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PII: S1367-9120(18)30240-2
DOI: https://doi.org/10.1016/j.jseaes.2018.06.017
Reference: JAES 3547

To appear in: Journal of Asian Earth Sciences

Received Date: 2 March 2018
Revised Date: 3 June 2018
Accepted Date: 4 June 2018

Please cite this article as: Yan, D-P., Zhou, Y., Qiu, L., Wells, M.L., Mu, H., Xu, C-G., The Longmenshan tectonic complex and adjacent tectonic units in the eastern margin of the Tibetan Plateau: A review, Journal of Asian Earth Sciences (2018), doi: https://doi.org/10.1016/j.jseaes.2018.06.017

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The Longmenshan tectonic complex and adjacent tectonic units in the eastern margin of the Tibetan Plateau: A review

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Abstract

The Longmenshan Tectonic Complex (LSTC), along the eastern margin of the Tibetan Plateau, the site of devastating earthquakes such as the magnitude 8.0 (Wenchuan) earthquake on 12 May 2008, preserves an exceptionally complete history of the tectonic evolution of the Yangtze block and its relations to adjacent tectonic units. Due to sequential tectonic superposition and tectonic reactivation, the tectonic nature of the LSTC, and in particularly the older history, has been profoundly debated and many different tectonic models have been proposed. Herein we summarize the current understandings of the major tectonic events that have shaped this important tectonic complex, highlighting problems left to be solved by future work, including:

(1) The nature and constraints for at least 6 regional tectonic events, i.e., building of the metamorphic basement (Ar), the Columbia/Nuna supercontinent (Pt1), the Rodinia supercontinent (Pt3), the Paleozoic passive continental margin (Pz), the Paleotethys orogeny (Mz) and the Neotethys orogeny (Kz); (2) Metamorphic basement exposures and their tectonic implications, including rock types and geochronological constraints for the Archean, Paleoproterozoic and Neoproterozoic basements; (3) Nature of the present LSTC and its affinity with adjacent tectonic units; (4) Consideration of the NE-striking Longmenshan thrust belt and arcuate-shape Yanyuan-Muli thrust belt as parts of a single tectonic feature; (5) Mountain-basin coupled systems recording past tectonic episodes.

We draw the following conclusions and tectonic models based on published research combined with our own recent studies: (1) The well preserved Archean Yudongzi gneiss group in the LSTC has a genetic affinity with the Kongling group, and thus belongs to the Yangtze block; (2) The Paleoproterozoic Hejiayan group, juxtaposed adjacent to the
Archean Yudongzi group, may represent a 2000-1800 Ma orogenic belt, which corresponds to the supercontinent Nuna/Columbia amalgamation event; (3) A Neoproterozoic trench-arc-basin system, which is reconstructed based on identification of a Neoproterozoic ophiolite complex, arc-type magmatic rock assemblages and volcaniclastic basinal deposits along the western margin of the Yangtze block and the LSTC, may represent the record of eastward subduction of the Neoproterozoic Mozambique oceanic lithosphere beneath the Yangtze block during the assembly of the Rodinia supercontinent; (4) A complete bidirectional Wilson cycle was reconstructed by the formation of the late Permian to the middle-late Triassic back-arc Ganze-Litang rift and ocean following the early Paleozoic Mianlue continental rift and ocean, and subsequent closure of the ocean basin by simultaneous bidirectional northward and southwestward subduction and later collision. This relatively uncommon bidirectional Wilson cycle might be attributed to the formation of the three-armed rift system in the eastern Paleotethys associated with the late Permian Emeishan Large Igneous Province in the LSTC; (5) A three-stage tectonic sequence of, in-sequence imbricate thrust in the LSTC during India-Eurasian collisional orogeny at 55-15 Ma, extrusion from 15-5 Ma and the plateau uplift since ~5 Ma resulting from lower crustal channel flow, is proposed for the formation of the present LSTC.

**Key Words:** Longmenshan belt, Columbia/Nuna supercontinent, Rodinia supercontinent, three-armed rift system, bidirectional Wilson cycle
1. Introduction

The Longmenshan Tectonic Complex (LSTC) along the eastern margin of the Tibetan Plateau is composed of the NE-striking Longmenshan thrust belt in the north and the arcuate-shaped Yanyuan-Muli thrust belt in the south (Figs. 1 and 2). The LSTC, which is bounded by the Triassic south Qinling-Dabie orogenic belt to the north, the Cenozoic eastern Tibet Plateau and the Triassic Songpan-Ganze terrane to the west, and the Yangtze block (including the western Sichuan foreland basin) to the east, extends ~800 km from northeast to southwest (Figs. 1 and 2). Active tectonics within the LSTC has been widely documented and is characterized by SE to SSE vergent overthrusting with repeated thrusting and denudation since 20 Ma (Arne et al., 1997; Ali et al., 2004), manifests recently by the devastating magnitude 8.0 Ms (Wenchuan) earthquake on 12 May 2008, the 7.0 Ms Lushan earthquake on 20 April 2013, and the 7.0 Ms Jiuzhaigou earthquake on 8 August 2017 (Burchfiel et al., 2008; Lu et al., 2008; Parsons et al., 2008; Hubbard and Shaw, 2009; Jia et al., 2010; Jin et al., 2010; Xu et al., 2016). Marking the present eastern margin of the Tibetan Plateau, the LSTC includes both the pre-collisional Longmenshan orogenic belt with defined tectonic domains of the hinterland belt, the foreland thrust belt and western Sichuan foreland basin (Xu et al., 1992), and the Cenozoic orogenic belt produced by the on-going collision between the Indian and Eurasian continents and associated gravitational relaxation (c.f., Arne et al., 1997; Clark and Royden, 2000; Meng et al., 2005; Lai et al., 2007; Burchfiel et al., 2008; Parsons et al., 2008).

The LSTC has experienced a rich and protracted tectonic history and many aspects of the history continue to be debated. Multiple tectonic episodes have been identified,
including: the formation of metamorphic basement, the assembly of supercontinent Rodinia, the breakup of Rodinia and the formation of the Sinian-Paleozoic passive continental margin, the Late Paleozoic continental rift and mantle plume, the Mesozoic Paleotethys orogenic cycle and the Cenozoic formation of the Tibetan Plateau during collision between the Indian and Eurasian continents, (e.g., SBGMR, 1991; Zhou et al., 2002; Yan et al., 2011; Li et al., 2016; Zheng et al., 2016). The superposition of younger deformation on older events (tectonic inheritance) has hindered interpretations of the older history. Nonetheless, efforts to look through the younger history have led to the development of new tectonic models for the LSTC (Yan et al., 2011, 2016). Moreover, new insights into the nature and superposition of these tectonic episodes has identified a number of scientific issues left to be answered:

1) Tectonic episodes: although at least six regional tectonic episodes have been identified, what characteristics define the major tectonic episodes and the deformational sequence? As is common in tectonic analysis, the superposition of younger events on the older ones has complicated studies of the older events.

2) Metamorphic basement: Are Archean rocks present within the LSTC? Metamorphic rocks of low metamorphic grade crop out along the margins of the South China Block, including the LSTC, have been determined to be of igneous origin with volcanic features and dated at 830-725 Ma (Li et al., 1995; Zhou et al., 2002; Zhao et al., 2011). However, the tectonic significance of these rocks has long been debated.

3) The LSTC: What is the importance of the Mesozoic shortening versus late Cenozoic shortening? Is the LSTC a foreland thrust belt of the Mesozoic Qinling-Dabie orogenic belt
and Songpan-Ganze terrane (Burchfiel et al., 1995; Chen and Wilson, 1996; Zhang et al., 2004; Jin et al., 2007)?

4) What are the differences and geological relationships between the NE-striking Longmenshan thrust belt in the north and the arcuate-shaped Yanyuan-Muli thrust belt in the south?

5) How do we establish the mountain belt-basin affinity between the LSTC and western Sichuan basin? Specifically, is the present LSTC, which couples with the western Sichuan foreland basin, inherited from the Paleo-Tethys domain?

In summary, great strides have been made in the past decades toward understanding the development of the LSTC, providing the basis for this review, in which we summarize results and consider possible interpretations. In this paper, we describe the main tectonic episodes, sequence, and their tectonic affinity with the adjacent terranes, and then reconstruct the tectonic evolution.

2. Tectonic division and geological setting

Here we describe six first-order tectonic units, identified based on their major tectonic boundaries, including sutures and regional faults, and their internal characteristics: (1) the South Qinling-Dabie orogenic belt and A’nyemaqen-Mianlue suture; (2) the Bikou terrane; (3) the Songpan-Ganze terrane; (4) the Yidun arc; (5) the Western Yangtze Block, and (6) the LSTC (Fig. 2 and Table 1).

The LSTC includes secondary-order tectonic units of the NE-striking Longmenshan thrust belt and arcuate Yanyuan-Muli thrust belt with several third-order tectonic units (Fig. 2; Table 1). The LSTC is separated from the Songpan-Ganze terrane by Maowen fault to
the west, and from the Yangtze block by Guanxian-Anxian fault and Muli fault to the east. To the north of the LSTC, the triangular Bikou terrane, is between the Longmenshan thrust belt and south Qinling-Dabie orogenic belt and is bounded by Qinchuan-Pingwu fault to the south and Fuya-Xueshan fault to the west. The terrane has an eastward wedge type merging into A’nyemaqen-Mianlue suture (Figs. 1 and 2) (Dewey et al., 1988; Burchfiel et al., 1989; Chang, 2000; Yin and Harrison, 2000; Zhang et al., 2004; Li et al., 2007; Xu J.F. et al., 2008; Ji et al., 2016). To the southwest, the Yanyuan-Muli thrust belt stretches west from the Xianshuihe fault across the southern Ganze-Litang suture and southern Yidun arc and is separated from the Qiangtang block by Jinshajiang suture (Fig. 2) (Yang et al., 2012; Cao et al., 2015; Li et al., 2018) (Figs. 1 and 2).

2.1 The South Qinling-Dabie orogenic belt and A’nyemaqen-Mianlue suture

The South Qinling-Dabie orogenic belt has an Archean crystalline basement of amphibolites and granulites and the Mesoproterozoic to the Early Neoproterozoic folded basement of greenschist and amphibolite facies metabasites and metasedimentary rocks. The cover sequences overlying the basement include Sinian tillite and dolomite, Paleozoic to Middle Triassic platform carbonate and clastic rocks, and locally, Cretaceous to Cenozoic conglomerates (Meng and Zhang, 2000), which are similar to the cover sequences of the Yangtze Block. Early Mesozoic granitoid plutons and dykes (220–180 Ma) are common in this belt (Zhou and Graham, 1996; Zhang et al., 2007).

The 1-5 km wide A’nyemaqen-Mianlue suture extends ~160 km from west to east along the boundary between the south Qinling-Dabie orogenic belt and the Yangtze Block (Feng et al., 1996; Li et al., 1999; Meng and Zhang, 2000; Zhang et al., 2002, 2005;
Ratschbacher et al., 2003; Dong et al., 2004; Zhang et al., 2004; Li et al., 2007; Yan et al., 2007; Xu J.F. et al., 2008; Yang et al., 2013; Ji et al., 2016) (Fig. 1). This suture dips north with variable dip angles and is composed of tectonic slices or blocks of the Late Triassic-Early Jurassic mélange. These blocks strongly sheared, contain ophiolitic material, arc volcanic rocks, the Paleozoic sedimentary rocks and Precambrian metamorphic rocks (Meng and Zhang, 2000; Xu J.F. et al., 2008). Radiolarians separated from the cherts and limestones associated with the ophiolitic blocks have yielded Early Carboniferous ages (Meng and Zhang, 2000). Metamorphic minerals in the ophiolites yield metamorphic ages of 208-242 Ma, using whole rock Sm-Nd, zircon U-Pb and mica Ar-Ar methods (Meng and Zhang, 2000; Zhang et al., 2004; Dong et al., 2011; Dong and Santosh, 2016; Ji et al., 2016; Qian et al., 2016). Thus, the A’nyemaqen-Mianlue suture marks a branch of the Paleo-Tethys ocean that closed in the Late Triassic during collision of the North China and South China blocks (Zhao and Coe, 1987; Meng and Zhang, 2000; Zhang et al., 2004; Yan et al., 2011).

2.2 Bikou terrane

The Bikou terrane includes basement of the Archean Yudongzi group, the Paleoproterozoic Hejiayan group, the Neoproterozoic Bikou and Hengdan groups, and a cover sequence of the Sinian and Paleozoic sedimentary rocks (GBGMR, 1989; SBGMR, 1989; SBGMR, 1991). The basement and cover sequences of the Bikou terrane share many similarities with those of the Western Yangtze Block (GBGMR, 1989; SBGMR, 1989; SBGMR, 1991) (Fig. 4).
The Bikou terrane has a structural style of a thrust complex with a thick-skinned thrust (Kzt) overprinting a cylindrical anticlinorium (Mzt). This anticlinorium has a westward plunging axis represented by the Archean Yudongzi group (Ar1) and the Paleoproterozoic Hejiayan group (Pt1t) in the eastern core, with the Neoproterozoic Bikou and Hengdan groups (Pt3t) and the Paleozoic (Pzt) strata occupying the western core and the limbs (Fig. 1). The NE-striking Qingchuan-Pingwu fault forms the southern boundary for ~200 km (Fig. 1), and dips NNW with variable angles. The Qingchuan-Pingwu fault combines with the Fuya-Xueshan fault to forming an arcuate-shaped thrust fault, which produced SSE-ward thrusting of the Bikou thrust complex during the Cenozoic Kzt (Fig. 2). In summary, the Bikou terrane shows similarities of rock successions and history of tectonic episodes to the LSTC, with tectonic episodes Ar1 to Kzt (Lu et al., 2010; Yan et al., 2011).

2.3 Songpan-Ganze terrane and Xianshuihe fault

The triangular shaped Songpan-Ganze terrane, which is covered by the Triassic flysch deposits in most of the regions, is different from most linear shaped orogenic belts on the Earth (Coney, 1970, 1972, 1980; Bruguier et al., 1997; Armstrong, 1982; Dewey, 1988; Andersen, 1998; Vanderhaeghe et al., 1999; Jolivet and Faccenna, 2000; Vanderhaeghe, 2012). Ages of more than one hundred silicic plutons in the Songpan-Ganze terrane range from the Permian to Cenozoic (GBGMR, 1989; SBGMR, 1991; Roger et al., 1995; Zhang, H.F. et al., 2006; Zhang, C.L., 2007; Yuan et al., 2010). These plutons are of variable composition and include calc-alkaline, alkaline, peralkaline and peraluminous rocks (Roger et al., 1995; Yuan et al., 2010).
The Xikang group in the Songpan-Ganze terrane has a ~7 km-thick Triassic flysch sequence that was intruded by a number of Mesozoic and Cenozoic granitic plutons (Fig. 1) (Rao et al., 1987; Mattauer et al., 1992; Nie et al., 1994; Zhou and Graham, 1996; Bruguier et al., 1997; Chang, 2000; Zhang et al., 2008; Zhou et al., 2008). This group is conformably underlain by the Paleozoic shallow marine sequences of the western passive continental margin of the Yangtze Block. The flysch sequence was mainly derived from the Qinling-Dabie orogenic belt, created by collision between the North China and South China blocks during the Triassic (Fig. 1) (SBGMR, 1991; Yin and Nie, 1993; Burchfiel, 1995; Zhou and Graham, 1996; Yan et al., 2003a, 2008a; Weislogel et al., 2006, 2010; Zhang et al., 2008). However, the flysch provenance has also been proposed from the Yidun arc in the west (Wang et al., 2013a, 2013b), and the Kunlun-Qiliang orogenic belt in the northwest (She et al., 2006).

The NW-striking Xianshuihe fault, a currently active, sinistral, strike-slip fault, cuts through the Songpan-Ganze terrane. The fault zone is composed of fault breccia, gouge and protomylonite, indicating brittle and brittle-ductile deformation (Wang et al., 1998; Wang and Burchfiel, 2000; Li et al., 2015; Shi et al., 2016). The 12-13 Ma Gonggashan granites intruded the fault zone during shearing, suggesting crustal channel flow initiated at the Miocene (Fig. 1) (Roger et al., 1995; Wang et al., 1998; Bai et al., 2010; Zhang et al., 2017).

### 2.4 Yidun arc and bilateral sutures

The Yidun arc is divided into Zhongza terrane (Zhongza micro-block) to the west and eastern arc on the basis of stratigraphy and lithology (Chen et al., 1987; Reid et al., 2005,
The Zhongza micro-block, which is composed of Paleozoic carbonates, intercalated mafic volcanic rocks and younger intrusions, is a micro-continental fragment rifted from the Yangtze Block during the Late Permian opening of the Ganze-Litang Ocean (Chen et al., 1987; Chang, 1997; Zhang et al., 1998; Reid et al., 2005, 2007; Cao et al., 2015) (Figs. 2 and 5). The Permian basalts exposed in the Zhongza micro-block have a composition similar to the Emeishan basalts, suggesting an extensional setting associated with the Emeishan mantle plume (Song et al., 2004; Xiao et al., 2008).

The eastern Yidun arc is composed of mudstones, volcanic rocks and intrusions, which were interpreted as the products of the westward subduction of the Ganze-Litang ocean (Mo et al., 1993, 1994; Hou et al., 2003; Reid et al., 2005; Cao et al., 2015). The volcanic rocks are mostly calc-alkaline andesites with basalt-rhyolite and shoshonitic assemblages (Mo et al., 1994). Numerous plutons with zircon U-Pb ages of 215-225 Ma (Reid et al., 2007; Weislogel, 2008) crop out along the western side of the Ganze-Litang suture. Further to the west, the 94-104 Ma plutons that intrude the eastern Yidun Arc have been interpreted as products of intra-continental extension (Fig. 5) (Reid et al., 2007).

Integrated volcanic and sedimentary sequences, felsic intrusions, deformational and metamorphic series, new tectonic model of the Paleo-Tethys Yidun arc was suggested (Cao et al., 2015) (Fig. 5). The initial eastward subduction of the Paleo-Jinshajiang ocean during the Late Permian produced the Yidun volcanic arc and a back-arc rift, which evolved into the Ganze-Litang ocean and continued magmatism in the Yidun volcanic and plutonic arc complex during the Early-Middle Triassic (Hou et al., 2003; Reid et al., 2007; Zhu et al., 2011; Cao et al., 2015) (Fig. 5A-B). The onset of the Ganze-Litang back-arc rift
was simultaneous with the formation of the Emeishan large igneous province (ELIP) (Song et al., 2004; Xiao et al., 2008). The collision of the Qiangtang Block with the Yidun arc during 241-224 Ma resulted in the Jinshanjiang orogen with ductile shear zones and Barrovian metamorphic belts, and the final closure of the Ganze-Litang ocean during 224-214 Ma, which probably produced the orogenic plateau and then transferred to extensional collapse (Fig. 5C-D) (Cao et al., 2015).

2.5 Western Yangtze Block (western Sichuan basin and Kangding complex)

The western Yangtze Block includes the western Sichuan foreland basin and the Kangding complex (Fig. 2), and comprises the Mesoproterozoic to Neoproterozoic basement rocks overlain by a late Neoproterozoic (the Nanhuan and Sinian) to Cenozoic cover sequence (Figs. 3 and 4). The basement rocks are exposed mainly along the Kangding complex, which are referred to as the Mesoproterozoic Hekou and Huili groups and the Neoproterozoic Yanbian group (Fig. 4) (Zhou et al., 2002a, 2006b; Zhao et al., 2007a, 2007b, 2008, 2009a, 2009b, 2010a, 2010b, 2013b; Sun et al., 2009). The Mesoproterozoic Hekou and Huili groups include marble, amphibolite, conglomerate, and schist, interbedded with basalt, with metamorphic grades of amphibolite to greenschist facies (SBGMR, 1991; Zhao et al., 2012). The Neoproterozoic Yanbian group of the Kangding complex consists of greywacke–slate succession and are included as part of the folded basement of the Yangtze Block (SBGMR, 1991; Sun et al., 2009). A thick (>10 km) cover sequence of the Nanhuan, Sinian to middle Triassic include clastic, carbonate, and meta-volcanic rocks (SBGMR, 1991; Mattauer, 1992; Xu et al., 1992; Yan et al., 2003b, 2006, 2009). The Upper Triassic, Jurassic, Cretaceous and Cenozoic strata, which
are entirely continental sequences, filled in the foreland basins during the Mesozoic and Cenozoic, respectively (HBGMR, 1990; SBGMR, 1991; Yan et al., 2011).

The western Sichuan basin, which is cut into two parts by the Xianshuihe sinistral strike-slip fault, is presently delimited between the foreland thrust belt to the west and the Longquanshan uplift to the east (Fig. 2). This basin has long been thought to represent the Cenozoic flexural basin corresponding to the SE-ward migration of the foreland thrust belt (Burchfiel et al., 1995; Yan et al., 2011). Recent results have revealed two phases of basin development for the western Sichuan Basin, i.e., a Late Triassic foreland basin overprinted and overlain by a Cenozoic foreland basin (Li et al., 2015a).

Striking north-south, the Kangding complex is a fault bounded block, 100 km long and 30 km wide (Figs. 1 and 2) (Zhou et al., 2002a). Numerous faults cut the complex and divide it into distinct rock slices. The eastern and western boundary faults are a series of the Mesozoic low-angle normal faults, whereas sinistral strike-slip faults present in the southwest and thrust faults in the west (Zhou et al., 2002a) (Fig. 2). Interaction of these faults were interpreted as a tranpressional restraining bend, giving rise to the rapid uplift and exhumation during the Cenozoic (Zhang et al., 2017).

2.6 Longmenshan tectonic complex

For purposes of clarity, we will divide the LSTC into the Longmenshan thrust belt to the north and Yanyuan-Muli thrust belt to the south (Table 1, Fig. 2). Both are separated by the Xianshuihe fault (Fig. 2).

2.6.1 Longmenshan thrust belt
The NE-striking Longmenshan thrust belt extends ~500 km from the NW-striking Xianshuihe fault in the southwest to Hanzhong (basin) in the northeast (Fig. 1). Three main NE-striking faults define the thrust belt: from hinterland to foreland, these are the Maowen fault, the Beichuan-Yingxiu fault, and the Guanxian-Anxian fault (Fig. 2).

Both the Beichuan-Yingxiu and Maowen thrust faults show dextral strike-slip kinematics (Kirby et al., 2002; Xu Z.Q. et al., 2008; Yan et al., 2008a, 2011). The Maowen fault is ca. 275 km long and dips 30-50ºNW. This fault is marked by a major zone of mylonite and breccia, which yielded ages of ~220 Ma by matching stratigraphic sequence and has been reactivated probably since the Late Miocene (Dirks et al., 1994; Burchfiel et al., 1995; Chen et al., 1995; Worley and Wilson, 1996; Arne et al., 1997; Xu Z.Q. et al., 2008; Tian et al., 2013; Wang et al., 2014; Zheng et al., 2016).

The Beichuan-Yingxiu fault extends for more than 350 km along a NE direction and dips 40º-60º NW (Burchfiel et al., 2008; Parsons et al., 2008; Jin et al., 2010; Zheng et al., 2016). This fault is also marked by a zone of mylonite and breccia. It has been active since ~230 Ma using glass matrix zircon U-Pb and mica ⁴⁰Ar/³⁹Ar methods (Dirks et al., 1994; Burchfiel et al., 1995; Chen et al., 1995; Worley and Wilson, 1996; Arne et al., 1997; Xu Z.Q. et al., 2008; Zheng et al., 2016). A rupture along the Beichuan-Yingxiu fault caused the 8.0 Ms Wenchuan earthquake on May 12, 2008 (Burchfiel et al., 2008; De Michele et al., 2010). The Beichuan-Yingxiu fault divides the Longmenshan thrust belt into a hinterland belt to the northwest and a foreland thrust belt to the southeast (Chen and Wilson, 1996; Worley and Wilson, 1996; Arne et al., 1997; Meng et al., 2005; Jin et
al., 2007; Yan et al., 2011). The hinterland and foreland thrust belts have remarkably different Mesozoic sequences and structural styles.

The Guanxian-Anxian thrust fault dips irregularly to the northwest with angles of 30-60°. This fault crosscuts the Late Triassic Xujiahe Formation through the Quaternary sediments, indicating the Cenozoic activity (SBGMR, 1991; Yong et al., 2003; Xu Z.Q. et al., 2008; Yan et al., 2008a, 2008b).

2.6.1.1 Hinterland belt

The hinterland belt is bounded by the Maowen and Beichuan-Yingxiu faults (Fig. 2). This belt is characterized by a number of domal complexes of metamorphic rocks, including the Jiaoziding, Pengguan-Xuelongbao, Baoxin and Danba uplifts (Figs. 2 and 3). The domal complexes consist of Mesoproterozoic to Neoproterozoic paragneiss, mica schist, graphite-bearing sillimanite-garnet gneiss (khondalite), amphibolite, marble, and quartzite (Huangshuihe group and its equivalent Bikou group and Kangding group), which correspond to the Huili and Yanbian groups of the basement of Yangtze Block (Fig. 4D) (Zhou et al., 2002a, 2002b, 2006a; Yan et al., 2003a, 2008a, 2008b; Sun et al., 2009).

Unconformably overlying the basement rocks along the domal complexes are the Sinian metaclastic rocks, dolomite and tillite. The Sinian is unconformably overlain by Cambrian-Ordovician volcanic rocks, carbonates, and cherts, Silurian phyllonite (known as the Maoxian group), Devonian quartzite (known as the Weiguan group), and the Carboniferous to the Permian carbonate rocks and basalts (SBGMR, 1991; Yan et al., 2008a, 2008b). Triassic strata, referred to as the Xikang group and composed mainly of a low-grade metamorphic flysch sequence, tectonically overlie the Paleozoic sequences (SBGMR, 1991; Yan et al., 2011) (Fig. 4D).
A detachment fault in the hinterland belt separates the Sinian and Paleozoic strata of greenschist facies in the hanging wall from footwall amphibolite facies rocks of the domal complexes (Figs. 1 and 2). Significant tectonic removal of the strata across the detachment indicates the presence of a large-magnitude low-angle normal fault that records SE-directed extension (Figs. 4D). This extension occurred during the Early to Middle Jurassic, which has been constrained by zircon U-Pb and $^{40}$Ar/$^{39}$Ar ages of 160-198 Ma (Zhou et al., 2002a, 2008; Yan et al., 2003a, 2008a, 2008b, 2011; Liu et al., 2008).

Alternative interpretations, however, have been presented for the formation and exhumation of the domal complexes based on variable geological data. The typical Danba domal complex in the southern Longmenshan thrust belt (Figs. 1 and 3) is interpreted as a regional scale antiform of the Neoproterozoic basement, overlain depositionally by the Paleozoic metasedimentary and metavolcanic rocks and Triassic turbidites (Xikang group) (Mattauer et al. 1992; Huang et al. 2003a, 2003b; Harrowfield and Wilson 2005; Zhou et al. 2008). Structurally above the domal complexes, the Triassic Xikang group and the Paleozoic sequence are generally affected by tight upright to close folds and related thrust faults coeval with the development of an E-W trending and steeply dipping axial planar foliation (Huang et al., 2003a, Harrowfield and Wilson, 2005, Weller et al., 2013, Jolivet et al. 2015; Billerot et al., 2017). This axial planar foliation is folded and replaced by a composite foliation that is common in the Danba domal complex (Harrowfield and Wilson, 2005). This complex is characterized by roughly concentric metamorphic isograds (biotite, garnet, staurolite, kyanite, sillimanite) delineating a Barrovian-type metamorphic gradient reaching partial melting as indicated by the presence of migmatites (Billerot et al., 2017). Most authors have proposed that the formation and exhumation of the domal complexes
occur dominantly in a context of transpression as a result of Lower Mesozoic collision between the South China and North China blocks (Mattauer et al., 1992; Huang et al. 2003a; Roger et al., 2004; Harrowfield and Wilson, 2005; Weller et al., 2013; Jolivet et al., 2015).

2.6.1.2 Foreland thrust belt

The foreland thrust belt between the Beichuan-Yingxiu fault and Guanxian-Anxian fault is represented by thrust-related structures and assemblages, including nappes, tectonic windows, fault-related folds and imbricate thrusts and duplexes (Fig. 6). The foreland thrust belt is sub-divided into the northern and southern segments. The northern segment is adjacent to the South Qinling-Dabie orogenic belt, whereas the southern segment is adjacent to the Xianshuihe strike-slip fault (Fig. 1). There is no clear geological boundary between them but rather a gradual transition of geological characteristics from north to south.

Metamorphic complexes, which are equivalent to the Huangshuihe group in the hinterland belt and the basement of the Yangtze Block, only crop out in the southern segment (Figs. 1 and 3). The cover sequences overlying the metamorphic complexes include the Sinian, Paleozoic and Triassic similar to that in the Western Yangtze Block (SBGMR, 1991; Yan et al., 2008a, 2008b; Yan et al., 2011) (Fig. 4F). The Triassic strata known as the Xujiahe Formation (T₃ₓ) are variably unconformably or structurally overlain by Jurassic to Cretaceous clastic rocks (Yong et al., 2003; Yan et al., 2011) (Fig. 4F).

2.6.2 Yanyuan-Muli thrust belt

The arcuate-shaped Yanyuan-Muli thrust belt in the south LSTC extends ~400 km from the NS-striking Jinshajiang suture in the southwest to the Xianshuihe fault in the
northeast (Figs. 1 and 2). This belt shares a similar tectonic framework to that of the Longmenshan thrust belt (Fig. 2). The Muli thrust fault has a sinuous trace for more than 400 km with a major salient and reentrant, and mainly dips 20°-65° NW (SBGMR, 1991; Yan et al., 2003a, Burchfiel et al., 2008; Parsons et al., 2008; Burchfiel et al., 2012; Zheng et al., 2016). This fault zone is marked by breccia and mylonite and has been estimated to have been active since the late Triassic (Xu Z.Q. et al., 1992; 2008; Yan et al., 1997, 2003a). The Muli fault divides the Yanyuan-Muli thrust belt into a hinterland belt to the northwest and a foreland thrust belt to the southeast (Fig. 2) (SBGMR, 1991; Xu et al., 1992; Yan et al., 1997, 2003a, 2011; Jin et al., 2007; Cao et al., 2015).

The hinterland belt is marked by a number of domal complexes, including the Taka, Jianglang, Changqiang and Qiasi domal complexes, which is similar to the hinterland belt of the Longmenshan thrust belt (Yan et al., 1997, 2003a) (Figs. 1 and 2). These domal complexes, which have rocks of the Liwu and Qiasi groups, are composed of mica schist, graphite-bearing sillimanite-garnet gneiss (khondalite), amphibolite, marble, and quartzite with Meso- to Neo-proterozoic ages; these rocks have been interpreted to represent the Yangtze basement (SBGMR, 1991; Yan et al., 2003a, 1997). A basement detachment fault with phyllonite and micro-breccia fault rocks was identified, separating the domal complexes from the Paleozoic sequence, that resulted in variable tectonic removal of the cover sequences (Yan et al., 2003a).

The cover sequences of both in the hinterland and foreland thrust belts have similar lithological compositions and include the Sinian, unconformity overlain by Cambrian-Ordovician volcanic rocks, carbonates, and cherts, Silurian phyllonite and basalt, Devonian quartzite, carbonate interlayered with basalt, and Carboniferous to Permian
carbonates and basalts (SBGMR, 1991; Xu et al., 1992; Yan et al., 2003a, 2008a, 2008b; Song et al., 2004) (Fig. 4E). The Triassic strata disconformity overlie the Paleozoic strata and consist of carbonate and clastic rocks, unconformably or structurally overlain by Jurassic to Cretaceous clastic rocks (SBGMR, 1991; Yong et al., 2003; Wang et al., 2013a) (Fig. 4E). The Paleogene and Neogene sporadically crop out within the intermountain and piedmont basins and are mainly coarse clastic rocks, including loosely cemented conglomerates and coarse sandstones with thin layers of black mudstone (Fig. 4E) (Zhang Y.X., 2013).

3. Archean meta-volcanic and intrusive rocks (Arv)

The Archean metamorphic rocks have only been reported in the northernmost LSTC, represented by the Yudongzi group (Arv) (Figs. 1 and 7). The Yudongzi group (Arv), located in the northwestern of the Yangtze Block and northeastern margin of Bikou terrane, is composed of the Yudongzi gneiss group, the Longwanggou gneissic intrusion (ArI) and the Huangniping gneissic intrusion (Arh) (Fig. 7). The group consists of amphibolites, leptite, quartzite, banded iron formation (BIF), greenschist and schist in association with TTG gneiss and leucogranite (Qin et al., 1990, 1994; Zhang et al., 2001). The Yudongzi group, together with the Proterozoic to the Devonian rocks, was sliced and extruded along the A’nyemaqen-Mianlue tectonic melange and cut by ductile shear zones with NWW-SEE striking penetrative foliations (Fig. 7). The Yudongzi group experienced greenschist facies to epidote-amphibolite facies metamorphism with prograde metamorphic mineral assemblage of amphibole + biotite + muscovite, indicating temperatures of ~500°C to ~800°C (Zhou et al., in preparation).
The Yudongzi gneiss group was intruded by the coeval Longwanggou and Huangniping gneissic intrusions, which yielded zircon rim U-Pb age of ~2600 Ma (Zhou et al., 2018, in preparation). This age result is consistent with that of a whole-rock Sm–Nd isochron age of 2688 ± 100 Ma for 13 amphibolite samples (meta-volcanic rocks) and a zircon upper intercept age of 2693 ± 9 Ma for the gneissic leucogranite that intruded the Yudongzi group (Zhang et al., 2001). Although further isotopic dating is still needed (Zhao and Cawood, 2012), the Yudongzi group belongs to the Neoarchean, which defines the Archean tectonic event (Ar$_t$).

4. Paleoproterozoic and Columbia tectonic event (Pt$_{1t}$)

The Paleoproterozoic metamorphic Hejiayan group crops out southeast of the Yudongzi group in the northernmost LSTC (Fig. 7). The Hejiayan group contains schist series of chlorite-albite schist, epidote-chlorite-albite schist, actinolite epidote schist and sercite-quartz schist, and Heimulin foliated ultrabasic rocks. All these rocks experienced greenschist-facies metamorphism. The protolith assemblages are probably island-arc basaltic volcanic rocks and ultrabasic intrusions, which have yielded a zircon core U-Pb age of ~1933 Ma (GRT-SBGMR, 1996; Zhou et al., in preparation). This rock assemblage, which are blocks in a melange matrix with components of siliceous, pillow basalts, peridotite and serpentinite, indicates a Precambrian ophiolite melange (GRT-SBGMR, 1996; Zhang et al., 2001) (Fig. 7). Thus the ~1933 Ma Hejiayan volcanic rocks imply a tectonic episode of volcanic arc construction in the Paleoproterozoic (Pt$_{1t}$).

The supercontinent Nuna shares a common configuration with the core elements of Laurentia and Siberia (Zhao et al., 2002, 2011; Evans and Mitchell, 2011; Zhang et al.,
The exotic Yangtze Block accreted to the Rae Craton at 2400–2300 Ma and was involved in the assembly of Nuna, along with Laurentia and Siberia (Wang et al., 2016). These events of amalgamation in the interval 2320-1800 Ma, identified in the southwestern Yangtze Block and northern Vietnam, include metamorphic events at 2030–1950 Ma and 1850-1800 Ma in the Thelon and Akitkan orogens of northwest Laurentia and Siberia, respectively (Wang et al., 2016).

The Hejiayan group in the northmost of the LSTC has composition of volcanic arcs and ophiolitic melange is probably associated with orogenesis at continental collisional margins during the Pt_{11}. The age at ~1933 Ma is synchronous with the Nuna assemblage orogens occurred in the southwestern Yangtze Block. Although geochemistry and age constraints are still under research, the spatial and temporal link between the southwestern Yangtze Block and the northern LSTC probably define the Pt_{11} of the Nuna assemblage orogen along the western Yangtze Block (Fig. 8).

5. Neoproterozoic metamorphic basement and Rodinia tectonic event (Pt_{3t})

The Neoproterozoic basement is well exposed in the LSTC and its adjacent western Yangtze Block (Fig. 3). The basement is exposed along the domal metamorphic complexes, including Bikou terrane, Jiaoziding, Penguan-Xuelongbao, Baoxin, Danba, Jianglang (Taka), Changqiang and Qiasi domal complexes in the hinterland belt of the LSTC, and the Kangding complex in the western Yangtze Block (Zhao et al., 1994; Zhou et al., 2002a; Yan et al., 2003a, 2008a, 2008b) (Fig. 3).

During the past few decades, many studies have focused on the geology, petrology, geochemistry and geochronology of the intrusions, as well as the metamorphic, volcanic
and sedimentary rocks within the domal complexes in the LSTC and western Yangtze Block (Pei et al., 2007, 2009; Zhou et al., 2002a, 2006a; Druschke et al., 2006; Xiao et al., 2007; Zhao et al., 2007, 2008, 2009a, 2009b, 2013a, 2013b; Yan et al., 2008a, 2008b; Sun et al., 2009). Although a variety of tectonic settings and genesis of these rocks represented due to the divergence of views, some commonalities are reached including tectonic settings (Pt3l) of ophiolite complexes, magmatic arcs, backarc and forearc basins (Fig. 9).

5.1 Ophiolite complex

Tens of small-scale bodies of hornblende gabbros and olivine gabbros have been distinguished within the metamorphic complexes (SBGMR, 1991; Zhao et al., 2017) (Fig. 1). For example, the recently reported Shimian ophiolite, including gabbro and serpentinized peridotite intruded by mafic dikes within the Kangding complex has characteristics of a supra-subduction zone ophiolite complex (Sun and Vuagnat, 1992; Li et al., 1997; Zhao et al., 2017). The peridotite has low REE and trace element contents, suggesting a source of depleted mantle. Chromites from the peridotite have low contents of TiO2 and Fe2O3, with moderate Cr/(Cr+Al) and Mg/(Mg+Fe2⁺) ratios (Zhao et al., 2017). These spinel compositions associated with strong melt depletions are similar to those of supra-subduction zone peridotites. The mafic dikes and gabbros are chemically similar to MORB-affinity tholeiitic basalts and boninite-series volcanic rocks in the Izu-Bonin-Mariana arc system, and are dated at ~800 Ma by zircon U-Pb (Dilek et al., 2008; Kusky et al., 2011; Whattam and Stern, 2011; Zhao et al., 2017). Although a number of similar mafic rock assemblages exposed along the LSTC have yet to receive detailed study, the serpentinized peridotite, mafic dikes and gabbros, together with their geochemistry, define
a supra-subduction zone ophiolite complex, and record the accretion of oceanic lithosphere along a trench to the western Yangtze Block (Zhao et al., 2017) (Fig. 10A-D).

5.2 Arc magmatic signatures

The Neoproterozoic granitoid intrusions in the LSTC, from northeast to southwest, are represented by the intrusions within the domal complexes of the Bikou terrane, Jiaoziding, Xuelongbao-Pengguan, Baoxing and Kangding (Fig. 3) (Zhou et al., 2002a, 2002b, 2006a; Druschke et al., 2006; Xiao et al., 2007; Zhao et al., 2007, 2009a, 2009b; Yan et al., 2008b; Liu et al., 2009a; Pei et al., 2009; Sun et al., 2009). Three rock types, adakites, mafic intrusions and granitic intrusions, have been identified.

Adakitic plutons include the ones within the Xuelongbao complex, Datian of the Danba complex, and the Huatan and Mopanshan plutons of the Kangding complex (insert in Fig. 3). Pluton within the Xuelongbao domal complex in the middle of the Longmenshan thrust belt are composed of tonalite and granodiorite with adakitic affinity, and display high Sr contents and Sr/Y ratios, depletion in HREE, variable enrichment in LREE, and positive Sr and negative Nb and Ti anomalies in the primitive mantle-normalized trace element spider diagram (Zhou et al., 2002a, 2006a; Zhao et al., 2017). These geochemical characteristics suggest derivation from adakite-like magmas (Zhou et al., 2006b; Zhao and Zhou, 2007a) (Fig. 9A). The pluton has been dated at 748 ± 7 Ma using SHRIMP zircon U–Pb (Zhou et al., 2006b). In the Mianning–Xichang area, south of the Kangding complex, the Mopanshan adakite is characterized by low MgO, Cr and Ni contents, high Rb/Sr and Sr/Y ratios and negative $\varepsilon_{Nd(t)}$ values, and was dated at 782 ± 6 Ma using LA-ICPMS zircon methods (Huang et al., 2009).
Taking together the geochemical and isotopic characteristics, the presence of relict zircons (1.16–0.83 Ga) and the Mesoproterozoic zircon Hf model ages (1.06–1.27 Ga), the adakites could be interpreted as derived from melting of a thickened continental lower crust (Huang et al., 2009) or melting of a subducted oceanic slab. Both possibilities are compatible with a compressional tectonic setting, ruling out an intra-continental extensional setting. Considering that the adakites exposed within Xuelongbao, Danba and Kangding complexes occur roughly along the trend of the LSTC in the western margin of the Yangtze Block (Zhou et al., 2006b; Zhao and Zhou, 2007a) (Fig. 3 and insert), we consider that these adakitic rocks are most likely the melting products of a subducted oceanic slab, together with evidences of arc-sedimentary sequences, normal-arc granites and arc-related mafic-ultramafic intrusions, suggesting an eastward supra-subduction tectonics along the western margin of the Yangtze Block (Zhao and Zhou, 2007b) (Fig. 9A).

The mafic intrusions are generally exposed and mixed cropout with granitic plutons (Fig. 3). The Baoxing domal complex is located in the south segment of the Longmenshan thrust belt and consists mainly of metamorphic gabbroic, dioritic gneisses, tonalitic and granodioritic gneisses, and massive monzogranites. The gabbros and gabbrodiorites are characterized by low SiO$_2$ contents, high Mg# values and Cr, Co, and Ni contents, significant enrichment in LREE and LILE, depletion in HFSE (e.g., Nb, Ta, Zr, and Hf) and positive zircon $\varepsilon_{\text{Hf}}$ values (Zhao et al., 2007a; Meng et al., 2015). These gabbroic rocks were proposed to derive from partial melting of depleted lithospheric mantle that had been metasomatized by subduction-derived fluids or melts (Zhao and Zhou, 2007a; Meng et al., 2015) (Fig. 9B). The tonalite, granodiorite and monzogranite exhibit enrichment in Rb, Ba,
Th, and Pb and depletion in Nb, Ta, and Ti, and have low Sr/Y and (La/Yb)_N ratios and high Y and Yb contents, and positive ε_{Hf} values, indicating a juvenile crust source derived from partial melting of metamorphic basalts or metagreywacks in the lower crust (Meng et al., 2015). The Baoxing plutonic complex were dated at 848 ± 4 Ma for gabbro, 799 ± 5 Ma and 802 ± 6 Ma for gabbrodiorite, and 773 ± 5 Ma and 769 ± 5 Ma for granite, using LA-ICPMS zircon U–Pb method (Meng et al., 2015).

In the Yanbian region of the south Kangding complex, the Tongde plutonic complex intruded into the Kangding metamorphic complex, and consists of diorite, quartz diorite and minor gabbro, showing arc-type geochemistry and calc-alkaline affinities. The Tongde pluton was dated at 825 ± 7 Ma and 820-810 Ma by the SHRIMP U–Pb zircon method (Li Z.X. et al., 2003; Munteanu et al., 2010). Both the Gaojiacun and Lengshuiqing mafic intrusions, which intrude the Tongde pluton, show pronounced negative Nb–Ta and Zr–Hf anomalies, high ε_{Nd(T)} values (+1.5 to +6.0), and initial 87Sr/86Sr ratios of 0.705–0.706, suggesting a typical arc assemblage formed on the western edge of the Yangtze Block (Zhou et al., 2006b; Zhao and Zhou, 2007a). Both mafic intrusions were dated at 812 ± 3 and 806 ± 4 Ma, respectively, by the SHRIMP zircon U–Pb method (Zhou et al., 2006b). Additionally, some mafic dykes in the Yanbian area of the south Kangding complex show OIB and MORB-like geochemical affinities, which were dated at 792 ± 13 and 761 ± 14 Ma, respectively, by the SHRIMP zircon U–Pb method (Zhu W.G. et al., 2008).

In addition, the hornblende and olivine gabbroic intrusions that crop out in the southern the Kangding complex have tholeiitic and arc-like geochemical compositions, and show obvious depletion of Nb, Ta and Ti, and relatively low ε_{Nd(T)} values (−0.12 to −1.73) with variable 87Sr/86Sr ratios (0.7045–0.7075) (Zhao and Zhou, 2007a). These small-scale
intrusions were dated at 738 ± 23 and 746 ± 10 Ma, respectively, using SHRIMP zircon U-Pb geochronology (Zhao and Zhou, 2007a).

Large scale granitic plutons include the Jiaoziding of the northern segment and the Pengguan in the southern segment of the LSTC, and the Kangding pluton in the western Yangtze Block (Fig. 3). The intrusion within the Jiaoziding domal complex shows enrichment in LREE, depletion in Ta, Nb and Ti, and enrichment in Rb, Ba and Sr, which are compatible with peraluminous and S-type granite (Pei et al., 2009). Using SHRIMP zircon U–Pb methods, the foliated granite and massive granite within this pluton were dated at 793 ± 11 Ma and 792 ± 11 Ma, respectively (Pei et al., 2009). These rocks were thought to be the result of crustal thickening caused by active continental margin subduction or arc–continent collisional orogeny during the Neoproterozoic in the western margin of the Yangtze Block (Pei et al., 2009).

Plutons within the Pengguan domal complex, which are located in the southern segment of the LSTC (Fig. 3), are dominantly composed of monzonitic granite, granodiorite, tonalite and diorite showing calc-alkaline affinity and metaluminous to weakly peraluminous geochemical compositions. These plutons have a relative low abundance of REE, enrichment of Rb, Sr, Ba and K, and depletion of Nb, Ta, P and Y, suggesting formation through mixing of underplated mantle-derived magma and the melting of lower crust in a subducted-related volcanic arc environment (Yan et al., 2008b; Zhang et al., 2008) (Fig. 9C). The granites were dated at 809 ± 3 and 844 ± 6 Ma using LA-ICP-MS zircon U-Pb geochronology (Yan et al., 2008b).

The Kangding metamorphic complex, as well as the Danba domal complex with its associated granitoids, has traditionally been considered as a part of the Archean
basement of the Yangtze Block (SBGMR, 1991). The gneissic granitoids within the Kangding and Danba complexes are dominantly tonalite, granodiorite and monzogranite, and are enriched in LREE with positive $\varepsilon_{\text{Nd}}(t)$ values, and significantly depleted in Nb, Ta, P and Ti, suggesting a subduction-related setting (Zhou et al., 2002a, 2002b). The Kangding gneissic granites were dated at 797 ± 10, 795 ± 13 Ma, 796 ± 14 Ma and 764 ± 9 Ma, whereas the protolith of the Danba gneissic complex was dated at 824 ± 14 Ma, and the monzogranite within the Danba complex was dated at 826 ± 29 and 767 ± 24 Ma, respectively, by SHRIMP U–Pb zircon (Zhou et al., 2002a, 2002b; Liu S.W. et al., 2009b).

Integrating the elemental and isotopic geochemistry and the age results, the hornblende gabbros, and mafic intrusions were probably derived from a source strongly modified by subducted slab fluids, whereas the olivine gabbros came from a mantle source modified by subducted slab melts during the Neoproterozoic (Zhao and Zhou, 2007a) (Fig. 9B). Geochemical data and isotopic results reveal the granitic plutons have a TTG composition (insert in Fig. 3) with magmatic arc signatures. The similar ages for the deformed granite and massive granite suggest that the granitoids in the Longmenshan tectonic complex and Kangding region were formed in a compressional tectonic setting, which most likely was a magmatic arc above a subduction zone during the Neoproterozoic (830 to 760 Ma) (Zhou et al., 2002a, 2002b; Zhou et al., 2006b; Zhu W.G. et al., 2008) (Fig. 9C).

5.3 Fore-arc and back-arc deposits

The Bikou terrane in the northern LSTC consists of a volcanic assemblage of the Bikou group, and a correlative volcanic clastic turbidite sequence of the Hengdan group with lower amphibolite to middle greenschist facies metamorphism (Figs 1 and 2). Detrital
zircon studies of the Hengdan group have found euhedral, volcanic grains varying from ca. 850 to 700 Ma with a peak near 770 Ma (Druschke et al., 2006). The Hengdan group contains a thick succession of coarsening-upward volcaniclastic marine sediments, which has provenance from the volcanic Bikou group to the south, and has been interpreted to represent a fore-arc basin during the Neoproterozoic southward subduction beneath the Yangtze Block (Druschke et al., 2006).

The Yanbian group in the south Kangding complex is a well-preserved Neoproterozoic volcanic-sedimentary sequence (SBGMR, 1991). This group consists of a lower sequence of basaltic lavas with a thickness of ~1500 m, and an upper sequence of flysch deposits with a thickness of ~3500 m. The flysch sequence contains typical deep marine turbidites consisting mainly of fine-grained volcaniclastic sandstones and mudstones, indicating a submarine fan depositional system (Sun et al., 2008a, 2008b, 2009). The lavas have variable bulk-rock compositions with SiO$_2$ ranges from 45.3 to 50.7 wt%, Al$_2$O$_3$ from 12.8 to 16.8 wt%, and TiO$_2$ from 1.3 to 2.9 wt%. Although the incompatible trace elements, including Nb, Ta, Zr, Hf, Ti, and HREE, are similar to those of MORB, the lavas show features of island-arc tholeiites with pronounced enrichments in Rb, Ba, U, Sr, and Pb. These lavas are characterized by low initial $^{87}$Sr/$^{86}$Sr ratios (0.7030 to 0.7040) and strongly depleted $\varepsilon_{Nd(t)}$ values (+3.8 to +8.0) (Sun et al., 2008a, 2008b, 2009). The sandstones contain abundant feldspar, lithic fragments of andesitic and felsic volcanic rock, minor amount of quartz and have an average composition of Q (16%) F (35%) and L (49%), suggesting a proximal source and an undissected to arc setting. The sandstones and mudstones have intermediate SiO$_2$/Al$_2$O$_3$ (typically 3-6), high Fe$_2$O$_3$ + MgO contents (5-12 wt%), and moderate to high K$_2$O/Na$_2$O ratios (generally 0.1-1 and 1-10 for
sandstones and mudstones, respectively) (Sun et al., 2007, 2008a, 2009). These rocks have strong negative Nb-Ta anomalies, slight depletion of Zr-Hf, La and Th, but moderate enrichment of V, Cr, Ni, and Sc. They show LREE enrichment (La/Yb-N = 5.3-7.4) with flat HREE, and pronounced negative Eu anomalies (Eu/Eu-center dot = 0.6-0.74) in chondrite-normalized REE patterns, similar to post-Archean shales (Sun et al., 2008a, 2008b).

The age of the Yanbian group is constrained by detrital zircon geochronology and the age of a cross cutting pluton. The Yanbian group has detrital zircon ages from ca. 865 Ma to 1000 Ma with two peaks at ca. 900 Ma and 920 Ma, and is intruded by the 860 Ma Guandaoshan dioritic pluton, constraining its youngest depositional age at ca. 865 Ma. Geochemical data of the group suggests an back-arc basin setting and intermediate-felsic volcanic source, which is consistent with a back-arc basin scenario for the basaltic lavas in the lower Yanbian group (Sun et al., 2007, 2008a, 2009).

Integrating the characteristics of the ophiolite, adakitic rocks, mafic rocks, granitic intrusions and deposits within the metamorphic complexes (Fig. 3), a tectonic configuration of the Neoproterozoic trench-arc-basin system can be established (Fig. 9B). The trench is revealed by the newly distinguished Shimian ophiolitic melange, and a magmatic arc including mafic, adakitic and granitic rocks might extend more than 500 km from Hannan in the north LSTC to the south of Kangding complex on the western margin of the Yangtze block; and local preserved deposits support the presence of back- and fore-arc basins (Fig. 9D).

The Proterozoic trench-arc-basin system along the LSTC and western margin of the Yangtze block suggests that the western margin of the Yangtze block was an active
margin in the Rodinia reconstruction (Yan et al., 2002; Zheng et al., 2006). This system has geochemical, isotopic and geochronological similarities to the northeastern Madagascar, Seychelles island and Malani in India (Tucker et al., 2001), which probably represent a native Andean-type margin on the edge of Rodinia (Yan et al., 2002; Zhou et al., 2002b; Zhao et al., 2017). We therefore correlate the western margin of the Yangtze block with the northeastern margin of the India Plate which had an active arc above an eastward subduction zone in the Neoproterozoic time (Yan et al., 2003a; Zheng Y.F., 2006) (Fig. 9E).

The dawn of 725-750 Ma rift, which corresponds to the formation of Nanhua basin within the Yangtze block, might represent initial break up of the Rodinia supercontinent (Fig. 9E). However, the Nanhua sequences were previously distinguished only within the Yangtze block (Fig. 4G). The equivalent strata in the LSTC have not been identified.

6 Sinian to Paleozoic passive continental margin (Pz₁)

The Sinian (Late Neoproterozoic, 630-542 Ma) to Paleozoic sedimentary sequences represent a well recognized passive continental margin Pz₁¹ (SBGMR, 1991; Mattauer et al., 1992; Xu et al., 1992;). This margin was stable until the development of a super-plume, effusive basaltic volcanism of the Emeishan basalt, and localized extension Pz₁² during the late Permian.

Sinian to Carboniferous passive continental margin and formation of the Mianlue ocean (Pz₁¹)

The Sinian rock record includes the Doushantuo and Dengying formations, which unconformably cover the metamorphic basement (metamorphic complex). The
Doushantuo formation is well exposed in the LSTC and its adjacent regions but has not been documented in the Songpan-Ganze terrane (Fig. 4). This formation includes black shale, mudstone, marlstone and sandstone with local phosphorite (SBGMR, 1991; Huang et al., 2003b; Roger et al., 2010; Zhang et al., 2017). In general, clastic grains in Sinian rocks of the LSTC and the western Yangtze block are coarser than those in the South Qinling-Dabie orogenic belt and Bikou terrane (comparing Fig. 4D-G with Fig. 4A-B), indicating littoral to shallow sea clastic assemblage with westward deepening of the sea water (SBGMR, 1991).

The Dengying formation conformably covers the Doushantuo formation, with widespread outcrops in the LSTC and western Yangtze block. This formation is composed of dolomite and dolomitic limestone with bedded chert bands and locally phosphorite (SBGMR, 1991; Huang et al., 2003b; Roger et al., 2010) (Fig. 4). The rock assemblage represents a transition from carbonate platform marginal facies to restricted platform facies (SBGMR, 1991).

Cambrian-Ordovician strata unconformably overlie Sinian rocks in the LSTC and its adjacent South Qinling-Dabie orogenic belt and western Yangtze block. The Cambrian-Ordovician strata include interlayers of carbonite and clastic rocks (i.e., sandstones, siltstones and shales), indicating shallow sea facies. Sedimentary or tectonic omission of most of the Cambrian-Ordovician strata around the domal complexes was interpreted as a north-south striking paleohigh belt, i.e., the Xikang-Yunnan axis from the LSTC to Kangding complex belt (Huang, 1947; SBGMR, 1991) (Fig. 4).

The Silurian is represented by muddy and sandy flysch with limestone known as the Maoxian group in the Bikou terrane, Songpan-Ganze terrane and hinterland belt of the
LSTC (Fig. 4B-D), and shallow marine lime-mud flat in the South Qinling-Dabie orogenic belt, foreland belt of the LSTC and western Yangtze block (Fig. 4A, F-G). The rock assemblages indicate a westward deepening from stable shallow marine platform facies to relative deep-water deposits, perhaps indicating the initial development of the Songpan-Ganze ocean (SBGMR, 1991) (Fig. 4).

Throughout the LSTC and its adjacent regions, Devonian and Carboniferous strata are well exposed with carbonates dominant, except where covered by the Triassic flysch in most of the the Songpan-Ganze terrane (Fig. 4). Lithofacies and sedimentary sequence reveal a westward deepening of marine facies, from lime-mud flat and algal flat facies in the foreland thrust belt to shallow sea or slope facies in the hinterland belt of the LSTC, to deep sea facies in the Songpan-Ganze terrane (SBGMR, 1991) (Fig. 4).

To the northmost of the LSTC, the Paleozoic Mianlue ocean is represented by a number of ophiolite suites, ophiolitic melange and oceanic island-arc volcanic rocks identified along the Mianlue suture (Fig. 1). These rock assemblages, which are distributed in the Nanping-Kangxian-Lueyang-Mianxian, have been widely investigated (Li et al., 1996; Lai and Yang, 1997; Lai et al., 2000, 2004; Xu et al., 2000a, b; Zhang et al., 2004; Dong et al., 2011). Details for the rock assemblage are available in Zhang et al. (2004) and Dong et al. (2011).

The initial spreading of the Mianlue ocean is represented by bimodal volcanic rocks that consist of meta-basalts, dacites and rhyolites with enrichment of LREE, Th, U, Sr and Zr and minor Ti negative anomalies in the west of Lueyang along the Mianlue suture (Li et al., 1996; Lai et al., 1998; Xu et al., 2000a, b; Zhang et al., 2004) (Fig. 2). Petrological and geochemical features indicate the rocks were derived either in a rift (Li et al., 1996) or in a
transitional setting where an initial continent rift was expanding into a mature oceanic basin (Zhang et al., 2004). Based on a summary of the petrological, geochemical and geochronological results, initial rifting and formation of the juvenile ocean may have occurred in the Devonian to the Carboniferous (Dong et al., 2011) (Fig. 4).

Integrating the above results of sedimentary facies and rock assemblages, the shallow sea deposits along the LSTC imply a stable passive continental margin from the Sinian to the Carboniferous. To the northmost of the LSTC the development of the Mianlue ocean initiated in the Devonian to Carboniferous (Roger et al., 2010) (Fig. 4). We then define this tectonic event as the Paleozoic tectonic event Pz₁.

6.2 Permian rift, Emeishan basalt and mature Mianlue ocean (Pz₂)

Permian rocks are widespread in the LSTC and its adjacent regions, with carbonate strata roughly equivalent to that in the western Yangtze block. These rocks include carbonates of the Liangshan, Qixia, Maokou, Wujiaoping and Changxing formations, from lower to upper (Fig. 4). The Emeishan basalt occurs between the Maokou and Wujiaoping formations and is exposed in the southern Sonpan-Ganze terrane and Yidun arc, south of the LSTC and western Yangtze block (SBGMR, 1991; Song et al., 2004). The Emeishan basalts, previously named as the Emeishan Large Igneous Province (ELIP), have been interpreted as products of a mantle plume (e.g. Zhou et al., 2000; Xu et al., 2001; Lo et al., 2002; Li et al., 2015b; Deng et al., 2016). Basalt assemblages of the ELIP have been dated at 260-250 Ma using LA-ICPMS and SHRIMP zircon U-Pb methods (Xu et al., 2001; Lo et al., 2002; Song et al., 2004; Shellnutt and Zhou, 2007; Jian et al., 2009; Wang et al., 2014; Li et al., 2015b; Li et al., 2016).
The center of the mantle plume has been determined by the recognition of a 1 km-scale domal uplift during initial Emeishan eruptions (He et al., 2003a, 2003b, 2006, 2009, 2010). The overall radiating patterns of mafic dyke swarms of the ELIP in the Yongren area, Yunnan province, was thought to coincide with the maximum pre-eruptive domal uplift and close to the high-temperature picrites (Li et al., 2015).

Basalts within the ELIP are geochemically divided into low-Ti and high-Ti types (Xu et al., 2001). The parent magmas of the low-Ti basalts, which were generated by higher degrees of partial melting (16%) of a distinct mantle source ($\epsilon_{\text{Nd}}(t) = +2$, $^{87}\text{Sr}/^{86}\text{Sr}(t) = 0.705$) around the spinel–garnet transition zone, record the main episode of flood basalt emplacement (Xu et al., 2001). The eruption of low-Ti type magmas is concentrated in the lower part of the basalt column. The association of the eruption of the low-Ti basalts within incipient extensional features, which are lacking in the higher parts of the basalt succession, along the southern LSTC might imply an aulacogen along the LSTC (Meng et al., 2005) (Fig. 10).

The less abundant high-Ti basalts overlying the low-Ti basalts were generated by low degrees of partial melting (1.5%) of a mantle source that has $\epsilon_{\text{Nd}}(t)$ of $\sim +5$ and $^{87}\text{Sr}/^{86}\text{Sr}(t)$ of $\sim 0.704$ in the garnet stability field (Xu et al., 2001). The evolution from low-Ti basalts of higher degrees of partial melting of the mantle to high-Ti lavas with lower degrees of partial melting imply that it starts out with a thicker lithosphere and lower geotherm, and then evolves with thinner lithosphere and higher geotherm (Xu et al., 2001).

At least three geochemical types of A-type granites are spatially and temporally associated with the ELIP basalts: the Panzhihua and Taihe peralkalines granites, the Woshui metaluminous syenites and the Ailanghe peraluminous granite. These granitoids
have found along the NS-striking Panzhihua rift (Shellnut and Zhou, 2007). The 260 Ma peralkalines granites in Panzhihua and Taihe have ASI of 0.76–1.12, Na+K/Al of 0.78–1.2 and high Fe* values (0.92–0.99) with negative Eu anomalies (Eu/Eu*=0.22–0.98). The 260 Ma metaluminous syenites in Woshui have ASI of 0.84–1.0, Na+K/Al of 0.91–1.01 and moderately high Fe* (0.79–0.81) and positive Eu anomalies (Eu/Eu*=0.82–1.91). Both the peralkaline and metaluminous rocks have mantle isotopic signatures (εNd(T)=+1.3–+3.2) and were probably derived from the ELIP mantle plume source. The 251 Ma peraluminous granites in Ailanghe have ASI of 0.97–1.29, high Fe* values (0.82–0.91) and negative Eu anomalies (Eu/Eu*=0.10–0.37) with crustal isotopic signature (εNd(T)=−5.7–−6.7), indicating possible derivation from melting of Yangtze block basement rocks by basaltic underplating (Shellnut and Zhou, 2007). Therefore, the association of high-Ti and low-Ti basalts and A-type granites, and their geochemistry, suggest a continental rift tectonic setting for the Panxi belt, for at least ~9 m.y. from 260 Ma to 251 Ma (Wang et al., 2014) (Fig. 10).

Late Permian mafic igneous rocks are also present in the Songpan-Ganze terrane and Yidun arc, covered in turn by early Triassic calc-alkaline volcanic rocks (SBGMR, 1991; Yang et al., 2011; Wang et al., 2013a, 2013b Cao et al., 2015). The late Permian basalts and metagabbros, which have geochemical characteristics of LREE enrichment (La/Sm=3.4-4.3), HREE depletion (Gd/Yb=2.4-4.3), variable trace elements of Zr/Nb=4.3-11.3, La/Nb=0.7-1.7, Ba/Nb=4.3-41.6, Th/La=0.1-0.2, and εNd(t) values of 0.3-4.8, are virtually identical to the basalts of the ELIP (Song et al., 2004). The similar geochemical characteristics indicate that parental melts of the basalts in the Songpan–Ganze terrane
and Yidun arc were derived from the same source regions as the ELIP (Song et al. 2004), suggesting a tectonic setting of continental rift.

The early Triassic volcanic rocks are enriched in LREE ($\text{La}_N/\text{Yb}_N = 3–24$), have mostly negative Eu anomalies ($\text{Eu}^* = 0.2–0.9$), and exhibit negative Nb and Ta anomalies with ($\text{Nb}/\text{La})_N$ of 0.21–0.91 and ($\text{Nb}/\text{Th})_N$ of 0.05–0.49. Fractionation of the HREE is limited ($\text{Gd}_N/\text{Yb}_N = 1.0–2.5$) (Wang et al., 2013a, 2013b; Yang et al., 2011). The early Triassic volcanic rocks and their coeval intrusions along the Yidun arc defines an oceanic affinity volcanic arc (Yang et al., 2014). Therefore, the Yidun arc and Songpan-Ganze terrane experienced a similar evolution of continental rifting leading to development of an ocean basin from the late Permian to the early Triassic (Fig. 10), followed by subduction along the Yidun arc.

In summary, the location of initial impingement of the Late Permian Emeishan mantle plume is recognized in the Yongren area, Yunnan province. A continental rift developed during plume-lithosphere interaction, within the Panxi region (Kangding complex), with one rift arm developing from a continental rift to an oceanic rift along the Yidun arc and Ganze-Litang suture, and a possible second arm, an aulacogen, developing along the LSTC seems, and the third one continental rift roughly along the Kangding complex (Panxi rift) to define a late Permian three-armed rift system (Fig. 10). The implication of this hypothesis is that LSTC may represent Triassic tectonic inversion of a late Permian aulacogen. This hypothesis can be tested by further studies in the LSTC.

North of the LSTC, the late Permian development of the Mianlue ocean is represented by typical oceanic ophiolite suites with peridotitic compositions, as represented in the Wenjiagou-Zhuangke to the west of Lueyang and in the Anzishan to...
the west of Mianxian (Fig. 2). Basalts from Wenjiagou-Zhuangke and Anzishan ophiolites – characterized by strong depletion of LREE in the chondrite-normalized REE patterns, low concentrations of HFSE of Nb, Ta, La, Ce, Pr, P, Nd, Zr, Sm, Eu and Ti and flat HFSE distribution patterns in the primitive mantle-normalized trace element distribution diagrams – display typical N-MORB chemical compositions (Dong et al., 2011). The geochemistry of these ophiolitic basalts indicates a derivation from a depleted mantle source, and the integrated petrological and geochemical characteristics suggest development of mature spreading within the Mianlue ocean (Lai and Yang, 1997). These ophiolitic rocks, which were deformed and metamorphosed during the middle to late Triassic, are thought to be Late Paleozoic to the Early Triassic in age (Fig. 11) (Dong et al., 2011, 2013).

7 Mesozoic composite tectonics (Mz)

Here we describe two Mesozoic deformation phases evident in the LSTC, a Late Triassic (Mz\textsuperscript{1}) phase of major transpression, and a latest Triassic to Jurassic phase of extension (Mz\textsuperscript{2}). Both tectonic episodes may be affiliated with the closing and subsequent deformations of the Ganze-Litang ocean in the southwest and Mianlue ocean in the north of the LSTC, respectively (Zhang et al., 2004; Dong et al., 2011; Yan et al., 2011; Cao et al., 2015; Xu et al., in preparation).

7.1 The Mz\textsuperscript{1} Tectonics

Within the LSTC, the Mz\textsuperscript{1} tectonics has been widely described (Chen et al., 1995; Worley and Wilson, 1996; Arne et al., 1997; Harrowfield and Wilson, 2005; Roger et al., 2008; Yan et al., 2008b, 2011). This tectonic event is characterized by large-magnitude
transport of nappes, metamorphism, extensive igneous activity and related sedimentary basins.

The Mz1 assemblage of thrust faults and columnar fold and metamorphism were identified throughout the LSTC and adjacent Songpan-Ganze terrane (Bruguier et al., 1997; Zhang et al., 2004; Weislogel et al., 2006; Enkelmann et al., 2007; Yan et al., 2011; Billerot et al., 2017). The folds are upright-inclined with shapes changing from open to isoclinal depending on lithological types, NW-SE striking, shallow plunging axes and upright spaced cleavages in Songpan-Ganze terrane, while inclined, isoclinal folds with top-to-the-SSW kinematics, shallowly plunging axes and associated penetrative cleavage characterize folds within the LSTC (Worley and Wilson, 1996; Yan et al., 2011). Coeval arcuate-shape thrust faults have variable ESE- to WNW-dip direction within the LSTC. The Mz1 within the LSTC has a fold-thrust fault system (Worley and Wilson, 1996; Jia et al., 2006). Integrated with mineral lineations on foliation, NNW- or NW-dipping fold axial plane cleavage (original), S-C fabrics and “α”-type pressure shadows, the Mz1 was characterized by oblique transpression with top-to-the-SSW thrusting and sinistral strike-slip faulting, which is consistent with NW- or WNW-ward underthrusting of the South China block underneath the North China block (Liu et al., 2005).

The Mz1 metamorphism is characterized by regional greenschist rocks, local development of high-pressure blueschist facies rocks in the north and middle of the LSTC. The regional greenschist facies is represented by metamorphic mineral assemblage of chlorite + muscovite + albite + orthoclase + biotite + quartz (Liu H.et al., 2008). The blueschist facies rocks in the Bikou terrane are represented by metamorphic mineral assemblages of Calcite-Amphibole + Epidote + Chlorite + Phengite and Sodaclase-
Amphibole + Epidote + Chlorite + Phengite (Wei, 1993, 1994; Xu C.G. et al., 2018). The Barrovian metamorphic rocks in the Danba terrane have metamorphic facies from sericite- to kyanite-grade, which has estimated P-T conditions from ~3-5 kbar and ~410-530°C (biotite zone) to 5.3-8 kbar and 570-600°C (staurolite and kyanite zones) (Huang et al., 2003a). A number of the age dates include metamorphic minerals of garnet was dated at 204 Ma using Sm-Nb method, muscovite and biotite were dated at 237-220 Ma using $^{40}\text{Ar}/^{39}\text{Ar}$ method (Huang et al., 2003a, 2003b; Zhou et al., 2008; Yan et al., 2011). The metamorphic ages are equivalent within error to those of 226-215 Ma (zircon U-Pb ages) adakitic/I-type to high Ba-Sr granitic intrusions, which have relatively high $I_s$ and low $\varepsilon_{Nd}$ values in the LSTC and the adjacent Songpan-Ganze terrane (Roger et al., 2004; Zhang et al., 2006; Xiao et al., 2007; Zhang et al., 2007; Lu et al., 2010; Yuan et al., 2010).

The Mz$_1^1$ deformation, metamorphism and magmatism reveal a tectonic event of crustal thickening, which were interpreted as a result of the South China block subducted underneath the North China block (Wei et al., 1994; Faure et al., 2001; Yan et al., 2011; Xu et al., in preparation). However, the uppermost Upper Triassic Xikang group with fine-grained flysch deposits in the Songpan-Ganze terrane, while coarse clastic rocks near the Longmenshan suggest that the LSTC was uplifted prior to the thickening of the Songpan-Ganze terrane (SBGMR, 1991; Yan et al., 2011) (Fig. 4C-F). Early Jurassic strata contain a basal conglomerate and unconformably overlie Late Triassic strata, demonstrating that Mz$_1^1$ deformation terminated at ~208 Ma (Zhang et al., 2004; Yan et al., 2008b; Yan et al., 2011) (Fig. 4).

7.2 The Mz$_2^2$ Tectonics
The Mz² Tectonics is characterized by folds, and a variable scale of ductile shear zones with penetrative foliation, mineral and stretching lineations, sheath folds, and S-C fabrics (Worley and Wilson, 1996; Yan et al., 2011; Billerot et al., 2017). The ductile shear zones around the domal complexes separate the Proterozoic metamorphic complexes from middle- to shallow- metamorphosed cover sequences in the hinterland belt of the LSTC (Figs. 2 and 6). These ductile shear zones show top-to-SE or ESE shear senses and are interpreted as thinning or removing the stratigraphic sequence by extension (Zhou et al., 2002b, 2008; Yan et al., 2003a, 2008a, 2008b, 2011; Liu et al., 2008) (Figs. 2, 6 and 11). P-T conditions of the ductile shear zones were revealed at 260-310°C and 3.9-6.2 kbar for the Bikou terrane by metamorphic mineral assemblage of Chlorite + Muscovite + Actinolite + Orthoclase + Albite + Quartz (Liu et al., 2008), 265-405°C and 3.1-4.8 kbar for the Pengguan-Xuelongbao complex by metamorphic mineral assemblage of Garnet + Biotite + Plagioclase + Muscovite + Quartz (Yan et al., 2008a), and 640-680°C and 4.8-6.3 kbar (Sillimanite + Biotite + Muscovite + Quartz + Garnet ± Ilmenite ± Plagioclase, or Hornblend + Plagioclase ± Garnet ± Clinozoisite ± Biotite ± Titanite + Quartz in sillimanite zone) to 660-720°C and 5.8-6.2 kbar (Plagioclase + K-Feldspar + Quartz + Muscovite + Biotite ± Garnet ± Sillimanite in metapelitic migmatite zone) following a clockwise P-T-t path for the Danba complex (Huang et al., 2003a). These P-T conditions are consistent with mid-crustal prograde metamorphism with variable lower greenschist facies to upper amphibolite facies metamorphism. Mineral separates were dated at 197-183 Ma (⁴⁰Ar/³⁹Ar muscovite) in the Bikou terrane (Yan et al., 2008a, 2011), and 166-159 Ma (⁴⁰Ar/³⁹Ar amphibole) and 168-158 Ma (SHRIMP U-Th-Pb monazite and tiantite), 177 Ma (SHRIMP
zircon) for the Danba complex (Huang et al., 2003a, 2003b; Zhou et al., 2008), indicating progressive SW-ward development of the extensional tectonics.

The Mz$_t^2$ faults, which are represented by high-angle normal faults controlling the Early Jurassic half-graben basins, most likely represent a high-angle normal fault system formed at shallower structural levels (Yan et al., 2011) (Figs. 6 and 11). At this time, 211-205 Ma A-type granitic plutons intruded the northwestern Songpan-Ganze terrane (Zhang et al., 2006, 2007; Yuan et al., 2010; De Sigoyer et al., 2014). The association of normal faults and A-type granites suggests development of an extensional Songpan-Ganze turbidite basin, with regional timing constraints suggesting initiation in the northwest, progressing to the southeast (Douce and Alberto, 1997; Zhang et al., 2008; Yan et al., 2011).

Therefore, the domal complexes with ductile-brittle deformation, metamorphism, A-type granites and the Early Jurassic grabens within the hinterland belt of the LSTC might have resulted from SE-directed extensional tectonics during the late Late Triassic to the Early Jurassic, in a manner similar to that of North American Cordilleran metamorphic core complexes (c.f. Lister and Davis, 1989). The Mz$_t^2$ extensional tectonics are consistent with the collision between the Yidun arc and Songpan-Ganze terrane along the Ganze-Litang suture in a slab rollback setting (Yan et al., 2011; Yang et al., 2012).

8 The Cenozoic orogenic plateau superimposing (Kz$_t$)

The Cenozoic to recent LSTC overprinted the earlier Mz$_t^1$ and Mz$_t^2$ deformations and formed at the margin of a vast orogenic plateau, forming a foreland fold-thrust belt (Fig. 12). The Cenozoic tectonics of the LSTC has been widely investigated, and a number of
tectonic models have been proposed (Burchfiel et al., 1995; Bai et al., 2010; Yan et al., 2011; Wang E.Q., 2012; Sun M. et al., in preparation). Three tectonic events have been recognized: (1) imbricate thrusting with SE-ward migration (Kz₁¹), (2) formation of the Xianshuihe sinistral strike-slip fault (Kz₂²) and, (3) plateau uplift (Kz₃³) (Arne et al., 1997; Richardson et al., 2008; Tan et al., 2010; Yan et al., 2011; Wang, D. et al., 2012; Cook et al., 2013; Tian et al., 2013; Wang et al., 2016; Sun et al., in preparation).

8.1 Kz₁¹ imbricate thrusting

The Kz₁¹ is represented by thrust motion along the Maowen and Beichuan-Yingxiu faults in the Longmenshan thrust belt, and the Muli and Yanyuan thrust faults in the Yanyuan-Muli thrust belt (Fig. 2). As described above, these faults dip to the northwest or north with dip angles of 40°-60°, and have top-to-the-SE or SSE motion (Fig. 13b) (SBGMR, 1991; Xu et al., 1992; Worley and Wilson, 1996; Yan et al., 1997, 2011; Sun et al., in preparation). Although there are extensive geochronologic constraints for the Kz₁¹ in the LSTC, as a whole, the age of the Kz₁¹ was roughly dated at 55-15 Ma with the initiation of activity of the Yanyuan-Muli thrust belt at ~55 Ma followed by ~50 Ma activity of the Longmenshan thrust belt using A/ZFT (apatite/zircon fission track), (U-Th)/He and ⁴⁰Ar/³⁹Ar methods (Richardson et al., 2008; Yan et al., 2011; Wang E.Q. et al., 2012; Sun et al., in preparation).

In the Longmenshan thrust belt, initial uplift and denudation of the Pengguan-Xuelongbao domal complex was inferred to be middle Tertiary (51-31 Ma), or perhaps the Cretaceous (70 Ma), based on zircon/apatite (U-Th)/He and biotite ⁴⁰Ar/³⁹Ar thermochronology (Arne et al., 1997; Kirby et al., 2002; Yan et al., 2011; Wang et al., 2012). The well preserved Paleocene to Eocene Minshan Formation (E₁-₂m) and the
Eocene Lushan Formation (E$_2$l) in the foreland basin (i.e., the western Sichuan foreland basin), composed of coarse-grained clastic rocks, suggests activity of the southern LSTC at 55-35 Ma (Figs. 2E, 2G and 12A).

The previously mentioned imbricate thrust assemblages are composed of the Maowen fault and Beichuan-Yingxiu fault in the Longmenshan thrust belt and the Moli fault and Yanyuan fault in the Yanyuan-Muli thrust belt (SBGMR, 1991; Xu et al., 1991; Yan et al., 2011). Although the timing of initial motion for each of the faults is not well constrained, along-strike thrusting activity of SE-ward or SSE-ward in-sequence kinematics, from the Longmenshan thrust belt to the Yanyuan-Moli thrust belt, is evident from prior studies (Fig. 12A).

**8.2 Kz$_t^2$ strike-slip faults and northward extrusion**

Kz$_t^2$ is characterized by the formation of the NW-striking, sinistral-strike slip Xianshuihe fault, which cuts through and divides the LSTC into the Longmenshan thrust belt in the north and Yanyuan-Muli thrust belt in the south (Figs. 2 and 12B). This fault zone, which has mylonite and was intruded by the ~12 Ma Gongga Shan granitic plutons, was estimated to be active at ~15 Ma (Roger et al., 1995; Wang et al., 1998, 2014; Li et al., 2015a; Zhang et al., 2017). At about the same time, the Maowen and Beichuan-Yingxiu faults initiated dextral-strike slip motion, perhaps as a conjugate to the Xianshuihe fault (Enkelmann et al., 2006; Lei, 2012; Zhang et al., 2017; Sun et al., 2018b) (Fig. 12B). The conjugate strike-slip faults reveal an eastward maximum principal compressive stress, which resulted in northward extrusion of the north Songpan-Ganze terrane and southward extrusion of the south Songpan-Ganze terrane, respectively (Fig. 12B). The north and south extrusion, which are dominated by the eastward maximum principal compressive
stress, are consistent with the crustal ductile channel flow (Enkelmann et al., 2006; Burchfiel et al., 2008; Bai et al., 2010; Wang et al., 2012).

8.3 Kz$_3^3$ plateau uplift

The Kz$_3^3$ is characterized by rapid uplift of the LSTC and formation of the foreland thrust system (Fig. 12C). A number of thermochronological results, including apatite fission track (AFT) and (U-Th)/He, reveal rapid cooling of the LSTC, Songpan-Ganze terrane and southwestern Qinling since ~5 Ma (Kirby et al., 2002; Reid et al., 2005; Enkelmann et al., 2006; Godard et al., 2009; Yan et al., 2011; Lei, 2012; Wang et al., 2012; Li et al., 2017; Sun et al., 2018a, under preparing). More than 3000 m uplift of the plateau were estimated based on AFT results and studies of the paleo-planation surface (Sun et al., in preparation). Additionally, the 2008 Wechuan 8.0 Ms and 2013 Lushan 7.0 Ms earthquakes are the results of the Kz$_3^3$ activities of the LSTC (Fig. 12C).

The foreland thrust system is composed of the frontal Guanxian-Anxian fault, several blind thrust faults, and the Longquanshan foreland uplift bounding the western Sichuan basin. (Figs. 2 and 12C). Coevally with uplift of the LSTC, the western Sichuan basin was uplifted and denudated ~4 Km based on AFT results (Richardson et al., 2008). Coupling with coeval uplift of the LSTC, formed the Pliocene lake (i.e., N$_2^x$ Xigeda Formation) and deposited the Quaternary in the southwestern Sichuan foreland basin (Zhang Y.X., 2013; Wang et al., 2016; Sun et al., 2018a, in preparation (Fig. 12C).

Therefore, the present LSTC, i.e., generally called Longmenshan belt, was built by collisional orogenic affinity in-sequence imbricate thrust (Kz$_1^1$), northward extrusion (Kz$_1^2$) and internal uplift of the plateau (Kz$_1^3$). Combined with the Kz$_1^1$, Kz$_1^2$ and Kz$_1^3$, a nature of
the orogenic plateau for the LSTC and Songpan-Ganze terrane could be defined (Rey et al., 2001, 2012; Vanderhaeghe, 2012).

9. Discussion

Although currently represented by a thrust belt along the sharp topographic gradient marking the eastern margin of the Tibetan Plateau, the Longmenshan records a protracted geologic history including Archean basement relicts (Ar$_1$), the Columbia/Nuna supercontinent (Pt$_{11}$), Rodinia supercontinent (Pt$_{31}$), the Paleozoic passive continent (Pz$_{1}$), the Mesozoic orogenic cycle (Mz$_{1}$) (contraction followed by extension) and the development of the Cenozoic orogenic plateau (Kz$_{1}$) define a complicated tectonic history of the LSTC. In the past decades, studies focus on distinguishing and accurate constraining these tectonic relics and events, which enable us to answer and respond to the five questions mentioned in the introduction, i.e., tectonic episodes, metamorphic basement, nature of the present LSTC and its affiliation with adjacent tectonic units, geological relationship between the NE-striking Longmenshan thrust belt in the north and arcuate Yanyuan-Muli thrust belt in the south, and coupling of the mountain and basin. Based on the understanding of the present tectonic framework, we discuss the tectonic episodes and their natures, and then summarize the orogenic cycles to build the present LSTC.

9.1 Archean basement and Columbia/Nuna supercontinental cycle

The Yudongzi gneiss group in the Bikou terrane were formed during the Archean with igneous zircon U-Pb ages of 2600-2693 Ma (Fig. 7) (Zhang et al., 2001; Zhao and Cawood, 2012; Zhou et al., 2018, in preparing). The Archean Yudongzi gneiss group has a metamorphic grade of upper amphibolite facies and is composed of TTGs with banded
iron formation (BIF) and leucogranite (Zhang et al., 2001; Zhou et al., 2018). Both the age results and rock composition, which are similar to the Kongling complex in the northeast Yangtze Block (Zhang et al., 2001; Zhao and Cawood, 2012), reveal close affinity between the Bikou terrane and the Kongling complex. The rare exposures of the Yudongzi gneiss group might be a part of the enigmatic Archean crystalline basement core of the Yangtze block, and probably represents the early stages of formation of the South China craton (Ren et al., 1986a, 1986b, 2016). Thus, relics of the Archean rocks within the LSTC indicate the cratonic nature for the crystalline basement.

The Hejiayan group is exposed adjacent to the Yudongzi gneiss group and has an age of ca.1933 Ma for protolith (GRT-SBGMR, 1996; Zhang et al., 2001). These rocks are the only Paleoproterozoic metamorphic rocks identified within the LSTC and thus contain the unique record for Paleoproterozoic events (Pt1t) (Fig. 8). The Hejiayan group includes greenschist facies rocks with protolith assemblages of island-arc basalt and ultrabasic intrusions, implying a possible Paleoproterozoic ophiolite melange (GRT-SBGMR, 1996). Although additional structural and petrological studies are needed to clarify the history of these rocks, they probably represent ophiolite melange that is coeval with the Nuna/Columbia supercontinent assembly and the associated orogenic belt (Pt1t) in the southwestern Yangtze block (GRT-SBGMR, 1996; Dong et al., 2015; Zhou et al., 2018) (Fig. 7).

The recognition of relict Archean crystalline basement (Ar1) and the Paleoproterozoic Nuna supercontinent basement (Pt1t), not only confirm the cratonic nature of the LSTC and the Yangtze block (SBGMR, 1991; GRT-SBGMR, 1996; Zhao and Cawood, 2012), but also build a tight spatial and temporal link between the Yangtze block and Nuna...
supercontinent (Wang et al., 2016). Formation of the metamorphic basement dated at ca.1933 Ma represents the initial accretion of the Archean Yangtze block to the Rae craton along the LSTC during the Nuna orogeny (2320-1800 Ma) (Zhao et al., 2002; Evans and Mitchell, 2011; Zhang et al., 2012; Pisarevsky et al., 2014; Wang et al., 2016). Therefore, we suggest that the LSTC developed at the margin of the Archean Yangtze craton, which was sutured and aggregated to the Nuna supercontinent by the Paleoproterozoic orogeny (Zhao et al., 2002; Evans and Mitchell, 2011; Zhang et al., 2012; Pisarevsky et al., 2014; Wang et al., 2016) (Fig. 8).

9.2 Rodinia supercontinental cycle

The well exposed Neoproterozoic igneous, sedimentary and metamorphic rocks in the LSTC and Yangtze block have been widely reported. These rocks in the LSTC are mainly exposed in the core of the domal complexes, including the Bikou group in the Bikou terrane, the Jiaoziding complex, the Huangshuihe group in the Pengguan-Xuelongbao, the Baoxin and Danba complex, and the Qiasi group in the Jianglang (Taka), Changqiang and Qiasi domal complexes (Figs. 2 and 4), which show structural and petrological similarity to the Kangding complex in the western Yangtze block (Fig. 3) (Yan et al., 2002, 2008b; Zhou et al., 2002a, 2002b, 2006a, 2006b; Druschke et al., 2006; Xiao et al., 2007; Sun et al., 2008a, 2008b, 2009; Pei et al., 2009; Zhao et al., 2011, 2017).

The ophiolitic complex is represented by the Shimian ophiolite and tens of small-scale bodies of hornblende gabbro, olivine gabbro and serpentinitized peridotite within the metamorphic complexes. The ophiolitic complex was dated at ~800 Ma, which is interpreted as relict oceanic slabs along a possible trench by the eastward subduction of the Neoproterozoic Mozambique ocean (Zhou et al., 2002a; Zhao et al., 2017) (Fig. 9A-C).
The Neoproterozoic intrusions, exposed mainly within the domal complexes, include adakites, mafic and granitic plutons. Adakites dated at 748-830 Ma were proposed to be a product of wet-slab melting of the subducted plate (Zhou et al., 2006b; Huang et al., 2009; Zhao and Zhou, 2007a) (Fig. 9A). The 738-812 Ma mafic intrusions and granitic plutons have geochemical and isotopic compositions of depleted lithospheric mantle and were proposed to derive from partial melting of mantle that was metasomatized by subduction-derived fluids or melts (Zhou et al., 2006b; Zhao et al., 2007a; Zhao and Zhou, 2007a; Zhu et al., 2008; Meng et al., 2015) (Fig. 9B). The 848-764 Ma granites, including tonalite, granodiorite and monzogranite, have geochemical and isotopic compositions consistent with a juvenile crustal source, derived from partial melting of amphibolites or metagreywacks in the lower crust (Zhou et al., 2002a, 2002b; Yan et al., 2008b; Liu S.W. et al., 2009b; Pei et al., 2009; Munteanu et al., 2010; Meng et al., 2015) (Fig. 9C). Therefore, the adakites, mafic and granitic intrusions of the LSTC and the western margin of the Yangtze block consistently indicate a magmatic arc, which is interpreted to be genetically connected with the eastward subduction of the Neoproterozoic Mozambique ocean (Fig. 9A-D).

The 850-700 Ma volcanioclastic turbidite sequence of the Hengdan group in the Bikou terrane was interpreted as a forearc basin, with provenance from the Bikou group volcanic rocks to the south (Druschke et al., 2006). Correspondently, the ~870 Ma Yanbian group flysch sequence in the south Kangding complex, which has characteristics of submarine fan deposits, is interlayered with arc-related lavas (Sun et al., 2007, 2008a, 2008b, 2009). Petrological, geochemical and isotopic results consistently point to a back-arc basin setting for the Yanbian group (Sun et al., 2007, 2008a, 2008b, 2009). Thus, a convergent
margin, volcanic arc system has been proposed along the western margin of the Yangtze block.

The polarity of the Neoproterozoic trench-arc-basin system and geometry of the subsequent collisional orogenic belt have been reconstructed based on integration of previous studies of the ophiolitic complexes, adakitic rocks, mafic rocks, granitic intrusions and back-arc and fore-arc deposits along the LSTC and western margin of the Yangtze block (Fig. 9A-C) (Yan et al., 2002, 2008b; Zhou et al., 2002a, 2006a, 2006b; Druschke et al., 2006; Xiao et al., 2007; Sun et al., 2008, 2009; Pei et al., 2009; Zhao et al., 2011, 2017). This trench-arc-basin system has geochemical, isotopic and geochronological similarities to the northeastern Madagascar, Seychelles island and Malani in India (Tucker et al., 2001), and probably represented an Andean-type margin on the edge of the Rodinia supercontinent. We therefore correlate the western margin of the Yangtze block with the northeastern margin of the Indian Plate, both being an active arc above an eastward dipping subduction zone (Zhou et al., 2002a) (Fig. 9E).

However, a number of scientific problems, which concern the reconstruction of the Rodinia supercontinent along the LSTC, are not yet solved. For example, is there a record of inception of 725-750 Ma rifting, which corresponds to the formation of Nanhua basin within the Yangtze block, within the LSTC? Does the eastward subduction of the Mozambique ocean match with a westward subduction along the east side of the Yangtze block (Zhou et al., 2002a; Li XH et al., 2009) (Fig. 9D)? Except for an accretionary orogenic process suggested by the subduction-related trench-arc-basin system, possible collisional orogeny, orogenic plateau and post-orogeny are not yet distinguished.

9.3 East Paleo-Tethys Wilson cycle
Based on the Paleozoic passive continental margin of the Yangtze block, the continent breakup initiated along the northern margin of the Yangtze block represented by the ~440 Ma continental rifting, which was then transferred into the Paleozoic Mianlue ocean between the North China (North Qinling-Dabie orogenic belt, Fig. 2) and South China blocks (Li et al., 1996; Lai et al., 1998; Xu et al., 2000a, 2000b; Zhang et al., 2004; Dong et al., 2011, 2015) (Fig. 11). Although this breakup signifies the initiation of the Paleo-Tethys cycle, the LSTC marks the boundary of the Yangtze block to the western passive continental margin did not essentially change, until the formation of the possible late Permian three-armed rift system (Figs. 4D-E, 10).

The three-armed rift system proposed in this paper is based on the ELIP basalt-dominated rock assemblages and their spatial-temporal distribution. The LSTC exposes only the low-Ti type magmas, which regionally, are found only in the lower part of the basalt sequence, indicating the preservation of the initial eruptive materials and a NE-trending depositional trough or aulacogen. However, both the low-Ti basalt and the overlying high-Ti basalts, together with the coeval A-type granites, are distributed along the Kangding complex in the NS-striking Panzhihua rift (Fig. 10) (Xu et al., 2001; Shellnut and Zhou, 2007; Wang et al., 2016). Along the Ganze-Litang suture zone and its adjacent Yidun arc and Songpan-Ganze terrane, the late Permian continental basalts, together with the early Triassic oceanic affinity calc-alkaline volcanic rocks and intrusions, reconstruct a tectonic process from the late Permian continental rift to the early Triassic Ganze-Litang ocean (SBGMR, 1991; Song et al., 2004; Yang et al., 2012, 2014; Cao et al., 2015; Wang et al., 2013a, 2003b) (Figs. 5 and 10). Therefore, this three-armed rift system is composed of an aulacogen along the LSTC, a NS-trending continental rift along the
Kangding complex (Fig. 1), and an oceanic rift along the Ganze-Litang and Yidun arc. The identification of the mantle plume centre (He et al., 2003a, 2003b, 2006, 2009, 2010) and associated radial mafic dyke swarms (Li et al., 2015) of the ELIP could further refine the configuration of this three-armed rift system, although the original pattern during the late Permian to the early Triassic was not been constructed.

Subduction and closure of the Mianlue and Ganze-Litang oceans occurred almost simultaneously in the middle to late Triassic (Zhang et al., 2004; Yan et al., 2008b, 2011; Dong et al., 2011, 2016) (Figs. 4, 5 and 11). Although widely overprinted by the subsequently deformation, the Mz\textsuperscript{1} within the LSTC and Songpan-Ganze terrane is well preserved with representative NW-SE or WNW-ESE striking recumbent folds and thrust faults, greenschist metamorphism and adakitic granites (Burchfiel et al., 1995; Chen et al., 1995; Worley and Wilson, 1996; Arne et al., 1997; Bruguiére et al., 1997; Zhang et al., 2004; Harrowfield and Wilson, 2005; Weislogel et al., 2006; Wilson et al., 2006; Enkelmann et al., 2007; Roger et al., 2008; Yan et al., 2008b, 2011; Billerot et al., 2017). The Mz\textsuperscript{1} fault-fold system, together with kinematic markers including mineral lineation on spaced axial planar cleavage, S-C fabrics and “σ”-type pressure shadows within local ductile shear zones, reveals top-to-the-SW thrusting with dextral strike-slip faulting (Worley and Wilson, 1996; Jia et al., 2006). Structural assemblage and kinematics of Mz\textsuperscript{1} within the LSTC have affinity with the kinematics during northward subduction of the Mianlue oceanic plate beneath North China block, and subsequent collision, to produce top-to-the-south thrusting (Liu et al., 2005; Yan et al., 2011) (Fig. 11). However, the Mz\textsuperscript{1} of the LSTC may have not been significantly affected by the closure of the Ganze-Litang ocean, which has been proposed to have subducted southwestward underneath, and to
have collided with, the Yidun arc (Cao et al., 2015). This implies that the Ganze-Litang ocean probably had an original WNW orientation during the middle to late Triassic (Pullen et al., 2008).

The Mz$t^2$, which is represented by the structural assemblage of faults, recumbent folds, variable scale of ductile shear zones with penetrative foliations, stretching lineations, sheath folds, and S-C fabrics, have been recognized along the flanks of the domal complexes within the hinterland belt (Burchfiel et al., 1995; Worley and Wilson, 1996; Yan et al., 2011; Billerot et al., 2017). This deformation, which was firstly identified as faults accomplishing the omission of stratigraphy and interpreted as normal faults by Burchfiel et al. (1995), has been further described by a number of subsequent studies. The evidence includes variable thinning or omission of the stratigraphic sequence around the domal complex, ductile shear zones within the dome cores with top-to-SE or ESE kinematics, and middle to upper greenschist facies retrograde metamorphism (Zhou et al., 2002b, 2008a; Huang et al., 2003a; Yan et al., 2003a, 2008a, 2008b, 2011; Liu et al., 2008), locally preserved early Jurassic half-graben basins bound by high-angle normal fault system (Yan et al., 2011) (Figs. 2, 6 and 11), and coeval 211-205 Ma A-type granitic plutons in the western Songpan-Ganze terrane (Zhang et al., 2007; Yuan et al., 2010). We propose a history of progressive extensional tectonics, produced by roll-back subduction of the Songpan-Ganze terrane underneath the Qiangtang terrane after collision along the Ganze-Litang suture (Pullen et al., 2008; Yan et al., 2011; Yang et al., 2012). Therefore, the Paleozioc to the Mesozoic LSTC in the east Paleo-Tethys experienced plume-related continental rifting (Pz$t^1$) in which one arm developed into an ocean ridge, producing the Ganze-Litang ocean basin (Pz$t^2$), which was then closed by northward and southwestward
subduction underneath the North China block and the Qiangtang block ($M_{zt1}$), respectively. The evolution from continental rifting, to subduction, and finally to plate collision record a complete Wilson cycle (Wilson, 1966). However, this variant of the Wilson cycle involves closure of the Mianlue and Ganze-Litang oceans by subduction in opposite directions along trenches to the north and south of the LSTC. The bidirectional subduction of the Songpan-Ganze lithosphere requires there to be a tear fault along the LSTC (De Sigoyer et al., 2014). Thus, the Paleozoic to Mesozoic LSTC has a key record for reconstructing a "bidirectional" Wilson cycle in the eastern Paleo-tethys.

9.4 The Cenozoic orogenic plateau superimposing ($K_{zt}$)

The present LSTC, that is, what is generally called the Longmenshan belt in most literature, was finally built during the collision of the Indian and Eurasian continents by the Cenozoic superimposition of the Tibetan plateau and the Sichuan basin (Fig. 13). Much research effort has focused on the Cenozoic tectonics, including both regional and more local, detailed investigations, leading to a number of proposed models (c.f., Burchfiel et al., 1995; Bai et al., 2010; Wang E.Q., 2012; Yan et al., 2011; Sun M. et al., 2018, in preparation). Three tectonic episodes are generally recognized: imbricate thrusting with a SE-ward thrust migration ($K_{zt1}$), formation of the Xianshuihe sinistral strike-slip fault and conjugate dextral strike-slip faults of the LSTC ($K_{zt2}$), and internal plateau uplift associated with continued thrusting in the LSTC ($K_{zt3}$) (Arne et al., 1997; Richardson et al., 2008; Yan et al., 2011; Wang et al., 2012; Cook et al., 2013; Tian et al., 2013; Sun M. et al., 2018, in preparation).

The $K_{zt1}$ imbricate thrusts consist of both tectonically reactivated, northwest-dipping $M_{zt1}$ and $M_{zt2}$ thrust faults as well as forward propagation of new thrusts in the foreland
(SBGMR, 1991; Xu et al., 1992; Worley and Wilson, 1996; Yan et al., 1997, 2011; Sun et al., 2018). This thrusting is roughly constrained between 55-15 Ma, while the initial ages were a little older in the Yanyuan-Muli thrust belt than that in the Longmenshan thrust belt, based on low-temperature thermochronology studies (Richardson et al., 2008; Yan et al., 2011; Wang E.Q. et al., 2012; Sun et al., 2017; Li et al., 2018). The initial age results are consistent with the constraints provided by development and infilling of a foreland basin by the Paleocene to Eocene Minshan Formation (E\textsubscript{1-2}m) and the Eocene Lushan Formation (E\textsubscript{2}l) in the southern segment (Figs. 2E, 2G and 12A). The sequence of activity on thrust faults, including the Maowen fault and Beichuan-Yingxiu fault, as well as the Muli fault and Yanyuan fault, together with the geometry of the fault and fold system, indicates SE-ward or SSE-ward, in-sequence kinematics, which is a far field response to India-Euroasian plate collision as suggested by previous studies (Burchfiel et al., 2008; Hubbard and Shaw, 2009; Jia et al., 2010; Jin et al., 2010; Xu et al., 2016) (Fig. 12A).

Kz\textsubscript{1}2 is characterized by the formation of the Xianshuihe sinistral strike-slip fault, and the conjugate dextral strike-slip of the LSTC. The two conjugate strike-slip faults, which were accurately dated at 15-10 Ma, resulted in the NNE-ward extrusion of the north Songpan-Ganze terrane and southward extrusion of the south Songpan-Ganze terrane (Roger et al., 1995; Wang et al., 1998, 2014; Enkelmann et al., 2006; Lei., 2012; Li et al., 2015; Zhang et al., 2017; Zhang et al., 2017; Sun et al., 2018) (Figs. 2 and 12B). Simultaneous granitic intrusion along the Xianshuihe fault, together with geophysical investigations, suggests that the initiation and movement of low viscosity crust, in the geometry of channel flow was probably produced by an eastward maximum principal
compressive stress and crustal thickening (Enkelmann et al., 2006; Burchfiel et al., 2008; Bai et al., 2010; Wang et al., 2012) (Fig. 12B).

The internal uplift of the plateau Kz$_t^3$, although was recently proposed initiating since the Oligocene (Hoke, 2018; Linnemann et al., 2018), has been constrained between 5-0 Ma by FT and (U-Th)/He dating. This event is characterized by forward thrusting (Kirby et al., 2002; Reid et al., 2005; Godard et al., 2009; Yan et al., 2011, 2016; Lei, 2012; Wang et al., 2012). This tectonic episode was believed to have resulted in more than 3000 m of plateau uplift and the corresponding Pliocene to Quaternary deposits (c.f., N$_2$x Xigeda formation), as well as the occurrence of 2008 Wechuan 8.0 Ms, 2013 Lushan 7.0 Ms, and recently 2017 Jiuzhaigou 7.0 Ms earthquakes (Sun et al., 2018, in preparation) (Fig. 12C).

The Cenozoic development of the present LSTC, i.e., the so called Longmenshan belt, includes in-sequence imbricate thrusting (Kz$_t^1$), northward extrusion (Kz$_t^2$). Given the active faulting associated with dextral oblique shortening, this suggests that the Longmenshan itself is still undergoing crust thickening, and whether in response to shortening or lower crustal flow, the plateau itself may have now reached a critical elevation wherein the crustal cannot support any additional elevation, so that uplift is compensated for by collapse processes (Kz$_t^3$), implying a nature of the orogenic plateau (Rey et al., 2010; Vanderhaeghe, 2012). This orogenic plateau, which was previously revealed by paleomagnetic results (Chen et al., 1995; Otofuji et al., 1998; Yoshioka et al., 2003), geodetic studies (Zhang et al., 2008) and field geologic observations (Tapponnier et al., 2001), is consistent with the Cenozoic continuous and staged thickening of the eastern Tibetan Plateau and SE-ward expansion (Royden et al., 1997; Clark and Royden, 2000; Tapponnier et al., 2001; Zhang et al., 2004b; Bai et al., 2010; Wang et al., 2012,
2014), but other than the suggestion of expansion to the WNW, north of the Sichuan Basin (Enkelmann et al., 2006). Geodynamics of the southeastward expansion of the LSTC and its adjacent regions was suggested to be responsible by the continued middle to lower crustal channel flow (Burchfiel et al., 2008; Yan et al., 2009).

3. Conclusions

In this overview, we integrate previous studies with our recent results for the Longmenshan tectonic complex (LSTC), along the eastern margin of Tibetan plateau, and draw the following conclusions:

1. The LSTC preserves the Archean Yudongzi gneiss group, which has a genetic affinity with the Kongling group in the northern Yangtze block, and may represent part of its Archean nucleus.

2. The Paleoproterozoic Hejiayan group, which crops out adjacent to the Archean Yudongzi group, may be part of an 2000-1800 Ma orogenic belt developed during accretion to the Nuna/Columbia supercontinent.

3. The combination of Neoproterozoic tectonostratigraphic elements, including an ophiolite complex, arc-type magmatic rock assemblages and volcaniclastic, probable forearc basin deposits, suggest the presence of a Neoproterozoic trench-arc-basin system along the western margin of the Yangtze block within the LSTC. This trench-arc-basin system represents the eastward-subduction of the Neoproterozoic Mozambique ocean underneath the Yangtze block during the formation of the Rodinia supercontinent, although the Nodinian orogenic belt has not been yet distinguished.
4. A complete “bidirectional” Wilson cycle is recorded in the formation of the late Permian to the middle-late Triassic back-arc Ganze-Litang rift and ocean following the early Paleozoic Mianlue continental rift and ocean, and near simultaneous bidirectional northward and southwestward subductions and collisions. This uncommon bidirectional Wilson cycle might be attributed to the formation of the late Permian ELIP three-armed rift system in the LSTC of the eastern Paleo-Tethys.

5. We summarized three tectonic stages for the formation of present LSTC. Collisonal processes along the India-Eurasian boundary lead to far field orogeny in which in-sequence imbricate thrusting at 55-15 Ma, in which Triassic south- and southeast-vergent thrusts were reactivated and new frontal thrusts developed. Extrusion at 15-5 Ma is characterized by the formation of the sinistral strike-slip Xianshuihe fault, and the initial motion of dextral strike-slip Beichuan-Yinxiu fault, and northward extrusion of the north Songpan-Ganze terrane and southward extrusion of the south Songpan-Ganze terrane. The intrusion of the 15-10 Ma Gongga granitic pluton suggests an initial crustal ductile channel flow along the Xianshuihe fault. The plateau uplift and continued shortening along the LSTC has occurred since ~5 Ma.

Acknowledgments
This study was supported by research grants from the NSFC (Projects 41672216, 41372212) and National Basic Research Program of China (2014CB440903). We thank Profs. Gao Jianfeng, Zhao Junhong, Wang Wei and Dr. Cao Wentao for assistance on an earlier draft and constructive comments. Graduate students, Haiying Zhang, Men Ning, Zhemin Li and Shuhang Gu, are gratefully acknowledged for assistance in the field.
References


Dilek, Y., Furnes, H., Shallo, M., 2008. Geochemistry of the Jurassic Mirdita Ophiolite
(Albania) and the MORB to SSZ evolution of a marginal basin oceanic crust. Lithos
100, 174–209.
the NE margin of Qinghai-Tibet Plateau: evidences from the central Longmen
Dong, Y.P., Liu, X.M., Li, W., Yang, Z., Sun, S.S., Cheng, B., Zhang, F.F., Zhang, X.N.,
He, D.F., Zhang, G.W., 2015. Mesozoic intracontinental orogeny in the Qinling
Mountains, central China. Gondwana Research 30, 144-158.
Dong, Y.P., Liu, X.M., Neubauer, F., Zhang, G.W., Tao, N., Zhang, Y.G., Zhang, X.N., Li,
W., 2013. Timing of Paleozoic amalgamation between the North China and South
Tectonic evolution of the Qinling orogen, China: review and synthesis. Journal of
Asian Earth Sciences 41, 213–237.
subduction-related magmatic rocks in the Dahong Mountains, northern Hubei
Province: constraint on the existence and subduction of the eastern Mianlue oceanic
basin. Science in China (Series D) 47, 366–377.


tectonostratigraphy, geochronology, and deformation history. Tectonophysics 366, 1–53.


temperature thermochronology adjacent to the eastern margin of the Tibetan Plateau,


Sun, C.M., Vuagnat, M., 1992. Proterozoic ophiolites from Yanbian and Shimian (Sichuan Province, China) - petrography, geochemistry, petrogenesis, and geotectonic environment. Schweizerische Mineralogische Und Petrographische Mitteilungen. 72, 389-413


Wilson, P. J. T., 1966. Did the Atlantic close and then re-open?. Nature 211, 676-681


Xu, J.F., Wang, Q., Yu, X.Y., 2000a. Geochemistry of high-Mg andesites and adakitic andesite from the Sanchazi block of the Mian-Lue ophiolitic melange in the Qinling


Yan, D. P., Zhou, M. F., Song, H. L., Malpas, J., 2002. Where was South China located in the reconstruction of Rodinia? Earth Science Frontiers 9, 249-256.


Yin, A., S. Nie., 1993. An indentation model for North and South China collision and the development of the Tanlu and Honam fault systems, eastern Asia, Tectonics 12, 801-813.


Strata-bound Copper Deposit, Yunnan Province, Southwest China. Economic Geology 107, 357-375.


Figure captions:

Fig. 1 Geological map of the Longmenshan Tectonic Complex (LSTC) and its adjacent Songpan-Ganze terrane, western Sichuan Basin, and SW-Qinling orogenic belt in the northeast margin of the Tibet Plateau (Edited base on Huang and Li, 2001). Inset map indicates tectonic location of the geological map.

Fig. 2 Division for the tectonic units of the LSTC and its adjacent regions. Only first-order tectonic units are divided except third-order tectonic units for the LSTC.

Fig. 3 Simplified geological map showing the outcrop of basement complexes, including the metamorphic Archean and Proterozoic rocks. Insert map shows the rock types in Ab-An-Or triangular projection (Zhao and Zhou, 2007b; Zhao and Zhou, 2008).

Fig. 4 Stratigraphic correlation diagram includes synthesis columnar in: A. South Qinling Orogenic belt, B. Bikou terrane, C. Songpan-Ganze terrane, D. Longmenshan thrust belt-Hinterland belt, E. Yanyuan-Muli thrust belt, F. Longmenshan thrust belt-Foreland belt, and G. Western Yantze Block (Synthesized edited after GBGMR, 1989; SBGMR, 1989; SBGMR, 1991; and related 1:200 000 regional geological maps).

Fig. 5 Schematic model for the tectonic evolution of Ganze-Litang suture zone and adjacent area under current E–W direction, showing the formation and closing of the Ganze-Litang ocean (Modified based on Cao et al., 2015).
Fig. 6. Geological section transects the middle part of the Longmenshan thrust belt. (A) Strip geological map of a belt from Xuecheng to Bailuchang; (B) the corresponding geological section, which transects the Songpan - Ganze terrane, Longmenshan thrust belt and Sichuan Basin; (C) Seismic profile with Structural interpretation of the foreland thrust belt and Sichuan Basin; (D) Summarized the geochromological constraints for the Beichuan-Yinxiu faults. Location of (A)-(B) is shown in Fig. 1, and location of (D) is shown in (A). (A), (B) and (D) are from Yan et al. (2011) and (C) is from Zheng et al. (2016).

Fig. 7 Simplified geological map showing Yudongzi and Hejiayan groups (edited based on GRT-SBGMR, 1996 and Zhou et al., in preparation).

Fig. 8 Schematic reconstructions showing position of the Yangtze Block within the configuration of Columbia/Nuna supercontinent (Eglington et al., 2013; Pehrsson et al., 2015; Wang W., 2016).

Fig. 9 Proposed schematic models for Neoproterozoic reconstructions. A-C: Neoproterozoic subduction beneath the western margin of the Yangtze block, showing the formation of adakitic plutons, gabbros and arc-like granites along the western margin of the Yangtze block during the Neoproterozoic from 860 to 740 Ma (Zhao and Zhou, 2007a, 2007b; Zhao and Zhou, 2008). D: A proposed Neoproterozoic tectonic reconstruction of the Yangtze block by Zhou et al. (2002a); E: a possible reconstruction of the Yangtze block/South China block in the Rodinia supercontinent (Yan et al., 2002).
Fig. 10 Distribution of the ELIP basalts and a possible late Permian three-armed rift system.

Fig. 11 Schematic model for the Wilson cycle of the A'nymaqen-Mianlue suture zone (modified after Dong et al., 2011).

Fig. 12 Tectonic model showing the Cenozoic three-stage tectonic evolution of the LSTC and its adjacent area (Sun et al., 2018, in preparation).

**Table:**

Table 1 Tectonic divisions of the LSTC and its adjacent regions
Table 1 Tectonic division of the LSTC and its adjacent regions

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Highlights

1. The Longmenshan Tectonic Complex experienced at least 6 regional tectonic events
2. Reconstruction reveals a Rodinian trench-arc-basin system
3. The Longmenshan Tectonic Complex was bounded by Paleozoic passive continental margin and Yangtze Craton
4. A Paleotethys orogenic belt was superposed by a Neotethys orogenic Plateau
Graphical abstract