Late Triassic tectonic inversion in the upper Yangtze Block: insights from detrital zircon U–Pb geochronology from southwestern Sichuan Basin

Zhaokun Yan[1,2,3], Yuntao Tian[3,4*], Rui Li[3], Pieter Vermeesch[3], Xilin Sun[5], Yong Li[2], Martin Rittner[3], Andrew Carter[6], Chongjian Shao[2], Hu Huang[2], Xiangtian Ji[2]

[1] *State Key Laboratory of Mineral Deposits Research, School of Earth Sciences and Engineering, Nanjing University, Nanjing 210023, China*
[2] *State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation (Chengdu University of Technology), Sichuan Chengdu, 610059, China*
[3] *Department of Earth Sciences, University College London, London, WC1E 6BT, UK*
[4] *School of Earth Sciences and Engineering, Sun Yat-sen Unversity, Guangzhou, 510275, China*
[5] *Cluster Geology and Geochemistry, VU University Amsterdam, De Boelelaan 1085, 1081 HV Amsterdam, The Netherlands*
[6] *Department of Earth and Planetary Science, Birkbeck University of London, Malet Street, Bloomsbury, London WC1E 7HX, UK*

*Corresponding author:
Yuntao Tian
School of Earth Sciences and Engineering
Sun Yat-sen University
Guangzhou, China
Email: tianyuntao@mail.sysu.edu.cn

ABSTRACT

The Sichuan Basin and the Songpan-Ganzi terrane, separated by the Longmen Shan fold-and-thrust belt (the eastern margin of the Tibetan Plateau), are two main Triassic depositional centers, south of the Qinling-Dabie orogen. Closure of the Paleo-Tethys Ocean during the Middle – Late Triassic saw the Sichuan Basin region, located at the western margin of the Yangtze Block, transition from a passive continental margin into a foreland basin. In the meantime, the Songpan-Granze terrane evolved from a marine turbidite basin into a fold-and-thrust belt. To understand if and how the regional sediment routing system adjusted to these tectonic changes, we applied detrital zircon U-Pb analyses to representative stratigraphic samples from the southwestern edge of the Sichuan Basin to monitor sediment provenance. Integration of the results with paleocurrent and published detrital zircon data from other parts of the basin identified a marked change in provenance between Early-Middle Triassic samples, dominated by Neoproterozoic (~700-900Ma) zircons sourced mainly from the northern Kangdian basement to the south, and Late Triassic sandstones that contain a more diverse range of zircon ages, sourced from the Qinling, Longmen Shan and Songpan-Ganzi terrane. This change reflects a major drainage adjustment in response to the Late Triassic closure of the Paleo-Tethys Ocean and significant shortening in the Longmen Shan thrust belt and the eastern Songpan-Ganzi terrane. Further, at late Triassic time, the northern Kangdian

basement was inverted from uplift and erosion into subsidence. Considering the eastward paleocurrent and depocenter geometry of the upper Triassic deposits, the subsidence of the northern Kangdian basement probably resulted from the eastward shortening and loading of the Songpan-Ganze terrane over the western margin of the Yangtze Block in response to the Late Triassic collision between Yangtze Block, Yidun arc and Qiangtang Terrane along the Ganzi-Litang and Jinshajiang sutures.

INTRODUCTION

The Sichuan Basin, the western margin of the Yangtze block, shares common borders with four major tectonic terrains – the Qinling-Dabie orogen to the north, the Songpan-Ganzi terrane (i.e. the eastern Tibetan Plateau) to the west, the Yidun Arc to the south and the eastern Sichuan fold-and-thrust belt to the east (Fig. 1). Numerous structural, geochronological, and sedimentary studies suggested that these areas had experienced a significant phase of crustal shortening and rock exhumation during the Triassic closure of the Paleo-Tethys Ocean (Burchfiel *et al*., 1995; Zhang *et al*., 1995; Yin, 1996; Meng & Zhang, 2000; Li *et al*., 2003a; Wang *et al*., 2005; Jia *et al*., 2006), and the Sichuan Basin changed from a passive continental margin to a foreland basin.

In the context of these changes, the provenance of sediments deposited in the Sichuan Basin have seen extensive study, much based on detrital zircon U-Pb geochronology work (Deng *et al*., 2008; Chen, 2011; Luo *et al*., 2014; Zhang *et al*., 2015; Li *et al*., 2016; Shao *et al*., 2016; Zhu *et al*., 2017). Results from previous work suggest that the sediments in the basin were mainly sourced from the Qinling-Dabie orogen, to the north, and the Longmen Shan thrust belt and the Songpan-Ganzi terrane to the west. However, most of those previous studies focused on the post-Late Triassic foreland basin sediments in the western and northern part of the Sichuan Basin (Fig.1). The provenance of pre-Late Triassic passive continental margin clasts remains elusive. Constraining the provenance of the sediments deposited before and after the Late Triassic tectonic inversion could provide significant insights into whether the sediment routing system into the basin had significantly changed by the inversion event.

Previous sedimentary and stratigraphic studies suggested that during the Early – Middle Triassic, the southwestern basin margin was bounded by a highland, as indicated by a lateral sedimentary facies transition from clastic to carbonate away from the basin edge to interior (Liu & Tong, 2001; Long *et al*., 2011; Zhao *et al*., 2012; Tan *et al*., 2014; Wei *et al*., 2014). The highland consists of Neoproterozoic basement and is referred to as the Kangdian basement (named as the Kangdian Oldland or Kangdian Axis by Chinese researchers) (Li, 1963; Luo, 1983; Wang *et al*., 1983; Dai *et al*., 2012; Tan *et al*., 2013) (Fig. 1). However, the lithology of Late Triassic sediments in the southern Sichuan Basin is similar to those in other parts of the basin, sourced mainly from the Longmen Shan thrust belt and the Qinling-Dabie orogen. This implies that a significant change in sediment provenance might have occurred during the Late Triassic basin inversion. To test this, we applied detrital zircon geochronology to nine Early-Late Triassic sandstone and one volcanic tuff outcrop samples collected from the southwestern part of the Sichuan Basin. The results are interpreted together with previously mapped stratigraphic correlations and paleocurrent data, so as to constrain the paleogeographic evolution of the southwestern margin of the Sichuan Basin during Early-Late Triassic time, and to test if the crustal shortening and rock exhumation during the Triassic had influenced the sedimentary delivery network in the basin margin.

GEOLOGICAL SETTING

The southwestern part of Sichuan Basin is bounded by the Kangdian basement to the south and Songpan-Ganzi terrane and Longmen Shan to the west (Figs. 1, 2). The Triassic regional tectonism and geological evolution of these major terranes is summarized below.

Regional Tectonism

Triassic evolution of the Sichuan Basin and surrounding regions was controlled by the Middle - Late Triassic closure of the Paleo-Tethys Ocean along the Mianlue suture, forming the Qinling-Dabie orogen (e.g., Zhang, *et al*., 1995; Yin, 1996; Meng, & Zhang, 2000; Li, *et al*., 2003), and the Litang and Jinshajiang sutures north and south of the Yidun Arc (Fig. 3, e.g., Reid *et al*., 2005; Roger *et al*., 2008; Pullen *et al.*, 2008; Roger *et al.*, 2010; Yuan *et al*., 2010; Wang *et al*., 2013). During the process, margins of the Sichuan Basin, especially the Longmen Shan and Songpan-Ganzi turbidite terrane to the west, has been significantly shortened (e.g., Huang *et al*., 2003; Yan *et al*., 2011; Weller *et al*., 2013; Zheng *et al*., 2016), inducing several kilometers of flexural subsidence along the margins of the Sichuan Basin (e.g., Guo *et al*., 1996; Li, *et al*., 2003; Meng et al., 2005). In Cenozoic time, margins of the Sichuan Basin were reactivated by the Indo-Asian collision and the subsequent outward growth of the Tibetan Plateau (Liu-Zeng et al., 2008; Wang et al., 2012; Tian et al., 2012, 2013).

Sichuan Basin

The Phanerozoic geological evolution of the Sichuan Basin can be divided into three major stages: a passive margin stage characterized by platform carbonates during Paleozoic to Middle Triassic time (Xu *et al*., 1997), a Late Triassic foreland basin characterized predominantly by continental siliciclastic sedimentation and a terrestrial foreland basin or intracratonic stage from the Jurassic to Queternary (Li *et al*., 2003a). The eastern and central Sichuan Basin experienced a prolonged phase of denudation since late Cretaceous time, as shown by thermochronological studies (Tian *et al*., 2012). In this study, we focus on the Triassic strata in the southwest that consists of Feixianguan, Jialingjiang, Leikoupo, Maantang, Xiaotangzi and Xujiahe Formations, from bottom to top (Fig. 3).

(1) The marine Feixianguan Formation is widely distributed in the Sichuan Basin, but shows marked lateral lithofacies variations. The formation consists of purple shale and sandy shale, interbedded with grey limestone, oolitic limestone, marl and sandstone in the western Sichuan Basin, but changes into limestone toward the eastern basin (BGMRSP, 1997). The biostratigraphic age of the formation is early-early Triassic (BGMRSP, 1997). Several volcanic ash beds at the bottom of the formation compare well with the ash sequence of the Global Stratotype Section (Meishan section) (Huang *et al*., 2017) that has ash beds (~252Ma) (Burgess *et al*., 2014) providing a quantitative constraint for the age of the Feixianguan Formation. The isopach map of this formation shows a depocenter located in the center of the Sichuan basin (Fig. 4a).

(2) The marine Jialingjiang Formation conformably overlies the Feixianguan Formation, and is mainly composed of limestone and dolomite (BGMRSP, 1997). In the formation, Late-Early Triassic bivalves, ammonites, foraminiferas and conodonts have been discovered (BGMRSP, 1997). The top of the formation is marked by a widespread thin layer (the thickness is 10s cm – 1 m) of altered tuff (named as "green-bean rocks" in early Chinese literature) (Zhu & Wang, 1986), that has been dated to ~247 Ma

by ID-TIMS, LA-ICP-MS or CA-TIMS (Ovtcharova *et al*., 2006; Xie *et al*., 2013; Lehrmann *et al*., 2015).

(3) The marine Leikoupo Formation mainly consists of dolomite and argillaceous dolomite, interbedded with limestone and gypsum layers (BGMRSP, 1997). It contains Middle Triassic bivalves and ammonites such as *Progonoceratites, Beyrichites* (BGMRSP, 1997). The boundary between the Leikoupo and underlying Jialingjiang formations is the altered tuff. The isopach map of this formation shows a depocenter located in the center of the Sichuan basin (Fig. 4b).

(4) The marine Maantang Formation, distributed in the western Sichuan Basin, mainly consists of marine black mudstone and shale interbedded with siltstone, marl, oolitic and bioclastic limestones and sponge reefs (BGMRSP, 1997; Li *et al*., 2003a). It is regarded as Carnian in age on the basis of its fossil content (Shi *et al*., 2016). The Kuahongdong Formation represents equivalent coeval strata in the southwestern margin of the Sichuan Basin, and is composed of conglomerate, mudstone, argillaceous limestone and argillaceous dolomite (BGMRSP, 1997).

(5) The Xiaotangzi Formation, is composed of black marine shale, mudstone, quartz arenite, lithic arenite and siltstone, and can be divided into three parts: a lower part, composed of black shale interbedded with quartz arenite, a middle part, composed of lithic arenite and black shale, and an upper part, composed of arkose. The formation coarsens upwards and is thought to represent a transition from marine shelf to delta environments. It has an early Norian age based on its fossil content (Li *et al*., 2003a).

(6) The Xujiahe Formation conformably overlies the Xiaotangzi Formation in the western Sichuan Basin, and unconformably overlies Middle Triassic limestone of the Leikoupo Formation in the central and eastern Sichuan Basin. Widely distributed in the Sichuan Basin, the lithology and facies of the formation changes from coarse-grained sediments, including alluvial conglomerate bodies along the front of the Longmen Shan thrust belt, to fine-grained lacustrine deposits in the basin interior. Two depocenters, located in front of the middle segment of the Longmen Shan thrust belt and areas to the south, have developed (Fig. 4c). Depositional age of the formation is late Norian to Rhaetian based on the fossil content (WGCMSPISB, 1984; Li *et al*., 2003a).

Previous sedimentary studies suggested that the clastic deposits of Feixianguan, Jialingjiang and Leikoupo formations in the southwestern margin of the Sichuan Basin were sourced from the south, as shown by a facies transition from clastic to carbonate deposits from the margin to the interior of the basin (Feng *et al*., 1997; Tan *et al*., 2014; Sun *et al*., 2015). The Kangdian basement might be the source of Upper Triassic sediments, as suggested by studies on the detrital mineral assemblage, sedimentary system and conglomerate composition (Xie *et al*., 2006; Jiang *et al*., 2007; Shi *et al*., 2010). However, nonmarine Upper Triassic sediments unconformably overlie rocks of the Kangdian basement (BGMRSP, 1991) indicating that the region was likely an area of deposition rather than erosion (Liu & Tong, 2001; Yi *et al*., 2014).

Kangdian Basement

The Kangdian basement forms the western margin of the Yangtze Block and extends for over 700 km from Kangding in the north to Yuanmou in the south (Zhou *et al*., 2002a; Zhu *et al*., 2011). It is located in the western margin of the Yangtze Block (Fig. 1), and it mainly consists of Precambrian basement. It is overlain by marine Paleozoic cover and locally by Upper Triassic to Cenozoic terrestrial sediments (BGMRSP, 1991). Extensive Neoproterozoic magmatism (mainly ~740–870 Ma) is probably associated with the breakup of the supercontinent Rodinia due to a mantle plume (Li *et al*., 2003b), or the subduction of the Mozambique oceanic slab beneath the western margin of the Yangtze Block (Zhao & Zhou, 2007; Sun *et al*., 2009).

There is a debate on the geological evolution of Kangdian area throughout the Paleozoic and Mesozoic. One school of thought is that the Kangdian area was a region of erosion between the Ordovician and Carboniferous (Li, 1963), followed by a rift subsidence stage from Late Permian to Jurassic (Luo, 1983; Guo et al., 1996). A different point of view is that the Paleozoic - Mesozoic geological evolution of the region can be divided into three stages: a stable marine platform from the Cambrian to Early Permian, an uplift stage affected by Emeishan mantle plume from Late Permian to Middle Triassic, and transtensional subsidence during the Late Triassic and Jurassic (Chen et al., 1987; Feng *et al*., 1994; Wang *et al*., 1994; He *et al*., 2003; Chen et al., 2011).

Longmen Shan

The Longmen Shan is approximately 500km long and 30-50km wide, and defines a major part of the highly dissected eastern margin of Tibetan Plateau. Neoproterozoic lithologies, surrounded by Paleozoic sedimentary strata, cropout in the Longmen Shan. Zircon U-Pb analyses of the Neoproterozoic basement rocks yielded mainly ages of 770-890 Ma (Fu *et al*., 2013), which is similar in age and petrology of Neoproterozoic magmatism of Kangdian Basement.

The Longmen Shan thrust belt experienced three phases of intra-continental orogenic shortening in the early Mesozoic and late Cenozoic. Various lines of geochronological and structural evidence have been reported for the late Triassic formation of the Longmen Shan thrust belt (Huang *et al*., 2003; Yan *et al*., 2011; Weller *et al*., 2013). The second phase of deformation is characterized by contemporaneous hinterland-ward shearing and foreland-ward thrusting in the back and front sides of the Longmen Shan thrust belt (e.g., Tian et al., 2016). Synkinematic mica $^{40}Ar/^{39}Ar$ geochronological analyses suggest the deformaton is of late Cretaceous – early Paleogene time belt (Tian et al., 2016). The last phase of deformation has occurred during the late Cenozoic. During this phase, pre-existing structures were reactivated by the eastward growth of the Tibetan Plateau (e.g. Wang *et al*., 2012; Tian *et al*., 2013).

Songpan-Ganzi terrane

Songpan-Ganzi terrane currently form a triangular fold belt wedged between the North China block, Yangtez block, and Qaidam block (Fig. 1). More than 80% of the Songpan-Ganzi terrane is covered by thick Triassic turbidites, which was mainly sourced from the Qinling-Dabie orogen to the northeast and terranes to the north (Enkelmann *et al*., 2007; Ding *et al*., 2013). By latest Triassic, the Songpan - Ganzi basin had shallowed, as documented by coeval coal-bearing clastic deposits(BGMRSP, 1991; Chang, 2000). In response to the closure of the paleo-Tethys Ocean the flysch basin evolved into a fold belt during late Triassic time (Xu *et al*., 1992; Roger *et al*., 2011). Jurassic – Cenozoic deposits, have been recently reported in the western part of the terrane (Ding et al., 2013).

The Songpan-Ganzi terrane was intruded by Late Triassic–Jurassic granitoids (Roger *et al*., 2011). with ages in the range 228 - 153 Ma(Roger, *et al*., 2004; Zhang, *et al*., 2006; Xiao, *et al*., 2007; Zhang, *et al*., 2007; Weislogel, 2008; Yuan, *et al*., 2010). Metamorphic grade varies across the Songpan-Ganzi terrane. In general, the metamorphic overprint is relatively strong along the terrane margins where mudstones were metamorphosed to phyllite, but weak within the interior (Chang, 2000).

PREVIOUS DETRITAL ZIRCON STUDIES

Over the past decade, the provenance of the Upper Triassic clastic sediments in the Sichuan Basin has been intensively studied, especially by detrital zircon geochronology (Fig. 1), but this has led to conflicting conclusions. Deng *et al*. (2008) reported age spectra of four Upper Triassic sandstone samples from the western Sichuan Basin and the eastern Songpan-Ganzi terrane, and suggested that the Upper Triassic Xujiahe Formation was sourced from the Songpan-Ganzi terrane and Longmen Shan thrust belt. By contrast the study of Chen (2011) based in the northern and western parts of the Sichuan Basin indicated that the Qinling orogen to the north was the main source of sediments. Recently work by Luo *et al*. (2014), Zhang *et al*., (2015) and Shao *et al*., (2016), suggest that the Longmen Shan thrust belt and the Songpan-Ganzi terrane in the west and the Qinling-Dabie orogen in the north were the source of the Upper Triassic sediments in the western and northern Sichuan Basin, respectively. Zhang *et al*. (2015) and Shao *et al*. (2016) also indicated the minor role of the north Yangtze Block in supplying sediments to the northern Sichuan Basin. Shao *et al*. (2016) suggested that sediments of the western, southern and eastern parts of basin shared the same sources that include the southern North China Block and Qinling orogen, and the eastern Songpan-Ganzi terrane via the Longmen Shan thrust belt. Zhu *et al*. (2017) reported age spectra of four Middle-Upper Triassic sandstone samples from the southwestern Sichuan Basin, and suggested that Middle Triassic sediments mainly sourced from the Kangdian basement and Emeishan Large Igneous Province to the south, whereas Upper Triassic sediments mainly from the Songpan-Ganzi terrane and Yidun Arc to the west with a minor component from the Qinling orogen to the north and Jiangnan Xuefeng thrust belt (southeastern Yangtze Block) to the east. Importantly, all these previous studies focused on the Upper Triassic; little is known about the source of the Lower Triassic clastic rocks. One of the core aims of this study therefore, is to try and resolve the ongoing debate about the sources of the Triassic sediments.

SAMPLING AND ANALYTICAL METHODS

Ten samples were collected from the Longcanggou, Longmendong and Chuanzhu sections in the southwestern part of the Sichuan Basin. The sections expose all lithologic formations of the Triassic sediments (Figs. 5 and 6). Details of the stratigraphy and sedimentology features of the sections are provided in the supplementary material. The samples include two samples from the Early Triassic Feixianguan (T_1f) and Jialingjiang Formation (T_1j), one volcanic tuff sample from the boundary between the Jialingjiang Formation (T_1j) and Leikoupo (T_2l), two samples from the Middle Triassic Leikoupo Formation (T_2l) and five samples from the Upper Triassic Maantang (T_3m) Xiaotangzi (T_3xt) and Xujiahe formations (T_3x) (Figs. 5 and 6).

Where possible, more than 100 U/Pb ages were derived by LA-ICP-MS using the facilities at the London Geochronology Centre, University College London, which include a New Wave NWR193 excimer laser ablation system and an Agilent 7700x quadrupole mass spectrometer. The laser was set to produce ~2.5 J/cm^2 energy density at 8 Hz repetition rate for 25 seconds. The spot diameter was set to 25 μm for all analyses. Repeated measurements of internal U/Pb age standard Plešovice [TIMS reference age of 337.13 ± 0.37 Ma (Sláma *et al*., 2008)] and NIST-610 silicate glass (Jochum *et al*., 2011) were used to correct for instrumental mass bias and laser-pit-depth-dependent isotopic fractionation. GJ-1 (Jackson *et al*., 2004) and 91500 zircon (Wiedenbeck *et al*., 2004) were used as external standards. Data reduction was processed using the GLITTER software package (Griffin *et al*., 2008).

The paleocurrent data were determined in the field based on cross-bedding and ripples in sandstone beds. The orientations of trough cross laminations were measured using the method described by DeCelles *et al.* (1983).

RESULTS

Paleocurrent

Paleocurrent data were collected from 7 sites, as summarized in the Fig. 2. The paleocurrent in the Feixianguan formation, measured in the Longcanggou section (L01), is eastward (Fig. 5), as determined from cross-bedding in sandstone beds. The results, derived from cross-bedding and current ripples in sandstone in the Longcanggou (L02), Chuanzhu (C01, C02) and Hanyuan areas (YD01, SQ02, HY01), indicates eastward and southeastward paleocurrent directions for the Xiaotangzi and Xujiahe Formations (Fig. 5).

Zircon U-Pb isotopic results

In total, 1132 detrital zircons from nine detrital samples analyzed in this study. The U–Pb data for each sample are presented in supplementary Table. As with convention, we only consider U-Pb ages that were no more than 15% discordant or 5% reverse discordant. The data are visualized as kernel density estimate (KDE, Vermeesch, 2012) plots.

Altered tuff

Sample SZ02 (102°51′42.92″ E, 29°40′47.12″N) of the altered tuff was collected from the boundary between the Leikoupo and Jialingjiang formations in the Longcanggou section. 30 of 34 analyses yielded concordant ages. The data are concordant within analytical error and define a weighted mean $^{206}Pb/^{238}Pb$ age of 246.5 ±1.7 Ma (n=26) (Fig. 7), which is similar to the previous studies in other sites of the Yangtze Block (Ovtcharova *et al.*, 2006; Xie *et al.*, 2013; Lehrmann *et al.*, 2015). The complete U–Pb isotopic data and calculated dates are presented in supplementary Table 1.

Lower Triassic Feixianguan and Jialingjiang Formations

Sample LCG01 (102°51′42.92″ E, 29°40′47.12″N), a grey-green fine-grained sandstone, was collected from the Feixianguan Formation in the Longcanggou section (Fig. 6). ninety-nine of 156 analyses yielded concordant ages, which exhibit a wide spectrum from ca. 243±3Ma to 2.4Ga. The KDE plot of this sample shows a major peak at ~800Ma, and three minor peaks at ~248Ma, ~510Ma and ~950Ma (Fig. 8a).

Sample LMD02 (103°25′5.73″ E, 29°34′46.76″N), a grey-purple coarse sandstone, was collected from the Jialingjiang Formation in Longmendong section (Fig. 6). Among 129 analyses, 123 analyses yield concordant ages. Nearly all ages are between 730 - 880 Ma, showing a dominant peak at ~800 Ma in the KDE plot (Fig. 8b).

Middle Triassic Leikoupo Formation

Two samples (grey coarse sandstone), LCG03 (102°51′35.19″ E, 29°40′51.35″N) and LCG04

(102°51′35.05″ E, 29°40′51.18″N), were collected from the Leikoupo Formation in Longcanggou section (Fig. 6). one hundred and thirty-six out of 153 single zircon dates of the sample LCG03 are concordant. The ages exhibit a wide range from ca. 242±3Ma to 2.5Ga, with 74% lying between 730 Ma and 880 Ma, showing a dominant mode at ~800Ma (Fig. 8c), similar to the lower sample LMD02 from Jialingjiang Formation.

One hundred and fifty-two out of 157 single zircon dates of the sample LCG04 are concordant. The ages exhibit a wide range from ca. 233±3Ma to 3.0Ga; but most of them fall between 230 Ma to 1050 Ma (89%). The KDE plot of the sample shows a mode at ~800Ma, and three minor peaks at ~248Ma, ~510Ma and ~950Ma (Fig. 8d).

Upper Triassic Maantang and Xujiahe Formation

Two samples (grey sandstone), LCG05 (102°51′34.05″E, 29°40′51.18″N) and LCG06 (102°51′34.05″E, 29°40′51.18″N), were collected from the Maantang Formation and the upper part of Xujiahe Formation in the Longcanggou section (Fig. 6). One hundred and forty-nine of 154 single zircon dates of the sample LCG05 are concordant. Most ages cluster at ~1800 Ma, with minor peaks at ~250 Ma, ~800 Ma and ~2500 Ma (Fig. 8e). Their age spectra are significantly different from the lower ones (Fig. 8a-d). Ninety-nine of 110 single zircon dates of the upper Triassic sample LCG06 are concordant. The KDE plot shows five peaks at ~246 Ma, ~440 Ma, ~758 Ma, ~1870 Ma and ~2480 Ma, respectively (Fig. 8f).

Three samples (grey sandstone), CZ05 (103°24′6″E, 29°37′23″N), CZ01 (103°24′22″E, 29°37′20″N), and CZ03 (103°24′43.2″E, 29°37′27″N), were collected from the upper part of the Xujiahe Formation in the Chuanzhu section (Fig. 6). The KDE plots of these samples are similar, showing peaks at ~276 Ma, ~429 Ma, ~1030 Ma, ~1860 Ma and ~2470 Ma (Fig. 8g-i).

DISCUSSION

Detrital sources

Zircon spectra of potential sources

As suggested by previous detrital zircon studies of the Sichuan Basin (Deng *et al*., 2008; Weislogel *et al*., 2010; Chen, 2011; Luo *et al*., 2014; Zhang *et al*., 2015; Shao *et al*., 2016; Zhu *et al*., 2017), potential source terrains for the Triassic strata include eastern Songpan-Ganzi terrane, northern and southern Kangdian, Longmen Shan thrust belt, Qinling orogen, southeastern Yangtze Block .

We compiled zircon U-Pb ages of the crystalline and clastic rocks exposed in these potential source areas (Fig. 9). The detrital zircon U-Pb age spectrum of the eastern Songpan-Ganzi terrane shows three major peaks at ~290Ma, ~ 430Ma, ~1870Ma, and two minor peaks at ~770Ma, ~950Ma, ~2480Ma (Fig. 9f). The northern Kangdian basement is characterised by two major peaks at ~800Ma and ~930Ma, and a minor peak at ~260Ma (Fig. 9g); whereas the southern Kangdian basement is more complex, with peaks at ~810Ma, ~1840Ma, and three minor peaks at ~2310Ma and ~2430Ma (Fig. 9h). The Longmen Shan thrust belt produces three major peaks at ~520Ma, ~750M and, ~945Ma (Fig. 9i). The Qinling orogen is characterised by three major peaks at ~440Ma, ~815Ma and ~ 1995Ma, and three minor peaks at ~260Ma, ~1830Ma and ~2465Ma (Fig. 9j). The southeastern Yangtze Block yields a dominant peak at ~815Ma (Fig. 9k).

It is worth noting that ratios between components of the age spectra of potential source areas may not representative, even though hundreds of single ages have been compiled. This is because the spectra are mostly derived from a collection of few detrital studies of Neoproterozoic sediments, covering little parts of the source area (Figs. 9g, 9i and 9j). For example, the age data of north Kangdian basement are mostly (336 out of 407) derived from the detrital zircon U-Pb age of Neoproterozoic Yanbian Group (Zhou *et al*., 2006 and Sun *et al*., 2009), 37 out of 407 dates are crystallization ages of Neoproterozoic igneous rocks, which are of ~800 Ma (Fig. 9g), whereas the rest 34 dates from Upper Permian sandstone samples are of ~260 Ma, which is likely derived from Emeishan igneous province (He et al., 2007). Further, the areas of these rock types and the abundances of zircon therein are significant variable. For these reasons, our data interpretation ignores the proportions of age peaks.

Detrital sources of the Lower and Middle Triassic strata

Detrital zircon age of four Lower and Middle Triassic samples (LCG01, LMD02, LCG03, LCG04,) defines a prominent peak at ~810 Ma. It is worth noting that two of four sample (LCG01, LCG04) exhibits three minor peaks at ~255 Ma, ~535 Ma and ~970 Ma, which are missing from the samples LCG 02 and LMD02 (Fig. 8).

The ~810 Ma age peak presents in two potential source areas, the northern Kangdian basement and the southeastern Yangtze Block). The most likely source is the northern Kangdian basement. The age spectra of crystalline rocks of the northern Kangdian basement is dominated by the peak at ~800 Ma, similar to that of the Lower and Middle Triassic sediments. However, the bulk age spectra of the northern Kangdian basement also include a major peak at ~930 Ma, which forms a minor component in the Lower and Middle Triassic sediments. This suggests the Neoproterozoic meta-sediments, from which the ~930 Ma age peak were derived (Fig. 9g), were not a major source, probably because the exposure of the meta-sediments is relatively limited.

Further, detrital zircon age spectra of Lower and Middle Triassic samples include a minor peak at ~535 Ma that has only been recognized in the Longmen Shan (Figs. 9a, i), indicating the Longmen Shan was possibly also a source of sediments. Furthermore, the interpretation in terms of the source area is also consistent with the eastward paleocurrent directions of these Lower and Middle Triassic sediments (Fig. 5).

Furthermore, our zircon age compilation for the northern Kangdian basement also shows a minor peak at ~255 Ma, derived from the Emeishan basalt (He et al, 2007). However, this age peak is either minor or absent from the age spectra of the lower and middle Triassic strata. This is probably because of the relatively lower concentration of zircons in mafic rocks.

The southeastern Yangtze Block cannot be ruled out as a possible source; but the possibility is very low. If the southeastern Yangtze Block were the source, it would require a long drainage system to deliver the sediments into the southwestern Sichuan Basin via the northern Kangdian, because the southeastern Yangtze Block and the southwestern Sichuan Basin were separated by a N-S striking depocenter, running across the central part of the basin (Fig. 4a), where coeval deposits are composed of carbonate, shale and mudstone (Hu, *et al.*, 2010; Tan, *et al.*, 2014; Sun, *et al.*, 2015).

Detrital sources of the Upper Triassic strata

In contrast to the Lower-Middle Triassic samples, detrital zircons from the Upper Triassic samples (LCG05, LCG06, CZ05, CZ01, CZ03), which exhibit southeastward paleocurrent directions (Fig. 5), are characterized by multiple age peaks at ~270 Ma, ~435 Ma, ~775Ma and ~1010 Ma, ~1840Ma and 2480 Ma (Fig. 9b). Detrital zircon data of the coeval sediments in the southwestern, western and northern Sichuan Basin, as reported in previous studies, yield similar age spectra (Figs. 9c, d, e), indicating that they may have the same or similar sources, including the Qinling orogen, Longmen Shan thrust belt, and eastern Songpan-Ganzi terrane (Chen, 2011; Luo *et al*., 2014; Zhang *et al*., 2015; Shao *et al*., 2016).

Similar age spectra are shown by the Triassic turbidites of the eastern Songpan-Ganzi terrane (Weislogel *et al*., 2010; Ding *et al*., 2013; Zhang, 2014), which may have shared similar sources as the Sichuan Basin. Alternatively, the eastern Songpan-Ganzi terrane may have experienced a phase of shortening in response to the late Triassic intracontinental orogeny along the Longmen Shan thrust belt (Li *et al*., 2003a; Yan *et al*., 2011; Zheng *et al*., 2016). From this perspective, it is speculated that the eastern Songpan-Ganzi terrane might also be a source region for the Upper Triassic detritus of the Sichuan Basin.

To summarize, the detrital zircon results presented above suggest the source areas for the detritus of the southwestern Sichuan Basin changed significantly from the Northern Kangdian basement to the Qinling orogeny - Longmen Shan thrust belt - eastern Songpan-Ganzi terrane at late Triassic time. Such a change indicates the adjustment of the Triassic sediment route system, which has significant palaeogeographic and tectonic implications.

Tectonic and palaeogeographic implications

Despite of the significant change in the detrital zircon spectra, palaeocurrent of the Lower, Middle and Upper Triassic strata has barely changed. They are mostly eastward. This indicate that the Kangdian Basement, which is now south of the study area, was located west (Fig. 10a), indicating that the basement should have experienced considerable eastward displacement relative to the Sichuan Basin. Such an interpretation is consistent with the late Mesozoic and Cenozoic deformation history of the region. Further, as indicated by the migration of the Mesozoic depocenters in the Sichuan Basin, Meng *et al* (2005) suggest the Basin has experienced considerable clockwise rotation during Mesozoic time. Further, late Cenozoic left-lateral strike-slip along the Xianshuihe fault has displaced the Kangdian basement eastward from the Longmen Shan by ~80 km (Wang *et al*., 2009; Tian *et al*., 2014).

Upper Triassic sediments in the Sichuan Basin were mainly sourced from the Qinling orogeny and the Longmen Shan thrust belt, as suggested by previous studies (Fig. 9, 10b) (Deng *et al*., 2008; Chen, 2011; Luo *et al*., 2014; Zhang *et al*., 2015; Shao *et al*., 2016; Zhu *et al*., 2017). The sediment route system is mostly eastward and southeastward, as indicated by the paleocurrent (Fig. 5). The similarity in detrital zircon signal between the upper Triassic sediments and the eastern Songpan-Ganzi terrane indicates that the eastern Songpan-Ganzi terrane might also have been significantly shortened and unroofed, providing detritus for the western and southern Sichuan Basin. The Late Triassic shortening of the Songpan-Ganzi turbidites might relate to several possible processes, including (1) westward subduction of the Ganzi–Litang Ocean during the Late Triassic (Hou *et al*., 2004), (2) collision between Yidun arc and the Songpan-Ganzi terrane at the end of the Triassic (Hou *et al*., 2004; Wang *et al*., 2013b), (3) intra-continental transpressional shortening between the eastern Songpan-Ganzi terrane and the Sichuan Basin, forming the Longmen Shan thrust belt(e.g., Li *et al*., 2003a; Harrowfield and Wilson, 2005; Wang and Meng, 2008), and (4) slab retreat or rollback of Paleo-Tethys lithosphere (e.g., de Sigoyer *et al*., 2014; Pullen *et al*., 2008; Zhang *et al*., 2015).

Late Triassic uplift and unroofing of the Longmen Shan thrust belt is required to provide detritus for the Upper Triassic deposits, as discussed above. This speculation is consistent with other lines of evidence. First, the presence of klippen of Paleozoic and Precambrian rocks over Triassic sediments in the eastern front of the Longmen Shan thrust belt indicate that these structures were formed during the Late Triassic or later. Second, the oldest U–Th–Pb monazite and Sm–Nd garnet ages (204-190 Ma), derived from metamorphosed rocks in the Danba Antiform, immediately south of the Longmen Shan thrust belt, were interpreted as dating the timing of Barrovian metamorphism associated with the deformation (Huang *et al*., 2003; Weller *et al*., 2013). Third, muscovite $^{40}Ar/^{39}Ar$ dating of early Paleozoic schist and Neoproterozoic Pengguan complex from the northern and middle Longmen Shan yielded ages between 237-208 Ma and 235-226 Ma, respectively, which were interpreted as minimum age constraints for Mesozoic crustal shortening (Yan *et al*., 2011; Zheng *et al*., 2016).

As indicated by our palaeocurrent and detrital zircon results, the northern Kangdian basement was uplifted and unroofed to provide the detritus for the Lower and Middle Triassic sediments in the southwestern Sichuan Basin (Fig. 10a). However, in late Triassic time, the basement subsided significantly in Late Triassic time (Fig. 10b), as indicated by the presence of Upper Triassic sediments (~1 km, Guo et al., 1996) over the basement rocks (Fig. 2). The subsidence of the basement might result from the eastward shortening and loading of the Songpan-Ganze terrane over the western margin of the Yangtze Block in response to the Late Triassic collision between Yangtze Block, Yidun arc and Qiangtang Terrane along the Ganzi-Litang and Jinshajiang sutures (Fig. 10b). This interpretation is also supported by the eastward paleocurrent and the development of a ~1.5-km-thick late Triassic depocenter in areas south of the sampling sites (i.e. the location of the northern Kangdian basement) (Fig. 4c). Such a tectonic reconstruction differs from previous models, suggesting continuous Late Permian to Jurassic subsiding as a rift (Luo, 1983; Guo et al., 1996), or early Mesozoic transtensional subsidence by strike-slip faulting (Chen et al., 1987; Feng *et al*., 1994; Wang *et al*., 1994; He *et al*., 2003; Chen et al., 2011).

CONCLUSIONS

Triassic sediments in the southwestern Sichuan Basin record different detrital zircon geochronology signals. Detrital zircon age spectra of Lower and Middle Triassic samples are similar and characterized by a dominant age mode at ~810 Ma, with three minor peaks at ~255Ma, ~535Ma and ~970Ma. In contrast to the Lower-Middle Triassic samples, detrital zircon spectra of Upper Triassic samples are characterized by multiple age peaks at ~270 Ma, ~435 Ma, ~775Ma and ~1010 Ma, ~1840Ma and ~2480 Ma.

Our data reveal a major change of provenance during the Upper Triassic in response to multiple tectonic events. The sediments in the southwestern Sichuan Basin is supplied by the highland of the Yangtze Block (the northern Kangdian Basement) during the Early-Middle Triassic passive continental margin stage. During the Upper Triassic, the Sichuan Basin was inverted into a foreland basin and the Longmen Shan thrust belt and possibly the eastern Songpan-Ganzi terrane was uplifted in response to the closure of the Paleo-Tethys Ocean and intra-continental shortening along the Longmen Shan thrust belt, becoming the main source areas of the southwestern and western Sichuan Basin. The Late Triassic sediments in the southwestern Sichuan Basin have recorded the collision and subsequent continuing convergence between Qiangtang Block and Yangtze Block. This study highlights the importance of tectonic events in reorganizing drainage and sediment supply in foreland basins. The Late Triassic evolution of foreland basin in the Upper Yangtze Block Sichuan Basin have been strongly controlled by collision and subsequent continuing convergence between Qiangtang Terrane and Yangtze Block, challenging the previous view that the foreland basin was mainly controlled by the collision between northern China Block ang Yangtze Block.

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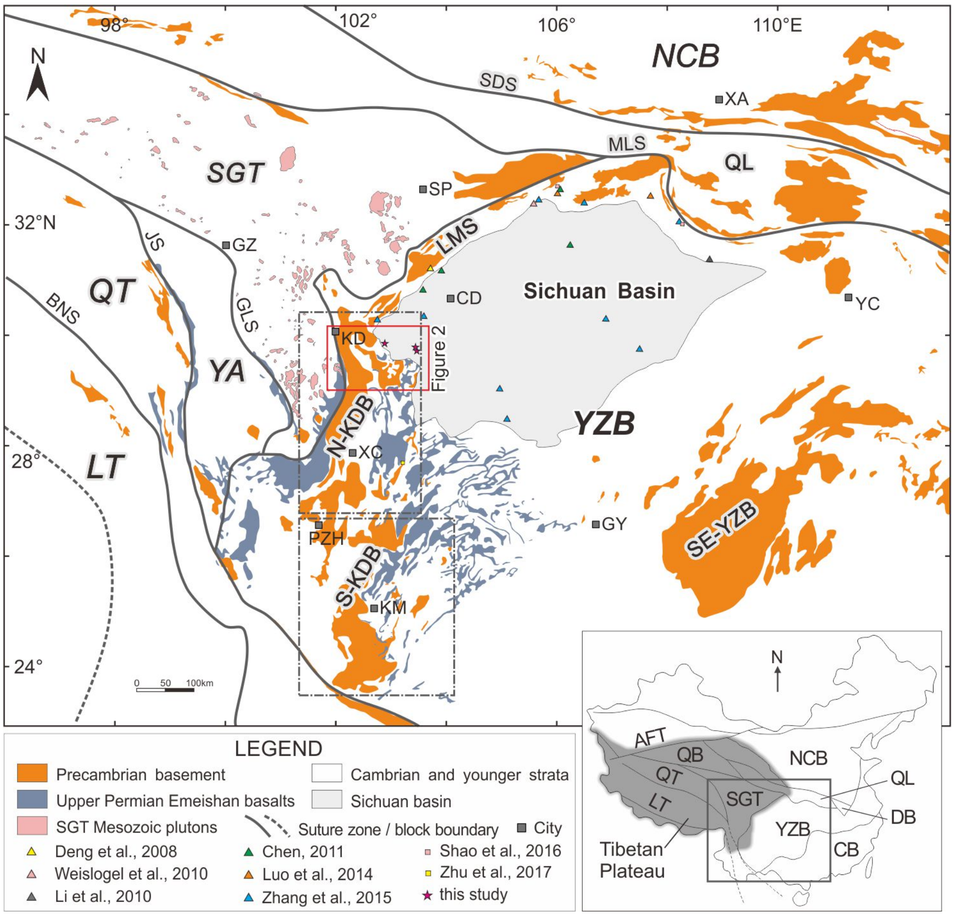

Fig. 1. Simplified tectonic map of the Upper Yangtze Block and adjacent regions. Sites of previous detrital zircon geochronology studies of the Sichuan Basin are shown in the figure. Inset shows main tectonic elements of China. ATF, Altyn Tagh fault; CB, Cathaysia Block; CD, Chengdu; DB, Dabie orogen; GLS, Ganzi-Litang suture; GY, Guiyang; GZ, Ganzi; JS, Jinshajiang suture; KM, Kunming; LT, Lhasa terrane; MLS, Mianlue suture; N-KDB, Northern Kangdian basement; NCB, North China Block; PZH, Panzhihua; QB, Qaidam Block; QL, Qinling orogen; QT, Qiangtang terrane; S-KDB, Southern Kangdian basement; SDS, Shangdan suture; SGT, Songpan-Ganzi terrane; SP, Songpan; XA, Xi'an; XC, Xichang; YC, Yichang; YA, Yidun arc; YZB, Yangtze Block. Modified from Tian *et al*. (2012a) and Wang & Pan, (2013). The distribution of the Upper Permian Emeishan basalts is modified from Xu *et al*. (2004).

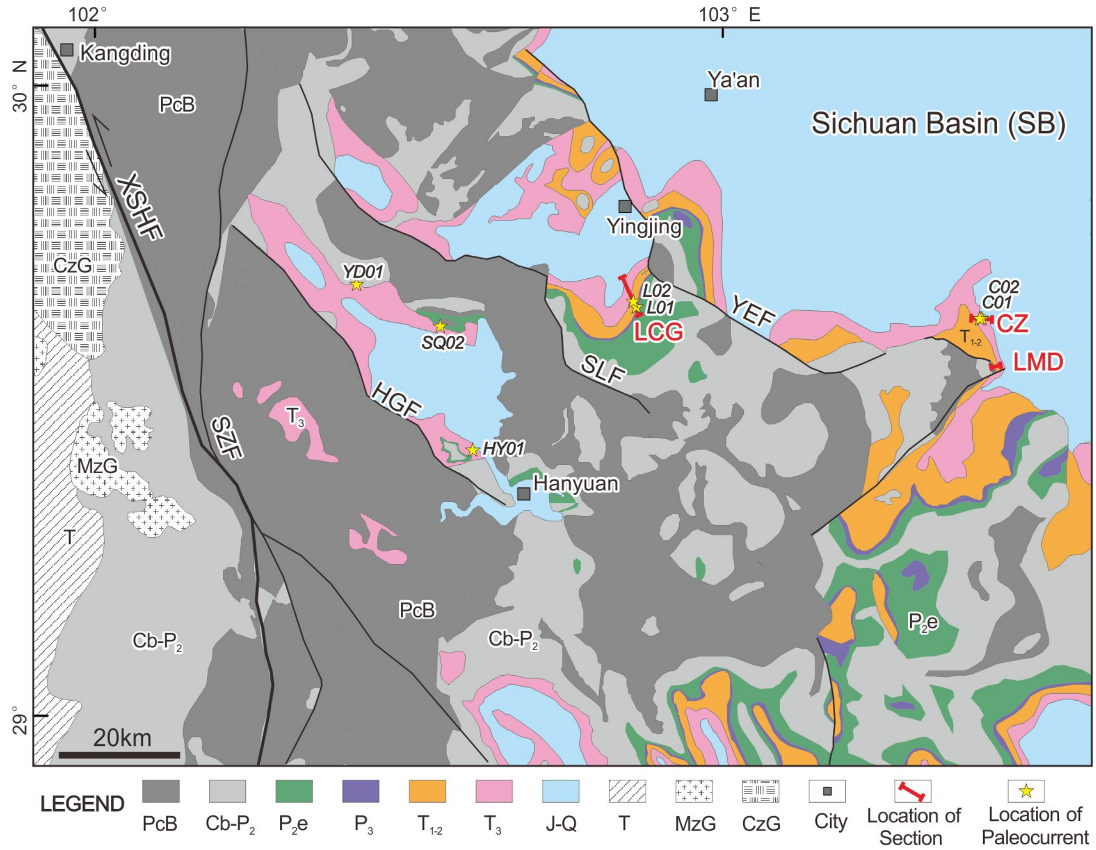

Fig. 2. Generalized geological map of the study area, modified from BGSP (1974). The location is shown in Fig. 1. Abbreviations: PcB — Precambrian Basement; Cb-P_2 — Cambrian - Middle Permain; P_2e — Upper Permain Emeishan basalts; P_2 — Upper Permian Xuanwei Formation; T_{1-2} — Lower and Middle Triassic; T_3 — Upper Triassic; J-Q — Jurassic to Quaternary; T — Triassic in the eastern Songpan-Ganzi terrane; CzG — Cenozoic Granite; HGF — Hanyuan-Ganluo fault; MzG — Mesozoic Granite; SLF — Sanhe-Leibo fault; SZF — Shimian-Zhaojue fault; XSHF — Xianshuihe fault; YEF — Yingjing-Emei fault. Red solid lines and text makes the localities of the Longcanggou (LCG), Chuanzhu (CZ) and Longmendong (LMD) sections, from which samples were collected.

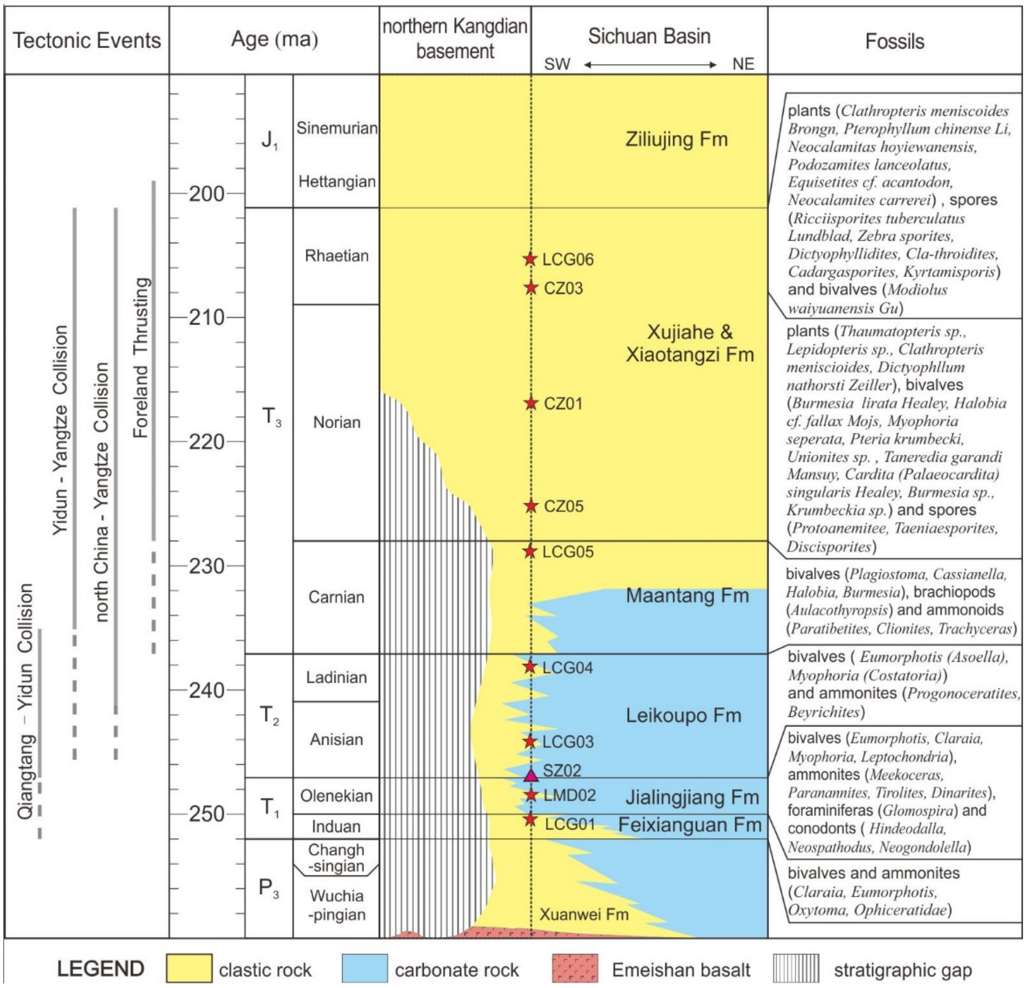

Fig. 3. Stratigraphic nomenclature, age of the southern Sichuan Basin and northern Kangdian Oldland. The time of foreland thrusting is after Zhang *et al.* (1995), Yin (1996); Meng, & Zhang (2000), Li *et al.* (2003); the time of Yidun – Yangtze collision is after Reid et al. (2005), Roger et al. (2008), Yuan *et al.* (2010), Wang *et al.* (2013); the time of Qiangtang- Yidun collision is after Reid et al. (2005), Pullen et al. (2008), Roger et al. (2008), Roger et al. (2010). Time scale is from Gradstein *et al*. (2012). P_3 — the Late Permian; T_1 — the Early Triassic; T_2 — the Middle Triassic; T_3 — the Late Triassic; J_1 — the Early Jurassic.

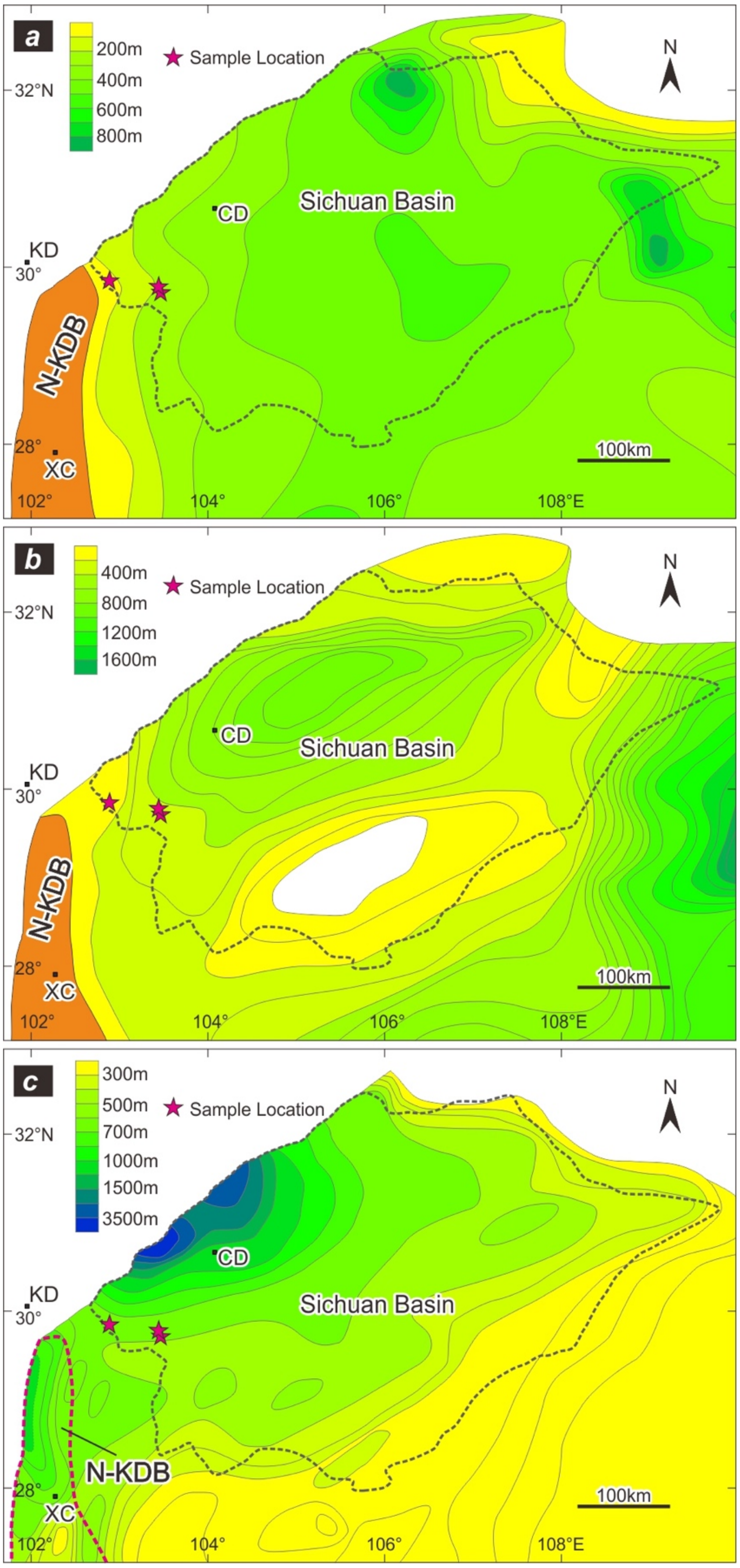

Fig. 4. The isopach of the Lower Triassic Feixianguan (a), Middle Triassic Leikoupo (b) and upper Triassic Xujiahe (c) formations in the Upper Yangtze Block, including the Sichuan Basin and surrounding regions (modified after Guo et al. 1996). Abbreviations for towns: CD = Chengdu, CQ = Chongqing, KD = Kangding, XC = Xichang.. Note that at late Triassic time, the northern Kangdian basement (N-KDB) was inverted into a depocenter from erosion.

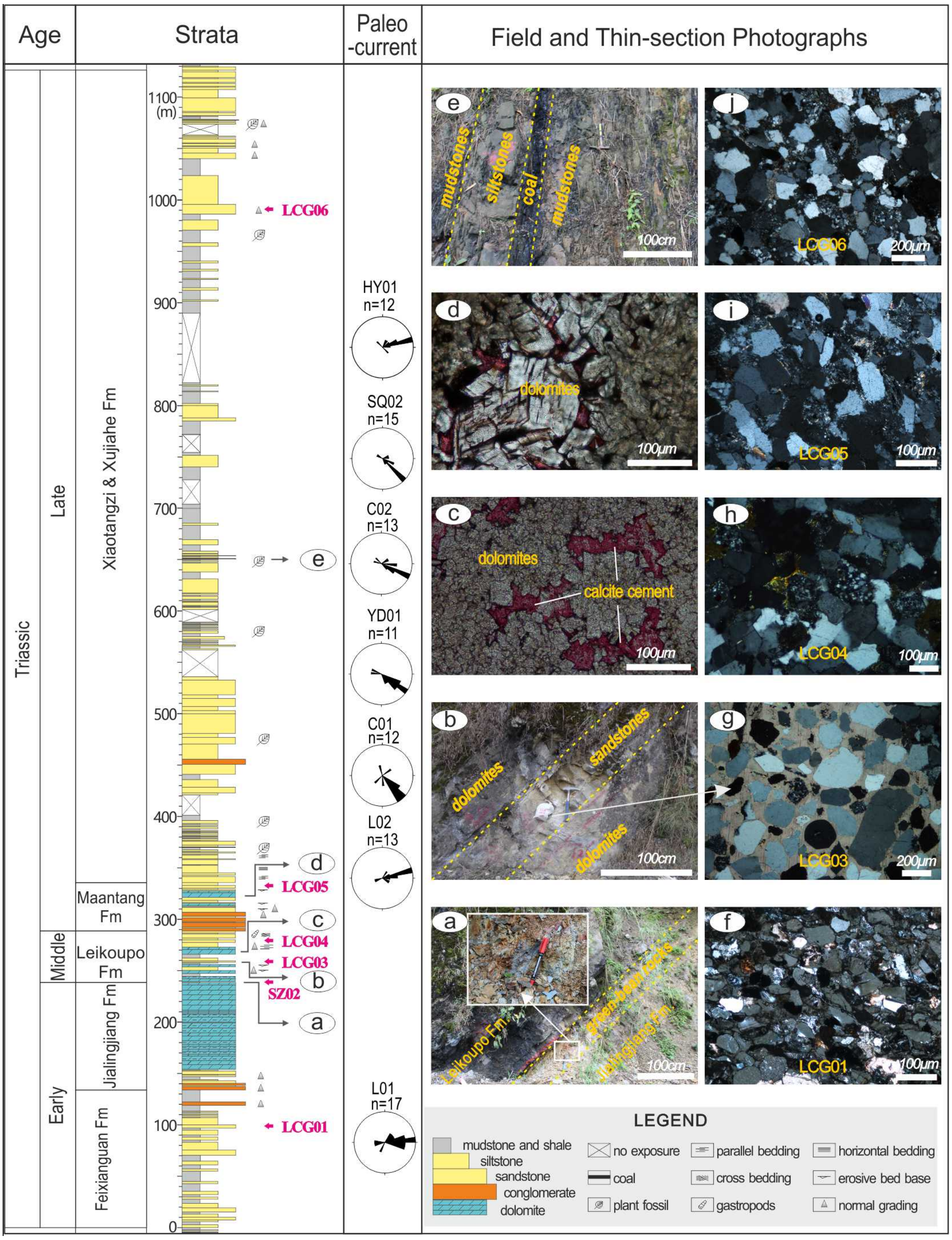

Fig. 5. Stratigraphy, rose diagrams of paleocurrent and thin-sections for the Longcanggou section. The locations of paleocurrent measurements are shown in Fig. 2. (a) Boundary (the " altered tuff") between the Lower Triassic Jialingjiang Formation and Middle Triassic Leikoupo Formation; (b) Dolomites interbedded between sandstones (sample LCG03); (c) Thin-section photograph of dolomites from the Leikoupo Formation; (d) Dolomites from the upper Mantang Formation; (e) Siltstones and mudstones interbedded with coal from upper part of Xujiahe Formation; (f, g, h, i, and j) Thin-sections of sandstone from the LCG01, LCG03, LCG04, LCG05 and LCG06, collected from the Feixianguan (LCG01), Leikoupo (LCG03, LCG04), Mantang (LCG05) and Xujiahe (LCG06) Formations.

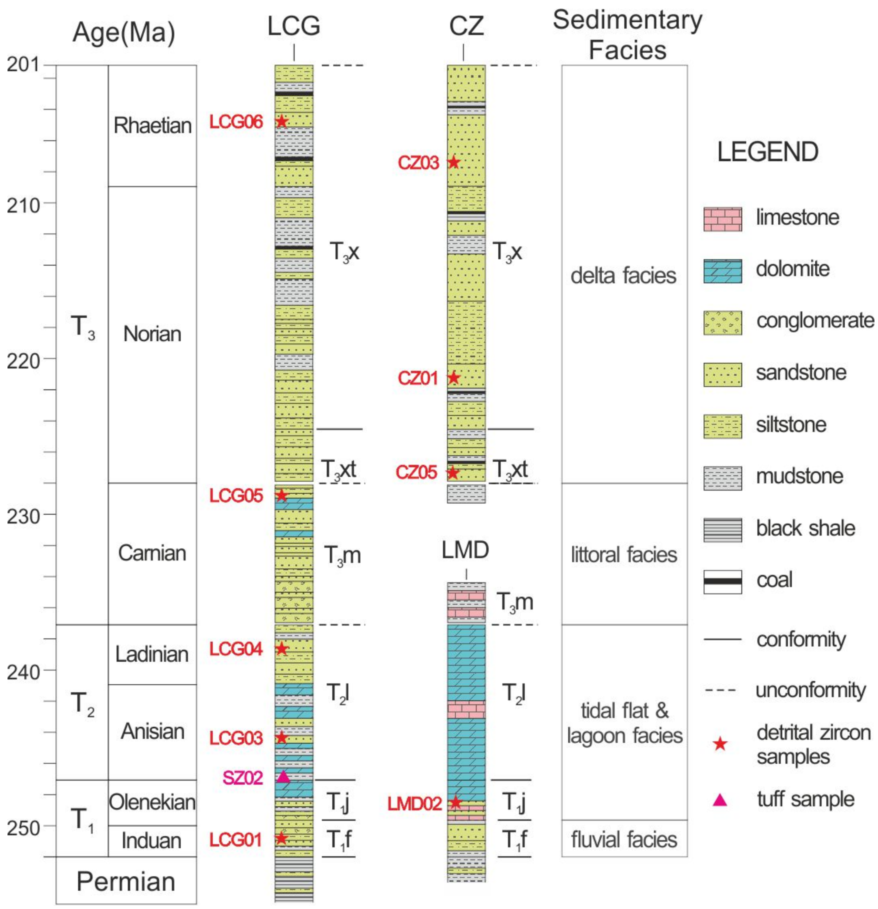

Fig. 6. Comparison of Triassic stratigraphy in the southwestern Sichuan Basin. CZ (Chuanzhu) section is compiled from WGCMSPISB (1984) and LMD (Longmendong) section from Lin *et al*. (1982), Xu *et al*. (1997) and BGMRSP (1997), with the sedimentary facies after Zhao *et al*.(1996); T_1f — Feixianguan Formation; T_1j — Jialingjiang Formation; T_2l — Leikoupo Formation; T_3m — Maantang Formation; T_3xt — Xiaotangzi Formation; T_3x—Xujiahe Formation; T_1—the Early Triassic; T_2—the Middle Triassic; T_3 — the Late Triassic. Time scale is from the Gradstein *et al*. (2012), which is consistent with the tuff results derived from the sample SZ02 from the Longchanggou (LCG) section (see Fig. 7).

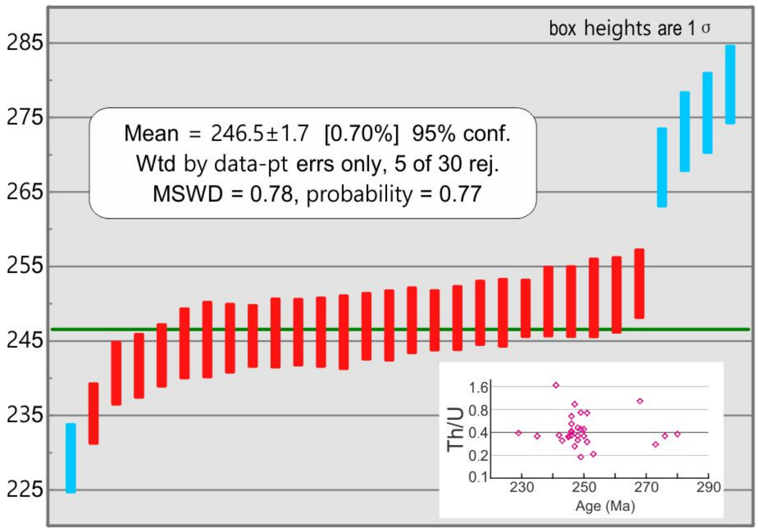

Fig. 7. U–Pb zircon ages of the altered tuff (sample SZ02 this study). Blue dates are rejected by

ISOPLOT for calculating the weighted mean age.

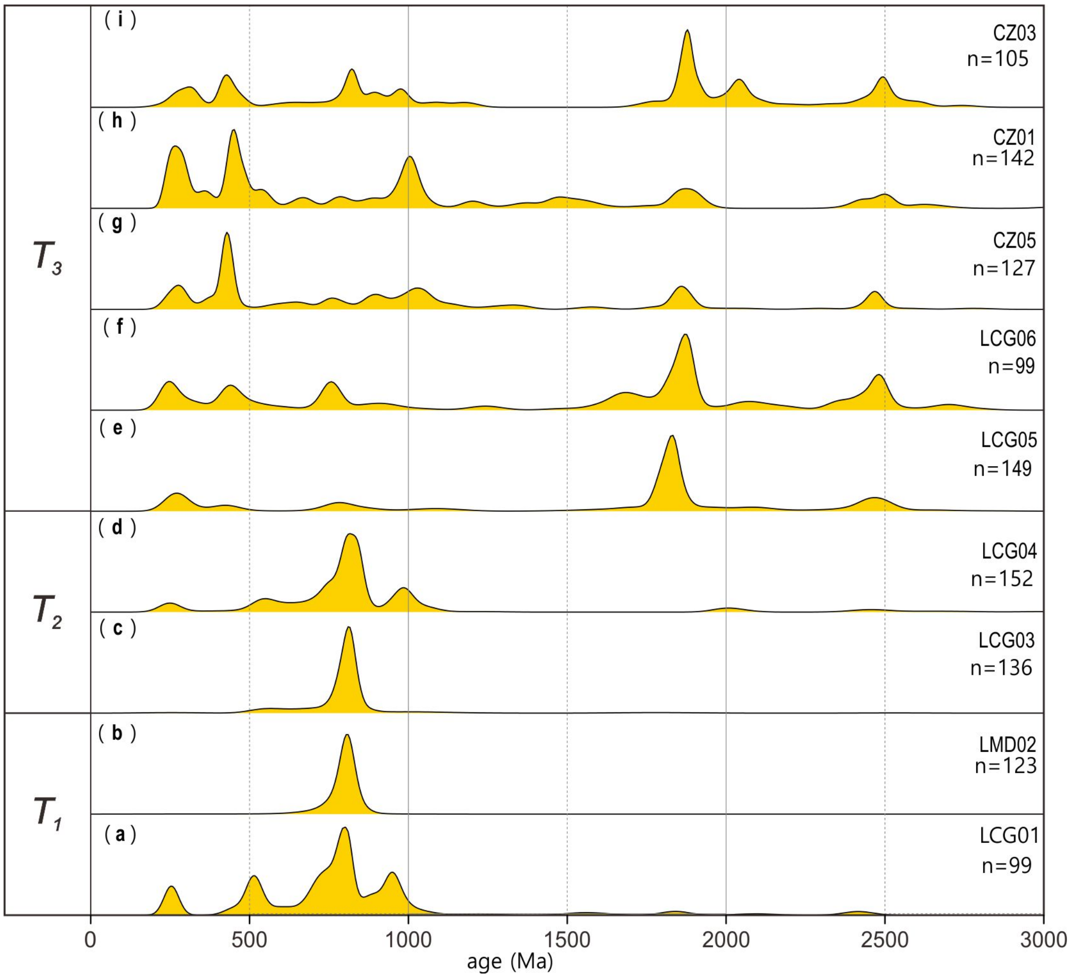

Fig. 8. Kernel Density Estimation (KDE) plots of the detrital zircon U-Pb data for samples LCG01, LMD02, LCG03, LCG04, LCG05, LCG06, CZ05, CZ01 and CZ03, respectively. T_1, T_2 and T_3 are Early, Middle and Late Triassic, respectively.

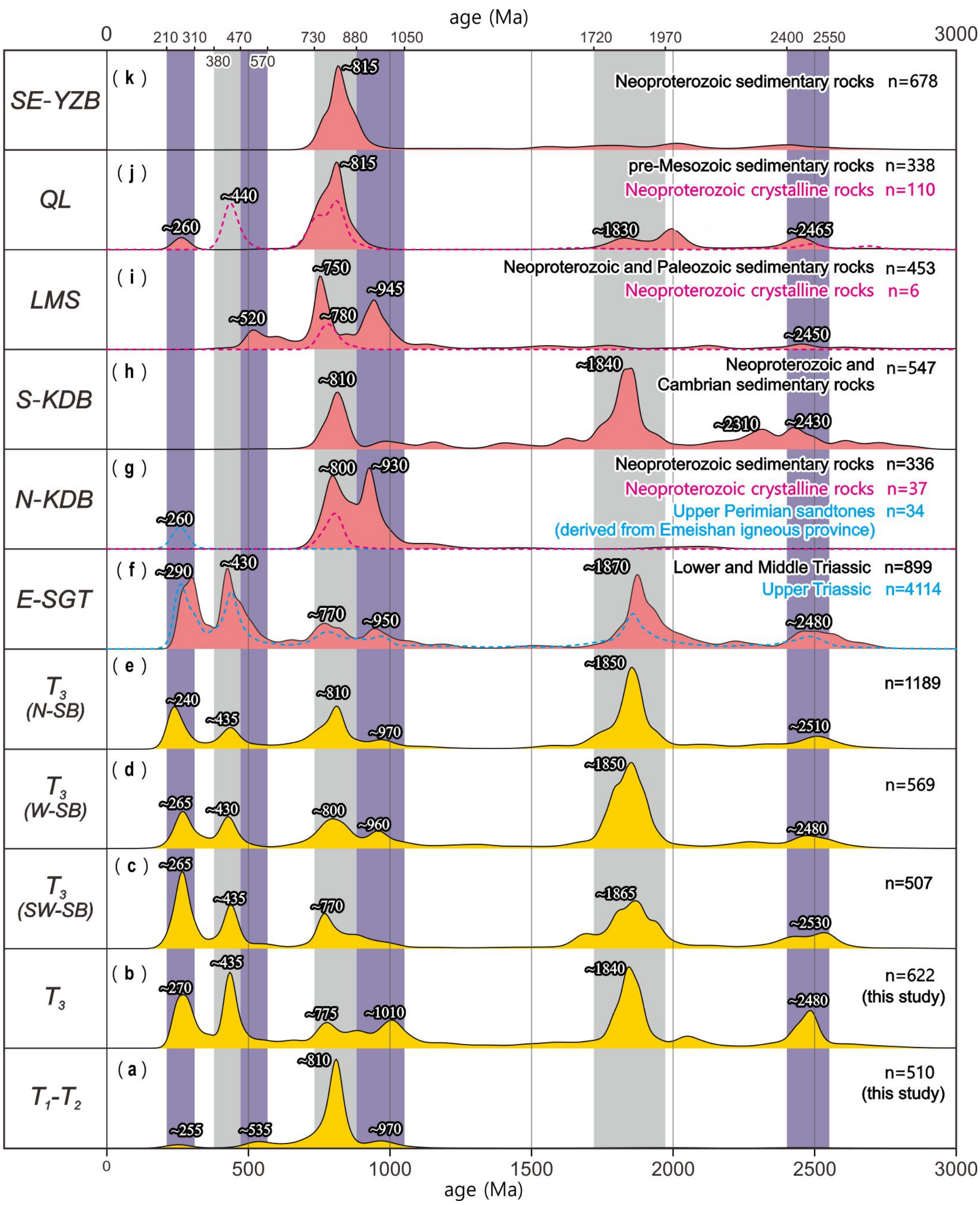

Fig. 9. KDE plots for the detrital zircon ages of the Triassic sediments of the Sichuan Basin and potential source areas. (a-b) Age spectra of the Lower-Middle and Upper Triassic sediments in the southwestern Sichuan Basin. (c-e) Spectra of the Upper Triassic sediments in the southwestern, western and northern Sichuan Basin, reported in previous studies (Deng *et al*., 2008; Weislogel *et al*., 2010; Chen, 2011; Luo *et al*., 2014; Zhang *et al*., 2015; Shao *et al*., 2016; Zhu *et al*., 2017). Spectra of potential areas, including (f) E-SGT (eastern Songpan-Ganzi terrane), compiled from the Lower-Middle Triassic sedimentary rocks (black solid line) (Weislogel *et al*., 2006, 2010; Enkelman, 2007; Ding *et al*., 2013; Wang et al., 2013) and the Upper Triassic sedimentary rocks (blue dash line) (Wang et al, 2007; Weislogel *et al*., 2006, 2010; Ding et al., 2013; Wang et al., 2013; Zhang et al., 2014,2015), (g) N-KDB (northern Kangdian Basement), compiled from both crystalline (red dash line) (Roger & Calassou, 1997; Guo *et al*., 1998; Shen *et al*., 2000; Li *et al*., 2001; Li *et al*., 2002; Zhou *et al*., 2002b; Shen *et al*., 2003; Li *et al*., 2003b; Zhou *et al*., 2006a; Lin *et al*., 2006b; Yan *et al*., 2006; Zhao *et al*., 2006; Geng *et al*., 2007; Huang *et al*.,

2009; Lin, 2010; Ruan, 2013; Meng *et al*., 2015) and sedimentary rocks (black solid line) (Zhou *et al*., 2006a; He *et al*., 2007; Sun *et al*., 2009), (h) S-KDB (southern Kangdian Basement), compiled from sedimentary rocks (Sun et al., 2009; Wang *et al*., 2012), (i) LMS (Longmen Shan thrust belt), compiled from both crystalline (red dash line) (Zhou *et al*., 2006b; Meng *et al*., 2015) and sedimentary rocks (black solid line) (Duan *et al*., 2011; Chen *et al*., 2016), (j) QL (Qinling orogen), compiled from both crystalline (red dash line) (Li *et al*., 2016 and references therein) and sedimentary rocks (black solid line) (He *et al*., 2007; Wang *et al*., 2013a), (k) SE-YZB (southeastern Yangtze Block), compiled from sedimentary rocks (Wang *et al*., 2010; Wang & Zhou, 2012).

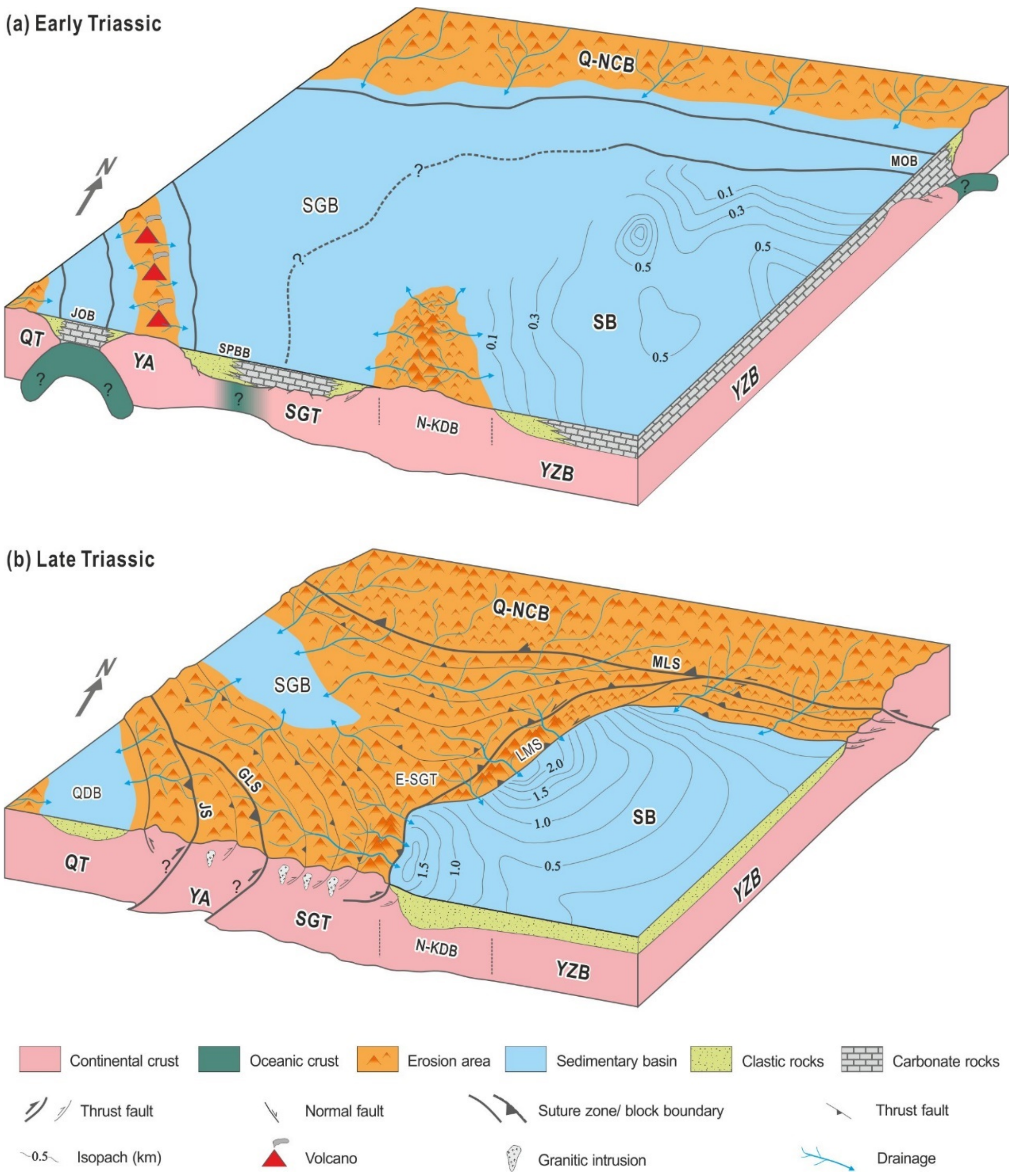

Fig. 10. Models for Triassic tectonic evolution of the Upper Yangtze Block and its link to adjacent structural belts. E-SGT, Eastern Songpan-Ganzi terrane; GLS, Ganzi-Litang suture; JOB, Jinshajiang

Ocean Basin; JS, Jinshajiang suture; LMS, Longmen Shan thrust belt; LSB, Longmen Shan basement; MLS, Mianlue suture; MOB, Mianlue Ocean Basin; N-KDO, Northern Kangdian basement; QDB, Qamdo Basin; Q-NCB, Qingling Terrane and Northern China Block; QT—Qiangtang terrane; SB, Sichuan Bsin; SE-SGT, eastern Songpan-Ganzi terrane; SGB, Songpan-Ganzi Basin; SGT— Songpan-Ganzi terrane; SPBB, Songpan back arc Basin; YA—Yidun arc. The tectonic evolution between Qiangtang terrane and northern Kangdian basement is after Roger *et al.* (2008)