et al., 2005; Cawood et al., 2007; Chatterjee et al., 2007; Simmat and Raith, 2008; Yin et al., 2010a, 2010b). However, the timing of this metamorphic event is coeval with the Miles Orogeny (~680—630 Ma, Durocher et al., 2003; ~650 Ma, Czarnota et al., 2009; ~750—720 Ma, Bagas, 2004) that occurred in northern Australia. The synchronous development of these events in both the central Lhasa subterrane and northern Australia likely indicates a paleographical connection between these two geological provinces during the late Neoproterozoic.

Third, although the data are still limited, the presence of late Devonian–early Carboniferous (~370–350 Ma) (see above) calc-alkaline magmatism in both the southern Lhasa and Western Qiangtang subterranes (Li et al., 2006b; Dong et al., 2010b; Pullen et al., 2011) does not support the popular Paleozoic reconstructions depicting a passive continental margin extending from Tethyan Himalaya, Greater India, and Lhasa to Qiangtang. However, this observation is consistent with crustal melting accompanying back-arc basin development evolved into what is known as the Songdo Tethyan Ocean south of the present-day Lhasa Terrane (Yang et al., 2009) (see below). Therefore, the Lhasa Terrane is most likely not a part of the present-day Tibetan Plateau system; it can instead be linked paleogeographically with the late Precambrian—early Paleozoic northern Australia (Zhu et al., 2011b).

Traditionally, the Amdo basement has been interpreted as representing the basement of the Lhasa Terrane (cf. Allègre et al., 1984; Xu et al., 1985; Dewey et al., 1988; Yin and Harrison, 2000; Pan et al., 2004; Guynn et al., 2006). If this were the case, the metamorphic rocks from the Amdo basement would be expected to have detrital zircon signature similar to that of the central Lhasa subterrane. However, such a signature has not been observed in the detrital zircon data from the Amdo basement (Guynn et al., 2012) (Fig. 4g), which instead displays a signature (peak at ~950 Ma) similar to that of the Western Qiangtang and Tethyan Himalaya (Fig. 4h and b) rather than central Lhasa subterrane (peak at ~1170 Ma) (Fig. 4d, e and f). Although more data are needed to substantiate this finding, the existing information indicates that the Amdo microcontinent may not have been part of the Lhasa Terrane as previously thought.

The glacial-marine diamictites and basalt interlayers that are common in the Permo-Carboniferous strata of the Tethyan Himalaya, central Lhasa, and Western Qiangtang subterranes as well as in northern Australia (Fig. 3) are missing in the Eastern Qiangtang subterrane. These geological observations, together with the occurrence in the Eastern Qiangtang of coral fossils in the Lower Carboniferous (BGMRXAR, 1993; Li et al., 2009a,b,c) and the Upper Permian plant fossils (Li et al., 2006b) that are typically found in the Yangtze craton and in the Cathaysian continent (cf. Pan et al., 2004; Li et al., 2009a), suggest a possible provenance link between the Eastern Qiangtang and one of these continents. The detrital zircon data recently available (cf. He et al., 2011) appear to support this link, but need further validation with additional data.

6.2. Tectonomagmatic nature and evolution since the Early Paleozoic

6.2.1. Andean-type active continental margin during the early Paleozoic

The occurrence of the early Paleozoic granitoids (530—470 Ma) in the Tethyan, High, and Lesser Himalayas have been previously attributed to several different tectonic scenarios. Murphy and Nance (1991) interpreted them as a magmatic result of supercontinental breakup, whereas Meert and Van der Voo (1997) considered these granitoids as an artifact of collision during the final assembly of Gondwana. Yin and Harrison (2000) proposed that the early Paleozoic granitoids formed as a result of a subduction zone dipping beneath the Indian continent. Recently, Cawood et al. (2007) suggested that these granitoids were a result of an Andean-type subduction of the proto-Tethyan Ocean lithosphere beneath the northern margin of the Indian continent. They also suggested that the Bhimphedian Orogeny along the proto-Tethyan Ocean margin and the coeval Ross—Delamerian Orogeny along the proto-Pacific Ocean margin of Gondwana might represent a trans-Gondwana margin orogeny that began around 510 Ma at the termination of the Gondwana assembly (Cawood and Buchan, 2007).

Although the broad extent of the early Paleozoic deposition at the northern margin of eastern Gondwana may suggest a passive margin setting, we consider the lack of evidence of substantial rifting or continuous subsidence in the early Paleozoic, in a manner analogous to the deposition in Iran (Horton et al., 2008), more compatible with the Andean-type active margin setting, as proposed by Cawood et al. (2007). In this model, the rhyolites and granitoids (~501−492 Ma) in the southern and central Lhasa subterranes (Ji et al., 2009b; Dong et al., 2010a; Zhu et al., 2012) can best be interpreted as products of the subduction of the proto-Tethyan Ocean lithosphere beneath the Australian continent (Fig. 7b). This interpretation is consistent with the stratigraphical observation indicating an active margin setting for the late Cambrian magmatism in the central Lhasa subterrane (Ji et al., 2009b). Likewise, the granite magmatism in the Amdo (~530−470 Ma; Guynn et al., 2012) and Western Qiangtang subterranes (476–464 Ma; Pullen et al., 2011) may represent a continental arc of magmatic activity associated with the subduction of the proto-Tethyan Ocean lithosphere and the subsequent crustal anatexis at the Indian continent. We therefore conclude that the Western Qiangtang and Amdo, palegeographically situated in the northern margin of the Indian continent, and the Lhasa Terrane, palegeographically located in the northern margin of the Australian continent, represent an early Paleozoic Andean-type magmatic arc facing the proto-Tethyan Ocean.

6.2.2. Back-arc extensional setting during the Late Devonian–Early Carboniferous

After the Bhimphedian Orogeny, which ceased at ~470 Ma, the northern margin of Gondwana was characterized by passive margin evolution (Cawood et al., 2007) that likely persisted until the

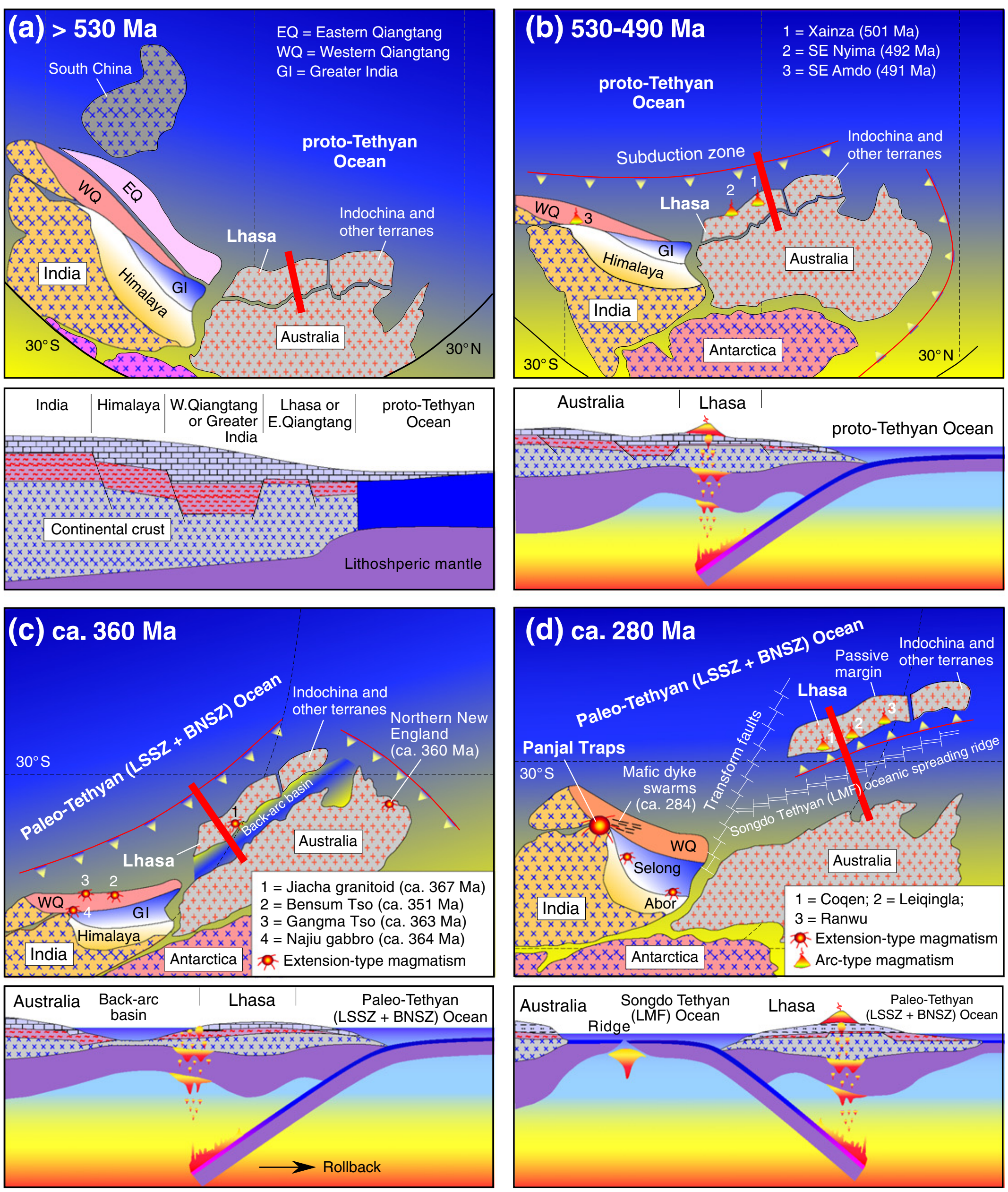

Fig. 7. Schematic illustrations of the nature and evolution of the Tibetan Plateau from the late Neoproterozoic to Mesozoic (modified from Lawver et al., 2004). Note that these illustrations only emphasize the geology and evolutional history of the Qiangtang and Lhasa Terranes in the present-day Tibetan Plateau, they can be refined and improved with parallel studies on the geology of Indochina and other terranes (e.g., SW Borneo, Sibumasu, and West Burma) that have been interpreted to be located to the outboard of the northern margin of the Australia continent (cf. Metcalfe, 2009, 2011; Hall, 2011; Zhu et al., 2012). A red bar in each paleogeography indicates the location of the cross-sections. Abbreviations are the same as in Fig. 1.

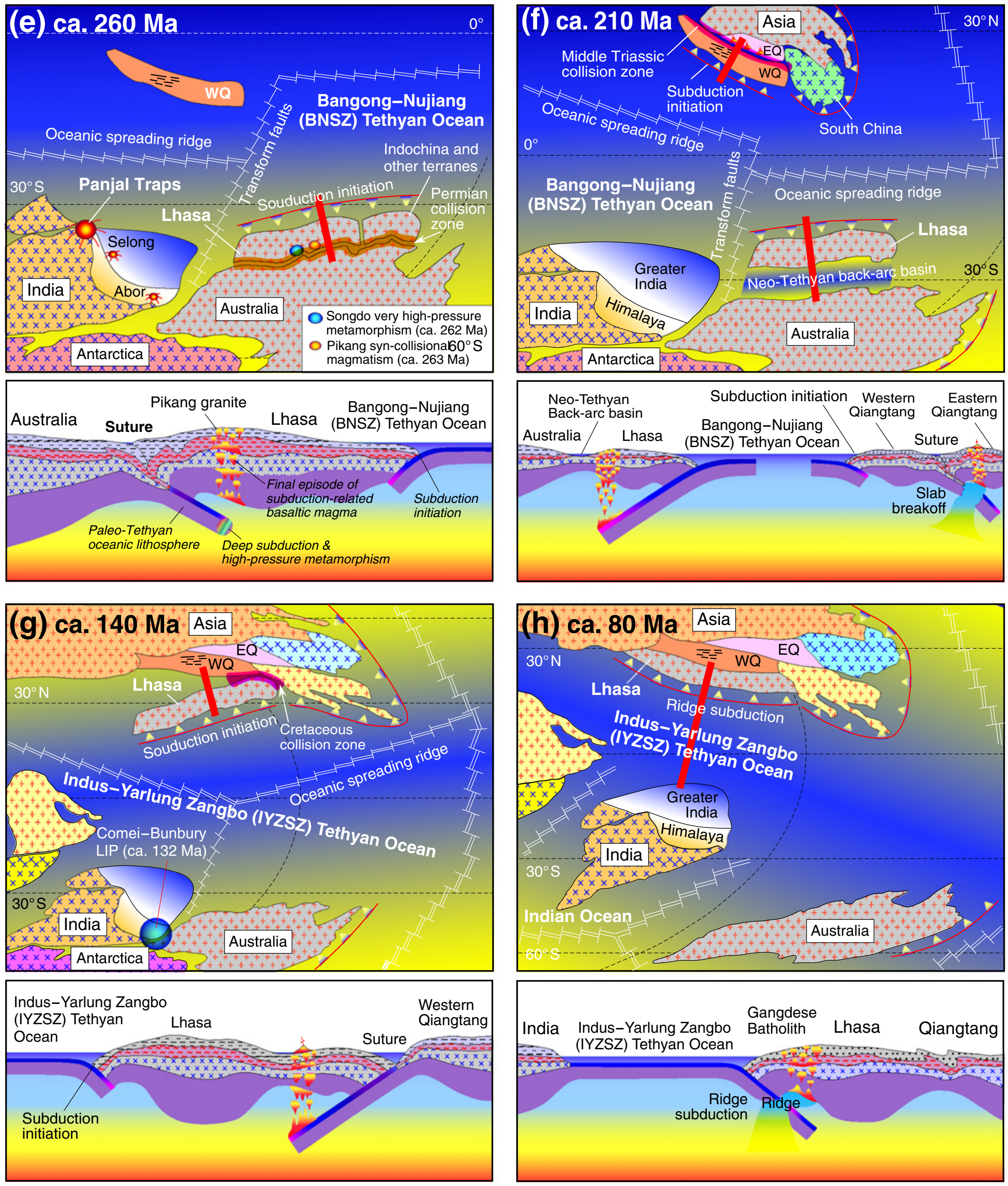

Fig. 7 (*continued*).

Devonian, at which time the Paleo-Tethyan Ocean began opening. Paleomagnetic, biogeographical, and tectonostratigraphic data indicate that the Paleo-Tethyan Ocean initially opened as a back-arc basin in the late Ordovician 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 the proto-Tethyan Ocean lithosphere (Stampfli and Borel, 2002; von Raumer et al., 2002; Ferrari et al., 2008). The Paleo-Tethys was already a wide ocean around the equator during the Devonian—Triassic (cf. Metcalfe, 1996, 2009, 2011; Stampfli and Borel, 2002; von Raumer et al., 2002; Ferrari et al., 2008; Hara et al., 2009) and was being consumed at a north-dipping subduction beneath the Hun superterrane (Stampfli and Borel, 2002), Kazakhstan (Metcalfe, 2011), and North China (Pan et al., 2004) in the Devonian. The calc-alkaline and metaluminous granitoids (367–364 Ma) in the Western Qiangtang and southern Lhasa subterranes (Mu et al., 2005; Dong et al., 2010b; Pullen et al., 2011) indicate that a subduction zone may have also existed along the southern rim of the Paleo-Tethyan Ocean during the latest Devonian (Fig. 7c). Subsequent magmatism (~350 Ma) in the Western Qiangtang subterrane (Li et al., 2005b) (Fig. 6) was most likely associated with the rollback of the subducting Paleo-Tethyan Ocean lithosphere. This rollback would have caused slab steepening and locally induced asthenospheric upwelling and decompression melting, resulting in significant contributions of mantle-derived materials to the mature crust-derived granitoid melts. We infer that the late Devonian–early Carboniferous magmatism occurred in a broad back-arc region (Fig. 7c), as indicated by the presence of carbonate and fine-grained detritus (Fig. 3).

A similar back-arc system was also suggested by Murphy et al. (2011) for the eastern peri-Gondwanan terranes. This system is analogous to that described by Collins and Richards (2008) for the Tasman orogenic system in eastern Australia (Fig. 7c) and by Zhu et al. (2009a, 2011a) for the early Cretaceous magmatism in the central and northern Lhasa subterranes. It is predicted that the back-arc region would have developed and evolved into the Songdo Tethyan Ocean located to the south of the present-day Lhasa Terrane (Li et al., 2009a; Yang et al., 2009), ultimately resulting in the isolation of the Lhasa Terrane within the Paleo-Tethyan Ocean during the Carboniferous–Middle Permian (Zhu et al., 2010) (Fig. 7d).

6.2.3. Extensional and continental margin arc systems during the Permian

The early Permian Panjal Traps in NW India (Fig. 2) are generally thought to represent a major magmatic episode comparable in magnitude to that of tholeiitic continental flood basalts (CFB) related to continental breakup (cf. Vannay and Spring, 1993; Garzanti et al., 1999; Chauvet et al., 2008). Our recent work suggests that the Panjal magmatism may have extended eastward to the Bhote Kosi and Selong areas in the Tethyan Himalaya (Zhu et al., 2010). The Permian granites of Yunam (~284 Ma) and Parkatchic (~270 Ma) (Fig. 2) in the High Himalaya were genetically associated with the voluminous flows of the Panjal Traps (Spring et al., 1993; Noble et al., 2001). All of these magmatic activities in the Tethyan and High Himalayas have been attributed to a continental rifting event that occurred along the northern margin of the Indian Gondwana, ultimately resulting in the opening of the Indus-Yarlung Zangbo Tethyan Ocean (cf. Spring et al., 1993; Garzanti et al., 1999; Noble et al., 2001; Chauvet et al., 2008).

We envision that the Western Qiangtang subterrane was located adjacent to the northern margin of the Indian continent and that the mafic dike swarms widely distributed in the Western Qiangtang subterrane were emplaced adjacent to the Panjal Traps in NW India (Fig. 7d). Such a paleographical connection, combined with the similarity in age between the dike swarms in the Western Qiangtang (ca. 284 Ma; Zhai et al., 2009) and the Panjal Traps (~284 Ma, assumed to be represented by the Yunam granite; Spring et al., 1993), indicate that the mafic dike swarms in the Western Qiangtang may have been genetically associated with the Panjal plume activity in NW India (Fig. 7d). Thus, it is likely that the separation of the Western Qiangtang from the Indian continent and the opening of the Indus-Yarlung Zangbo Tethyan Ocean north of the Indian continent may have been induced by the Panjal plume activity.

In contrast to the Permian extension-type tectonomagmatic events documented in both the Tethyan Himalaya and Western Qiangtang subterranes, geological and geochemical evidence indicates a contractional regime from subduction to syn-collision in the Lhasa Terrane prior to the Middle Permian (Geng et al., 2009; Yang et al., 2009; Zhu et al., 2009b, 2010). These different geodynamic regimes identified in present-day southern Tibet led Zhu et al. (2009b, 2010) to propose that the Lhasa Terrane should be taken out of the continuous Paleozoic Qiangtang–Lhasa–Greater India–Himalaya reconstructions and isolated in the Paleo-Tethyan Ocean, at least for the Carboniferous–Middle Permian (Fig. 7d). The spatial relationship of the continent–arc volcanic rock, eclogite, and syncollisional S-type granite indicates that the isolated Lhasa Terrane may have experienced the northward subduction of the Songdo Tethyan Ocean lithosphere as represented by the Songdo eclogite (Yang et al., 2009; Zhu et al., 2010) and subsequent Lhasa—northern Australia collision at the end of the Middle Permian (~263 Ma) (Fig. 7e) (Zhu et al., 2009b). This inferred paleogeographical connection between the Lhasa Terrane and northern Australia and the associated orogenic events are supported strongly by the Upper Permian stratigraphical gap and the Permian–Triassic unconformity (Fig. 3) in the Northern Perth Basin and Carnarvon Basin of northern Australia (Mory and Backhouse, 1997; Archbold, 1999; Crostella and Backhouse, 2000). Given the different geodynamic regimes in the present-day Tethyan Himalaya, Western Qiangtang, and Lhasa Terrane, a major transform fault system may have existed between the Western Qiangtang and the Lhasa Terrane during the Permian (Fig. 7d and e).

6.2.4. Extension-related tectonomagmatic events during the Late Triassic

The Upper Triassic silicic magmatic rocks in the Eastern and Western Qiangtang subterranes have been interpreted as part of a magmatic arc developed due to the northward subduction of the Longmu Tso-Shuanghu Tethyan oceanic lithosphere (e.g., Li, 1987, 1995, 2009a; Zhai et al., 2011a) or as a magmatic complex developed in an extensional setting following the rollback of the subducting Tethyan oceanic lithosphere along the Jinsha suture (Kapp et al., 2000, 2003). Recent studies on stratigraphy and magmatic rock geochemistry indicate that these rocks were most likely associated with extensional tectonics in response to slab breakoff of the subducted Longmu Tso-Shuanghu Tethyan oceanic lithosphere beneath the Eastern Qiangtang subterrane (Fu et al., 2010; Zhang et al., 2011). The magmatism (225—202 Ma) and exhumation (227—203 Ma) of the metamorphic rocks were synchronous events following the peak deformation (244–223 Ma) that occurred in the LSSZ (Fig. 5b) and after the development of a regional angular unconformity between these volcanic rocks and their underlying strata (cf. Fu et al., 2010). Thus, the Western Qiangtang should have collided with the Eastern Qiangtang prior to the emplacement of the magmatic rocks (possibly during the Middle Triassic). It is speculated that the Western—Eastern Qiangtang collision may have triggered the northward subduction initiation of the Bangong—Nujiang Tethyan Ocean lithosphere (Sengör et al., 1988; Niu et al., 2003) (Fig. 7f), which would account for the generation of the Jurassic magmatic rocks observed in the southern margin of the Western Qiangtang subterrane (Kapp et al., 2005b) and the Amdo basement (Guynn et al., 2006; Liu et al., 2010; Zhu et al., 2011a).

Recent studies indicated that the Bangong-Nujiang Tethyan Ocean lithosphere must have been subducted southward beneath the Lhasa Terrane (cf. Zhu et al., 2009a, 2011a). This subduction may have been triggered by the Lhasa–northern Australia collision (Sengör et al., 1988; Niu et al., 2003; Zhu et al., 2011a) that led to the closure of the Songdo Tethyan Ocean south of the central Lhasa subterrane (Yang et al., 2009) (Fig. 7e) during the Permian Gangdese Orogeny (ca. 263 Ma; Zhu et al., 2009b). The subsequent separation of the Lhasa Terrane from northern Australia resulting from the Indus-Yarlung Zangbo back-arc spreading (Fig. 7f) likely began in the mid- to late Triassic (Metcalfe, 1996, 2009, 2011; Zhu et al., 2011a), as indicated by the earliest radiolarian assemblages of Ladinian–Carnian age (237–217 Ma) from the IYZSZ (Matsuoka et al., 2002; Zhu et al., 2006a). This interpretation means that the southern edge of the Lhasa Terrane had only just formed as a passive margin of the Neo-Tethyan back-arc basin rather than as a mature active continental margin with a subduction zone during the late Triassic (Fig. 7f). Thus, we think that the late Triassic–early Jurassic magmatic rocks in the central and southern Lhasa subterranes cannot be attributed to the northward subduction of the Indus-Yarlung Zangbo Tethyan Ocean lithosphere as previously thought (Chu et al., 2006; Zhang et al., 2007d; Yang et al., 2008; Zhu et al., 2008a; Ji et al., 2009a). Instead, the rare occurrence of intermediate rocks indicates that they likely formed as a result of the anatexis of the mature continental crust in the central Lhasa (Liu et al., 2006; Zhang et al., 2007c) or the remelting of the pre-existing underplated mafic crust in the southern Lhasa subterrane under hydrous amphibolite facies conditions in a back-arc extensional region related to the southward subduction of the Bangong-Nujiang Tethyan Ocean lithosphere (Fig. 7f) (Zhu et al., 2011a). The late Triassic retrograde metamorphism (230—220 Ma; Li et al., 2009b; Dong et al., 2011b) identified in the central Lhasa subterrane may have occurred in such an extensional setting, making it possible to exhume the Songdo eclogite at that time (Avé Lallemant and Guth, 1989; Platt, 1993).

6.2.5. Tectonomagmatic response to the Lhasa—Qiangtang continental collision

Ophiolites along the BNSZ are overlain unconformably by clastic sequences with basal conglomerates that contain ophiolitic material in the Lower Cretaceous Dongqiao Formation (Barremian—Albian; 130—100 Ma) near Amdo (Bai et al., 2005) and Dongqiao (Zheng et al., 2003). This formation predates the transition from marine to non-marine conditions at 125—118 Ma as reported from the Nyima area (Kapp et al., 2007) to the west. These observations further show that the Lhasa—Qiangtang collision might have been a diachronous event during the Cretaceous that occurred from the east to the west (Fig. 7g) (cf. Yin and Harrison, 2000; Pan et al., 2004; Zhang et al., 2004; Kapp et al., 2007). Recent studies indicate that the final Lhasa–Qiangtang amalgamation occurred at ~113 Ma (Zhu et al., 2009a, 2011a), coeval with the rapid cooling of the Xiabie granite at ~108 Ma (Fig. 5a) due to its exhumation in response to initial slip of thrust in the Western Qiangtang (Kapp et al., 2007). All of these observations suggest that much of the early Cretaceous magmatism (130—110 Ma) and coeval tectonic events in the northern Lhasa subterrane to the south of the BNSZ (Zhu et al., 2009a, 2011a) and in the southern margin of the Western Qiangtang to the north of the BNSZ (Kapp et al., 2005b, 2007) might have occurred in response to the Lhasa–Qiangtang continental collision. The initial northward subduction of the Indus-Yarlung Zangbo Tethyan Ocean lithosphere beneath the southern Lhasa subterrane may have been triggered by the Lhasa–Qiangtang collision (Sengör et al., 1988; Niu et al., 2003; Zhu et al., 2011a). The emplacement of subduction-related adakite-like rocks (~137 Ma) (Fig. 7g) formed from magmas derived from the partial melting of the Indus-Yarlung Zangbo Tethyan Ocean lithosphere at depths of 70–85 km (Drummond and Defant, 1990; Zhu et al., 2009d) supports this interpretation.

6.2.6. Tectonomagmatic response to the India—Asia continental collision

Followed by the Indus-Yarlung Zangbo Tethyan mid-ocean ridge subduction around 100—80 Ma (Fig. 7h) and the subsequent continued subduction of the Tethyan ocean floor beneath the southern Lhasa subterrane (cf. Zhang et al., 2010a), the northward-moving Indian continent collided with the Eurasia continent. The timing of the initial collision is a subject of much debate. Although some researchers suggest that it may have occurred as late as 34 Ma (Aitchison et al., 2007), many others argue that it should have occurred in the early Cenozoic, around 65—55 Ma, based on geological, biostratigraphic, magmatic, and paleomagnetic constraints (Searle et al., 1987; Yin and Harrison, 2000; Mo et al., 2003, 2007, 2008; Chung et al., 2005; Ding et al., 2005; Leech et al., 2005; Garzanti, 2008; Chen et al., 2010; Dupont-Nivet et al., 2010; Liebke et al., 2010; Najman et al., 2010; Chu et al., 2011; Yi et al., 2011; Zhu et al., 2011a). The coeval magmatism (~43 Ma) and significant crustal thickening documented in both the southern Lhasa subterrane (Mo et al., 2007; Guan et al., 2012) and the Tethyan Himalaya (Aikman et al., 2008; Zeng et al., 2011) further confirm that the India—Asia continental collision likely occurred prior to ~43 Ma. Therefore, the Linzizong volcanism and synchronous plutonism in the southern Lhasa subterrane represent the magmatic responses to the India–Asia continental collision (Mo et al., 2003, 2008) rather than being the products of active continental margin magmatism predating the India–Asia collision (Allègre et al., 1984; Coulon et al., 1986; Harris et al., 1988a, 1988b; Pearce and Mei, 1988).

6.3. Generation of simultaneous magmatism on both sides of a suture in a continent—continent collision zone

The new observations and interpretations presented above indicate that the Tibetan Plateau has experienced three distinct continent—continent collisional events since the Mesozoic. These events include the Eastern Qiangtang—Western Qiangtang collision in the Middle Triassic, Qiangtang—Lhasa collision in the early Cretaceous, and the India—Asia collision in the early Cenozoic. Each one of these collisions was accompanied by the emplacement of magmatic rocks straddling the suture zones (Fig. 5a). The presence of mafic rocks with within-plate basalt affinity associated with these collisions was a result of slab breakoff-related mantle dynamics in the collision zone (cf. Ferrari, 2004). Numerical modeling indicates that slab breakoff triggers the localized asthenospheric upwelling window and causes the eduction and exhumation of the buoyant crustal material in the subduction channel under the orogen (cf. Duretz et al., 2011). As a result, the decompression melts with within-plate basalt affinity from chemically enriched subslab asthenosphere intrude or underplate the overriding plate and also flow into the subducting plate accompanying the buoyant crustal material within the subduction channel (Fig. 8). Thus, magmatism induced by mantle-derived melts in response to slab breakoff simultaneously occurs both the overriding and subducting plates (Fig. 8) as observed in the Tibetan Plateau. Such a mechanism may also be applicable to explain the Eocene magmatism in both western and eastern Turkey and Iran, where volcanic and plutonic rocks straddle different suture zones in narrow belts (Dilek and Altunkaynak, 2007, 2009; Dilek et al., 2010). We therefore propose that the collision-related magmatism occurring on both sides of a suture zone and the within-plate basalt affinity of associated mafic rocks may be two good indicators of slab breakoff in a continent—continent collision zone.

6.4. Continental growth

The early Paleozoic granitoids in the Himalayas and the late Devonian–early Carboniferous granitoids in the Western Qiangtang and southern Lhasa subterranes indicate the convergent plate margin magmatism as a result of the subduction of the proto-Tethyan and Paleo-Tethyan Ocean lithosphere, respectively (cf. Cawood et al., 2007; Zhang et al., 2008b; Zhu et al., 2012). The magmatism at these margins contributed negligibly to the continental crust of the northern margin of Gondwana because the Paleozoic granitoids are volumetrically small and are derived largely from the anatexis of the existing mature continental crust; some of the magmatic rocks in the overriding plate may have been eroded away and then recycled back into the mantle. The same is true for the early Cretaceous magmatic rocks emplaced in the Andean-type active margin associated with the northward subduction of the Indus-Yarlung Zangbo Tethyan Ocean lithosphere beneath the southern Lhasa subterrane. Although these rocks were derived from a juvenile crustal source, they are volumetrically minor and restricted to small plugs and apophyses, and many of them may have been eroded due to orogenic uplift and erosion (Wu et al., 2010). Nevertheless, it is possible that the extensive Late Cretaceous magmatism associated with the Indus-Yarlung Zangbo Tethyan mid-ocean ridge subduction (Zhang et al., 2010a) may have contributed significantly to the formation of the crust of the southern Lhasa subterrane because their isotopic composition clearly shows that juvenile crust was the dominant source (Ji et al.,

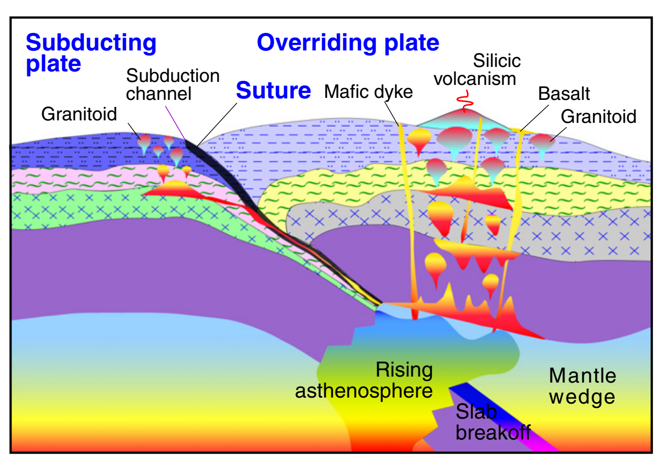

Fig. 8. Generation of simultaneous magmatism occurring on both sides of a suture zone in a continent—continent collision zone.

2009a; Zhu et al., 2011a). Thus, crustal addition through subduction zone magmatism and crustal loss through sediment subduction and subduction erosion are both recorded in the Tibetan Plateau geology, suggesting that accretionary orogens may not always be sites for net continental growth through time (cf. Niu et al., 2007; Mo et al., 2008; Cawood et al., 2009; Niu and O'Hara, 2009).

Regarding the extensive syncollisional Linzizong volcanic successions and coeval plutonic rocks in the southern Lhasa subterrane, the whole-rock isotopes and zircon $\varepsilon_{Hf}(t)$ values suggest their mantle origin and the partial melting of the retained Indus-Yarlung Zangbo Tethyan Ocean lithosphere beneath the India—Asia collision zone (Mo et al., 2007, 2008). These observations and the presence of coeval mafic rocks (Dong et al., 2005; Mo et al., 2005; Yue and Ding, 2006) indicate that the addition of mantle-derived magmas was volumetrically important to the growth of the continental crust in the southern Lhasa subterrane (cf. Mo et al., 2007, 2008; Zhu et al., 2011a). The growth of the continental crust in the northern Lhasa subterrane is in many ways analogous to crust formation in the southern Lhasa subterrane. For example, the presence of mafic rocks and the predominantly positive zircon $\varepsilon_{Hf}(t)$ values for the widespread early Cretaceous syncollisional magmatic rocks in the northern Lhasa subterrane suggest the significant addition of mantle-derived magmas to the crust formation (cf. Zhu et al., 2011a). Thus, the extensive syncollisional magmatic responses to the early Cretaceous Qiangtang–Lhasa collision in the northern Lhasa subterrane and to the early Cenozoic India—Asia collision in the southern Lhasa subterrane further support the concept that continental collision processes produce and preserve juvenile crust, contributing significantly to the net growth of continental crust (cf. Mo et al., 2008; Cawood et al., 2009; Niu and O'Hara, 2009; Hawkesworth et al., 2010; Zhu et al., 2011a).

It is evident that the southern margin of the Asian continent has grown significantly by means of continent–continent collision during the Mesozoic, as demonstrated by the accretion of the Western Qiangtang into the Eastern Qiangtang in the Middle Triassic (Fig. 7f) and the Lhasa Terrane into the Western Qiangtang in the early Cretaceous (Fig. 7g). In addition, the importance of microcontinental accretion in the history of the Tibetan Plateau is also well documented, as shown by the presence of the Amdo and Jiayuqiao microcontinents along the BNSZ (Pan et al., 2004). However, it is unclear how important or extensive the accretion of major oceanic arcs, plateaux or seamounts has been in the crustal growth of the Tibetan Plateau, even though the mélange occurrences throughout the plateau include material potentially derived from such tectonic entities. Thus, future field-based structural geochemical and geochronological studies of different terranes and subterranes of the Tibetan crustal mosaic should be conducted to investigate these possible missing links in plateau assembly and growth.

7. Summary

1) The ophiolitic rocks in the Tibetan Plateau are predominantly of a supra-subduction zone type, reflecting the different preservation potential of different types of oceanic lithosphere during subduction.
2) A Proterozoic crystalline basement must be present beneath the Tethyan Himalaya, the central Lhasa subterranes, the Amdo microcontinent, and may be locally present in the southern Lhasa and Western Qiangtang subterranes, whereas such a basement in the northern Lhasa and Eastern Qiangtang subterranes is likely absent or needs more data to confirm. The geology of the central Lhasa subterrane and Tethyan Himalaya is largely similar to that of northern Australia.
3) Geological and detrital zircon data provide convincing evidence that the Lhasa Terrane originated from the Australian Gondwana and that the Western Qiangtang and Amdo microcontinent derived from the Indian Gondwana.
4) The Cambro-Ordovician magmatism (530–470 Ma) in the Western Qiangtang and Lhasa Terrane (501 — 492 Ma) may represent the continent–arc magmatic activity associated with the subduction of the proto-Tethyan Ocean lithosphere and subsequent crustal anatexis events that occurred in the northern margins of the Indian and Australian continents, respectively.
5) The late Devonian–early Carboniferous magmatism occurred in a broad back-arc region that would have developed and evolved into the Songdo Tethyan Ocean south of the present-day Lhasa Terrane. Such back-arc spreading likely resulted in the isolation of the Lhasa Terrane within the Paleo-Tethyan Ocean during the Carboniferous–Middle Permian.
6) The mafic dike swarms in the Western Qiangtang were genetically associated with the Panjal plume activity in NW India. The separation of the Western Qiangtang from the Indian continent and the opening of the Indus-Yarlung Zangbo Tethyan Ocean north of the Indian continent were related to the Panjal plume activity.
7) The Late Triassic—Early Jurassic magmatic rocks both in the southern and central Lhasa subterranes and in the Eastern Qiangtang subterrane were most likely emplaced in extensional settings associated, respectively, with the development of the Indus-Yarlung Zangbo Tethyan back-arc basin and with the slab breakoff of the subducted Longmu Tso-Shuanghu Tethyan oceanic lithosphere beneath the Eastern Qiangtang subterrane.
8) Emplacement of magmatic rocks occurring on both sides of a suture zone may be a result of slab breakoff-induced thermal state and magmatism in a continent—continent collision zone, as exemplified by the early Cretaceous Qiangtang—Lhasa collision zone and the early Cenozoic Lhasa—India collision zone and the related magmatic events.
9) Although our tectonic model summarized here takes into account the latest data on the ophiolites, basement rocks and their sedimentary covers, and magmatic rocks, as well as the new detrital zircon data from the Paleozoic metasedimentary rocks in Tibet, it can be refined through parallel studies on the geology of other terranes in the broader India–Eurasia–Indonesia convergent system (e.g., Indochina, SW Borneo, Sibumasu, Metcalfe, 2009, 2011; West Burma, Hall, 2011). Our synthesis and model in this paper should provide stimulation for the ongoing efforts of the international scientific community to better constrain the tectonic and crustal evolution of the Tibetan Plateau.

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