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Geological Evolution of the Longmenshan Intracontinental Composite Orogen and the Eastern Margin of the Tibetan Plateau

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ABSTRACT: The Longmenshan Range is a tectonically composite intracontinental orogen. Its structure, deformation and spatial evolution reflect multiple kinematic eposides and variable dynamics especially during Post-Middle to Post-Late Triassic time. Field work, lower-temperature thermochronological data and U-Pb detrital zircon ages indicate document down-dip zonation and along-strike segmentation demonstrated by significant differences in geological structure, intensity of deformation and deformation-involved strata, uplift and cooling processes. Low-temperature thermochronology and U-Pb detrital zircon ages reveal a period of tectono-thermal quiescence with slow uplift and cooling during post Early Norian to Rhaetian orogeny, followed by rapid cooling and uplift during the Late Cenozoic accompanied by coeval southeastward thrusting and southwestward propagation of defromation. The Longmenshan Range formed by S-N striking compression exerted by the Qinling orogen, E-W striking compression by the Tibetan Plateau and SE-striking compression by the Yangtze Plate. We propose a southwestward propagation model for the Longmenshan Range based our observations of zonation, segmentation and composite evolutional processes during the Late Triassic superimposed by development of the differential uplift and cooling processes that shows southern segments of the Longmenshan Range during Post-Jurassic times.
KEY WORDS: tectonic zonality, segmentation, southwestward propagation, intercontinental orogen, Longmenshan, Tibetan Plateau.

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INTRODUCTION

Structure, deformation and dynamic evolution along plate boundaries and within continents provide important evidence about plate tectonics (Aitken, 2011; Spotila et al., 2007; Yin and Harrison, 2000; Molnar, 1988). If the long-term tectonic evolution of an orogen is significantly influenced by geodynamic processes operating on different scales in different blocks at different periods, then the dynamic evolution of the orogen and the superimposed present-day framework should reflect such composite kinematics and therefore deciphering patterns of structure and evolution processes of orogens is a worthwhile subject for studies of continental tectonics.

The Longmenshan Mountain Range ("shan" means "mountain" in Chinese) separates the eastern margin of the Tibetan Plateau from the western margin of the Yangtze continental plate (or South China Block). It has been the focus of geological study for nearly a century (e.g., Heim, 1934) due to its location and distinctive structures. One of the reasons is that the Longmenshan Range lies at the boundary between the West Pacific tectonic domain and the Tethys-Himalaya domain and has been affected by collision of the South China Block and North China Block in the Triassic Indo-Chinese Epoch and the Cenozoic Indian-Asian collision. The dynamics of its orogenic evolution are a key to understanding intercontinental structures in the eastern Tibetan Plateau during Mid-Cenozoic times (Yan et al., 2011; Royden et al., 2008; Harrowfield and Wilson, 2005; Worley and Wilson, 1996; Burchfiel et al., 1995; Chen et al., 1995; Luo, 1994). The Longmenshan Range and the Western Sichuan Basin in western China together constitute a typical thrust belt and foreland basin system (Fig. 1). Their structural features and evolutionary processes are a crucial guide to successful petroleum exploration in the western Sichuan Basin (Deng et al., 2012a; Jia et al., 2006; Meng et al., 2005; Li et al., 2003; Guo et al., 1996). Longmenshan is also a geomorphological boundary and gravity gradient zone between eastern and western China. The dynamic evolution of the Longmenshan Range is associated with the eastward growth of the Tibetan Plateau (Wang et al., 2012; Wilson and Fowler, 2011; Godard et al., 2009; Royden et al., 2008; Densmore et al., 2007; Kirby et al., 2002) and finally the relationship between structure and neotectonics has received significant attention since the "5.12" Wenchuan Earthquake in 2008 (Zhang et al., 2010; Hubbard and Shaw, 2009; Burchfiel et al., 2008).

In this article we systematically discuss different structures and evolutionary processes of the Longmenshan Range both along strike and down dip, based on field work, low-temperature thermochronological data and U-Pb detrital zircon ages. We propose a new tectonic model involving southwestward propagation of deformation to understand the continental dynamics of Longmenshan and adjacent areas.

GEOLOGICAL SETTING

The Longmenshan Mountain Range is 500 km long and 30 km wide, trends NE-SW (Fig. 1), and is located between the eastern margin of the Tibetan Plateau and the western boundary of the Sichuan Basin, extending from Guangyuan at the northern end to Ya'an, Sichuan Province at the southern end. It adjoins the Qinling Orogen to the north and the Kangdian Orogen to the south, is bounded by the Maoxian-Wenchuan fault to the northwest and separated from the Sichuan Basin by the Anxian-Guanxian fault in the southeast (Fig. 1). Structurally, Longmenshan Range is dominantly composed of a series of NE-SW thrust faults and klippen. It can be divided into two tectonic belts with contrasting stratigraphy, petrology, structure and metamorphism, separated by the NW-dipping Beichuan-Yingxiu fault; a western thrust belt and an eastern detachment belt. It can be further subdivided into northern, central and southern segments from the Anxian area at the north to the Huaiyuan area in the south (Fig. 1).

After the consolidation of its Archean and Proterozoic basement, the geological evolution of the Longmenshan area can be divided into two major stages. The first is a passive margin craton stage from Sinian to Middle Triassic times, dominated by construction of a carbonate platform. The second is bracketed by a stage of Post-Late Triassic orogenic movement characterized by thrusting, strike-slip faulting and foreland basin formation in a compression tectonic setting. During the Late Paleozoic, a number of extensional events attenuated the western passive margin of the South China Block (Guo et al., 1996; Liu, 1993; Long, 1991; Luo et al., 1988) and led to the formation of NE-trending syn-depositional normal faults, such as the Maoxian-Wenchuan and Beichuan-Yingxiu faults, and the deposition of sedimentary strata up to 6 000 m thick in the Longmenshan area and adjacent regions (Wang, 1996; Long, 1991). The peak of the extensional stage occurred

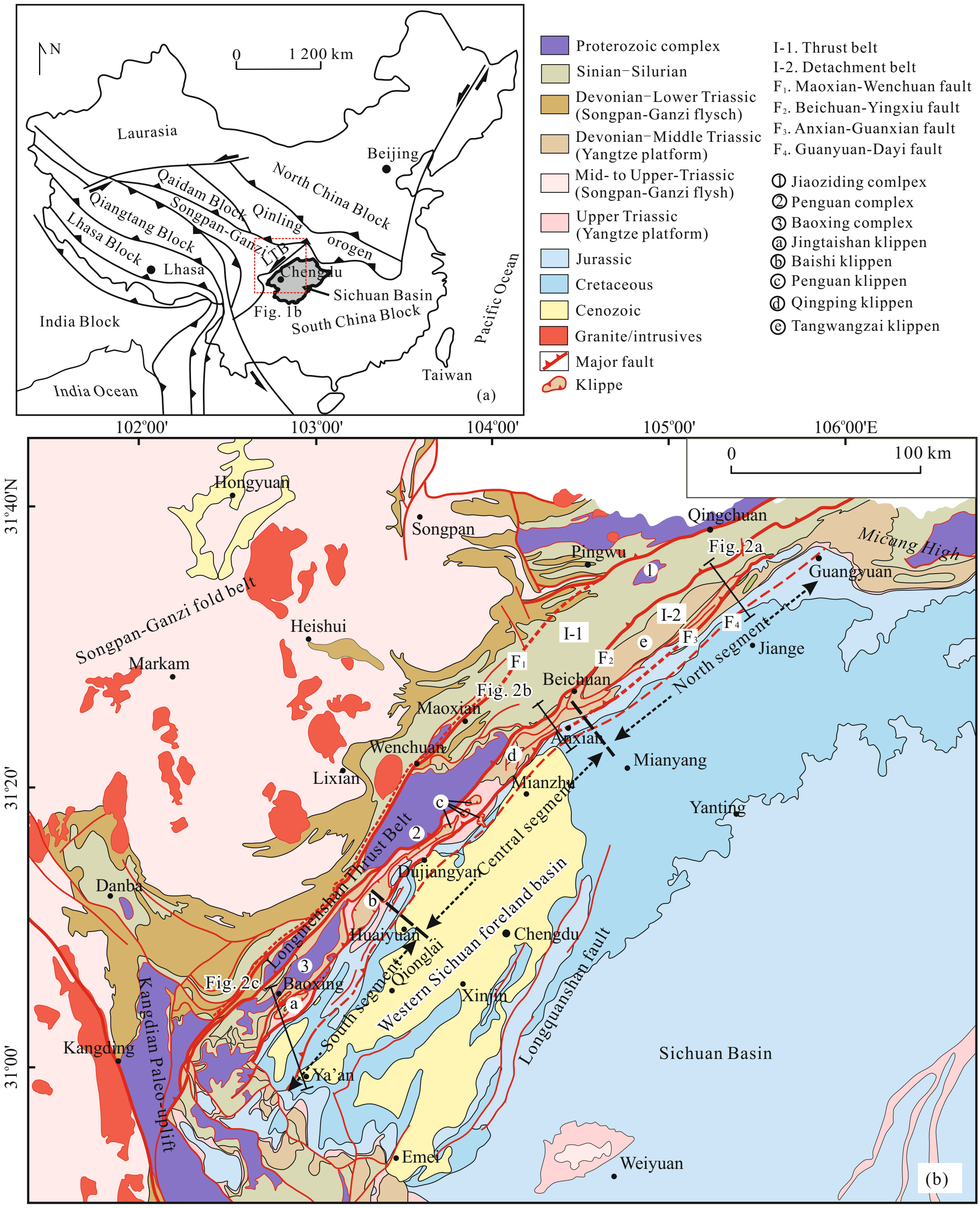

Figure 1. (a) Tectonic map of the Longmenshan Range and Sichuan Basin showing the location of major tectonic blocks (plates) and suture zones; (b) structural map of the Longmenshan Range and the western Sichuan foreland basin distinguishing three segments from NE to SW and two belts from NW to SE.

during the Late Permian when the Emeishan basalts were erupted in the southern part of the area, especially in the Panxi rift (He et al., 2007; Xu et al., 2001; Luo et al., 1988), and had a profound influence on the regional tectonic evolution. Pre-existing syn-depositional normal faults facilitated structural inversion and became thrust faults under a Late Triassic compressional regime. The less competent clastic sediments of the syn-extensional successions (e.g., the Silurian Maoxian Group and Devonian Weiguan Group) were deformed and metamorphosed during this orogenic phase. Since the Late Triassic, strong south-directed crustal deformation and associated metamorphism occurred at the eastern margin of the Tibetan Plateau, which resulted in the formation of transpressional thrusts and sinistral strike-slip deformation (Yan et al., 2011; Deng et al., 2010; Liu et al., 2009a; Harrowfield and Wilson, 2005; Meng et al., 2005; Worley and Wilson, 1996; Chen et al., 1995; Liu, 1993). The western Sichuan foreland basin formed at the same time in response to the thrust-imposed loads (Deng et al., 2012a; Meng et al., 2005; Li et al., 2003; Guo et al., 1996; Liu, 1993).

Tectonic deformation in the Longmenshan Range was initiated during the Paleo-Tethys Ocean closure represented by the Late Triassic orogeny (Liu et al., 2009a; Harrowfield and Wilson, 2005; Meng et al., 2005; Worley and Wilson, 1996; Chen et al., 1995). It probably occurred during Late Triassic to Early Jurassic across the western margin of the Yangtze Plate, followed by subsequent slow cooling and tectonic quiescence during the Early Jurassic to Cretaceous (Deng et al., 2012b; Zhang et al., 2006; Roger et al., 2004). There was subsequent reactivation during Cenozoic times as a distant result of the India-Asia continental collision (Wallis et al., 2003; Arne et al., 1997; Guo et al., 1996; Burchfiel et al., 1995). Some of the faults which formed at that time have remained active to the Present, most famously the “5.12” Wenchuan Earthquake of 2008, particularly in the southern and central segments of the Longmenshan Range (Densmore et al., 2007; Kirby et al., 2000).

STRUCTURAL FEATURES

NW to SE Dip Zonation

The Longmenshan Range is characterized by different structures and deformation features from NW to SE, separated by several NE striking faults (Fig. 1). The four main faults from NW to SE are: the Maoxian-Wenchuan fault (F_1), Beichuan-Yingxiu fault (F_2), Anxian-Guanxian fault (F_3) and Guangyuan-Dayi fault (F_4), which differ in structure, geometry, deformational intensity and time of origin (Table 1) (Li et al., 2008; Lin et al., 1996; Chen and Wilson, 1996; Luo, 1994; Dirks et al., 1994; Liu, 1993). These faults have had a significant partitioning effect on the strata and structural elements on either side, causing orogenic zonation in dip from NW to SE (Lin et al., 1996; Burchfiel et al., 1995; Chen et al., 1995; Dirks et al., 1994; Liu, 1993; Long, 1991). On this basis the Longmenshan Range can be divided into three belts separated by the four main faults mentioned above: namely the western part of the thrust belt, the eastern part of the detachment belt and the frontal extended belt (Table 1; Fig. 2). They display a progressive change in deformation mechanism (from ductile to brittle) from NW to SE, in deformation structures (from basement-involved structure to detachment imbricated thrust structure or thin-skin tectonic structure) and in deformed strata (from Precambrian to Quaternary).

The Longmenshan thrust belt between the Maoxian-Wenchuan and Beichuan-Yingxiu faults is mainly formed by a Pre-Sinian complex (e.g., the Pengguan massif) and Sinian-Devonian metamorphic rocks (Figs. 1 and 2) and characterized by basement-involved deformation and syn-fold cleavage with few faults. The detachment belt between the Beichuan-Yingxiu and Anxian-Guanxian fault is comprised by Silurian clastic rocks, Devonian–Middle Triassic carbonates and Upper Triassic Xujiahe Formation clastic rocks, particularly within the Baoxing complex in the southern segment (Fig. 2c). Its deformation is characterized by concentric folds and imbricate thrusts with numerous brittle faults and minor folds, indicating a weaker intensity in deformation than in the thrust belt. The detachment belt is particularly characterized by imbricate thrusts and klippen (Fig. 2).

The extended belt between the Anxian-Guanxian fault and the blind Guangyuan-Dayi fault is mainly comprised of Jurassic–Paleogene continental red-beds (Figs. 1 and 2). Its deformation is clearly weaker than that in the northwest, with dominant open-to-gentle folds and/or monoclinal structures. Southeastward thrusting throughout the Longmenshan Range is indicated by strata showing characteristic deformation (Table 1; Fig. 2).

Segmentation along Strike from NE to SW

Our field studies revealed a variety of different geologic features in basement properties, basement, strata ages, evolution history, deformation, subsidence and uplift and neotectonics along the strike of the Longmenshan Range (Table 2) dividing it into northern, central and southern segments from NE to SW (Fig. 1).

We have recognized several east-verging, basement-involved structures on different scales in the Longmenshan thrust belt, such as the Baoxing complex and the Jiaoziding complex. They have distinct magnetic and gravity properties that reflect differences in structure (Jin et al., 2009; Liu, 1993). Multi-level detachment layers occur throughout the Longmenshan Range, including a Cambro–Ordovician detachment layer and a Middle-to-Upper Triassic detachment zone. The Silurian detachment layer is widespread in the northern segment. The deformation styles in each of the segments of the Longmanshan show different intensities of deformation.

Even though there are many klippen in the detachment belt, their sizes and displacements are very variable. There is a single extremely large klippe in the northern segment, the Tangwanzai klippe (Fig. 1). But it has a much smaller displacement than the klippen in the central and southern segments. There are also some klippen in the extended belt of the southern segments that provide evidence that the age of the deformation-involved strata decreases from NE to SW (Figs. 1 and 2).

Eocene strata were deformed during the Cenozoic orogeny in the southern segment, representing a much younger event than the Lower Cretaceous deformation in the extended belt of the central and northern segments. Much stronger deformation indicated by fault-related folds, triangle zones and pop-up structures occurred in the extended belt of the southern segment compared with the northern segment. This resulted in differences in topography and gradients between the southern segment and the northern segment, probably reflecting different deformation and uplift in Cenozoic times.

DIFFERENTIAL UPLIFT AND COOLING

Uplift and cooling processes along transpressional boundary faults can be significantly different in space and time, especially under the control of multi-scale geodynamics asserted by different blocks. They can be further influenced by local structural complexity, crustal anisotropy, and heterogeneous strain. Although details of these phenomena have been well studied in the Longmenshan Range (Li et al., 2012; Wang et al., 2012; Godard et al., 2009; Clark et al., 2005; Kirby et al., 2002; Xu and Kamp, 2000;

Table 1 Comparison of the structural features in different zones of the Longmenshan

Segments	Southern segment	Central segment	Northern segment	Deformation-involved strata	
Zones	Thrust belt	Basement-involved thrust deformation, many folds with fewer faults, dominantly ductile deformation.	Pre-Devonian		
	Detachment belt	Thick- and thin-skinned tectonic structure-imbricate thrusts, klippen, shallower brittle deformations	Thin-skinned tectonic structures-imbricate thrusts, klippen, shallower brittle deformations	Thin-skinned tectonic structures-concentric folds and imbricate thrusts, mid-deep deformations with ductility	Silurian to Upper Triassic Xujiahe Formation
	Extended belt	Dominantly brittle deformations, open-to-gentle folds partially with fault in the core	Weak deformations with monocline strata, thrust faults on the surface	Weak deformations, with dominant monocline strata	Jurassic to Early Cretaceous

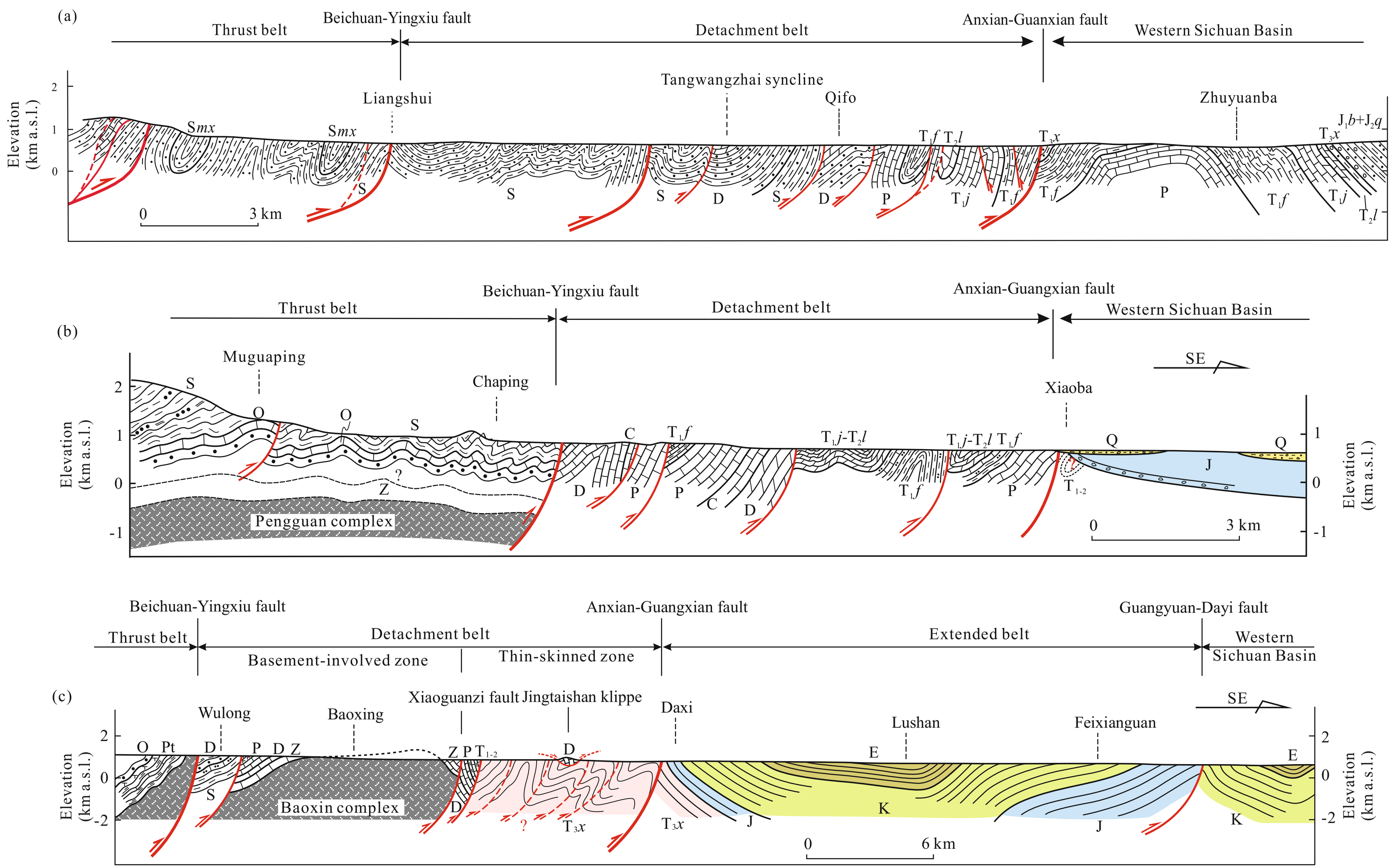

Figure 2. Structural profiles across the Longmenshan Range (locations as in Fig. 1). (a) Qingchuan-Jiange profile in the northern segment of the Longmenshan; (b) Qianfoshan-Anxian profile in the central segment; (c) Baoxing-Ya'an profile in the southern segment.

Table 2 Comparison of the structural feature of the segments in the Longmenshan

Segments	Southern segment	Central segment	Northern segment
Differential features	Baoxing complex, klippen	Pengguan complex, klippen	Jiaoziding complex, Tangwangzai syncline (sliding structure)
Tectonic setting	Primarily controlled by the India-Asia collision in the Cenozoic	Controlled by both the collision of South China and North China blocks in Late Triassic and the India-Asia collision in the Cenozoic	Primarily controlled by collision of South China and North China blocks in Late Triassic and by the evolution of the Qinling orogen
Foreland features	Late Cretaceous to Palaeogene subsidence center, widespread J_3–Q conglomerates	Late Triassic subsidence center with widespread T_3x–Q conglomerates	Late Jurassic to Early Cretaceous subsidence center, T_3x–J_1, and J_3–K_1 conglomerates
Deformation history	Relatively late, deformation from Late Cretaceous, by the Himalayan build-up	Relatively early, Yanshanian build-up and Himalayan reconstruction	Relatively Early, Late Triassic build-up with weak Himalayan reconstruction
Klippen (nappes)	Widespread klippen with larger sliding distance	Widespread klippen with a larger sliding distance	Few klippen with shorter sliding distance
Uplift and geomorphology	Late Cenozoic rapid uplift and cooling, great topographic slope and clear boundary between basin and mountains	Rapid uplift and cooling in Meso-Cenozoic, great topographic slope and clear boundary between basin and mountains	Rapid uplift and cooling in Mesozoic and slow in the Cenozoic, small topographic slope and obscured boundary between basins and mountains
Neotectonics	Relatively strong, coseismic fractures e.g., "5.12" Wenchuan earthquake extending from SW to NE along the strike	Relatively weak, coseismic fractures extend from SW to NE sub-parallel strike	

Arne et al., 1997; Liu, 1993) a systematic analysis of uplift and cooling process along the entire Longmenshan Range has not yet been carried out.

Low-temperature thermochronological data reveal that there were multiple rapid cooling and uplift events in the region (Fig. 3) during the Mesozoic–Cenozoic, e.g., during the Indo-Chinese Epoch (~200 Ma), Late Cretaceous (~100 Ma), Early Cenozoic (65–30 Ma) and Late Miocene Epoch (15–9 Ma) (Li et al., 2012; Godard et al., 2009; Clark et al., 2005; Kirby et al., 2002; Xu and Kamp, 2000; Arne et al., 1997; Liu et al., 1996). In general, very slow cooling and uplift occurred from the Mesozoic to the Early Cenozoic in the Longmenshan, with rates of <0.1 mm/a, known as the Yanshanian tectono-thermal quiescence ("Yanshanian" means "Jurassic-to-Cretaceous"). It was followed by rapid cooling and increase in uplift to rates of 0.15–0.3 mm/a (locally 0.9 mm/a) during the Late Cenozoic (15–9 Ma) (Fig. 3), assuming a geothermal gradient of ~25–30 ℃/km and a surface temperature of ~10 ℃.

There is a distinctly progressive change along strike from NE to SW in fission track and (U-Th)/He ages (Fig. 4). Later ages in the northern segment of

Longmenshan are of the Late Mesozoic to Cenozoic period, older than those in the central and southern segments which are concentrated in the Late Cenozoic, as documented by apatite fission track ages (AFT) (Li et al., 2012; Arne et al., 1997; Liu et al., 1996). This indicates nonsynchronous segmental uplift and cooling processes in different segments of the Longmenshan, or perhaps the data can be interpreted as indicating relatively quicker uplift and cooling in the central and southern segments compared with the northern segment during the Late Cenozoic.

Down the dip of the Longmenshan Range from NW to SE, the data show a high diversity of fission track ages and (U-Th)/He ages (Fig. 4), particularly in the central segment. In the northern segment, apatite fission track ages of the thrust belt and its western part show a subtly younger age from NW to SE, indicative of SE propagating cooling in the Cenozoic. Early Cenozoic AFT ages in the detachment belt are significantly younger than the Pre-Late-Cretaceous AFT ages in the western Sichuan Basin and the extended belt which include detrital age components with AFT ages higher than ~90 Ma.

There are similarly decreasing (U-Th)/He and fission track ages from NW to SE between the thrust belt and its western part in the central segment of Longmenshan. Apatite (U-Th)/He and fission track ages show a distinct decrease from the NW to SE in the detachment belt indicating southeastward propagating uplift and cooling in the Cenozoic. (U-Th)/He zircon ages are mostly less than ~40 Ma, thought to be a result of two-phase growth of the Longmenshan at 30–25 and 15–10 Ma, respectively (Wang et al., 2012).

EVOLUTION PROCESSES

The formation and tectonic evolution of the Longmenshan Range show southeastward-thrusting down dip from NW to SE and progressive propagation of compressive deformation along strike from NE to SW.

Late Triassic Orogenesis and Its Southwestward Propagation

During the Late Triassic, the Longmenshan experienced its most important tectonic change from an early passive continental margin to a foreland basin (Deng et al., 2012a; Meng et al., 2005; Li et al., 2003; Guo et al., 1996; Wang, 1996). During the same period, there were two major changes of depositional setting from marine carbonate to marine clastics, and from marine clastics to continental clastics (Liu et al.,

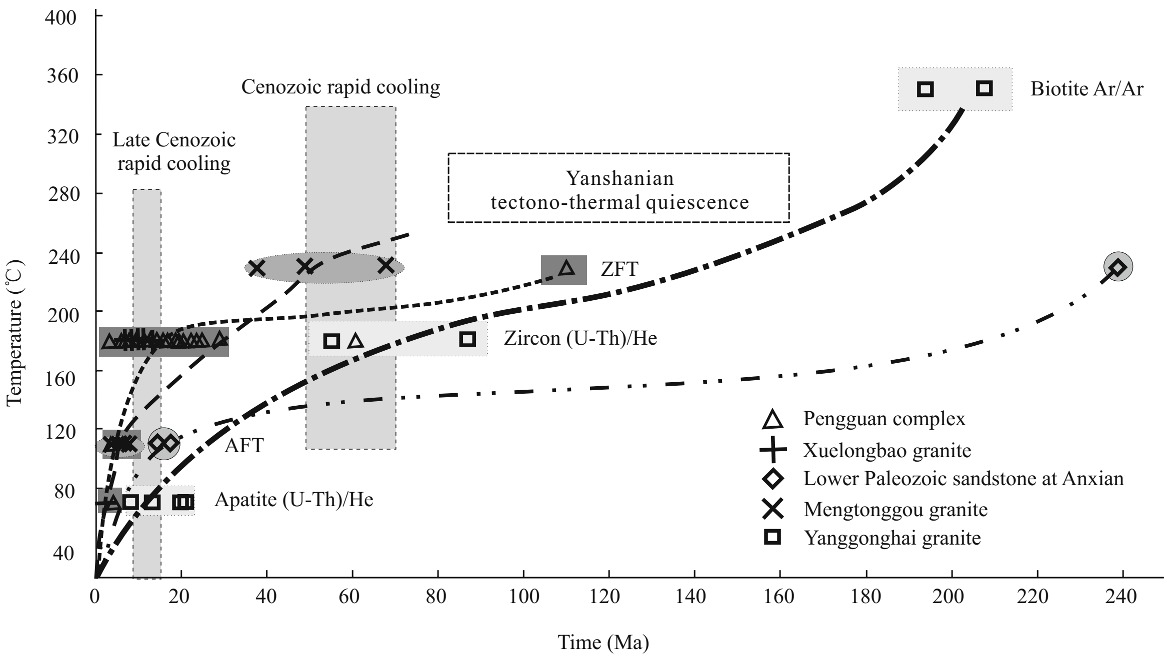

Figure 3. Cooling history of the central Longmenshan Range inferred from thermochronologic data (modified after Li et al., 2012).

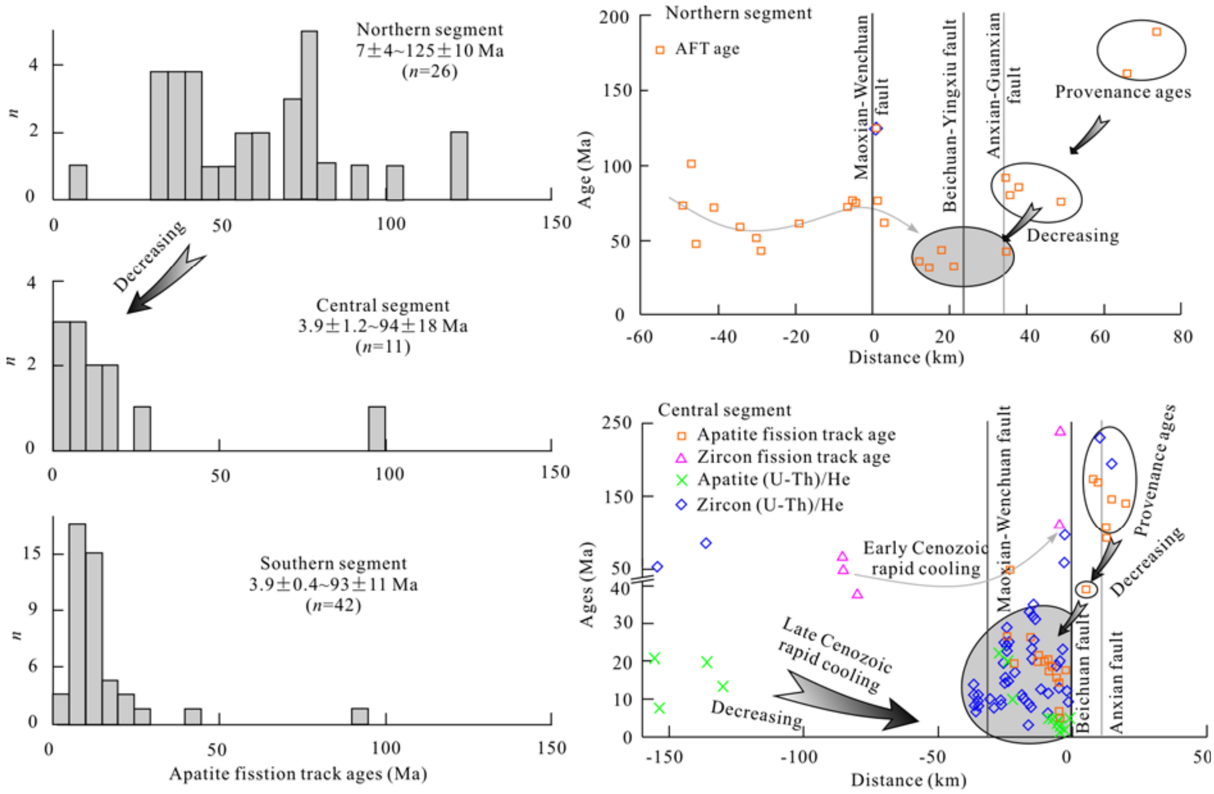

Figure 4. FT and (U-Th)/He ages along strike and down dip in the Longmenshan Range (Data from Wang et al., 2012; Tan et al., 2012; Li et al., 2011; Godard et al., 2009; Kriby et al., 2002; Arne et al., 1997; Liu et al., 1996).

2009b) but the timing and style of these transitions are not well constrained.

U-Pb detrital zircon ages (n=1 447) from sandstone of the Upper Triassic Xujiahe Formation in the western Sichuan foreland basin demonstrate stratigraphic compositional variability with different age peaks reflecting sediments sourced from different provenances, suggesting that dynamic uplift and exhumation process took place in Early Norian to Rhaetian times (Fig. 5). Early Norian sediments in the Xiaotangzi Formation in the western Sichuan foreland basin show a U-Pb age peak of 700–1 000 Ma indicating a source from the South China Block. But deposits of the Xinduqiao Formation deposited in the Songpan-Ganzi area lack this age peak, indicating that the Longmenshan was slightly uplifted in the Early to Late Norian, separating different provenances in the Sichuan Basin and Songpan-Ganzi area. This was followed by a significant uplift and cooling event in the Rhaetian which resulted in the formation of a unified provenance throughout the western Sichuan Basin indicated by the presence of the metamorphic rock detritus in the upper part of the Xujiahe Formation (Li et al., 1995; Cui et al., 1991). Paleoflow directions in the Xujiahe Formation conglomerates show a major change from NW in the Norian to the north to NE in the Rhaetian (Luo and Long, 1992; Cui et al., 1991). Furthermore, the Late Triassic conglomerates (T_3x) show a southwestward propagating distribution and decrease in angle of unconformable contacts with Lower Jurassic strata (Deng et al., 2012a; Liu et al., 2009a; Deng, 2007), indicative of a southwestward propagation of Longmenshan orogenesis. The first conglomerate in the northern segment of the Sichuan Basin including the Longmenshan extended belt crops out locally in T_3x^2, the first conglomerate in the central segment is in T_3x^4 and the first conglomerate in the southern segment is in J_1b, demonstrating along-strike propagation to the Dujianyan area, and later southwestward as far as the Baoxing area. The contact of the Late Triassic (T_3x) and Early Jurassic (J_1b) sedimentary sequences are locally angular unconformities or disconformities, specifically in the central and northern segments of the extended belt.

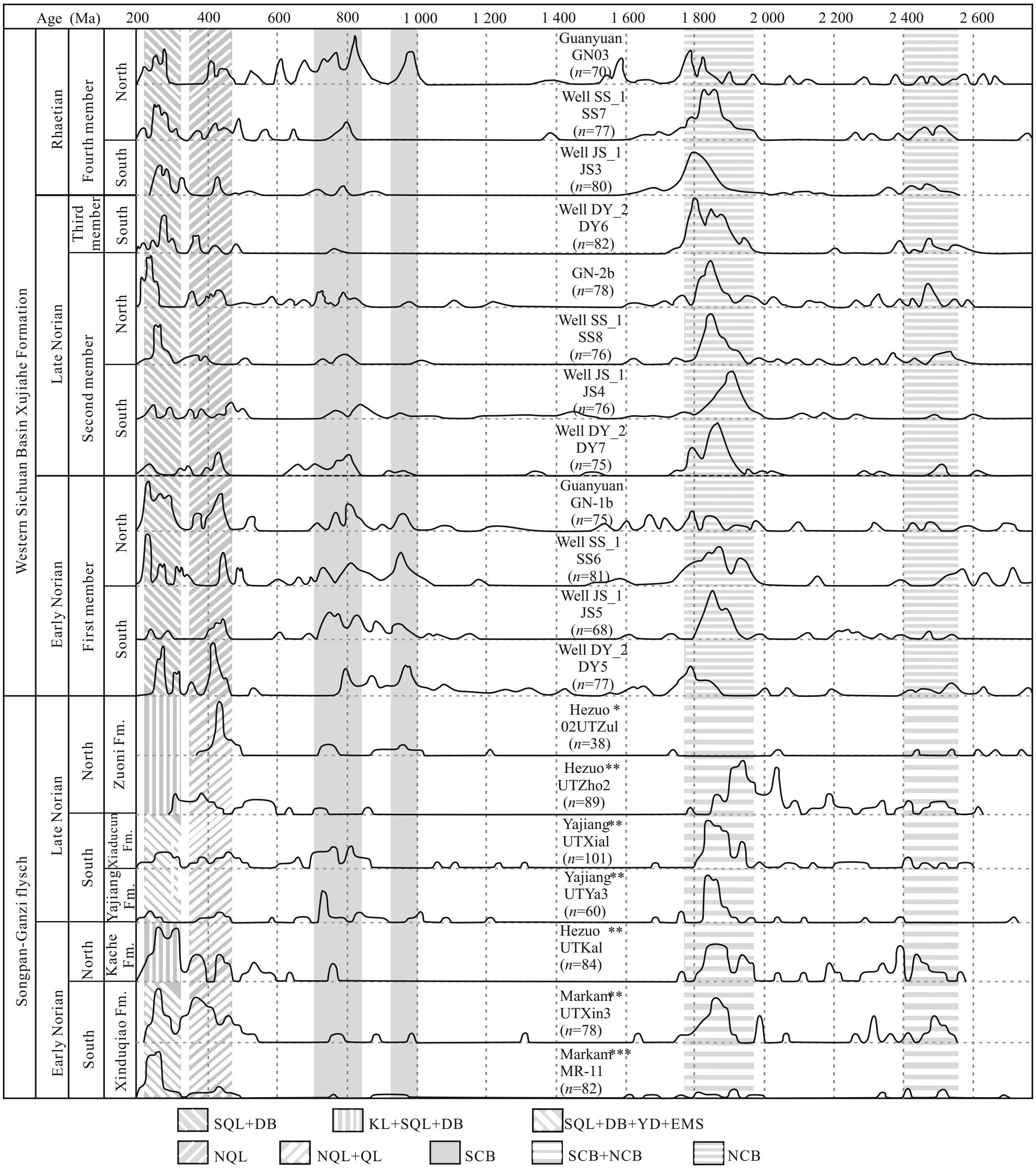

Figure 5. Comparison of the U-Pb detrital zircon age probability curves between western the Sichuan Basin and the Songpan-Ganzi flysch. (Labeled data from Weislogel et al., 2006(**); Enkelmann et al., 2007(*); Deng et al., 2008 (***). SQL. South Qinling; DB. Dabie; EKL. Eastern Kunlun; YD. Yidun; EMS. Emeishan; NQL. North Qinling; QL. Qilian; SCB. South China Block; NCB. North China Block.)

Farther southwest along strike, the angularity at the unconformity decreases as the contact gradually changes to conformable. We therefore suggest that thrusting and uplift of the thrust belt and detachment belt began during Early Norian time with deposition of the Xiaotangzi Formation or the first section of the Xujiahe Formation, and was followed by significant thrusting and uplift during the Rhaetian, with southwestward propagating orogensis accompanied by deposition of the fourth part of the Xujiahe Formation. This process reflects sinistral transpressional deformation during the Late Triassic Period (Harrowfield and

Wilson, 2005; Worley and Wilson, 1996; Chen et al., 1995; Dirks et al., 1994; Liu, 1993). The ages of the strata affected by deformation (Table 1) suggests that both the thrust belt and detachment belt in the northern and southern segments formed during this time period.

Yanshanian Tectonic-Thermal Quiescence

From Late Triassic to Middle Jurassic times, the Longmenshan Range experienced a period of thermal and tectonic quiescence accompanied by weak tectonic activity (Deng et al., 2012b; Li et al., 2012; Roger et al., 2010, 2004). In the western Songpan-Ganzi fold belt, Jurassic–Cretaceous strata are horizontal or have low dips and unconformably overly strongly folded Triassic to Paleozoic strata. Widespread Late Triassic to Early Jurassic igneous rocks have mostly been interpreted as post-orogenic (Yuan et al., 2010; Zhang et al., 2006; Roger et al., 2004). In contrast, a Jurassic sedimentary succession characterized by the deposition of continental clastics in the Western Sichuan foreland Basin is very similar throughout the region, indicating a relatively stable tectonic background (Wang and Xu, 2001; Guo et al., 1996) although conglomerates outcropping in the central and southern segments of the Longmenshan (Gou, 2001) suggested that thrusting and exhumation did take place there. The Longmenshan Range was subsequently rejuvenated during the Late Jurassic. The subsidence center migrated from the front of the central segment in the Late Triassic to the front of the northern segment during Late Jurassic to Early Cretaceous (Fig. 6) with deposition of >1 000 m of alluvial fan conglomerates (Meng et al., 2005; Guo et al., 1996; Cui et al., 1991).

Late Cretaceous Tectonic Changes and Orogenesis

A significant tectonic change occurred at the western margin of the Yangtze Plate and eastern margin of the Tibetan Plateau in the Mid-to-Late Cretaceous. Large-scale thrusting and folding occurred in the central and southern segments of the Longmenshan Range as long-distance effects of the collision of the Qiangtang and Lhasa plates. The onset is probably reflected by muscovite $^{40}Ar/^{39}Ar$ ages of 120–123 Ma from the Maoxian fault (Xu et al., 2008; Arne et al., 1997; Liu et al., 1996) and by widespread igneous intrusion in the Songpan-Ganzi flysch at ~100 Ma (Roger et al., 2010; Reid et al., 2005). At the same time the Sichuan Basin shrank due to the build-up of much of the E-W striking Yanshanian uplift (Li et al., 2011; Guo et al., 1996).

Since the Late Cretaceous a new subsidence center formed on the front of the southern segment of the Longmenshan Range where >2 000 m coarse clastic sediments accumulated (Fig. 6). There is an important change in Late Cretaceous and Neogene depositional contacts along and around Longmenshan. The contact between Upper and Lower Cretaceous strata changes from a disconformity in the north (e.g., at Banbianjie and Dayi) to conformity in the south while the contact between the Upper Cretaceous and Neogene strata shows northward decreasing angularity (Deng et al., 2012b). This may indicate that the western margin of the Yangtze Plate experienced an important tectonic transfer from the Paleo-Tethyan to Neo-Tethyan tectonic regime in Late Cretaceous times. Under the control of the distant effects of the collision of the Qiangtang and Lhasa plates, the Longmenshan Range is dominated by right-lateral transpressional thrust movements (Zhang et al., 2010; Burchfiel et al., 1995; Liu, 1993), indicating a northeastward propagation of stress field and deformation. At the same time strata in the Longmenshan extended belt and western Sichuan Basin Cenozoic including overlying unconformities were folded during Cenozoic Himalayan movements (Fig. 2c) suggesting that they formed during the Himalayan Epoch.

DISCUSSION

The formation and evolution of the Longmenshan Range is the result of southeastward thrusting in the dip direction and of progressive southwestward propagation of mountain-building along strike. In the dip direction from NW to SE deformation changed in character from ductile to brittle (Jin et al., 2009; Li et al., 2008; Chen and Wilson, 1996; Chen et al., 1995; Dirks et al., 1994; Liu, 1993). Along strike from NE to SW, the Longmenshan Range is characterized by southwestward weakening of ductility, increasing brittleness and a younger phase of deformation.

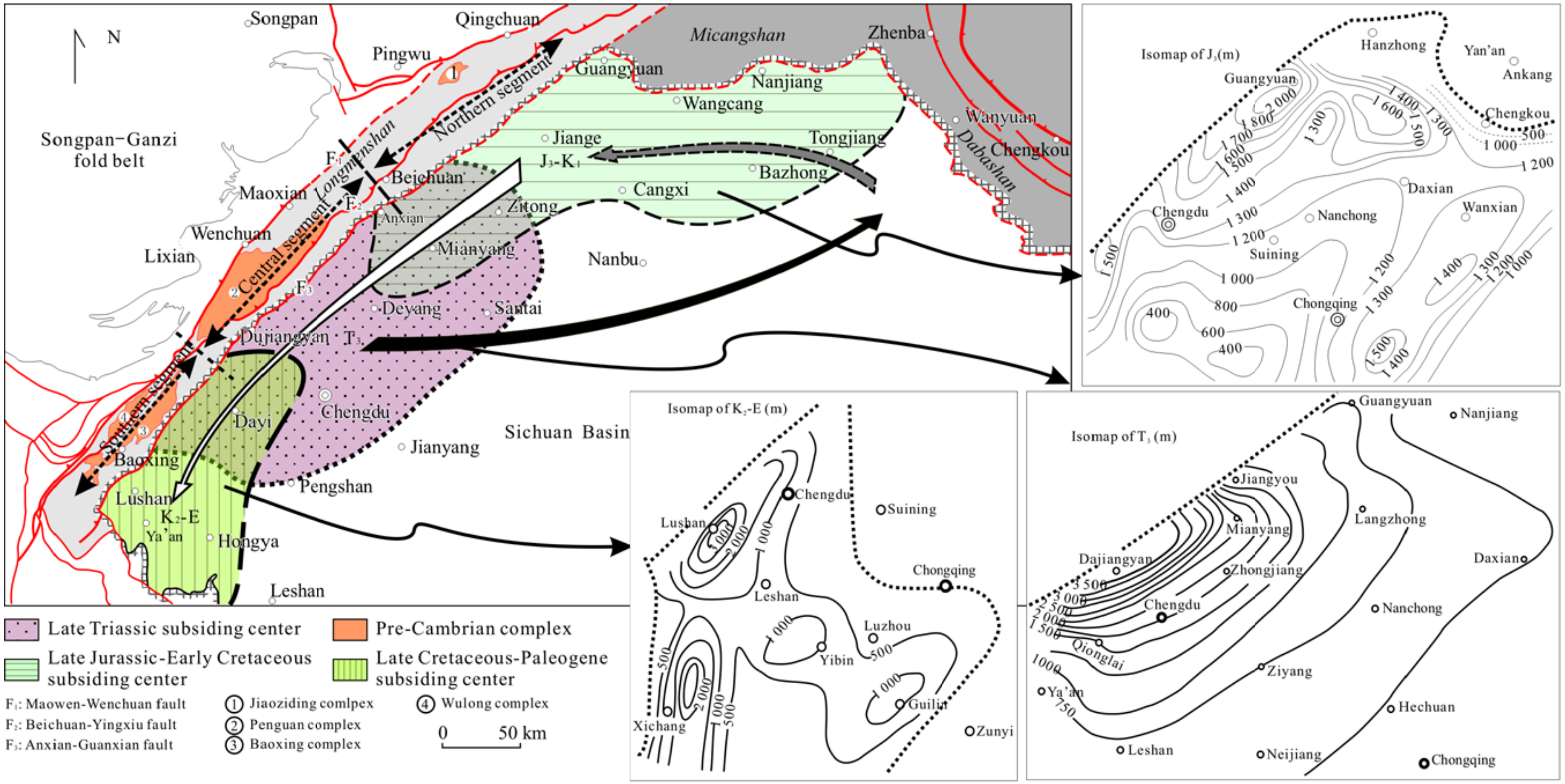

Figure 6. Migration of subsidence centers in the western Sichuan foreland basin from Late Triassic onward. Inset: isopach maps after Guo et al. (1996). SQL. South Qinling; DB. Dabie; EKL. Eastern Kunlun; YD. Yidun; EMS. Emeishan; NQL. North Qinling; QL. Qilian; SCB. South China Block; NCB. North China Block.

Changes in the distribution of Late Triassic conglomerates and a decrease in the angularity at the unconformity between Late Triassic (T_3x) and Early Jurassic (J_1b) strata are segmental features that indicate southwestward propagation of mountain development along strike.

Segmentation along strike, zonality in dip, conglomerate depositional patterns and changing character of unconformities are all results of tectonic movement in the Longmenshan Range that allow us to decipher the dynamic evolution of this mountain range. Because of the southeastward thrusting sequence and southwestward propagation of mountain building in space and time, and considering the presence of conglomerates and unconformities, we propose a southwestward propagating model of dynamic evolution (Fig. 7). The first southwestward propagation of mountain-building along strike occurred during the Late Triassic Indo-Chinese Epoch when the Longmenshan Range was characterized by transpressional thrusting and sinistral strike-slip with segmental features, deformation and deposition. In general, the thrust belt and the detachment belt in the northern and central segments formed at this time, primarily controlled by the collision of the South China and North China Blocks and subsequent intracontinental tectonic movements.

The Longmenshan Range subsequently experienced long-term tectono-thermal quiescence with little activity during the Jurassic-to-Cretaceous Yanshanian Epoch, followed by a significant tectonic regime change from Paleo-Tethyan to the Neo-Tethyan characterized by transpressional thrusting, dextral strike-slip and rapid uplift and cooling during Cenozoic time resulting in intensive deformation in the southern segment and its periphery. This indicates that construction of the thrust belt and detachment belt in the southern segment and extended belts of the Longmenshan Range (Fig. 7) as far as the eastern margin of the Tibetan Plateau and the western margin

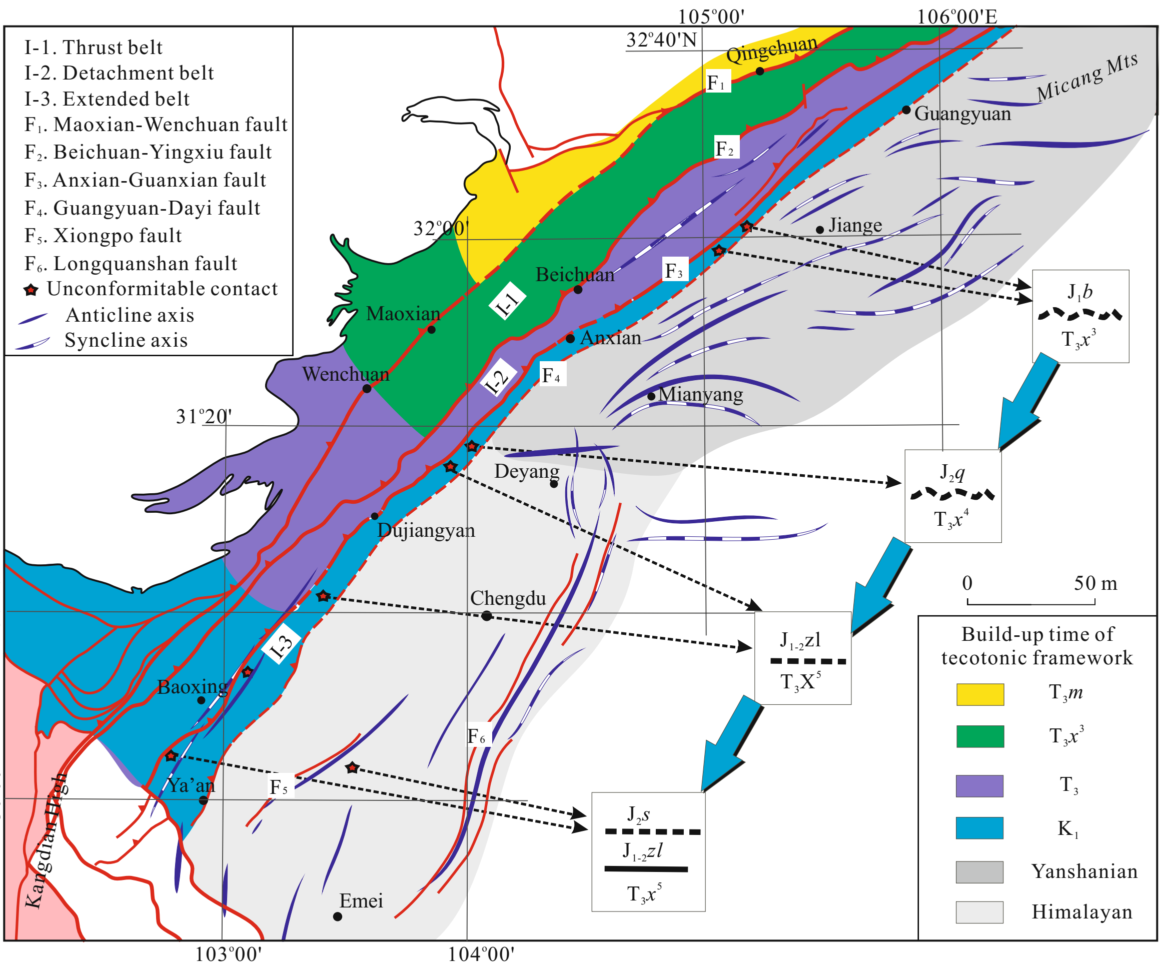

Figure 7. Conceptual model of the southwestward propagating evolution of the Longmenshan Range.

of the Yangtze Plate were primarily controlled by the collision of the Indian and Asian continental plates during Cenozoic time.

CONCLUSION

The Longmenshan Range is an intracontinental composite orogen controlled by multi-scale geodynamics. Forces included a SE stress applied by the Yangtze continental plate drifting northwestward, a NS stress applied by the Qinling orogen and an EW stress exerted by the Tibetan Plateau. The structures and tectonics of Longmenshan displays zonality of dip and segmentation along strike. The zonality of the Longmenshan from NW to SE is indicated by three tectonic belts separated by boundary faults with different structural features, intensity of deformation and strata involved in deformation. The belts can be further subdivided into three segments from NE to SW, displaying differences in deformation, uplift processes, and neotectonic activity.

Low-temperature thermochronology and U-Pb detrital zircon ages reveal a long-term period of tectono-thermal quiescence accompanied by slow uplift and cooling from Mesozoic to Early Cenozoic times following Early Norian to Rhaetian orogeny that was followed by rapid cooling and uplift which began in the Late Cenozoic. Most low-temperature thermochronology shows southeastward younger ages in the thrust and detachment belts down dip from NW to SE indicative of progressive southeastward uplift and thrusting. Along strike from NE to SW, there are southwestward decreasing low-temperature thermochronological ages reflecting southwestward propagation of uplift and cooling processes with a coeval sedimentary response.

We propose a southwestward propagation model of evolution of the Longmenshan Range based on our observations of dip zonality and segmentation along strike (Fig. 7), resulting from Post-Late Triassic multi-scale geodynamics. Our model portrays the development of the central and northern segments of the Longmenshan Range as mainly controlled by the Qinling orogen during Late Triassic time accompanied by superposed buildup of the southern segment. The evolution of the whole range was mainly controlled by the Tibetan Plateau during Cenozoic.

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