

The Coupling Relationship between the Uplift of Longmen Shan and the Subsidence of Foreland Basin, Sichuan, China

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Abstract: Depending on the analysis of the coeval sedimentary geometry and subsidence mechanism in the Longmen Shan foreland basin, three models about the coupling relationship between Longmen Shan uplift and foreland basin subsidence since the Indosinian have been proposed: (1) crustal shortening and its related wide wedge-shaped foreland basin, (2) crustal isostatic rebound and its related tabular foreland basin, and (3) lower crustal flow and its related narrow wedge-shaped foreland basin. Based on the narrow wedge-shaped foreland basin developed since 4 Ma, it is believed that the narrow crustal shortening and tectonic load driven by lower crustal flow is a primary driver for the present Longmen Shan uplift and the Wenchuan (Ms 8.0) earthquake.

Key words: coupling relationship, foreland basin subsidence, Longmen Shan uplift, eastern margin of Tibetan Plateau, Sichuan, China, Proto-Tethys

1 Introduction

The subsequent occurrence of the Wenchuan earthquake (Ms 8.0) in 2008 and the Lushan earthquake (Ms 7.0) in 2013 indicates that the Longmen Shan is an active orogenic belt. The coupling relationship between the uplift of the Longmen Shan and the subsidence of foreland basin has been a focus for geoscientists in recent years. Currently, three types of mechanisms have been proposed: (1) the crustal shortening mechanism, which suggests that the uplift of the Longmen Shan is the effect of upper crustal thrusting and shortening (Hubbard et al., 2009); (2) the crustal isostatic rebound mechanism, which means that the crustal isostatic rebound, resulted from the surface erosion unloading, drive the uplift of the Longmen Shan and the formation of high and steep topography (Fu et al., 2011; Molnar, 2012); and (3) the mechanism of channel flow or lower crustal flow, which implies that the lower crustal flow in the east of the Tibetan Plateau was barriered by the rigid crust (Sichuan Basin) and deposited

below the Longmen Shan, thus forming the very thick crust and high and steep topography (Burchfiel et al., 2008). Clearly, the scholars in China and abroad have significant controversies in the uplift mechanism of the Longmen Shan and its relationship with the seismogenic mechanism of the Wenchuan earthquake. Such controversies involve the following aspects.

(1) Is the uplift of the present-day Longmen Shan driven by upper crustal tectonism or lower crustal tectonism? How to distinguish between them? The former is represented by upper crustal shortening, and the latter is represented by lower crustal flow.

(2) Is the uplift of the present-day Longmen Shan driven by tectonic uplift or isostatic rebound? How to distinguish between them? Theoretically, the former is an uplifting process driven by tectonic load (including upper crustal shortening and lower crustal flow), while the latter is an uplifting process driven by denudation unloading.

(3) Is the uplift of the present-day Longmen Shan driven by the superposition of tectonic uplift and crustal isostatic rebound? Molnar et al. (2012) believed that the

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Longmen Shan uplift attributed to the superposition of crustal shortening and crustal isostatic rebound, with the predominance of the latter (85%). Densmore et al. (2007) considered that the Longmen Shan uplift was contributed by the superposition of tectonic uplift (upper crustal shortening or lower crustal flow) and crustal isostatic rebound, with the predominance of the former (62%–75%). Parker et al. (2011) indicated that the Wenchuan earthquake resulted in the Longmen Shan uplift, but also the co-seismic landslides. The co-seismic landslide volume ($5\text{--}15\text{ km}^3$) was greater than the co-seismic tectonic uplifting volume ($2.6\pm 1.2\text{ km}^3$), which indicates that the denudation unloading might lead to the material loss and downgrading of the Longmen Shan. All these scholars recognized the superposition of tectonic uplift and crustal isostatic rebound, which might be concurrent to affect the Longmen Shan uplift. However, their conclusions disagree in two aspects. First, tectonic uplift and crustal isostatic rebound are different in effects and contributions. The uplift and growth of the Longmen Shan are decided by the ratio between tectonic uplifting volume and denudation unloading volume. Second, it is outstanding whether the Longmen Shan uplift is attributed to the superposition of crustal shortening and crustal isostatic rebound or the superposition of lower crustal flow and crustal isostatic rebound.

(4) Is the uplift of the present-day Longmen Shan driven by the superposition of multi-period diverse uplifting mechanisms? The Longmen Shan, formed due to tectonism since the Indosinian, is the product of tectonic superposition since the Late Triassic. It preserves the uplifting mechanism and products of the Indosinian and Yanshan movements, and is also superimposed with the uplifting mechanism and products of the Himalayan movement, making it a complex superposed by diverse uplifting mechanisms in multiple periods. Moreover, the “Mesozoic Longmen Shan” and “Cenozoic Longmen Shan” may have different tectonic systems (e.g. basin-mountain system or basin-mountain-plateau system) and uplifting mechanisms (Xu Zhiqin et al., 2007; Wang Erqi et al., 2008).

In summary, the history of the Longmen Shan uplift shows the superposition of multi-period diverse uplifting mechanisms. How to distinguish these mechanisms from the prospective of geological evolution is one of the challenges in current studies. This paper propose the sedimentary record of foreland basin as a feasible evidence to identify the Longmen Shan uplift mechanism and its transformation process. In this paper, the sedimentary geometry and subsidence in the foreland basin are used to calibrate the Longmen Shan uplift mechanism and its transformation process in different geological periods.

Firstly, the sedimentary geometry of the Longmen Shan foreland basin is divided into three types, i.e. the Late Triassic wide wedge-shaped foreland basin, the Jurassic-Paleogene large tabular foreland basin, and the Neogene-Quaternary narrow wedge-shaped foreland basin. Secondly, the crustal shortening and tectonic load of the Longmen Shan are divided into three types, i.e. the strong crustal shortening and large (wide) tectonic load, the weak crustal shortening and small (narrow) tectonic load, and no tectonic shortening and no tectonic load (crustal isostatic rebound). Thirdly, According to the correspondence between the Longmen Shan uplift mechanisms (including crustal shortening, lower crustal flow and crustal isostatic rebound) and different types of foreland basin, three types of coupling relationships between the Longmen Shan and the foreland basin are established, namely, the crustal shortening related to the wide wedge-shaped foreland basin in the Late Triassic (early period), the crustal isostatic rebound related to the tabular foreland basin in the Jurassic-Paleogene (middle period), and the crustal flow related to narrow wedge-shaped foreland basin in the Neogene-Quaternary (late period) (Fig. 1).

2 Geological Setting

The eastern margin of the present-day Tibetan Plateau is composed of three primary structural units, i.e. plateau (the Sichuan-Qinghai block in the eastern Tibetan Plateau)-mountain (Longmen Shan)-basin (western Sichuan Basin), presenting as basin-mountain-plateau system (Fig. 2). These structural units are the twins formed in the conversion of the Mesozoic basin-mountain system and the Cenozoic basin-mountain-plateau system since the Late Triassic Indosinian movement. Although the eastern margin of present-day Tibetan Plateau presents as a basin-mountain-plateau system geomorphologically and corresponds to the India-Asia collision and the post-collision effect, the basin-mountain system formed before the formation of the Tibetan Plateau is the product of tectonism in the Indosinian-Yanshan period (Li Yong et al., 2006).

2.1 Tibetan Plateau

The eastern margin of the Tibetan Plateau is located to the west of the Maowen fault in the back margin of the Longmen Shan (Fig. 2). On surface, it presents as a high and gentle structural unit, which is high, wide, and flat. The geological body is composed of epizonal metamorphic rocks in the Songpan-Garzê fold belt. Its metamorphism, shortening and deformation occurred during the Indosinian. Since the Cenozoic, it has shown vertical uplifting as a whole and horizontal movement of the block (Wallis et al., 2003).

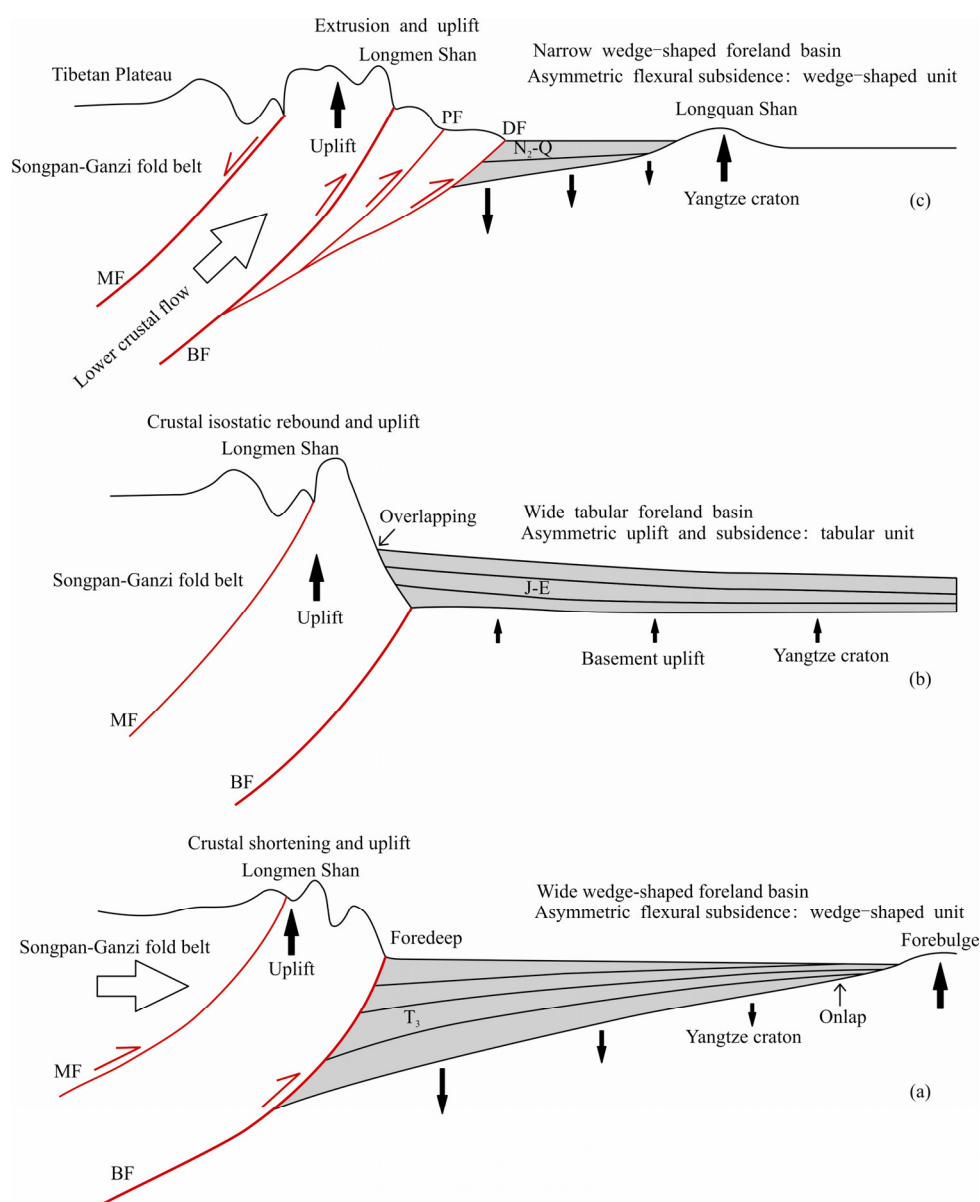


Fig. 1. Coupling relationship between the Longmen Shan uplift and foreland basin subsidence.

MWF: Maowen fault; BYF: Beichuan fault, PGF: Pengguan fault; DYF: Dayi fault. T₃: Upper Triassic; J-E: Jurassic-Paleogene; N₂-Q: Pliocene-Quaternary.

2.2 Longmen Shan

The Longmen Shan is marginal mountains between the Tibetan Plateau and the Sichuan Basin (Fig. 2). Aboveground, it presents as a high and steep structural unit, which extends to NE-SW trending, with a length of about 500 km, and a width of about 30–50 km, showing the features of “high, narrow, and steep”. It has a height difference greater than 5 km from the piedmont foreland basin (Chengdu Basin), suggesting that the Longmen Shan is the steepness variation zone with the largest steepness variation the marginal mountains of the Tibetan Plateau (Densmore et al., 2005; Li Yong et al., 2006; Godard et al., 2009).

The Longmen Shan is an independent intra-continental

orogenic belt. It develops the Maowen fault in the back margin, which is a detachment fault (ETD, Xu Zhiqin et al., 2007) or shear zone (Li et al., 2006), the Beichuan fault in the central region, which is a thrust with dextral slip fault, and the Pengguan fault in the front margin, which is a thrust with dextral slip fault (Li et al., 2006; Densmore et al., 2007). In the present-day Longmen Shan area, the horizontal movement rate is quite small (the movement rate of GPS is about 1–3 mm/a, Zhang et al., 2004), and the rate of vertical uplifting is also very small about 0.3–0.4 mm/a (Li Yong et al., 1994).

2.3 Foreland basin

The foreland basin is located in the western margin of

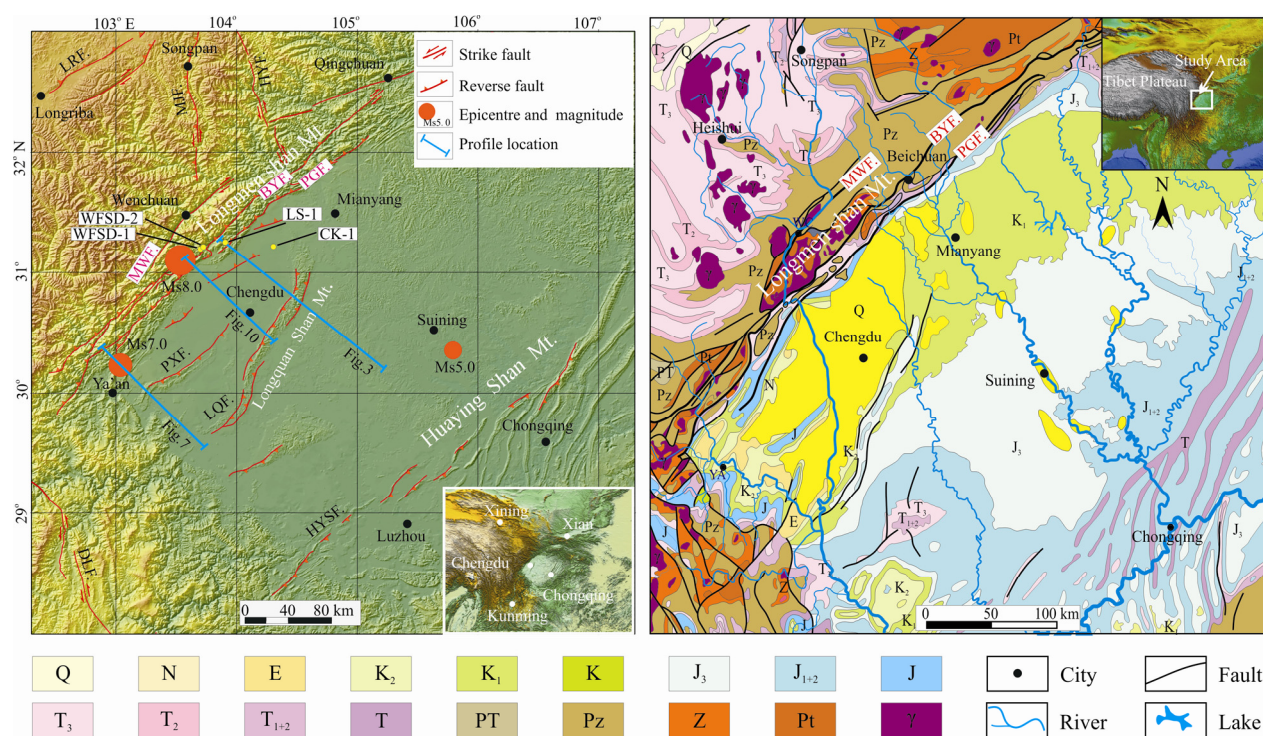


Fig. 2. Geological framework of the Longmen Shan and foreland basin.

LRF: Longriba fault; MJF: Minjiang fault; HYF: Huya fault; MWF: Maowen fault; BYF: Beichuan fault; PGF: Pengguan fault; PXF: Pujiang-Xinjin fault; LQF: Longquan Shan fault; HYSF: Huaying Shan fault; DLF: Daliang Shan fault. LS-1: Well Longshen 1; CK-1: Well Chuanke 1; WFS-1: WFS-1 drilling hole; WFS-2: WFS-2 drilling hole. Q: Quaternary; N: Neogene; K₂: Upper Cretaceous; K₁: Lower Cretaceous; K: Cretaceous; J₃: Upper Jurassic; J₁₊₂: Lower-Middle Jurassic; J: Jurassic; T₃: Upper Triassic; T₂: Middle Triassic; T₁₊₂: Lower-Middle Triassic; T: Triassic; PT: Permian+Triassic; Pz: Paleozoic; Z: Sinian; Pt: Proterozoic; γ: Igneous rocks.

the Yangtze craton (western Sichuan Basin) and the front margin of the Longmen Shan (Fig. 2). The characteristics of geomorphology are “low, wide, and flat”. On the surface, the Jurassic and Cretaceous sedimentary rocks are outcropped. With relatively gentle strata, the foreland basin is composed of NE-trending active tectonic belts in banded distribution. These belts (from west to east) include Longmen Shan piedmont fold deformation belt (the frontal extending belt), Chengdu Basin, Xiongpo anticline, Longquan Shan anticline, Weiyan uplift, and Huaying Shan fold belt.

The foreland basin is a superimposed foreland basin formed on the basis of the passive continental margin in the western margin of the Yangtze craton since Late Triassic (Li Yong et al., 1995; Li et al., 2003). It was filled by marine, paralic, and continent sedimentary rocks from Late Triassic to Quaternary, with a thickness of more than 8000 m, which presents as a shallowing and coarsening-upward sedimentary sequence (Figs. 3, 4). Evidently, the foreland basin has a long history of subsidence and complex evolution process and it has recorded the information of the Longmen Shan uplift. The sedimentary geometry and subsidence of the foreland basin are stratigraphic signatures to identify and calibrate the uplift mechanism of the Longmen Shan.

3 Crustal Shortening of the Longmen Shan and the Late Triassic Wide Wedge-shaped Foreland Basin

3.1 Restoration of prototype basin

The residual Late Triassic foreland basin is only distributed between the Longmen Shan and the forebulge (Figs. 4–6) with a width of about 200 km. However, it can be speculated from the latest drilling data that the place where the present-day Longmen Shan is located was a part of the Late Triassic foreland basin, and the width of the prototype basin is greater than 350 km at least. The conclusion can be verified by the following evidences.

First, both the surface outcrops and drilling cores in the front belt of Longmen Shan (between the Beichuan fault and the Pengguan fault) reveal that the Upper Triassic strata are abundant, suggesting that this belt was a part of the Late Triassic foreland basin. According to the drilling of Well Longshen 1 (Fig. 3, between the Beichuan fault and the Pengguan fault, with a drilling depth of 7180 m, according to Sinopec), the cumulative thickness of the Upper Triassic strata in this belt is 5293.00 m (greater than the thickness of Upper Triassic inside the foreland basin, which is 3017.5 m, Fig. 3, according to Well Chuanke 1). In the upper allochthonous system (six structural slices

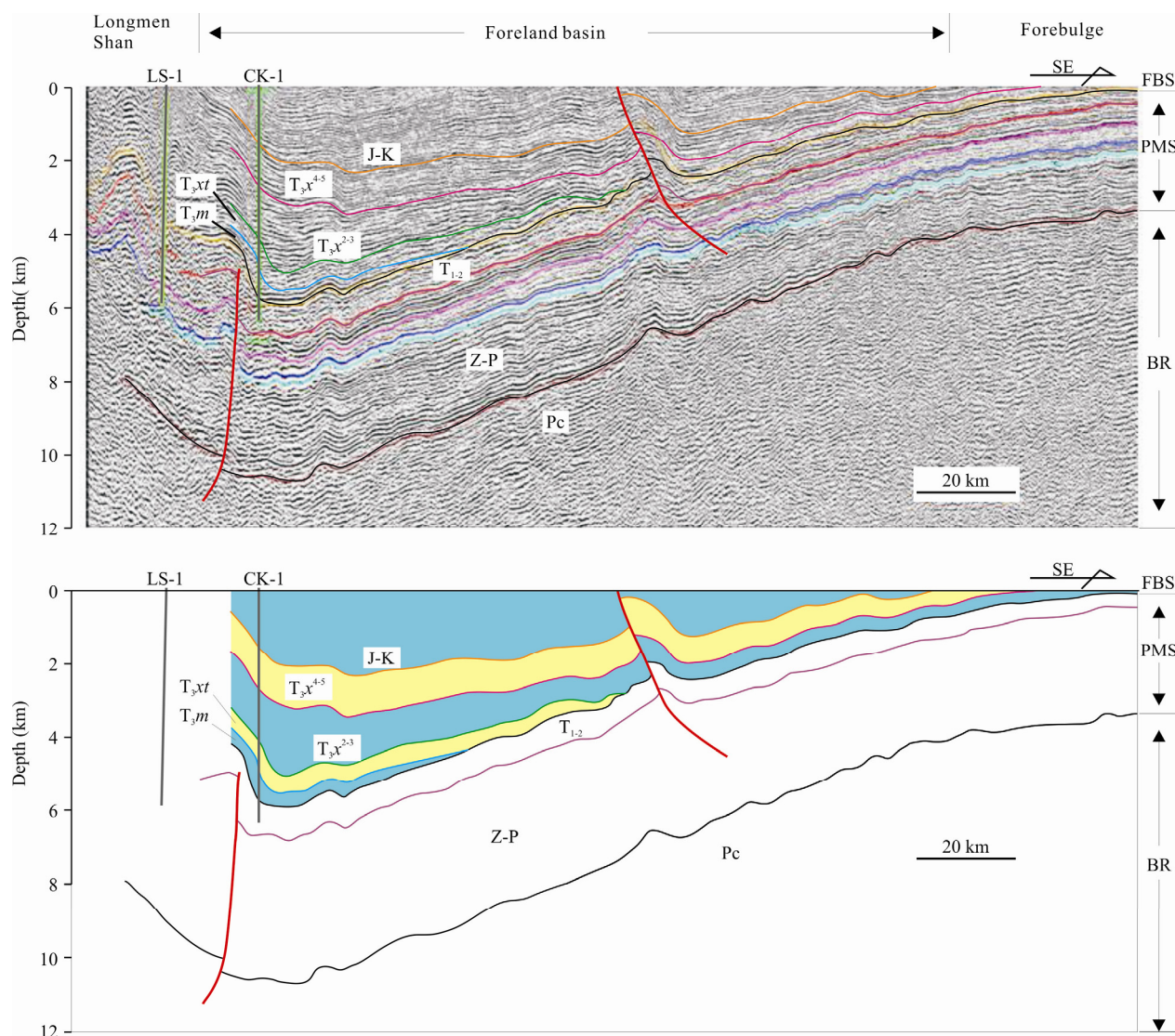


Fig. 3. Seismic reflection profile of the Longmen Shan and foreland basin.

BR: Basement rocks; PMS: Passive margin sequences; FBS: Foreland basin sequences. J-K: Jurassic-Cretaceous; $T_{3x^{4-5}}$: Member 4-5 of Xujiahe FM.; $T_{3x^{2-3}}$: Member 2-3 of Xujiahe FM.; T_{3xt} : Xiaotangzi Formation; T_{3m} : Ma'antang Formation; T_{1-2} : Lower-Middle Triassic; Z-P: Sinian-Permian; Pz: Pre-Sinian. Profile location is shown in Fig. 2, according to the data of Sinopec.

formed by the second and third Member of Xujiahe Formation), the cumulative thickness of the Upper Triassic strata reaches 4279.00 m. In the lower autochthonous system (including the second Member of Xujiahe Formation, Xiaotangzi Formation and Ma'antang Formation), the cumulative thickness of the Upper Triassic strata reaches 1014.00 m. Thereby, it is speculated that the front belt of the Longmen Shan was a part of the Late Triassic foreland basin, with a sedimentary thickness of more than 4000 m.

Second, a large quantity of the Upper Triassic strata have been found in the boreholes in the back belt of Longmen Shan (between Beichuan fault and Maowen fault), which indicates that the back belt was once a part of the Late Triassic foreland basin. According to the Wenchuan Fault Scientific Drilling Program, there are

very thick Late Triassic Carnian-Norian strata in the back belt of the Longmen Shan to the west of the Beichuan fault. Be interlayered with the Pengguan complex, the strata constitute the multi-layered structural slices. Thereby, it is speculated that the back belt of the Longmen Shan was once a part of the foreland basin during the Late Triassic Carnian-Norian, when the basin-mountain boundary was not acted by the present Beichuan fault. The orogenic wedge of the Longmen Shan in the Late Triassic was at least located to the west of the present Maowen fault or even further. In this study, the technology of structure balanced section was used to restore the crustal shortening of the Longmen Shan. The results (Fig. 7) indicate that the total shortening distance of the Longmen Shan was 146 km. It is suggested that the orogenic wedge of the Longmen Shan

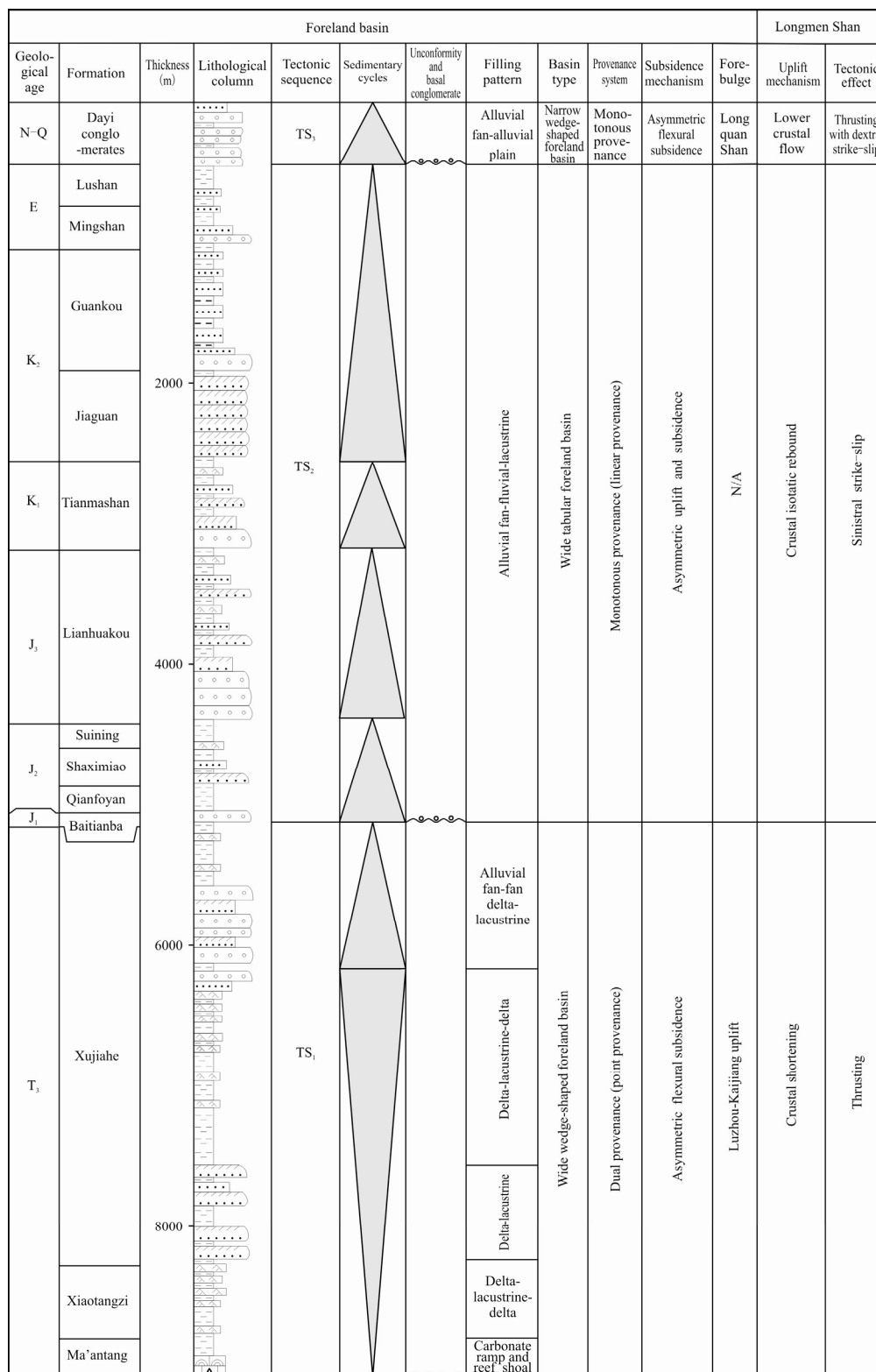


Fig. 4. Filling sequence and tectonic events of the Longmen Shan foreland basin.

in the Late Triassic was located at least is about 146 km to the west of the present location.

In summary, it is speculated that the present residual foreland basin might be only the distal part of the Indosinian foreland basin or the slope part of the

forebulge. The foreland basin might be at least about 350 km wide [the total shortening distance of the Longmen Shan (about 146 km) + the width of present residual foreland basin (about 200 km) = 346 km].

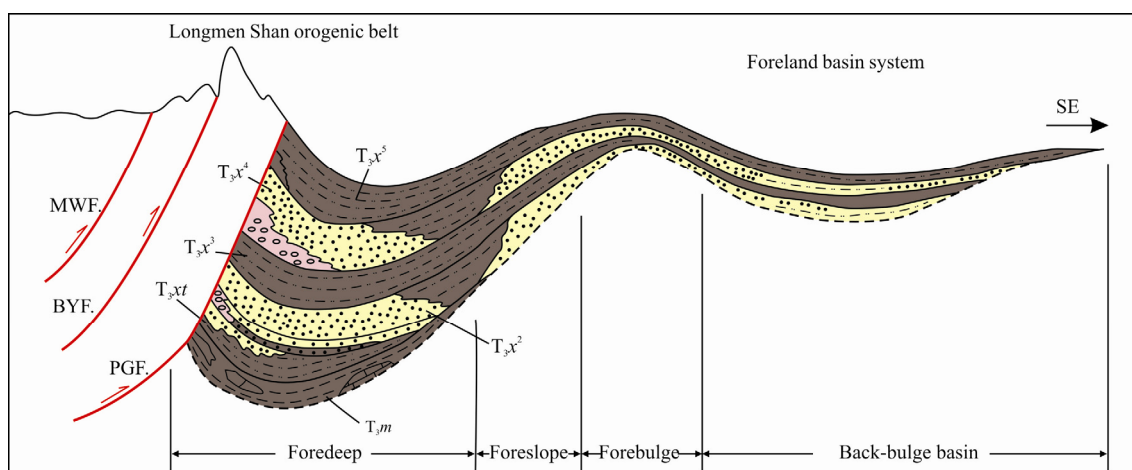


Fig. 5. Late Triassic Longmen Shan orogenic belt-foreland basin system.

MWF: Maowen fault; BYF: Beichuan fault; PGF: Pengguan fault. T_{3x^5} : Member 5 of Xujiache FM.; T_{3x^4} : Member 4 of Xujiache FM.; T_{3x^3} : Member 3 of Xujiache FM.; T_{3x^2} : Member 2 of Xujiache FM.; T_{3xt} : Xiaotangzi FM.; T_{3m} : Ma'antang FM.; T_2 : Middle Triassic; Pre- T_2 : Previous Middle Triassic.

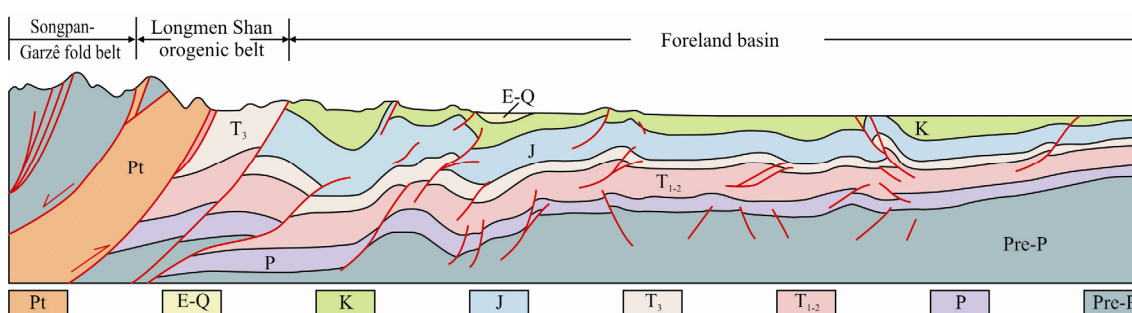


Fig. 6. Structural profile of the Longmen Shan (southern segment) and foreland basin.

Pt: Proterozoic; E-Q: Paleogene-Quaternary; K: Cretaceous; J: Jurassic; T_3 : Upper Triassic; T_{1-2} : Lower-Middle Triassic; P: Permian; Pre-P: Previous Permian. Profile location is shown in Fig. 2.

3.2 Foreland basin system and division of tectonic units

Geometrically, the residual Late Triassic Longmen Shan foreland basin presents as an asymmetric wedge-shaped basin which is thick in the west and thin in the east (Fig. 3). From west to east, it includes the tectonic units of orogenic wedge, foredeep, forebulge, back-bugle basin (Fig. 3, Fig. 5).

The Late Triassic Longmen Shan orogenic wedge belongs to the thrusting wedge in the west margin of the Yangtze craton, which is composed of "platform type" rocks in the west margin of the Yangtze craton, including the pre-Sinian complex, and the Sinian-Middle Triassic sedimentary rocks (Figs. 3), suggesting as an intraplate orogenic belt. The orogenic wedge might be located 146 km to the west of the present-day Longmen Shan. At that time, its palaeo-tectonic setting was similar to that of the current Taiwan orogenic belt and foreland basin (the Taiwan Strait is located on the Eurasia Plate).

The foredeep is located to the east of the orogenic wedge, possibly including the present-day Longmen Shan, including its back and frontal belt. The sedimentary filling body is wedge-shaped, with the features of asymmetric

framework and asymmetric subsidence. In the proximal edge (close to the Longmen Shan), the strata are very thick (>4000 m, according to Well Longshen 1, Fig. 3), with large subsidence rate (approximately 0.2 mm/a), serving as the subsidence center. The distal edge (close to foreland slope in the craton) has small thickness (about 1000 m) and low subsidence rate (about 0.05 mm/a), overlapping the forebulge (Kaijiang-Luzhou uplift) in the east. The forebulge is well developed, and the uplifting and denudation are intensive (Li Yong et al., 1995, 2006, 2011). In its east part, the back-bugle basin is developed (Fig. 5), where the strata are thin-only 500–600 m (Zheng Rongcai et al., 2015).

3.3 Basal unconformity

The basal unconformity of the foreland basin is located between the Middle Triassic Leikoupo Formation and the Upper Triassic, presenting as a regional angular unconformity-parallel unconformity-conformity. It contains scouring hollow, palaeo-karst (karren, cave, and karst breccia), palaeo-weathering crust, limonite, clay layer, quartz, chert, conglomerates (basal conglomerates) and etc.

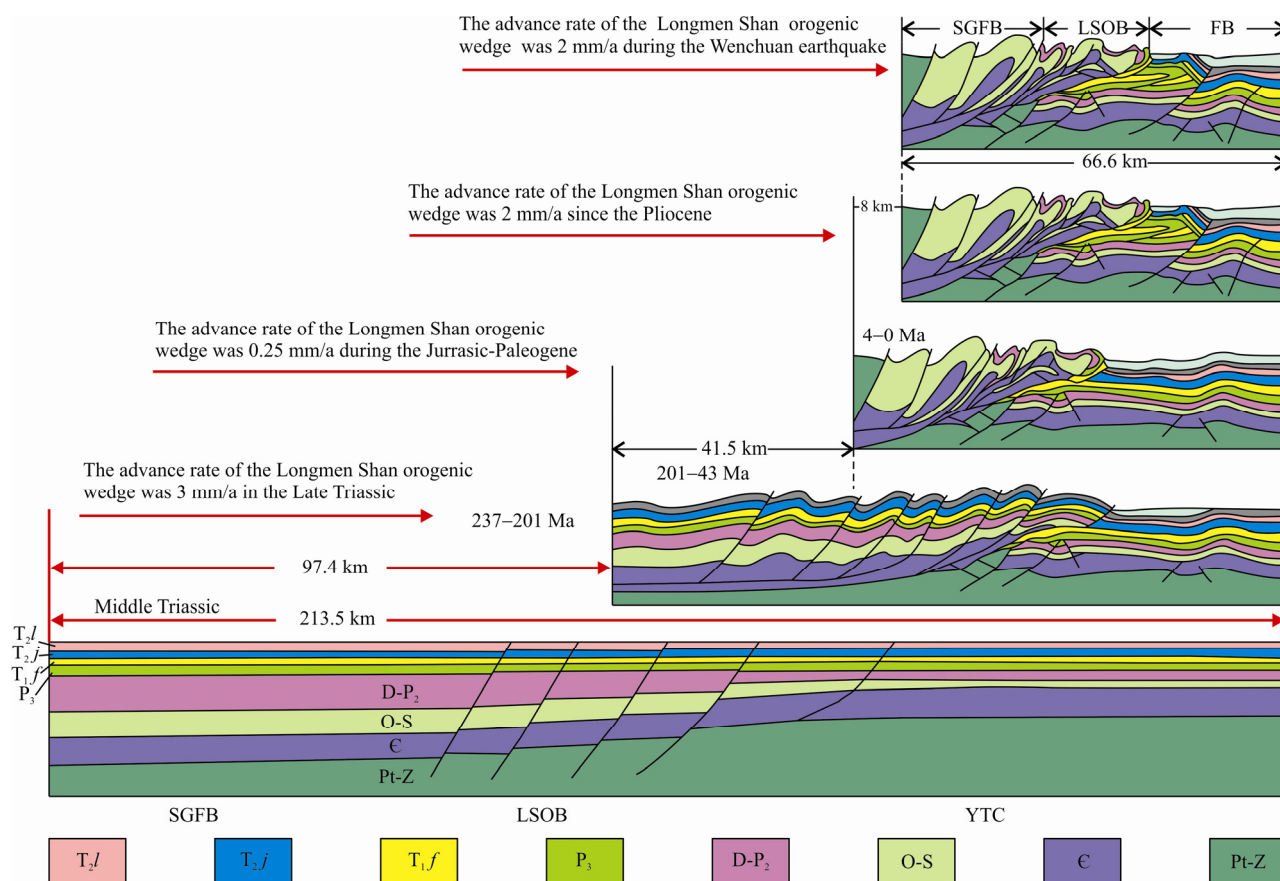


Fig. 7. Crustal shortening rate of the Longmen Shan since Late Triassic.

SGFB: Songpan-Garzê fold belt; LSOB: Longmen Shan orogenic belt; YTC: Yangtze Craton; FB: Foreland basin. $T_{2/l}$: Leikoupo Formation; $T_{2/f}$: Feixianguan Formation; $T_{1/f}$: Jialingjiang Formation; P-D: Permian-Devonian; S-O: Silurian-Ordovician; C: Cambrian; Z-Pt: Sinian-Proterozoic. Total crustal shortening rate of the Longmen Shan is 68.8% since Late Triassic, and total shortening distance is 146.9 km; Late Triassic is the major shortening period, with the maximum shortening rate of 3 mm/a.

The unconformity overlaps the underlying strata southeastward, revealing the transition from conformity to unconformity (Li Yong et al., 2011). Therefore, it is considered that the basal unconformity is a typical foreland flexural unconformity which marks the transformation of the western margin of the Yangtze craton from passive continental margin basin to foreland basin. Its formation period is in agreement with the initial emplacement of the Longmen Shan orogenic wedge, which was in the Late Triassic Carnian period.

3.4 Filling sequence and sedimentary geometry

The filling strata of the Late Triassic foreland basin include Ma'antang Formation, Xiaotangzi Formation and Xujiahe Formation from the Carnian to the Rhaetian, presenting as a tectonic sequence (Figs. 2, 6) bounded by regional unconformity in the top and bottom with a duration of 36 Ma (237–201 Ma). This set of strata is comprised of very thick marine to continental sediments, which is dominated by terrestrial clastic rocks and shale, interbedded with a small amount of carbonate rocks in the bottom. It has an coarsening-upward sequence and can be

divided into 3–4 coarsening-upward or fining-upward sequence or tectono-stratigraphic units (Li et al. 2003, 2014a, 2014b). In view of filling sequence, the bottom is the unconformity and the overlying carbonate and reefs (Ma'antang Formation), which (from west to east) contains the sedimentary facies combination of black shale-carbonate ramp and reef. The lower cycle (including Xiaotangzi Formation, Member 2 of Xujiahe Formation, and Member 3 of Xujiahe Formation) contains an coarsening-upward vertical stratigraphic texture, with the lower part being the lacustrine shale and the upper part being the fan delta coarse clastic rocks; from west to east, it evolves to a sedimentary facies combination of delta facies (fan delta, braided river delta)-lacustrine (swamp) facies-small shallow delta facies (Fig. 6). Large fan deltas and delta systems (coarse clastic rocks) are uniformly distributed in the west of the residual basin, the lacustrine systems are distributed in the central part of the basin, and the small shallow delta systems are mainly developed in the both sides of the forebugle. The upper cycle (including Member 4 of Xujiahe Formation and Member 5 of Xujiahe Formation) contains an fining-upward stratigraphic texture,

with unconformity in the bottom (Wang Jinqi et al., 1990; Li Yong et al., 1995; Li et al., 2003; Chen Bin et al., 2016), which was named the Anxian movement (Wang Jinqi et al., 1990). The lower part is composed of coarse clastic rocks of alluvial fan and fan delta, and the upper part is composed of lacustrine shale. From west to east, it presents as the sedimentary facies combination of alluvial fan (fan delta, braided river delta) facies-lacustrine (swamp) facies (Fig. 6). Large alluvial fan, fan delta and delta systems (coarse clastic rocks) are uniformly distributed in the western part of the residual basin and the lacustrine systems are distributed in the central and eastern parts of the basin.

3.5 Coupling mechanism between the Longmen Shan crustal shortening and Late Triassic wide wedge-shaped foreland basin

Allen et al. (1991) proposed two types of foreland basins by taking the Alps foreland basin as an example, namely, the early underfilled basin (equivalent to the Flysch stage) and the late overfilled basin (equivalent to the Molasse stage). They indicated that the shortening rate or advance rate of the orogenic wedge was the key factor that determined the flexural subsidence rate of the foreland basin.

Based on the Allen model, Li et al. (2003, 2013) proposed the coupling relationship between crustal shortening of the Longmen Shan and the subsidence of foreland basin. They suggested that the Late Triassic foreland basin was formed due to the flexural subsidence of the Yangtze craton as a result of the crustal shortening and tectonic load of the Longmen Shan. In particular, the crustal shortening rate or advance rate of the Longmen Shan is the key factor which determines the flexural subsidence rate of the foreland basin. Moreover, they adopted the one-dimensional elastic flexural mode to simulate the flexural subsidence generated when the Indosinian episodic tectonic load on the initial elastic plate (Yangtze craton). In summary, the Late Triassic foreland basin has the following characteristics. (1) The crustal shortening of the Longmen Shan is the dynamic mechanism which drives the evolution of foreland basin. The formation and evolution model of the Longmen Shan foreland basin is consistent with the elastic flexure model. The western margin of the Yangtze craton in the Indosinian period was a rigid plate, with a flexural rigidity of 5×10^{23} Nm (equivalent effective elastic thickness is 43–55 km). (2) In the Indosinian, the tectonic load of the Longmen Shan orogenic wedge was extremely huge, with a (NE) length of about 500 km, a (SE) width of about 320 km, a height of about 4 km (including about 2 km aboveground), and a front slope of 0.03%, corresponding

to a tectonic load of about 28×10^4 km³. (3) The width of foreland basin is about 350 km and the depth (maximum sedimentary loading thickness) of the flexural subsidence center is about 4 km, presenting as an asymmetrical wide wedge-shaped foreland basin. (4) The Late Triassic foreland basin is divided into the early (Carnian-Norian) underfilled basin (equivalent to the lower Xujiahe basin proposed by Wang Jinqi (1991)) and the late (Rhaetian) overfilled basin (equivalent to the upper Xujiahe basin proposed by Wang Jinqi (1991)). (5) The relationship between the advance rate of the orogenic wedge and the subsidence rate of the foreland basin is established. The advance rate of the Longmen Shan orogenic wedge was higher (15 mm/a) in early stage, contributing to the early underfilled foreland basin. The advance rate of the Longmen Shan orogenic wedge was low (5 mm/a) in late stage, contributing to the late overfilled foreland basin.

In this study, the technology of structure balanced section was employed to restore the crustal shortening rate of the Longmen Shan. The results indicate that the maximum crustal shortening rate (3 mm/a) of the Longmen Shan occurred in the Late Triassic (Fig. 7), which is similar to the simulated advance rate (5–15 mm/a, Li et al., 2003) of the orogenic wedge. Therefore, it is believed that the Late Triassic foreland basin was the wide wedge-shaped foreland basin formed under the conditions of intensive crustal shortening and tectonic load of the Longmen Shan in the Indosinian period. A huge orogenic wedge loaded on the western margin of the Yangtze craton, leading to the strong asymmetrical flexural subsidence in foreland, thereby forming the wide wedge-shaped basin (Fig. 5, Fig. 6).

4 Crustal Isostatic Rebound of the Longmen Shan and the Jurassic-Paleogene Tabular Foreland Basin

The Jurassic strata, widely distributed in most areas of the Sichuan Basin and to the east of the Longmen Shan, are observed as continuously-deposited red clastic rocks. The strata are gentle and stable, as tabular bodies with relatively stable thickness (Fig. 3). But the Cretaceous-Paleogene strata are not continuously distributed in space, and they are well preserved in the western Sichuan Basin, but absent in most areas of the central and eastern Sichuan Basin.

4.1 Basal unconformity and basal conglomerates

At the bottom of the Jurassic, there is a regional unconformity with the following characteristics. (1) The angular unconformity is only distributed in the Longmen Shan piedmont belt and the northwest margin of the basin.

Inside the basin, the parallel unconformity and conformity are predominant, presenting as the transition of angular unconformity-parallel unconformity-conformity. (2) As observed from the surface outcrops in the front belt of the Longmen Shan (Li Yong et al., 1995) and the seismic reflection profiles (Wang Jinqi et al., 1991), the Jurassic overlies the Upper Triassic Xujiahe Formation in form of angular unconformity; the underlying strata show intense tectonic deformation, while the overlying strata are gentle and weakly deformed and tend to overlap the Upper Triassic strata of the Longmen Shan front belt. (3) Above the unconformity interface, there are quartziferous basal conglomerates or quartziferous sandstones. The quartziferous conglomerates are mainly distributed in the middle-northern segment of the Longmen Shan front belt (e.g. the Jiange-Jinzishan conglomerates with a thickness of 264 m, and the Anxian conglomerates with a thickness of 100 m). The conglomerates show a high compositional maturity, being completely as quartziferous conglomerates. The conglomerates are well sorted with high level of roundness. Inside the basin, the quartziferous sandstones with different thicknesses is widely distributed above the unconformity interface, recording as a typical marker bed. Accordingly, it is believed that the basal unconformity and quartziferous basal conglomerates and its overlapping to the Longmen Shan are key evidences to calibrate that the Indosinian thrusting of the Longmen Shan was once stopped in the Jurassic.

4.2 Filling sequence and filling pattern

The filling strata of the Jurassic-Paleogene tabular foreland basin comprise the Jurassic (including Baitianba Formation, Qianfoya Formation, Shaximiao Formation, Suining Formation, and Lianhuakou or Penglaizhen Formation), the Cretaceous (including Tianmashan Formation or Chengqiangyan Group, Jiaguan Formation, and Guankou Formation), and the Paleogene (including Mingshan Formation and Lushan Formation) (Fig. 6). Both the top and bottom boundaries are regional unconformity interfaces, presenting as a separate tectonic sequence with the following characteristics. (1) The filling sequence consists of three major sedimentary cycles, namely, the Early-Middle Jurassic sedimentary cycle, the Late Jurassic-Early Cretaceous sedimentary cycle, and the Late Cretaceous-Paleogene sedimentary cycle. (2) Each sedimentary cycle has a fining-upward retrograding sequence. The lower part contains alluvial fan sediments which consist of debris flow conglomerates, and the upper part contains lacustrine sediments which consist of shale, siltstones and sandstones. (3) All lithostratigraphic units (Formations) are in conformity contact, indicating the substantially continuous deposition in this period and a

scarce of intensive tectonic deformation event. (4) Horizontally, the filling pattern of the Jurassic-Paleogene tabular foreland basin is the alluvial fan-lacustrine sedimentary system. The alluvial fan is located in the western margin of the basin, which is dominated by conglomerates and sandstones of alluvial fan and fan delta. It is only distributed in the front margin of the Longmen Shan orogenic belt, with a narrow range of only 20–30 km wide, indicating that the spatial distribution of alluvial fan is subject to the Longmen Shan, with mono-directional provenance.

The Jurassic presents as a tabular body with relatively stable stratigraphic thickness (Fig. 3, Fig. 6). The maximum thickness observed in the western basin is approximately 2000 m (according to Well Chuanke 1, Fig. 2 and Fig. 6), and it overlaps westward to the Longmen Shan with relatively stable thickness. However, the Cretaceous-Paleogene strata are not continuously distributed in space and not integrally preserved. This set of strata is well preserved in the western part of the basin, with a cumulative thickness of approximately 2000 m (Fig. 6), but absent in majority of the central-eastern part of the Sichuan basin (Fig. 2). It is worthy of noting that the Cretaceous-Paleogene strata are remained in the southern and southeastern parts of the Sichuan Basin (Fig. 2). Therefore, it is believed that there were the Cretaceous-Paleogene sediments in the Sichuan Basin, but these sediments were denudated later. Firstly, the Cretaceous-Paleogene sediments distributed in the southern and southeastern parts of the Sichuan Basin have similar stratigraphic sequence and sedimentary environment to the western part, indicating that they are the sediments formed contemporaneously in similar conditions. Secondly, on the surface, the Cretaceous-Paleogene sediments show irregular morphology as a result of denudation, which indicates that there were considerable Cretaceous-Paleogene sediments in the area, but they were denudated subsequently. Thirdly, the measurements of apatite fission track for the sediments in the Sichuan Basin indicate that about 1–4 km strata in the Sichuan Basin have been denudated after 40 Ma (Richardson et al., 2008, 2010), especially in the central-eastern part where the maximum denudation thickness is 4 km. The denudated strata are speculated as the Cretaceous-Paleogene.

4.3 Coupling mechanism between the crustal isostatic rebound of Longmen Shan and the Jurassic-Paleogene tabular foreland basin

Burbank (1992) proposed two types of orogenic belt-foreland basin coupling mechanism by taking the Himalayan foreland basin as an example, namely, the coupling mechanism between crustal shortening and

wedge-shaped foreland basin in the early stage, and the coupling mechanism between crustal isostatic rebound and tabular foreland basin in the late stage. With consideration to the unique features of the Jurassic foreland basin, and based on the Burbank model (1992), Li Yong et al. (1994, 1998, 2006, 2013) proposed the coupling mechanism of crustal shortening, crustal isostatic rebound of the Longmen Shan and the foreland basin, and indicated that crustal shortening and crustal isostatic rebound of the Longmen Shan were different dynamic mechanisms driving the formation and evolution of the foreland basin. The Longmen Shan was once in two states, i.e. crustal loading and denudation unloading. Accordingly, it is believed that the large Late Triassic wedge-shaped foreland basin is the marker for identifying the crustal shortening of the Longmen Shan and the large Jurassic-Paleogene tabular foreland basin is the marker for identifying the crustal isostatic rebound of the Longmen Shan. Thus, the relationships between crustal shortening and wedge-shaped foreland basin and between crustal isostatic rebound and tabular foreland basin of the Longmen Shan are established. Further, it is believed that the crustal isostatic rebound and surficial erosion unloading drove the uplifting of the Longmen Shan and the formation of high-steep topography during the Jurassic-Paleogene. Moreover, the Jurassic-Paleogene foreland basin is supposed as a tabular foreland basin formed by sedimentary loading under the conditions that there was no intensive crustal shortening and tectonic load (Fig. 2 and Fig.5).

In this study, the technology of structure balanced section was used to restore the Longmen Shan shortening rate. The results indicate that the minimum crustal shortening rate occurred in the Jurassic-Paleogene, which was only about 0.25 mm/a (Fig. 7). This reflects that the advance rate of the Longmen Shan orogenic wedge was extremely low in this period. Therefore, it is believed that the Jurassic-Paleogene foreland basin is the large tabular foreland basin formed by sedimentary loading under the conditions of weak tectonic shortening and weak tectonic load. According to the principle of isostasy, the denudation makes the crustal rocks gradually be stripped from the mountains, resulting in the material unloading on lithosphere. Thus, the original crustal rocks in the Longmen Shan were substituted by air, thereby leading to the “negative” loading on lithosphere, which further resulted in the crustal isostatic rebound and uplifting of the Longmen Shan, with high topography and high denudation rates. Although the isostatic rebound and denudation unloading of the Longmen Shan would not cause flexural subsidence of front areas, the materials unloaded from the Longmen Shan due to denudation were

transported to and accumulated in the foreland basin, thereby forming a huge amount of sedimentary loading and leading to the subsidence of the foreland basin. Therefore, the sedimentary loading is the major subsidence mechanism to trigger the formation of tabular foreland basin. In general, during the period of the Longmen Shan crustal isostatic rebound, the subsidence model of the foreland basin has the following features (Fig. 2). (1) The crustal shortening and tectonic loading of the Longmen Shan were small, no flexural subsidence occurred in the foreland, and the extent of forebulge uplift was not obvious. (2) The Longmen Shan was in denudation unloading state. The huge denudation unloading led to the isostatic rebound, high topography and high erosion rate of the Longmen Shan, and also resulted in the substantial migration and transportation of sediments to the foreland area, thereby forming sedimentary loading and leading to the subsidence of foreland area. (3) The basin was characterized by large width (more than 300 km), large time span (201–43 Ma), low subsidence rate (about 0.01 mm/a), thin sedimentary thickness (about 2 km), and tabular sedimentary filling bodies. (4) It showed the features of mono-directional provenance (from the Longmen Shan) and unilateral (lateral) filling, and the supply pattern was mainly dominated by the denudation of the Longmen Shan. (5) The basal unconformity and the quartziferous basal conglomerates or quartziferous sandstones were well developed, and overlapped to the Longmen Shan.

5 Lower Crustal Flow of the Longmen Shan and the Neogene-Quaternary Narrow Wedge-shaped Foreland Basin

The Longmen Shan foreland basin, the present Chengdu Basin (Li Yong et al., 1994, 1995), is distributed between the Longmen Shan and the Longquan Shan (Figs. 1–2). It presents as a linear basin extending in NE (NNE 30°–40°), with a length of 180–210 km and a width of about 50–60 km, covering an area of about 8400 km². Geomorphologically, it exists as the Chengdu Plain.

5.1 Basal unconformity and basal conglomerates

The filling strata of the Chengdu Basin overly the Jurassic, Cretaceous and Paleogene strata in form of angular unconformity (Figs. 1–2), and contains the weathering crust (Li Yong et al., 1994). The interface is well outcropped in Dayi (Fig. 8). Its underlying stratum is the Paleogene (Lushan Formation or Mingshan Formation) dipping southeastward with a dip of 40–43°. Its overlying stratum is the Neogene (Dayi conglomerates) dipping southeastward with a dip of 30°. The

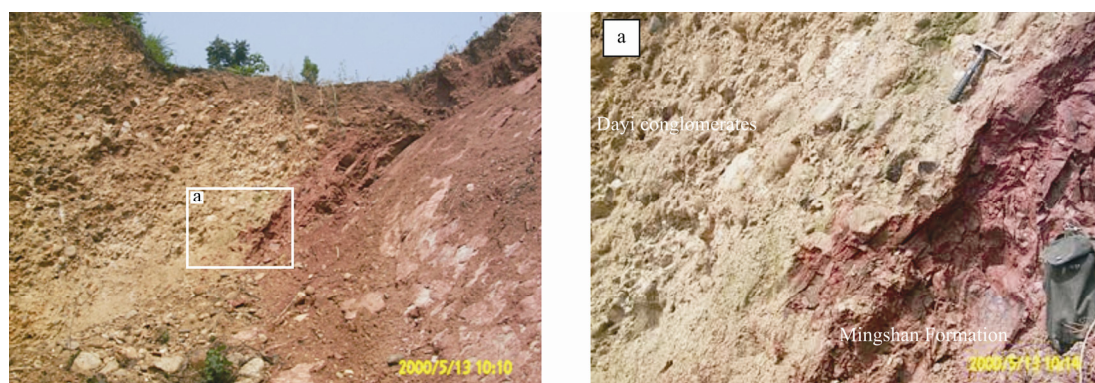


Fig. 8. Angular unconformity between the Neogene (Dayi conglomerates) and the Paleogene (Mingshan Formation) (Dayi).

unconformity interface reveals that the Chengdu Basin was formed due to the recurring flexural subsidence of the Neogene, but not the succession of the Mesozoic Longmen Shan foreland basin. The authors used the bottom age (about 4 Ma) of the Dayi conglomerates to limit the upper limit of the unconformity and used the top age (about 43 Ma) of the Lushan Formation to limit the lower limit of the unconformity. Besides, the tectonic event reflected by the unconformity was defined generally in 43–4 Ma.

5.2 Filling sequence and filling pattern

The filling sediments of the Chengdu Basin are uniformly semi-consolidated to loose, with the maximum thickness of 541 m. They consist of three fining-upward conglomerates layers, i.e. the Dayi conglomerates layer, the Ya'an conglomerates layer, and the upper Pleistocene-Holocene conglomerates layer. The Chengdu Basin demonstrates an obvious asymmetrical geometry, which is steep at the western margin and gentle at the eastern margin. The sedimentary basement level presents a step-wise dipping westward (Fig. 9), suggesting that the basin is a wedge-shaped foreland basin. According to the basement faults and sedimentary thickness and spatial distribution, the Chengdu Basin can be further divided into

the western margin sag zone, the central sag zone, and the eastern margin sag zone. The western margin sag zone is located between the Pengguan fault and the Dayi fault, with the maximum strata thickness of 253 m. The central sag zone is located between the Dayi fault and the Pujiang-Xinjin fault, with the maximum sedimentary thickness of 541 m. The eastern margin sag zone is located between the Pujiang-Xinjin fault and the Longquan Shan fault, with an extremely thin thickness of about 20 m. Modern geomorphology indicates that the Chengdu Plain is mainly composed of alluvial fans generated by the lateral rivers cutting the Longmen Shan (including Mianyu River alluvial fan, Shiting River alluvial fan, Jian Jiang alluvial fan, Min Jiang alluvial fan and Liang He alluvial fan), and upper-fan alluvial plains. It reflects the feature of mono-directional filling, with the clastic materials from the Longmen Shan (Fig. 2 and Fig. 9). Moreover, the transverse river systems are predominant.

5.3 Coupling mechanism between the Longmen Shan lower crustal flow and the Neogen-Quaternary narrow wedge-shaped foreland basin

Considering that the front region of Longmen Shan is lack of typical wide wedge-shaped foreland basin, Burchfiel et al. (1995) speculated that the Longmen Shan

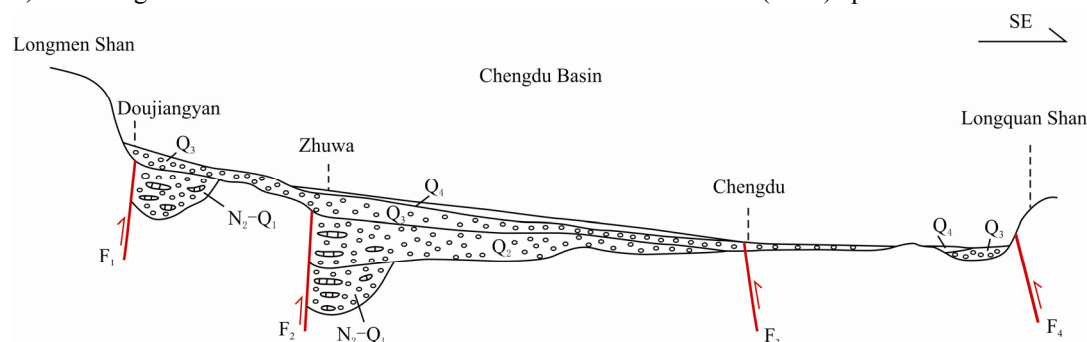


Fig. 9. Filling geometry of Neogene-Quaternary narrow wedge-shaped foreland basin (after Li Yong et al., 1994).

F₁: Pengguan fault; F₂: Dayi fault; F₃: Pujiang-Xinjin fault; F₄: Longquan Shan fault. N₂-Q₁: Pliocene- Lower Pleistocene. Q₂: Middle Pleistocene. Q₃: Upper Pleistocene; Q₄: Holocene. Profile location is shown in Fig. 2.

didn't experience intensive thrusting and shortening since the Late Cenozoic. Later, the Late Cenozoic lower crustal flow was proposed (Royden et al., 1997; Clark et al., 2000), and it advocated that the lower crustal flow was the dynamic source triggering the formation of the present high-steep topography of the Longmen Shan. Wallis et al. (2003) also agreed that "the Longmen Shan shortening and surface deformation since 4 Ma were related to the lower crustal flow in the east of the plateau".

This paper considers that the lower crustal flow of the Longmen Shan is also the dynamic source driving the evolution of the foreland basin during the Neogen to Quaternary time. In this study, the foreland basin which matches the lower crustal flow of the Longmen Shan since 4 Ma was taken as an evidence to validate the coupling relationship between the Late Cenozoic Longmen Shan lower crustal flow and front frontal flexural subsidence basin. According to the geological effect of the Longmen Shan lower crustal flow and the filling characteristics of narrow wedge-shaped foreland basin, the authors present the asymmetrical flexural subsidence model of the foreland basin driven by limited tectonic shortening and limited tectonic load generated due to the Longmen Shan lower crustal flow (Fig. 1). Its characteristics are introduced below.

(1) Limited crustal shortening of the Longmen Shan and flexural subsidence of foreland basin during the Neogene-Quaternary

The tectonic shortening of the present-day Longmen Shan was confined between the back margin fault and the front margin fault, which presented as limited crustal shortening (Li et al., 2006; Densmore et al., 2007). The back margin fault is shown as a large detachment fault or shear zone (Xu Zhiqin et al., 2007), and divides the Longmen Shan and the Tibetan Plateau into two geological bodies (the Sichuan-Qinghai block or the Songpan-Garzê fold belt). The Songpan-Garzê fold belt was formed in the Mesozoic (Wallis, 2003). In the Cenozoic, it reflected the massive movement of block and overall uplifting along the large boundary strike-slip fault; it was stable inside the block, but tectonic shortening was absent. In this period, the Longmen Shan demonstrated obvious tectonic shortening and uplifting; the tectonic shortening was confined in the Longmen Shan, being local shortening (Li et al., 2006; Densmore et al., 2007). The restoration of the Longmen Shan crustal shortening by using the technology of structure balanced section reveals that the minimum crustal shortening rate of the Longmen Shan occurred since the Pliocene (4 Ma), which was about 2 mm/a (Fig. 7).

The tectonic load of the Longmen Shan was confined between the back margin fault and the front margin fault,

which presented as limited (narrow) tectonic load. The Neogene-Quaternary foreland basin is shown as a narrow wedge-shaped foreland basin (Fig. 9), indicating that there was limited flexural subsidence. The Longmen Shan covers an area of about 15000–25000 km², with a length of about 500 km and a width of about 30–50 km, and with a surface elevation of 1–5 km. Densmore et al. (2005) used the one-dimensional elastic flexural model to simulate the flexural subsidence generated from the Longmen Shan tectonic load on the elastic plate (Yangtze craton). The results indicated that the geomorphological differentiation among the eastern margin of the Tibetan Plateau, Longmen Shan and the Chengdu Basin and the subsidence of the Chengdu Basin coincide with the elastic flexural modeling results. This suggests that the elastic flexural model can be used to simulate the flexural subsidence of the Chengdu Basin after narrow tectonic load, with the elastic thickness T_e of 15 km. Accordingly, it is believed that the limited crustal shortening of the Neogene-Quaternary Longmen Shan resulted in the limited subsidence of the foreland basin. It has the following characteristics. ① The Longmen Shan reflects a narrow (a width of about 40 km) limited tectonic load, with a volume of about $(4-10) \times 10^4$ km³ (Height: about 2 km, Width: about 40 km, Length: about 500 km). ② The Chengdu Basin presents as a narrow (a width of about 70 km) wedge-shaped foreland basin. With a length of 180 km, it is characterized by a small width (70 km), a small sedimentary thickness (541 km), a small tectonic load (approximately 0.72×10^4 km³ (Li et al., 2006)), a small flexural subsidence rate (0.14 mm/a), and asymmetric subsidence (larger subsidence rate in proximal part and smaller subsidence rate in distal part). ③ The Neogene-Quaternary foreland basin is a narrow wedge-shaped foreland basin formed under the conditions of limited crustal shortening and tectonic load of the Longmen Shan. The limited tectonic load on the western margin of the Yangtze craton resulted in the limited asymmetric flexural subsidence in the foreland area, thereby forming the narrow wedge-shaped foreland basin (Figs. 5–6).

Particularly, Wallis et al. (2003) considered that the outcrop of the Longmen Shan Pre-Sinian metamorphic complex (Pengguan complex and Baoxing complex) was the product of lower crustal flow or extrusion mechanism, and they used the lower crustal flow emplacement to interpret the uplift and erosion of the Pengguan complex in this period. Previous studies revealed that there were 2–3 cooling events in 43–4 Ma (Godard et al., 2009; Wang et al., 2013; Tan., 2016), which occurred respectively in 30–25 Ma, 20 Ma, and 4–10 Ma. The gravel of the Pengguan complex was firstly observed in the Late Neogene Dayi conglomerates (Li Yong et al., 1994). Therefore, it is

speculated that the deroofing time of the Longmen Shan Pre-Sinian metamorphic complex was 4 Ma. It is believed that the narrow crustal shortening and narrow tectonic load of the Longmen Shan in the Neogene-Quaternary period can be interpreted with the upper crustal shortening and tectonic load or density load resulted from the excursion of lower crustal flow. The limited crustal shortening and tectonic load resulted from the lower crustal flow of the Longmen Shan drove the limited flexural subsidence of the foreland basin.

(2) Limited crustal shortening of the Longmen Shan and limited flexural subsidence of foreland basin driven by the Wenchuan earthquake.

The limited Longmen Shan crustal shortening was driven by the Wenchuan earthquake, which is a thrusting with dextral slip earthquake (Xu et al., 2009; Li Haibing, et al., 2008; Li Yong et al., 2008; Li et al., 2013). The earthquake presented as the surface rapture combination of two NE-trending thrusting with dextral slip faults (the Pengguan fault and the Beichuan fault) that are nearly parallel in plane. The back fault (Maowen fault) didn't fracture in the Wenchuan earthquake, indicating that the Maowen fault was not one of the imbricated thrusting faults system of the present-day Longmen Shan (Beichuan fault and Pengguan fault zone). It is suggested that the thrusting and tectonic shortening of the Longmen Shan were concentrated the zone between the Beichuan fault and the Pengguan fault, and the surface apparent tectonic shortening rate was only 7%–28% (Li et al., 2013), indicating that the tectonic shortening caused by the Wenchuan earthquake was not integral and continuous, and was only distributed in the Longmen Shan. The parallel combination of thrust faults is unique, and it has not yet been found in other thrust fault belts globally. In this paper, the limited crustal shortening and tectonic load are defined as limited (narrow) crustal shortening.

The Wenchuan earthquake drove the limited (narrow) tectonic shortening of the Longmen Shan. The tectonic load was only distributed in the Longmen Shan area clamped by the back margin fault and the front margin fault. The Sichuan-Qinghai block to the west of the Maowen fault is dominated by the co-seismic subsidence (Zhang Peizhen, 2008), with no tectonic load. The foreland area to the east of the Pengguan fault is also dominated by the co-seismic subsidence, with no tectonic load. The tectonic loading is only distributed in the Longmen Shan, with a length (NE) of 220–240 km, a small width (from 30 km in the central segment to 3 km in the northern segment), and the tectonic load of $2.6 \pm 1.2 \text{ km}^3$ (de Michele et al., 2010). In this paper, the tectonic load with small or narrow area is called limited (narrow) tectonic load. Its newly-increased tectonic load is smaller,

with a magnitude as only one in ten thousand of the (overall) tectonic load of the Longmen Shan. It is believed that the narrow (limited) tectonic shortening and tectonic load caused by the Wenchuan earthquake supported the dominance of lower crustal flow in the Longmen Shan uplift. And the limited tectonic shortening and tectonic load phenomenon can only be interpreted by the upper crustal excursion driven by lower crustal flow.

The Wenchuan earthquake resulted in the asymmetric flexural subsidence of the foreland basin. In the western Sichuan Basin (Chengdu Basin) to the east of the Pengguan fault, asymmetric subsidence has been observed. Specifically, it shows greater subsidence volume in the NW side (proximal) close to the Longmen Shan, with the maximum subsidence volume up to 0.675 m; it has smaller subsidence volume in the SE side (distal) far away from the Longmen Shan; eastward to the Central Sichuan uplift, it presents as uplifting (Zhang Peizhen et al., 2008; Meng et al., 2015). This indicates the western Sichuan Basin (the Chengdu Basin) has asymmetric subsidence, with the features of flexural subsidence and small subsidence magnitude. Yan et al. (2016) used the one-dimensional elastic flexural model to simulate the flexural subsidence resulted from the tectonic load of the Longmen Shan driven by the Wenchuan earthquake on the elastic sheet (Yangtze craton). The results showed that the tectonic load generated by the earthquake is linearly correlated to the flexural subsidence of the Chengdu Basin, which is in agreement with the elastic flexural subsidence model of the orogenic belt tectonic load-foreland flexural subsidence. It proves the occurrence of coupling relationship between the limited tectonic subsidence of the Longmen Shan and the subsidence of the Chengdu Basin in short time scale.

In summary, it is believed that there is a coupling relationship between the Longmen Shan lower crustal flow and the Neogene-Quaternary narrow wedge-shaped foreland basin. According to the lower crustal flow mechanism, the rigid crust beneath the Sichuan Basin blocks the lower crustal flow and eventually accumulates under the Longmen Shan, thereby leading to the high-steep topography and thick crust of the Longmen Shan (Royden et al., 1997; Clark et al., 2000; Wallis et al., 2003; Burchfiel et al., 2008; Wang et al., 2012). The narrow tectonic shortening and narrow tectonic load of the Longmen Shan can be used to effectively interpret the geological phenomena related to the Longmen Shan and the Wenchuan earthquake, such as the tectonic geomorphology features of the Longmen Shan (the steepest marginal mountain of the Tibetan Plateau), back marginal shear zone, narrow crustal shortening zone (30–50 km), narrow tectonic load zone (30–50 km), outcrop of

Pre-Sinian complex (the final deroofing time is about 4 Ma), intensive positive isostatic anomaly (Li Yong et al., 1994), thrusting with dextral slip faults (two parallel surface rupture zones), the Wenchuan earthquake (Ms 8.0, 2008) in the central of the Longmen Shan, the Lushan earthquake (Ms 7.0, 2013) in the piedmont of the Longmen Shan, front narrow wedge-shaped foreland basin (Chengdu Basin), small surface horizontal movement rate (≤ 3 mm/a), and intensive lower crustal movement rate (incurring the Ms 8.0 Wenchuan earthquake). All these features have not occurred in other orogenic belts in the world, indicating that they are unique in the “Longmen Shan” uplifting mechanism. Therefore, it is believed that the lower crustal flow caused the uplift of lower crustal materials to the Longmen Shan upper crust or surface, thereby increasing the density and tectonic load of upper crustal rocks, resulting in limited tectonic shortening and limited tectonic load of the Longmen Shan, and driving the asymmetric flexural subsidence of the foreland area.

6 Conclusions

The Longmen Shan is a geological complex formed by the superposition of multiple and various tectonic uplift mechanisms. Its uplift process is historic and composite. The fillings in the foreland basin have recorded the evolution of the Longmen Shan since the Late Triassic. In this paper, with the foreland basin fillings as the stratigraphic signatures of the Longmen Shan uplift, and based on the foreland basin filling pattern and subsidence mechanism, the uplift mechanism of the Longmen Shan and its transition are calibrated. The following conclusions are made:

(1) According to the differences of the filling pattern and subsidence mechanism in different phases since the Late Triassic, three types of foreland basin can be suggested: the Late Triassic (early) wide wedge-shaped foreland basin, the Jurassic-Paleogene (interim) large tabular foreland basin, and the Neogene-Quaternary (late) narrow wedge-shaped foreland basin. It is believed that the filling pattern and subsidence mechanism of the foreland basin are evolutionary and convertible.

(2) With the wide wedge-shaped foreland basin as the sedimentary record to identify the Longmen Shan crustal shortening, the large tabular foreland basin as the sedimentary record to identify the Longmen Shan crustal isostatic rebound, and the narrow wedge-shaped foreland basin as the sedimentary record to identify the Longmen Shan lower crustal flow, the Longmen Shan uplift mechanisms have been divided into three types, i.e., the Late Triassic (early) crustal shortening, the Jurassic-Paleogene (interim) crustal isostatic rebound, and the

Neogene-Quaternary (late) lower crustal flow. It is considered that the uplift mechanism of the Longmen Shan is evolutionary and convertible.

(3) Three coupling relationships of basin and mountain are proposed, namely, the Longmen Shan crustal shortening and its related wide wedge-shaped foreland basin, the Longmen Shan crustal isostatic rebound and its related tabular foreland basin, and the Longmen Shan lower crustal flow and its related narrow wedge-shaped foreland basin.

(4) It is considered that the uplift mechanism of the Longmen Shan is evolutionary and convertible. The Late Triassic wide wedge-shaped foreland basin corresponded to the Indosinian cycle, which was the major period of the Longmen Shan crustal shortening. The Longmen Shan showed intensive tectonic load and greater orogenic advance rate during Late Triassic. The Jurassic-Paleogene tabular foreland basin corresponded to the Yanshan cycle; the Longmen Shan showed weakening tectonic load or lower orogenic advance rate, with the predominance of isostatic rebound. The Neogene-Quaternary narrow wedge-shaped foreland basin corresponded to the tectonic event of lower crustal flow in the eastern the Tibetan Plateau since 4 Ma.

(5) It is considered that the uplift process of the Longmen Shan is the product of the superposition of tectonic uplift and crustal isostatic rebound. The growth of the Longmen Shan relies on the competition between tectonic uplift volume and denudation unload volume. It is proposed that the present-day uplift process of Longmen Shan is attributed to the superposition of lower crustal flow and crustal isostatic rebound. Particularly, the tectonic uplift mechanism driven by the lower crustal flow is dominant.

Acknowledgements

This study is funded by China National Natural Science Foundation (No: 41372114, 41502116, 41340005, 40841010, 40972083, 41172162, and 41402159), geological survey from China Geological Survey (No: 121201010000150004-08 and 12120115004501-01), and the project of State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation (No: SK-0801).

Manuscript received July 18, 2016

accepted Dec. 11, 2016

edited by Liu Lian

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