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Editorial

# Recent advances on the tectonic and magmatic evolution of the Greater Tibetan Plateau: A special issue in honor of Prof. Guitang Pan

## 1. Introduction

The Greater Tibetan Plateau, also known in China as the Qinghai–Tibet Plateau or the Qingzang Plateau, is a tectonic amalgamation of numbers of continental collision events from the northwest in the early Paleozoic to the southwest in the Cenozoic (cf. Dewey et al., 1988; Pan et al., 2012; Yin and Harrison, 2000). These collision events resulted in orogenic belts that record the prolonged albeit complex histories of opening and closing of Tethyan ocean basins and associated tectonic and magmatic responses (cf. Chung et al., 2005; Pan et al., 2012; Song et al., 2014; Yin and Harrison, 2000; Zhu et al., 2013, 2015). Although many aspects related to these events have been recently synthesized with elegance by Pan et al. (2012) and Zhu et al. (2013) using data and observations made available since 2000, many scientific questions, such as the duration of oceanic basins, the collisional and accretionary processes of different terranes, the processes responsible for crustal growth, and the mechanisms for economic mineralization, remain underdeveloped and require further investigations with additional data.

In the last 5 years, there have been abundant new data obtained from field and laboratory efforts by multiple disciplines of the scientific community, offering state-of-the-art insights into the tectonic and magmatic evolution of the Greater Tibetan Plateau. In this special issue, some of these new findings and understandings are presented, dedicated to Prof. Guitang Pan for celebrating his 50 years' endless research on the geology of the Greater Tibetan Plateau and his instrumental scientific contributions.

## 2. Tribute to Prof. Guitang Pan

Guitang Pan (Fig. 1), a senior research professor of the Chengdu Institute of Geology and Mineral Resources (Chengdu, China), was born in 1941 in Zhejiang, China, and received a BS degree from the College of Beijing Geology (the predecessor of China University of Geosciences) in 1965. After graduation, Guitang worked at Southwestern Institute of Geology (the predecessor of Chengdu Institute of Geology and Mineral Resources) and developed his major academic career in this institute.

Guitang's research in 1990s includes the Cenozoic uplift of the Tibetan Plateau (Pan et al., 1990), the evolution of eastern Tethys (Pan et al., 1997), and the orogenic processes and associated mineralization in Sanjiang area in eastern Tibet (Pan et al., 2003). These investigations allowed Guitang to identify 10 metallogenic belts and reveal the relationships between tectonic settings and varying mineralization in the Sanjiang region, for which Guitang was honored a National Scientific and Technological Progress Award in 2005.

In response to the strategic plan by the Chinese Geological Survey in 2000, Guitang took the leadership to have completed a new set of 1:250,000 maps of the entire Greater Tibetan Plateau with new observations and high-quality data. On the basis of these large scale maps, Guitang and his colleagues timely synthesized 1:1,500,000 geological map of the Greater Tibetan Plateau (Fig. 1) (Pan et al., 2004), which has laid the foundation for subsequent basic research and mineral exploration. His innovative idea of "the composite island arc-basin systems" to interpret the evolution and formation of the Tibetan Plateau (Pan et al., 2012) has been widely welcomed by the scientific community with extensive recognition and citations, for which he was awarded the 2011 National Science and Technology Progress Grand Prize of China.

Guitang is one of a rare few geologists in China who investigated the geology of the entire Greater Tibetan Plateau. His life-time research has been devoted to problems of tectonics, mineralization, and evolution of the Greater Tibetan Plateau using field-based multidisciplinary (structural, stratigraphic, igneous, and metamorphic petrologic) approaches. Our present view on the origin and evolution of the Greater Tibetan Plateau would not be the same without Guitang's cornerstone contributions.

## 3. Contributions to this issue

The eighteen papers with new data and ideas in this issue encompass some of Guitang's research themes, including the evolution of Tethyan ocean basins, the generation of ophiolite and chromitite, the geodynamical processes along the southern geological margin of Asia (i.e., the active continental margin related to the Neo-Tethyan/Indian seafloor subduction), and the relationship between magmatism and mineralization (Fig. 2).

### 3.1. New insights into the evolution of Tethyan Ocean basins

The Tethyan Bangong–Nujiang Ocean was recorded by the extensive dismembered ophiolitic fragments within the Bangong–Nujiang suture zone (BNSZ) in central Tibet (Fig. 2). Sengör (1979) and Pan et al. (1983) proposed over 30 years ago that the Bangong–Nujiang Ocean lithosphere might have subducted southward beneath the Lhasa Terrane, separating from the northern margin of Gondwana, but this favored subduction polarity has not been widely considered by the scientific community because of the lack of supporting data.

This issue starts with a review article by Zhu et al. (2016-in this issue), who integrate multidisciplinary data available from the Lhasa–

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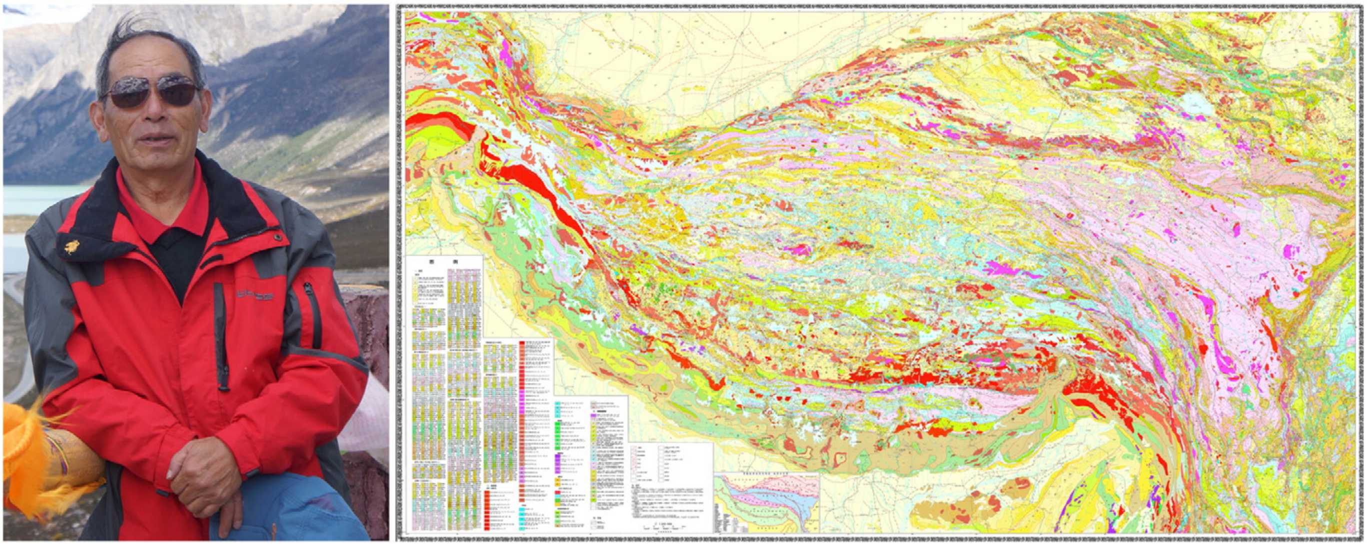

**Fig. 1.** A photo of Professor Guitang Pan (taken at Sanjiang by Di-Cheng Zhu, 2014) and the 1:1,500,000 geological map of the Qinghai–Xizang Plateau and adjacent areas (Pan et al., 2004).

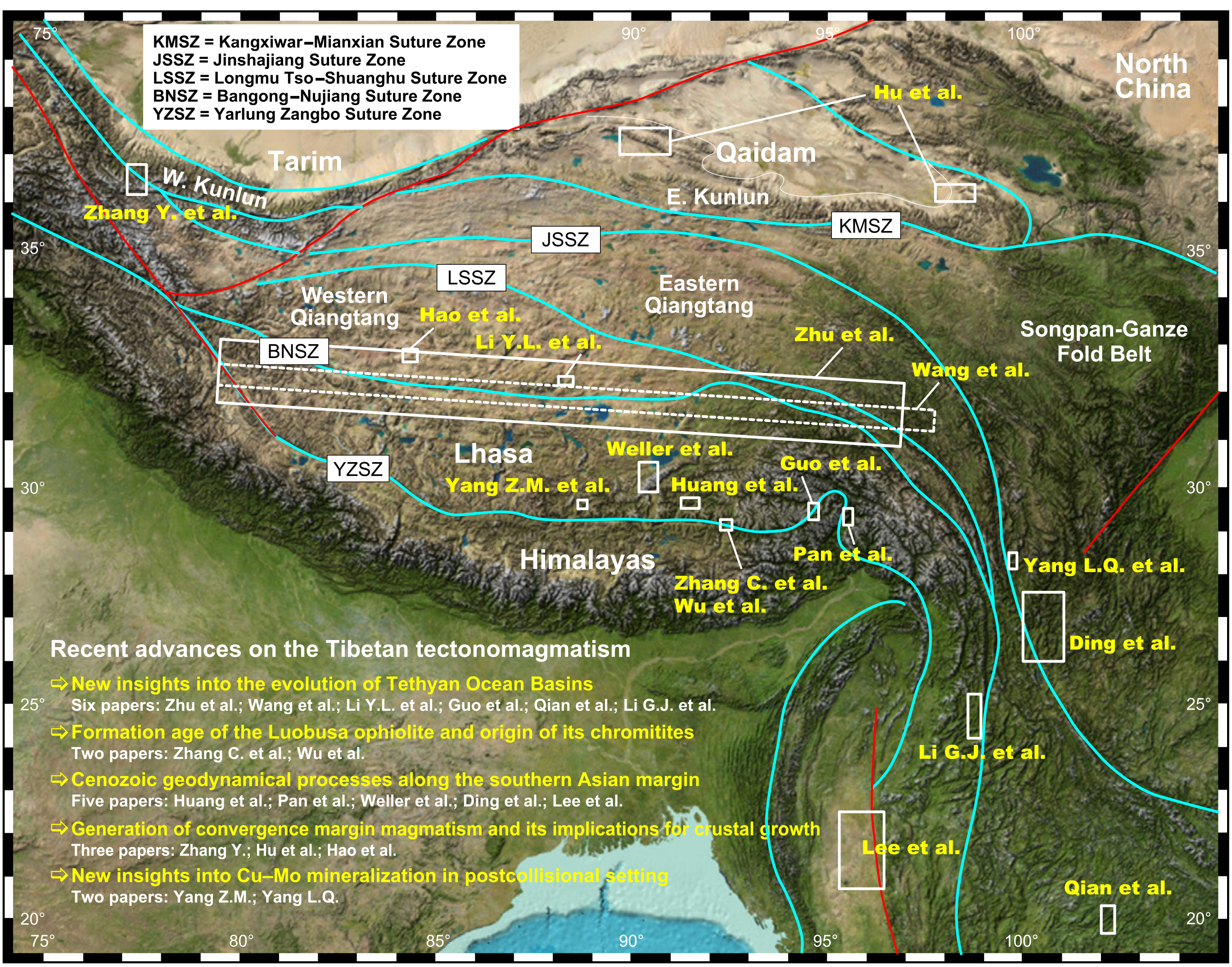


**Fig. 2.** *Location of study areas of the papers included in this issue.* Geographical map of the Greater Tibetan Plateau is from http://www.bodc.ac.uk/projects/international/gebco/gebco_world_map/.

Qiangtang collision zone (Fig. 2). They show that the collision zone is characterized by two Jurassic–Cretaceous magmatic arcs, one in the western Qiangtang Terrane to the north and the other in the northern Lhasa Terrane to the south, by the absence of Early Cretaceous high-grade metamorphic rocks, and by the presence of extensive 120–110 Ma magmatism throughout the collision zone with enhanced mantle contributions. These observations allow the authors to propose that the Tethyan Bangong Ocean floor may have subducted both to the north beneath the western Qiangtang Terrane and to the south beneath the Lhasa Terrane. The authors further argue that the Tethyan Bangong Ocean may have closed in the Late Jurassic–Early Cretaceous (most likely ca. 140–130 Ma) through arc–arc "soft" collision that occurred between two active continental margins rather than continent–continent "hard" collision that took place between a continent with a passive margin and a continent with an active margin.

Understanding the spreading and subduction histories of the Tethyan Bangong–Nujiang Ocean requires high-quality age data of the ophiolites and the knowledge of how subduction-related magmatism may extend laterally along the arc, but these have been hampered because of lacking reliable data. For this, Wang et al. (2016-in this issue) report the zircon U–Pb age and geochemical data of the mafic rocks associated with the ophiolites within the Bangong–Nujiang suture zone (Fig. 2). These data show MORB-like gabbros and leucogabbro with emplacement ages of 187−164 Ma, providing constraints on the presence of ocean crust along the length of the Bangong–Nujiang suture zone in the Early–Middle Jurassic time, which is corroborated by OIB-type basalts and gabbros of ~132–108 Ma in the literature. The authors argue that the Tethyan Bangong–Nujiang ocean basin must have undergone intra-oceanic subduction during the Early–Middle Jurassic and remained active until the Early Cretaceous. Y. L. Li et al. (2016b-in this issue) document the presence of ca. 149 Ma pluton from Kangqiong in the central segment of the western Qiangtang Terrane (Fig. 2). This pluton has small negative $\varepsilon_{Nd}(t)$ values with adakitic elemental characteristics (e. g., high MgO and Mg#) most consistent with an origin of partial melting of the subducting ocean crust plus minor crustal contamination during magma ascent. The presence of subducting ocean crust-derived pluton indicates the development of a west–east Late Jurassic magmatic arc in excess of 800 km, providing a robust constraint on the northward subduction of the Bangong–Nujiang oceanic lithosphere beneath the central segment of the western Qiangtang Terrane during the Late Jurassic.

The Paleozoic history of the Greater Tibetan Plateau is poorly constrained largely due to the rarity of magmatic rocks. In this issue, Guo et al. (2016-in this issue) report an integrated study of zircon U–Pb chronology and Hf isotopes on metasedimentary rocks of the Nyingchi Complex in the southern Lhasa Terrane (Fig. 2) with the results showing the presence of abundant 330–364 Ma detrital zircons. Provenance analysis indicates that the detritus was sourced from the Lhasa Terrane itself. In combination with coeval magmatic rocks reported in the literature, the authors suggest that the Lhasa Terrane was probably under an arc-back-arc setting in association with southward subduction of the Paleo-Tethys seafloor during the Late Devonian to Early Carboniferous. Qian et al. (2016-in this issue) report zircon U–Pb ages of 335.5 ± 3.3 Ma for a diabase dyke and of 304.9 ± 3.9 Ma for a coarse-grained basalt from Luang Prabang in northwest Laos (Fig. 2). Geochemical data of the mafic rocks suggest the presence of a back-arc basin along the Luang Prabang tectonic zone that resulted from the subduction of the Paleozoic Tethyan seafloor toward beneath the Sukhothai–Simao Block. G. J. Li et al. (2016-in this issue) report the presence of highly fractionated granites of 470−460 Ma age from the Baoshan Block in SE Tibet (Fig. 2). The primary magmas of these granites are interpreted as deriving from the partial melting of metasedimentary rocks with small amounts of mantle input. In combination with other available data, the ca. 470–460 Ma granites are attributed to the delamination of the thickened lithosphere following the final amalgamation of outboard Asian microcontinents onto the East Gondwana margin at ~490–475 Ma.

### *3.2. Age of the Luobusa ophiolite and origin of its chromitites*

The Yarlung Zangbo suture zone (YZSZ) in southern Tibet (Fig. 2) separates the Asian plate to the north from the Indian plate to the south and marks the site where the Neo-Tethyan Ocean lithosphere was consumed at a subduction zone dipping northward beneath the Asian plate. A series of ophiolitic massifs with chromitites are exposed along the YZSZ. Although these ophiolitic massifs have been investigated over 40 years, yet when and how the ophiolites and chromitites were formed remains controversial.

As one of the type ophiolitic massifs in the YZSZ, the Luobusa ophiolite in the eastern YZSZ has been proposed to be formed during the Jurassic (cf. Chan et al., 2015 and references therein), significantly older than the Early Cretaceous ophiolites (120−131 Ma) outcropped in the central and western YZSZ (cf. Hébert et al., 2012). In this issue, C. Zhang et al. (2016a-in this issue) report the precise SIMS zircon U–Pb age data for a gabbroic dyke (128 ± 1 Ma) cutting the serpentinites and an amphibolite (130.9 ± 1.3 Ma) outcropped within the Luobusa ophiolite (Fig. 2), identical within analytical uncertainty to the amphibolites that have been dated at 134.5 ± 6.9 Ma, 132.0 ± 3.4 Ma, and 134.1 ± 3.2 Ma by the LA-ICPMS titanite U–Pb method. These high-quality age data indicate that the Luobusa ophiolite was formed during the Early Cretaceous, coeval with (rather than older than) other ophiolites along the YZSZ and that the Luobusa ophiolite probably underwent the intra-oceanic emplacement immediately after its formation.

The Luobusa ophiolite contains the largest chromite deposit in China. The Luobusa podiform chromitites have been interpreted as the consequence of low-pressure reaction of peridotites with boninitic melts in the upper mantle (Zhou et al., 1996). However, the discovery of ultrahigh pressure minerals (cf. Yang et al., 2007) challenged this shallow origin of the Luobusa chromitites. In this issue, Wu et al. (2016-in this issue) carried out multi-anvil experiments in the magnesiochromite + $SiO_2$ system at temperatures of 1000–1600 °C and pressures of 5–15 GPa. The experimental results demonstrate that magnesiochromite is stable up to 14 GPa and decomposed into eskolaite together with a quench-modified ludwigite-structured phase at higher pressures. This depth corresponds to the top of the mantle transition zone at 410 km and represents the maximum depth for chromite crystallization and/or metamorphism, supporting a much deeper origin for the Luobusa podiform chromitites.

### *3.3. Cenozoic geodynamical processes along the southern margin of the Asian plate*

The southern margin of the Asian plate in southern Tibet experiences the Neo-Tethyan seafloor subduction, the India–Asia collision, and the underthrusting of the Indian continental lithosphere in the Cenozoic (cf. Chung et al., 2005; Zhu et al., 2015) and thus involves complicated geodynamical processes whose understanding remains far from satisfactory. For example, Huang et al. (2016-in this issue) report zircon U–Pb ages of earlier E–W trending (60−53 Ma) and later N–S trending (17−13 Ma) magmatic dykes from Dazi in the central Gangdese Batholith (Fig. 2). These two stages of dykes were interpreted as having derived from partial melting of a lithospheric mantle wedge in response to slab breakoff of the Neo-Tethyan oceanic lithosphere and of a thickened crust beneath the Lhasa Terrane due to the tearing or delamination of the subducted Indian lithosphere, respectively. To the eastern Gangdese Batholith near Motuo (Fig. 2), Pan et al. (2016-in this issue) identify abundant mafic intrusive rocks of ca. 69 and ca. 50 Ma. These rocks were interpreted as having derived from partial melting of metasomatized lithospheric mantle. The new data lead the authors to argue that the Late Cretaceous delamination may have resulted in the replacement of ancient lithospheric mantle by the juvenile lithospheric mantle in the eastern Lhasa Terrane.

Discrete pockets of fluid (termed "bright spots" in geophysics) are generally inferred to represent partial melt within the mid-crust beneath the Tibetan Plateau (cf. Brown et al., 1996). However, the surficial expression of such melt that refers to as mid-crust-derived Cenozoic silicic rocks is rarely identified so far. Weller et al. (2016-in this issue) analyze the magmatic and metamorphic history of the Western Nyainqêntanglha in the central Lhasa Terrane (Fig. 2). Their petrological and geochronological data reveal the presence of three tectonothermal events, including the 213—201 Ma tectonism that is suggested to have resulted from north-south Lhasa Terrane accretion, the 140—52 Ma magmatism that is attributed to subduction of the Neo-Tethyan oceanic lithosphere, and the 25—8 Ma magmatism that is interpreted as the product of partial melting of the thickened Tibetan Plateau mid-crust. The similarity between the present depth of the imaged "bright spots" (15–18 km) and the current exposure level of the Western Nyainqêntanglha (15–20 km) leads the authors to propose that the voluminous Miocene magmatism in the Western Nyainqêntanglha is the exhumed equivalent of geophysical "bright spots" imaged in the region.

To the southeastern Tibetan Plateau, the widespread Eocene–Oligocene potassic to ultrapotassic magmatic suites (ca. 35 Ma) have been linked to the uplift of the Tibetan Plateau (cf. Chung et al., 1998). However, the petrogenesis of the rock suites remain hotly debated. Ding et al. (2016-in this issue) investigate the Eocene adakite-like rocks that are widespread in western Yunnan, SE Tibet (Fig. 2). Their new geochemical data together with the literature data reveal a westward increase in zircon $\varepsilon_{Hf}(t)$ and whole-rock $\varepsilon_{Nd}(t)$ values. The adakitic rocks from the eastern and western parts of western Yunnan were interpreted as deriving from partial melting of Neoproterozoic mafic rocks and of late Paleozoic–Mesozoic mafic rocks, respectively, that underplated in the lower crust at varying stages as a result of the removal of thickened continental lithosphere.

Further to the southwest, the Myanmar is a region to investigate magmatic response to tectonic transition from oblique subduction to dextral movement of the Indian oceanic lithosphere along the trench. Lee et al. (2016-in this issue) examine the geochemistry of the volcanic rocks from the central Myanmar basin (Fig. 2) and identify a geochemical transition from mid-Miocene calc-alkaline intermediate-dominated compositions (≥15 Ma) to Quaternary calc-alkaline to alkaline basalt-dominated compositions (<1.0 Ma). These two events of volcanism have been interpreted as being derived from partial melting of a juvenile mantle wedge related to the subduction of Indian oceanic lithosphere and of differing magma source regions associated with the rollback of the Indian oceanic lithosphere, respectively. The magmatic gap in between is proposed to indicate a cessation of oblique oceanic subduction and a switch to dextral movement along the trench at ca. 15 Ma.

### *3.4. Generation of convergence margin magmatism and its implications for crustal growth*

The presence of the continental crust is one of the Earth's unique features compared to other planets in our Solar System. However, where and how the continental crust grows remains the topic of much debate (cf. Niu et al., 2013 and references therein). For example, continental crust growth is commonly postulated to occur at subduction zones by lateral accretion of island arc complexes and oceanic plateaus or by vertical addition by underplating of mantle-derived basaltic magmas (cf. Rudnick, 1995), but others argue that continental collision zones are the primary sites for net continental crust growth (cf. Mo et al., 2008; Niu and O'Hara, 2009; Niu et al., 2013). The Tibetan Plateau is an ideal site to verify the relative importance of each mechanism for continental crust growth as it preserves extensive magmatism in response to seafloor subduction to continental collision and to postcollisional collapse (cf. Chung et al., 2005; Niu et al., 2013; Zhu et al., 2013, 2015).

The Kunlun orogenic belt in the northern Tibetan Plateau is characterized by abundant igneous rocks of Triassic age. However, existing work is limited without insights into the petrogenesis of the rocks and their implications for continental crust growth. Y. Zhang et al. (2016b-in this issue) report the results of host granitoids and mafic magmatic enclaves (MMEs) synchronously emplaced at ca. 225 Ma from western Kunlun orogenic belt (Fig. 2). The MMEs were interpreted to represent cumulate formed from the common magma parental to the host granitoids. Model calculations suggest that isotopically more than 80% Paleo-Tethys ocean crust contributed to the source of the host granitoids, thus representing net continental crustal growth because of the significant juvenile crustal contribution with compositions resembling the model bulk continental crust. The authors argue that the hypothesis "continental collision zones as primary sites for net continental crust growth" applies to the continental crustal growth in general and to the west Kunlun orogenic belt in particular.

Hu et al. (2016-in this issue) study the coeval mafic dikes and rhyolitic volcanic rocks that are dated at 228—218 Ma from the eastern Kunlun orogenic belt (Fig. 2). The mafic dikes were interpreted to represent evolved alkaline basaltic melts derived from metasomatized subcontinental lithospheric mantle with crustal contamination. Such mantle-derived melts underplated and intruded the deep crust as juvenile crustal materials, whose melting triggered mixing with crustal materials and mantle-derived mafic melts to produce the felsic volcanic rocks. It is suggested that decompression melting of upwelling asthenosphere and induced melting of prior metasomatized mantle lithosphere (or even overlying crust) in response to postcollisional extension and related orogenic collapse are conceptually important for understanding the origin of the juvenile crust and continental crustal accretion through magmatism in the broad context of orogenesis.

The Bangong—Nujiang suture zone in central Tibet is considered as a site for lateral crustal growth by accretion of microcontinent (Pan et al., 2006; Zhu et al., 2013) or oceanic plateau (Zhang et al., 2014). Existing studies highlight the importance of magma underplating-related vertical crustal growth in the northern Lhasa Terrane (Sui et al., 2013; Zhu et al., 2011) as previously proposed for the southern Lhasa Terrane (Mo et al., 2007), but the importance of the vertical crustal growth in the western Qiangtang Terrane remains unclear. Hao et al. (2016-in this issue) study the Late Mesozoic intermediate–felsic intrusive rocks (ca. 150 Ma and 112 Ma) from the western Qiangtang Terrane (Fig. 2). They suggest that the ca. 150 Ma diorites were most likely associated with the interaction between sediment diapirs and the mantle wedge and the ca. 150 Ma granodiorites were probably produced by partial melting of a thickened ancient mafic lower continental crust, which differs significantly from the origin of the ca. 112 Ma granodiorite porphyries that were interpreted to be generated by partial melting of a newly underplated basaltic crust. This difference enables the authors to propose that the ancient lower crust in the western Qiangtang Terrane was gradually replaced by mantle-derived juvenile materials from the Late Jurassic to Early Cretaceous, indicating the presence of vertical crustal growth by basaltic magma underplating in a continental arc setting.

### *3.5. New insights into Cu–Mo mineralization in postcollisional settings*

Porphyry Cu–Mo deposits have been recognized to occur in postcollisional settings over a decade ago (see Hou et al., 2015 and references therein). However, the origin of ore-forming metals and sulfur and the role of former arc magmas in generating such deposits are still poorly understood. Such problems have been addressed by two papers in this issue.

The Jiru Cu–Mo deposit of the Gangdese arc in southern Tibet documents both arc magma-related Eocene (ca. 49 Ma) and postcollisional Miocene (ca. 16 Ma) porphyry Cu–Mo mineralization. Z.M. Yang et al. (2016b-in this issue) interpret the significant magmatic differentiation observed in the Jiru Eocene granitoids (Fig. 2) as a key factor that resulted in the increase of water content of residual magma and thus the formation of the ca. 49 Ma Cu–Mo mineralization. This allows the authors to further propose that sulfide precipitation at the base of lower crust during the Eocene arc magmatism is not needed in the formation of the postcollisional Miocene porphyry Cu–Mo deposit, implying that the origin of the ore metals and S for postcollisional porphyry Cu deposits is more complex than originally considered.

The Hongshan Cu–Mo deposit of the Yidun arc in southeastern Tibet is the largest late Cretaceous porphyry–skarn Cu–Mo metallogenic system in China, which was accompanied with coeval magmatism. L. Q. Yang et al. (2016a-in this issue) study the origin of the Hongshan granitoid porphyries (Fig. 2) and propose that these rocks were most likely derived from partial melting of combined juvenile (ca. 215 Ma) arc-related sources and ancient mafic lower crust as a result of oblique, intraplate extension due to asthenospheric upwelling along lithospheric-scale, transtensional faulting in and across the Yidun arc. The authors argue that the Hongshan Cu–Mo mineralization was related to high-degree partial melting of the lithosphere that contained metal accumulations in sulfides during the Triassic seafloor subduction.

## 4. Summary and future work

Tectonomagmatic events prior to ca. 460 Ma that were attributed to the Proto-Tethyan Ocean subduction and microcontinental amalgamation (G. J. Li et al., 2016a-in this issue) were accompanied by a period of magmatic lull (460−360 Ma) in the Tethyan Ocean margin of Gondwana. This magmatic lull inhibits investigations on the geodynamical processes associated with the evolution of Tethyan ocean basins during this time interval. Subsequent histories of the Tethyan Ocean north of the Lhasa Terrane may have been characterized by broadly coeval seafloor subductions toward the Lhasa Terrane (Guo et al., 2016-in this issue) and toward the Sukhothai–Simao Block in the Indochina margin (Qian et al., 2016-in this issue), both of which may have led to the development of back-arc basins during the Late Devonian to Carboniferous. Similar double-sided seafloor subduction of the Tethyan Ocean north of the Lhasa Terrane would also occur during the Mesozoic, as evidenced by the observations and interpretations of three papers included in this issue (Zhu et al., 2016-in this issue; Wang et al., 2016-in this issue; Y. L. Li et al., 2016b-in this issue). Nevertheless, future field-based interdisciplinary investigations by sedimentologists, metamorphic, and igneous petrologists, structural geologists, and geophysicists on the geology and lithospheric architecture of different suture zones should be conducted to verify the double-sided subduction hypothesis proposed for the closing of the Tethyan Ocean basins.

New high-quality data indicate that the Luobusa ophiolite, which contains podiform chromitites that may have originated from depths as deep as 410 km (Wu et al., 2016-in this issue), were formed at 134−128 Ma, coeval with (not older than) other ophiolites along the Yarlung Zangbo suture zone (C. Zhang et al., 2016a-in this issue). We propose that the counterclockwise rotation of the Greater Indian Plate from 130 to 120 Ma, related to its unzipping separation from Australia to East Antarctica (Coffin et al., 2002), is the possible mechanism that terminated the active spreading of the Neo-Tethyan ridge and stopped the formation of new oceanic crust, explaining the absence of ophiolites younger than 120 Ma within the Yarlung Zangbo suture zone. However, future work is urgently needed to resolve this “ophiolite puzzle” including why the mafic dykes within the Yarlung Zangbo ophiolites were quasi-synchronously formed at 130−120 Ma.

Several papers in this issue that report new data on specific magmatic rocks have discussed the relationships between magmatism and geodynamical processes (e.g., lithospheric delamination, Pan et al., 2016-in this issue; Ding et al., 2016-in this issue; slab rollback, Lee et al., 2016-in this issue; slab breakoff, Huang et al., 2016-in this issue), “bright spots” in the mid-crust (Weller et al., 2016-in this issue), crustal growth (Y. Zhang et al., 2016b-in this issue; Hu et al., 2016-in this issue; Hao et al., 2016-in this issue), and mineralization (Z. M. Yang et al., 2016b-in this issue; L.Q. Yang et al., 2016a-in this issue). We address that many important issues remain to be better resolved pertaining to the tectonomagmatic evolution of the Greater Tibetan Plateau, such as (1) the generation of large granitoid batholiths with respect to the continental crust growth, (2) deep processes involved in such extensive magmatism and their controls on the surface uplift of the plateau, and (3) the role of basaltic magma underplating during preexisting oceanic subduction in generating subsequent giant metallogenic mineralization.

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## References

Brown, L.D., Zhao, W.J., Nelson, K.D., Hauck, M., Alsdorf, D., Ross, A., Cogan, M., Clark, M., Liu, X.W., Che, J.K., 1996. Bright spots, structure, and magmatism in Southern Tibet from INDEPTH seismic reflection profiling. Science 274, 1688–1690.

Chan, G.H.N., Aitchison, J.C., Crowley, Q.G., Horstwood, M.S.A., Searle, M.P., Parrish, R.R., Chan, J.S.L., 2015. U–Pb zircon ages for Yarlung Tsangpo suture zone ophiolites, southwestern Tibet and their tectonic implications. Gondwana Research 27, 719–732.

Chung, S.L., Lo, C.H., Lee, T.Y., Zhang, Y.Q., Xie, Y.W., Li, X.H., Wang, K.L., Wang, P.L., 1998. Diachronous uplift of the Tibetan plateau starting 40 Myr ago. Nature 394, 769–773.

Chung, S.L., Chu, M.F., Zhang, Y.Q., Xie, Y.W., Lo, C.H., Lee, T.Y., Lan, C.Y., Li, X.H., Zhang, Q., Wang, Y.Z., 2005. Tibetan tectonic evolution inferred from spatial and temporal variations in post-collisional magmatism. Earth-Science Reviews 68, 173–196.

Coffin, M.F., Pringle, M.S., Duncan, R.A., Gladczenko, T.P., Storey, M., Müller, R.D., Gahagan, L.A., 2002. Kerguelen hotspot magma output since 130 Ma. Journal of Petrology 43, 1121–1139.

Dewey, J.F., Shackleton, R.M., Chang, C.F., Sun, Y.Y., 1988. The tectonic evolution of the Tibetan Plateau. Philosophical transactions of the Royal Society of London. Series A: Mathematical and physical sciences 327, 379–413.

Ding, H.X., Hou, Q.Y., Zhang, Z.M., 2016. Petrogenesis and tectonic significance of the Eocene adakite-like rocks in western Yunnan, southeastern Tibetan Plateau. Lithos 245, 161–173 (in this issue).

Guo, L., Zhang, H.F., Harris, N., Xu, W.C., Pan, F.B., 2016. Late Devonian-Early Carboniferous magmatism in the Lhasa terrane and its tectonic implications: evidences from detrital zircons in the Nyingchi Complex. Lithos 245, 47–59 (in this issue).

Hao, L.L., Wang, Q., Wyman, D.A., Ou, Q., Dan, W., Jiang, Z.Q., Wu, F.Y., Yang, J.H., Long, X.P., Li, J., 2016. Underplating of basaltic magmas and crustal growth in a continental arc: evidence from Late Mesozoic intermediate–felsic intrusive rocks in southern Qiangtang, central Tibet. Lithos 245, 223–242 (in this issue).

Hébert, R., Bezard, R., Guilmette, C., Dostal, J., Wang, C.S., Liu, Z.F., 2012. The Indus-Yarlung Zangbo ophiolites from Nanga Parbat to Namche Barwa syntaxes, southern Tibet: first synthesis of petrology, geochemistry, and geochronology with incidences on geodynamic reconstructions of Neo-Tethys. Gondwana Research 22, 377–397.

Hou, Z.Q., Yang, Z.M., Lu, Y.J., Kemp, A., Zheng, Y.C., Li, Q.Y., Tang, J.X., Yang, Z.S., Duan, L.F., 2015. A genetic linkage between subduction- and collision-related porphyry Cu deposits in continental collision zones. Geology 43, 247–250.

Hu, Y., Niu, Y.L., Li, J.Y., Ye, L., Kong, J.J., Chen, S., Zhang, Y., Zhang, G.R., 2016. Petrogenesis and tectonic significance of the late Triassic mafic dikes and felsic volcanic rocks in the East Kunlun Orogenic Belt, Northern Tibet Plateau. Lithos 245, 205–222 (in this issue).

Huang, F., Xu, J.F., Chen, J.L., Wu, J.B., Zeng, Y.C., Xiong, Q.W., Chen, X.F., Yu, H.X., 2016. Two Cenozoic tectonic events of N–S and E–W extension in the Lhasa Terrane: evidence from geology and geochronology. Lithos 245, 118–132 (in this issue).

Lee, H.Y., Chung, S.L., Yang, H.M., 2016. Late Cenozoic volcanism in central Myanmar: geochemical characteristics and geodynamic significance. Lithos 245, 174–190 (in this issue).

Li, G.J., Wang, Q.F., Huang, Y.H., Gao, L., Yu, L., 2016a. Petrogenesis of middle Ordovician peraluminous granites in the Baoshan block: implications for the early Paleozoic tectonic evolution along East Gondwana. Lithos 245, 76–92 (in this issue).

Li, Y.L., He, J., Han, Z.P., Wang, C.S., Ma, P.F., Zhou, A., Liu, S.A., Xu, M., 2016b. Late Jurassic sodium-rich adakitic intrusive rocks in the southern Qiangtang terrane, central Tibet, and their implications for the Bangong–Nujiang Ocean subduction. Lithos 245, 34–46 (in this issue).

Mo, X.X., Hou, Z.Q., Niu, Y.L., Dong, G.C., Qu, X.M., Zhao, Z.D., Yang, Z.M., 2007. Mantle contributions to crustal thickening during continental collision: evidence from Cenozoic igneous rocks in southern Tibet. Lithos 96, 225–242.

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

Niu, Y.L., O'Hara, M.J., 2009. MORB mantle hosts the missing Eu (Sr, Nb, Ta and Ti) in the continental crust: new perspectives on crustal growth, crust-mantle differentiation and chemical structure of oceanic upper mantle. Lithos 112, 1–17.

Niu, Y.L., Zhao, Z.D., Zhu, D.C., Mo, X.X., 2013. Continental collision zones are primary sites for net continental crust growth—a testable hypothesis. Earth-Science Reviews 127, 96–110.

Pan, G.T., Zheng, H.X., Xu, Y.R., Wang, P.S., Jiao, S.P., 1983. A preliminary study on Bangong Co-Nujiang Suture. Geological Memoirs of Qinghai–Xizang Plateau (12) — Geological Tectonics of "Sanjiang". Geological Publishing House, Beijing, pp. 229–242 (in Chinese with English abstract).

Pan, G.T., Wang, P.S., Xu, Y.R., Jiao, S.P., Xiang, T.X., 1990. Cenozoic tectonic evolution of the Tibetan Plateau. Geological Publishing House, Beijing, pp. 1–190 (in Chinese with English abstract).

Pan, G.T., Chen, Z.L., Li, X.Z., Yang, Y.J., Xu, X.S., Xu, Q., Jiang, X.S., Wu, Y.L., Luo, J.L., Zhu, T.X., Peng, Y.M., 1997. Geological tectonic evolution in the Eastern Tethys. Geological Publishing House, Beijing, pp. 1–197 (in Chinese with English abstract).

Pan, G.T., Xu, Q., Hou, Z.Q., Wang, L.Q., Du, D.X., Mo, X.X., Li, D.M., Wang, M.J., Li, X.Z., Jiang, X.S., Hu, Y.Z., 2003. Composite island-arc orogenic process, metallogenic system and resource evaluation in Sanjiang, southwest China. Geological Publishing House, Beijing, pp. 1–405 (in Chinese).

Pan, G.T., Ding, J., Yao, D.S., Wang, L.Q., 2004. Guidebook of 1:1,500,000 geological map of the Qinghai–Xizang (Tibet) Plateau and adjacent areas. Cartographic Publishing House, Chengdu, China, pp. 1–148.

Pan, G.T., Mo, X.X., Hou, Z.Q., Zhu, D.C., Wang, L.Q., Li, G.M., Zhao, Z.D., Geng, Q.R., Liao, Z.L., 2006. Spatial–temporal framework of the Gangdese Orogenic Belt and its evolution. Acta Petrologica Sinica 22, 521–533 (in Chinese with English abstract).

Pan, G.T., Wang, L.Q., Li, R.S., Yuan, S.H., Ji, W.H., Yin, F.G., Zhang, W.P., Wang, B.D., 2012. Tectonic evolution of the Qinghai–Tibet Plateau. Journal of Asian Earth Sciences 53, 3–14.

Pan, F.B., Zhang, H.F., Xu, W.C., Guo, L., Luo, B.J., Wang, S., 2016. U–Pb zircon dating, geochemical and Sr–Nd–Hf isotopic compositions of mafic intrusive rocks in the Motuo, SE Tibet constrain on their petrogenesis and tectonic implication. Lithos 245, 133–146 (in this issue).

Qian, X., Feng, Q.L., Wang, Y.J., Chonglakmani, C., Monjai, D., 2016. Geochronological and geochemical constraints on the mafic rocks along the Luang Prabang zone: carboniferous back-arc setting in northwest Laos. Lithos 245, 60–75 (in this issue).

Rudnick, R.L., 1995. Making continental crust. Nature 378, 571–577.

Sengör, A.M.C., 1979. Mid-Mesozoic closure of Permo-Triassic Tethys and its implications. Nature 279, 590–593.

Song, S.G., Niu, Y.L., Su, L., Zhang, C., Zhang, L.F., 2014. Continental orogenesis from seafloor subduction, continent collision/subduction, to orogen collapse, and orogen recycling: the example of the North Qaidam UHPM belt, NW China. Earth-Science Reviews 129, 59–84.

Sui, Q.L., Wang, Q., Zhu, D.C., Zhao, Z.D., Chen, Y., Santosh, M., Hu, Z.C., Yuan, H.L., Mo, X.X., 2013. Compositional diversity of ca. 110 Ma magmatism in the northern Lhasa Terrane, Tibet: implications for the magmatic origin and crustal growth in a continent–continent collision zone. Lithos 168–169, 144–159.

Wang, B.D., Wang, L.Q., Chung, S.L., Chen, J.L., Yin, F.G., Liu, H., Li, X.B., Chen, L.K., 2016. Evolution of the Bangong–Nujiang Tethyan ocean: insights from the geochronology and geochemistry of mafic rocks within ophiolites. Lithos 245, 18–33 (in this issue).

Weller, O.M., St-Onge, M.R., Rayner, N., Searle, M.P., Waters, D.J., 2016. Miocene magmatism in the Western Nyainqentanglha mountains of southern Tibet: an exhumed bright spot? Lithos 245, 147–160 (in this issue).

Wu, Y., Xu, M.J., Jin, Z.M., Fei, Y.W., Robinson, P.T., 2016. Experimental constraints on the formation of the Tibetan podiform chromitites. Lithos 245, 109–117 (in this issue).

Yang, J.S., Dobrzhinetskaya, L., Bai, W.J., Fang, Q.S., Rolbinson, P.T., Zhang, J.F., et al., 2007. Diamond- and coesite-bearing chromitites from the Luobusa ophiolite, Tibet. Geology 35, 875–878.

Yang, L.Q., Deng, J., Dilek, Y., Meng, J.Y., Gao, X., Santosh, M., Wang, D., Yan, H., 2016a. Melt source and evolution of I-type granitoids in the SE Tibetan Plateau: Late Cretaceous magmatism and mineralization driven by collision-induced transtensional tectonics. Lithos 245, 258–273 (in this issue).

Yang, Z.M., Hou, Z.Q., Chang, Z.S., Li, Q.Y., Liu, Y.F., Qu, H.C., Sun, M.Y., Xu, B., 2016b. Cospatial Eocene and Miocene granitoids from the Jiru Cu deposit in Tibet: petrogenesis and implications for the formation of collisional and postcollisional porphyry Cu systems in continental collision zones. Lithos 245, 243–257 (in this issue).

Yin, A., Harrison, T.M., 2000. Geologic evolution of the Himalayan–Tibetan orogen. Annual Review of Earth and Planetary Sciences 28, 211–280.

Zhang, K.J., Xia, B., Zhang, Y.X., Liu, W.L., Zeng, L., Li, J.F., Xu, L.F., 2014. Central Tibetan Meso-Tethyan oceanic plateau. Lithos 210–211, 278–288.

Zhang, C., Liu, C.Z., Wu, F.Y., Zhang, L.L., Ji, W.Q., 2016a. Geochemistry and geochronology of mafic rocks from the Luobusa ophiolite, South Tibet. Lithos 245, 93–108 (in this issue).

Zhang, Y., Niu, Y.L., Hu, Y., Liu, J.J., Ye, L., Kong, J.J., Duan, M., 2016b. The syncollisional granitoid magmatism and continental crust growth in the West Kunlun Orogen, China—Evidence from geochronology and geochemistry of the Arkarz pluton. Lithos 245, 191–204 (in this issue).

Zhou, M.F., Robinson, P.T., Malpas, J., Li, Z.J., 1996. Podiform chromitites in the Luobusa Ophiolite (Southern Tibet): implications for melt-rock interaction and chromite segregation in the upper mantle. Journal of Petrology 37, 3–21.

Zhu, D.C., Zhao, Z.D., Niu, Y.L., Mo, X.X., Chung, S.L., Hou, Z.Q., Wang, L.Q., Wu, F.Y., 2011. The Lhasa Terrane: record of a microcontinent and its histories of drift and growth. Earth and Planetary Science Letters 301, 241–255.

Zhu, D.C., Zhao, Z.D., Niu, Y.L., Dilek, Y., Hou, Z.Q., Mo, X.X., 2013. The origin and pre-Cenozoic evolution of the Tibetan Plateau. Gondwana Research 23, 1429–1454.

Zhu, D.C., Wang, Q., Zhao, Z.D., Chung, S.L., Cawood, P.A., Niu, Y.L., Liu, S.A., Wu, F.Y., Mo, X.X., 2015. Magmatic record of India–Asia collision. Scientific Reports 5, 14289. http://dx.doi.org/10.1038/srep14289.

Zhu, D.C., Li, S.M., Cawood, P.A., Wang, Q., Zhao, Z.D., Liu, S.A., Wang, L.Q., 2016. Assembly of the Lhasa and Qiangtang terranes in central Tibet by divergent double subduction. Lithos 245, 7–17 (in this issue).

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