The Late Triassic Longmenshan lateral foreland thrusting: New insights from geological evidence, mathematical modeling and 3D discrete element simulation

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Key points

- The new lateral extrusion model well explains the Late Triassic Longmenshan thrusting and the formation of the Xiaojin Arcuate Zone.
- Numerical modeling and 3D discrete element simulation first time used are applied to reproduce the thrusting and verify the new model.
- The lateral extrusion model has two critical factors, which are the wedge-shaped geometry and the bottom low-strength decollement.

Abstract

This work proposes a new lateral extrusion dynamic model based on geological evidence, mathematical modeling and 3D discrete element simulation to explain the southeastward thrusting during the closure of the Songpan-Ganze basin. The Late Triassic NE-SW compression caused by the northward movement of the Qiangtang Block and the resulting differential shortening within the wedge-shaped Songpan-Ganze terrane produced southeastward topographic gradient. The thick sedimentary pile, decoupled from the subducting basement by the low-strength decollement, was driven by gravity and laterally extruded, leading to the southeastward Longmenshan thrusting. Therefore, the Longmenshan thrust belt is a lateral foreland thrust belt of the Songpan-Ganze terrane. The mathematical modeling provides detailed description of the differential shortening occurred within the Songpan-Ganze terrane. The 3D discrete element simulation, which is first time used for the geological study of the Longmenshan area, clearly reproduces the dynamical process of the Longmenshan southeastward thrusting and well predicts the Xiaojin Arcuate Zone. Both mathematical modeling and discrete element simulation verify the new lateral extrusion dynamics and reveal that two key factors facilitate the lateral extrusion and foreland thrusting, which are the wedge-shaped geometry that produces differential shortening and lateral topographic gradient, and the low-strength decollement that decouples the extruded sedimentary pile from the basement. The lateral foreland thrust belt, which has specializations in its tectonic location and dynamic behavior, is a new kind of foreland thrust belt after pro-foreland thrust belt and retro-foreland thrust belt, and provides a new insight into the tectonic evolution of collisional orogens.

Plain language summary

The Longmenshan fault zone, located in the western Sichuan Basin, is a very important research field of structural geology, since many big earthquakes (e.g. the 2008 Wenchuan earthquake) happened here. Therefore, it is essential to understand the evolutionary history of the Longmenshan fault zone and reasons behind it. During the Late Triassic, the Longmenshan fault zone went into the active stage due to the closure of the Songpan-Ganze basin. However, it is unclear that what the power and how it dominates the Longmenshan fault zone. To solve this problem, we develop a new lateral extrusion model to explain the formation of the Longmenshan fault zone, and use several methods, including mathematical modeling and 3D discrete element simulation, to verify it. Our results coincident well with geological evidence. The new model suggests that the tectonic activities around Longmenshan during the Late Triassic are resulted from the lateral extrusion of highly deformed material in the Songpan-Ganze terrane. There are two critical factors that determine whether the material can be laterally extruded, which are the special wedge-shaped geometry of the Songpan-Ganze terrane and the bottom low-friction sedimentary layer. The new model provides us a new insight into the Longmenshan fault zone.

Key words: Lateral foreland thrust belt, Songpan-Ganze terrane, Lateral extrusion dynamics, Lateral foreland basin, Late Trisssic, discrete element simulation

1. Introduction

The Longmenshan thrust belt hosts a unique mountain-basin system in the eastern margin of the Tibetan Plateau (e.g., Burchfiel et al., 2008; Xu et al., 2008; Hubbard and Shaw, 2009). The crustal thickness changes from ~40 km in the east to 60-65 km in the west and the topographic elevation changes from 500 m above the sea in the Sichuan Basin to 4000-6000 m in the Songpan-Ganze terrane across the 40-50 km wide Longmenshan thrust belt (Xu et al., 2008). Moreover, the global positioning system (GPS) data suggested that the convergence across the Longmenshan thrust belt is slow (<3 mm/yr) (King et al., 1997; Chen et al., 2000; Xu et al., 2008; Hubbard and Shaw, 2009; Tian et al., 2013). Three major orogenic events have been documented in the Longmenshan area from Mesozoic to Cenozoic: (1) the Late Triassic compressional deformation in the course of the closure of Paleotethys; (2) the Late Jurassic to Early Cretaceous deformation; and (3) the Cenozoic reactivation of faults and rapid uplift related to the growth of the Tibetan Plateau (Burchfiel et al., 1995; Chen and Wilson, 1996; Worley and Wilson, 1996; Arne et al., 1997; Bruguier et al., 1997; Jia et al., 2006; Weislogel et al., 2006; Jin et al., 2007; Dong et al., 2011; Yan et al., 2011, 2018; Cook et al., 2013; Tian et al., 2013; Cao et al., 2015).

Cenozoic tectonic evolution of the Longmenshan thrust belt has been much studied and two end-member models have been proposed, including upper crustal thickening (e.g., Tapponnier et al., 2001; Hubbard and Shaw, 2009; Tian et al., 2016; Xu et al., 2008; Tan et al., 2017) and channel flow (e.g., Royden et al., 1997; Burchfiel et al., 2008; Godard et al., 2009; Zhao et al., 2012). Pre-existing Late Triassic structures may exert a great influence on Cenozoic deformation in the Longmenshan area. However, the role of pre-existing Late Triassic structures has not yet been well evaluated in these previous models. Studies concerning the Late Triassic tectonic evolution in this area mostly focus on the Songpan-Ganze terrane and it is less known regarding the dynamic mechanism of the Late Triassic Longmenshan southeastward thrusting during the NE-SW compression and shortening of the Songpan-Ganze basin caused by the northward movement of the Qiangtang Block. In the orogenic belts resulting from continent-continent collision, the foreland thrust belts in both pro-foreland system and retro-foreland system are perpendicular to the collision direction (Johnson and Beaumont, 1995; Naylor and Sinclair, 2008). However, the Longmenshan thrust belt lies at the lateral side of the main sutures (A'nyemaqen-Mianlue Suture to the north and the Jinshajiang-Yushu-Batang Suture to the south. Fig.1a) and the wedge-shaped Songpan-Ganze terrane (Fig.1a). Moreover, the unusual Xiaojin Arcuate Zone adjacent to the Longmenshan thrust belt displays an arcuate trend. Therefore, neither the pro-foreland system nor the retro-foreland system can well explain the tectonic evolution of the Late Triassic Longmenshan thrust belt and the corresponding western Sichuan foreland basin. Several studies suggested that the Late Triassic Longmenshan thrusting was resulted from the westward subsidence of the Yangtze Block (e.g., Luo, 1984) or the clockwise rotation of the Sichuan Basin (e.g., Wang and Meng, 2009). However, these models did not clearly reveal the dynamic relationship between the Longmenshan thrust belt and the Songpan-Ganze terrane, and could not explain the existence of the Xiaojin Arcuate Zone. The tectonic style and dynamics of the Late Triassic Longmenshan southeastward thrusting still remains controversial.

This paper explores the Late Triassic evolution of the Longmenshan thrust belt and its possible tectonic dynamics. Although Cenozoic deformation pervades in this region (Yan et al., 2011, 2018), widespread klippes in the middle segment of Longmenshan thrust belt and the adjacent Xiaojin Arcuate Zone provide a unique opportunity to reveal pre-Cenozoic events. We present geological evidence, results of mathematical modeling and 3D discrete element simulation. Our results suggest that the Late Triassic Longmenshan thrusting was a result of lateral extrusion of the thickened sedimentary pile within the wedge-shaped Songpan-Ganze terrane. Therefore, we use a lateral extrusion dynamics to explain the Late Triassic Longmenshan lateral foreland thrusting and its relationship with the Songpan-Ganze terrane. The 3D discrete element simulation first time used for the geological study of the Longmenshan area based on the new model clearly shows the dynamical process of the Longmenshan southeastward thrusting and well predicts the Xiaojin Arcuate Zone. The mathematical modeling and discrete element simulation reveal that two key factors facilitate the lateral extrusion and foreland thrusting, which are the wedge-shaped geometry and the low-strength decollement. The new model provides a comprehensive understanding of the Late Triassic Longmenshan thrusting and the tectonic evolution of the Eastern Tibetan margin.

2. Geological setting

The Longmenshan thrust belt, located in the eastern margin of the Tibetan Plateau, forms a major boundary between the Songpan-Ganze terrane and western Sichuan foreland basin (e.g., Burchfiel et al., 1995; Wilson et al., 2006; Yan et al., 2011, 2018).

Figure 1 here

2.1. Songpan-Ganze terrane

The wedge-shaped Songpan-Garze terrane, bounded by the Qiangtang, North China and Yangtze blocks (Fig.1a), was originally a branch of Paleotethys and comprised of thick Late Triassic flysch deposition (Zhuwo Formation and Xinduqiao Formation) (Roger et al., 2008, 2010), which was mainly derived from the Qinling-Dabie orogenic belt (Nie et al., 1994; Burchfiel et al., 1995; Yan et al., 2011, 2018). The northern boundary, marked by the A'nyemaqen-Mianlue Suture, and the southern boundary, marked by the Jinshajiang-Yushu-Batang Suture, accommodated the bidirectional subduction of Paleotethys during the Late Triassic orogeny (Yan et al., 2018). Prior to the Late Triassic orogeny, the thick Late Triassic flysch sequence was conformably underlain by the Middle-Lower Triassic and Paleozoic shallow marine sequences of the passive margin of the Yangtze Block (Burchfiel et al., 1995; Yan et al., 2011, 2018).

Following the onset of the Late Triassic orogeny, thick flysch sequences were folded into upright folds and intruded by a number of syn- and post-orogenic plutons due to the crustal thickening (Roger et al., 2004, 2008, 2010). Despite of the subsequently Cenozoic deformation, there was no deformation in these plutons, suggesting that the Late Triassic tectonic style within the Songpan-Ganze terrane, which was characterized by upright folds and thrust faults, greenschist metamorphism and widespread plutons, has been well preserved and hardly affected by the Cenozoic tectonic events (Burchfiel et al., 1995; Worley and Wilson, 1996; Arne et al., 1997; Harrowfield and Wilson, 2005; Roger et al., 2008, 2010; Yan et al., 2011, 2018). Therefore, the Xiaojin Arcuate Zone, within which the strike direction of steep foliations changes from NW-SE to NE-SW gradually and display an arcuate trend (Fig.1b), may have been finalized during the Late Triassic orogeny.

2.2. Longmenshan thrust belt

The NE-striking Longmenshan thrust belt extends from the Mianlue suture in the northeast to Xianshuihe fault to the southwest, and is defined by three major NE-striking thrust faults: the Wenchuan-Maowen fault, the Beichuan-Yingxiu fault and the Guanxian-Anxian fault, from west to east (Xu et al., 1992; Chen et al., 1995; Chen and Wilson, 1996; Worley and Wilson, 1996; Meng et al., 2005;

Jin et al., 2007, 2010; Yan et al., 2011, 2018) (Fig.1b). Both the Wenchuan-Maowen and Beichuan-Yingxiu fault has been active since Late Triassic and reactivated in the Cenozoic (Dirks et al., 1994; Burchfiel et al., 1995; Chen et al., 1995; Worley and Wilson, 1996; Arne et al., 1997; Xu et al., 2008; Tian et al., 2013), while the Guanxian-Anxian fault crosscuts the Late Triassic Xujiahe Formation through the Quaternary sediments, suggesting its Cenozoic activity (Xu et al., 2008; Yan et al., 2011, 2018).

The Beichuan-Yingxiu fault divides the Longmenshan thrust belt into a northwest hinterland belt and southeast foreland thrust belt, which have remarkably different Mesozoic-Cenozoic tectonic styles (Chen and Wilson, 1996; Worley and Wilson, 1996; Arne et al., 1997; Meng et al., 2005; Yan et al., 2011, 2018). The hinterland belt is characterized by several metamorphic domes (e.g., Xuelongbao Complex, Pengguan Complex, Danba Complex), while the foreland thrust belt is represented by thrust-related structures, including klippes, tectonic windows, fault-related folds and imbricate thrusts (Yan et al., 2008, 2011, 2018). Both belts have similar pre-Mesozoic sequences and remarkably different Mesozoic sequences. The Triassic strata in the hinterland belt is characterized by the Xikang Group, mainly composed of flysch, whereas the Triassic strata in the foreland thrust belt is represented by Xujiahe Formation continental clastic deposits, unconformably overlain by Jurassic clastic rocks (Yan et al., 2011, 2018).

2.3. Western Sichuan foreland basin

The western Sichuan basin is presently delimited between the Longmenshan thrust belt to the west and the Longquanshan uplift to the east, and three phases of basin development have been revealed: (1) Late Triassic-Early Jurassic; (2) Late Jurassic-Early Cretaceous, and (3) Late Cretaceous-Eocene (Chen et al., 1994a; Li et al., 2013). All three phase of sedimentation in the western Sichuan foreland basin were interpreted as the response to the three major orogenic phases mentioned above.

During the Late Triassic orogeny, the formation of the Longmenshan thrust belt loaded the Yangtze passive margin, resulting in flexural subsidence of the western Sichuan foreland basin, and the depositional environment changed significantly from shallow marine carbonate platform to terrestrial clastic basin (the Late Triassic Xujiahe Formation) (Chen et al., 1994b). Low temperature thermochronology studies suggest fast exhumation of Longmenshan during the Cenozoic (Arne et al., 1997; Enkelmann et al., 2006; Cook et al., 2013; Tian et al., 2013), while typical foreland deposits are absent in the coeval adjacent western Sichuan foreland basin. This may be due to the predominantly vertical displacements along the high-angle listric thrust faults in the Longmenshan thrust belt (Feng et al., 2015), which probably demonstrated the controlling effect of pre-existing Mesozoic structure on the Cenozoic tectonic evolution.

3. The lateral extrusion dynamics

3.1. Timing of formation of the Longmenshan klippes

A number of klippes with various shapes and sizes are located in the middle segment of the Longmenshan foreland thrust belt, including the Tangbazi Klippe, the Tiantaishan Klippe, Jiandingfeng Klippe and Xiaoyudong Klippe (Fig.2a). Most klippes were underlain by the upper Triassic Xujiahe Formation, including the Tiantaishan Klippe, Jiandingfeng Klippe, Xiaoyudong Klippe and most part of the Tangbazi Klippe. However, in the southeast part of the Tangbazi Klippe, the Paleozoic carbonate rocks were underlain by Jurassic clastic rocks, which was considered to be the concrete evidence that the Longmenshan klippes formed after Jurassic and probably during the Cenozoic thrusting (Wu, 2008). Later studies suggest that the rocks in the southeast part of the Tangbazi Klippe are brecciated limestone, which is assumed to have been generated by Cenozoic tectonic reworking (Xue et al., 2015). The geological evidence that (1) the newest strata in klippes is the Middle Triassic carbonate rocks; (2) most klippes sit on the Upper Triassic typical foreland Xujiahe formation; (3) the rocks sit on the jurassic strata in the southeast part of the Tangbazi Klippe is the result of Cenozoic tectonic reworking, strongly suggests that the Longmenshan nappes formed in the immediate aftermath of the deposition of Upper Triassic Xujiahe Formation and before the deposition of Jurassic strata (Xu et al., 1992; Dirks et al., 1994; Chen and Wilson, 1996; Worley and Wilson, 1996).

Figure 2 here

In this research, we conducted U-Pb dating of syn-tectonic calcite veins from the Longmenshan klippes to reveal their emplacement age. An excellent outcrop of contact relationship between autochthon and allochthon was observed near Huaiyuan Town (Fig.2b), where the fault fracture zone was clearly exposed, including fault breccia, fault gouge and cataclastic rocks (Fig.3). The secondary fault rupture planes in the hanging wall, which is composed of upper Permian carbonate rocks, contain calcite veins. U-Pb dating results of these calcite veins provide the lower limit of the fault activity (Roberts and Walker, 2016; Ring and Gerdes, 2016; MacDonald et al., 2019; Roberts et al., 2019).

Figure 3 here

Thirteen fresh samples were collected from calcite veins in the outcrop, each of which were analyzed with 100-200 laser ablation spots. Due to low U concentrations within most samples, only two yielded meaningful U-Pb ages (see Table S1 in Supporting Information S1). Sample CV1 contains higher amounts of common lead and most data points cluster close to the upper intercept in the Tera-Wasserburg plot, which provides an estimate of initial lead composition (^{207}Pb/^{206}Pb = 0.858 ± 0.012) and a lower intercept age of 173 ± 11 Ma (MSWD = 1.2, 1) (Fig.4a). Sample CV2-1 yields a linear array with a large spread between upper and lower intercepts in the Tera-Wasserburg plot, providing a lower intercept U-Pb age of 157.6 ± 6.0 Ma (MSWD = 1.6, 1) (Fig.4b). The initial lead composition (^{207}Pb/^{206}Pb = 0.852 ± 0.013) is consistent with that of sample CV1. Both samples yield ages that are the same within errors, leading us to argue for a mid-late Jurassic age (ca. 160-170 Ma) for these calcite veins. This result agrees with the isotopic dating of authigenic illite isolated from the bottom boundary fault of the largest Baishi-Goujia klippe (Zheng et al., 2014).

Figure 4 here

The results limit the latest formation time of the Longmenshan nappes. Synthesize the dating results and discussion on the stratigraphic contact relationship above, we infer that the present Longmenshan nappes probably emplaced during the Late Triassic thrusting, and have been reactivated and modified in various degrees by later tectonic events.

3.2. Structural analysis of the Xiaojin Arcuate Zone

The unusual Xiaojin Arcuate Zone, located at the southeastern corner of the Songpan-Ganze terrane and next to the Longmenshan belt, displays an arcuate trend (Fig.1b). As mentioned above, the Late Triassic tectonic styles within were hardly affected by the Cenozoic tectonic events (Burchfiel et al., 1995; Worley and Wilson, 1996; Arne et al., 1997; Harrowfield and Wilson, 2005; Roger et al., 2008, 2010; Yan et al., 2011, 2018). Therefore, the tectonic styles within the Xiaojin Arcuate Zone could provide useful information on the Late Triassic tectonic events.

Figure 5 here

Three profiles were measured to study the dip direction of nearly vertical strata (S_0) and the axial planes of the folds (S_1) (see Figure S1 in Supporting Information S1). The profile A-A' displayed that the strike direction of steep foliations (both S_0 and S_1) changed from NW-SE to NE-SW gradually and formed an arcuate trend. In the west of Xiaojin, the foliations mainly trended NW-SE, which was perpendicular to the collision direction. Heading east from Xiaojin, the strike direction of foliations gradually changed to E-W around Rilong, and eventually to NE-SW around Yingxiu, which was parallel to the collision direction. Both profile B-B' and profile C-C' suggested that the strike direction of foliations remained constant in the radius direction. Xiaojin Arcuate Zone indicates that the orientation of the major principal stress ($_1$) changed gradually from NE-SW in the west to NW-SE in the east (Fig.5).

3.3. The lateral extrusion dynamics

As discussed above, the Longmenshan nappes probably represented the front of a large-scale southeastward thrusting, and the Xiaojin Arcuate Zone represented a special stress variation near the Longmenshan area during the Late Triassic. The Longmenshan thrusting and the Xiaojin Arcuate Zone have close space-time relationship. Together they represented the special tectonic style at the southeast margin of the Songpan-Ganze terrane. Therefore, we use a lateral extrusion model to explain the Late Triassic southeastward Longmenshan thrusting and its relationship with the Songpan-Ganze terrane, where the lateral extrusion of the materials within the wedge-shaped Songpan-Ganze terrane along the weak basal decollement promoted southeastward thrusting. The lateral extrusion model can also well explain the Xiaojin Arcuate Zone, where the orientation of the major principal stress ($_1$) changed gradually from NE-SW in the west to NW-SE in the east (Fig.6).

Figure 6 here

Specifically, due to the resistance of the Yangtze block, the east part of the Qiangtang block was forced to bend and rotate, resulting in the wedge-shaped Songpan-Ganze terrane. The rotation of the east part of Qiangtang block led to differential shorting within the Songpan-Ganze terrane. The shorting was greater on the northwest side and smaller on the southeast side, which formed the southeastward inclined topographic gradient (Fig.6). Meanwhile, the Sichuan Basin provided an exit for the highly deformed material in the Songpan-Ganze terrane. When the lateral topographic gradient exceeded the critical conditions for lateral dynamic stability, the material within the Songpan-Ganze terrane would be driven by gravity and extruded along topographic gradient, leading to southeastward Longmenshan thrusting. The gradual change of the stress field from internal Songpan-Ganze terrane to Longmenshan thrust belt produced the Xiaojin Arcuate Zone (Fig.6).

The continuous lateral extrusion and thrusting led to crustal thickening around the Longmenshan area, which resulted in flexural subsidence and foreland deposits within the western Sichuan foreland basin. The western Sichuan basin, located at the lateral side of the Songpan-Ganze terrane, was a lateral foreland basin. Meanwhile, the leading edge of the Longmenshan lateral thrusting was pushed further southeastward and overlay the foreland deposits (The Xujiahe formation), which was the predecessor of the Longmenshan klippes.

4 Mathematical modeling of the lateral extrusion dynamics

4.1. Differential shortening and lateral topographic gradient

The lateral extrusion dynamics depends on the differential shortening within the wedge-shaped Songpan-Ganze terrane and corresponding lateral topographic gradient. The Songpan-Ganze basin was surrounded by three different blocks and filled with flysh deposits. The northern boundary, marked by the A'nyemaqen-Mianlue Suture, and the southern boundary, marked by the Jinshajiang-Yushu-Batang Suture, accommodated the bidirectional subduction of Paleotethys during the Late Triassic orogeny. The tectonic evolution of eastern margin of the Songpan-Ganze terrane was also affected by Bikou terrane and Yidun Arc, which was relatively complicated. To quantitatively study the lateral topographic gradient resulted from differential shortening, making appropriate simplification of geological system is required. Therefore, we establish a mathematical model base on following assumptions:

1) The Songpan-Ganze basin is surrounded by three different blocks (two compressional blocks and one blocking block) and closed by bidirectional subduction.

2) The movements of two compressional blocks are symmetric as mirror images.

Figure 7 here

Based on these assumptions, a coordinate system is built with its origin located at the center of the boundary between basin and blocking block (Fig.7). The closure of basin can be divided into two different stages.

Figure 8 here

In the first stage, two compressional blocks move towards each other symmetrically, which leads to homogeneous shortening in the Y direction (Fig.8). At the beginning, two compressional blocks are far from each other. Two accretionary wedges generated in front of two compressional blocks, respectively. With shortening going on, two accretionary wedges will meet at X-axis. After that, continuous homogeneous shortening will result in homogeneous uplift until two compressional blocks encounter the blocking block. Based on conservation of substance during shortening, we have:

$$\frac{1}{2}(2+\alpha)wh_1(x,0) = (1+k)wh_0 \qquad \text{Ep.4.1}$$

where is the topographic gradient in Y direction (compressional direction), w is half the width of the blocking block, $h_1(x, 0)$ is the thickness of material located on the x-axis when two compressional blocks encounter the blocking block, k is the shortening factor (the ratio between the movement distance Δy and half the width of the blocking block, $\Delta y/w$), h_0 is the original sedimentary thickness. Based on Eq.4.1, we have:

$$h_1(x,0) = \frac{2(1+k)}{2+\alpha}h_0 \qquad \text{Ep.4.2}$$

Therefore, the cover thickness at any point at the end of the first stage is:

$$h_1(x,y) = \frac{2(1+k)}{2+\alpha}h_0 + \alpha|y| \qquad \text{Eq.4.3}$$

In the second stage, two compressional blocks are blocked by the blocking block and rotate according to point A, B as a center, respectively, which leads to differential shortening. Toward the blocking block the shortening amount becomes smaller and so do the uplift amount. Different uplift amount results in lateral topographic gradient which inclines to the blocking block. Assuming that material within the compressional zone does not move laterally and remained in Y-Z plane, we have:

$$\frac{1}{2}(2+\alpha)(w+xtan\theta)h_2(x,0) = (1+k)wh_0 \qquad \text{Eq.4.4}$$

where $h_2(x, 0)$ is the thickness of cover when the rotation angle of compressional blocks is , is the topographic gradient in Y direction (compressional direction). Based on Eq.4.1, we have:

$$h_2(x,0) = \frac{2(1+k)w}{(2+\alpha)(w+xtan\theta)}h_0 \qquad \text{Eq.4.5}$$

Therefore, when the rotation angle of compressional blocks is , the thickness of cover at any point in basin is:

$$\mathrm{h}_2(x,y) = \frac{2(1+k)w}{(2+\alpha)(w+xtan\theta)}h_0 + \alpha|y| \qquad \text{Eq.4.6}$$

Eq.4.3 and Eq.4.6 describe the cover thickness at any point in two different shortening stages respectively. Eq.4.3 reveals that no lateral topographic gradient is established during the homogeneous shortening in the first stage. Based on Eq.4.6, we have the lateral topographic gradient (> 0) in X direction established during the differential shortening in the second stage is:

$$= \left|\frac{\partial h_2(x,y)}{\partial x}\right| = \frac{2(1+k)w\tan\theta}{(2+\alpha)(w+xtan\theta)^2}h_0 \qquad \text{Eq.4.7}$$

Eq.4.7 suggests that the rotation of compressional blocks and differential shortening is the key factor of establishing the lateral topographic gradient . Material within the compressional zone tends to move laterally driven by gravity when the lateral topographic gradient is positive. However, whether or not lateral movement occurs depends on the critical conditions for lateral dynamic stability of deformed cover under gravity.

4.2. The critical conditions for lateral dynamic stability

The critical conditions of the compressional zone are mainly governed by the balance of forces in X and Y direction. The deformation rate of compression zone is so small that the general equations of motion may be written as static equilibrium form:

$$\frac{\partial\sigma_x}{\partial x} + \frac{\partial\tau_{\mathrm{xy}}}{\partial y} + \frac{\partial\tau_{\mathrm{xz}}}{\partial z} = 0 \qquad \text{Eq.4.8.1}$$

$$\frac{\partial\tau_{\mathrm{xy}}}{\partial x} + \frac{\partial\sigma_y}{\partial y} + \frac{\partial\tau_{yz}}{\partial z} = 0 \qquad \text{Eq.4.8.2}$$

where and are the components of normal and shear stress tensor respectively.

However, it is quite difficult to solve Eq.4.8 in three-dimensional space. Therefore, we consider the points within two-dimensional X-Z plane. Based on the assumption that two compressional blocks move symmetrically as mirror images, Eq.4.8.2 is satisfied naturally and we have $\frac{\partial\tau_{\mathrm{xy}}}{\partial y} = 0$, since the stresses are also symmetric as mirror images with respect to the X-Z plane. Eq.4.8 can be simplified as:

$$\frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{\mathrm{xz}}}{\partial z} = 0 \qquad \text{Eq.4.9}$$

Figure 9 here

Let us enumerate the forces acting on the segment lying between x and $x+dx$, and integrate Eq.4.9 over z from 0 to H (the local thickness of the overlying cover measured along z-axis) (Fig.9). Then we have:

$$\int_0^H \frac{\partial \sigma_x}{\partial x} + \tau_{\mathrm{xz}}(H) - \tau_{\mathrm{xz}}(0) = 0 \qquad \text{Eq.4.10}$$

Here $\tau_{\mathrm{xz}}(H) = 0$, $\tau_{\mathrm{xz}}(0) = -$ gH where is the friction coefficient of basal decollement, , assumed constant, is the density of material and g is the acceleration of gravity. Therefore, Eq.4.10 can be written as :

$$\frac{\partial}{\partial x} \int_0^H \sigma_x + \mu \rho g H = 0 \qquad \text{Eq.4.11}$$

Figure 10 here

To determine the remaining unknown quantity $_x$ in Eq.4.11, we follow the similar method reported by Davis et al. (1983). A Mohr-circle representation of the stress at an arbitrary point displays the geometric relations of the maximum and minimum normal stresses ($_1$ and $_3$), and the normal stresses in X and Z direction ($_x$ and $_z$) (Fig.10):

$$\frac{1}{2}(\sigma_x - \sigma_z) = \frac{1}{2}(\sigma_1 - \sigma_3)\, cos2\gamma \qquad \text{Eq.4.12}$$

$$\frac{1}{2}(\sigma_1 - \sigma_3) = \frac{1}{2}(\sigma_x + \sigma_z) \sin \qquad \text{Eq.4.13}$$

where is the local angle between the axis of the maximum normal stress $_1$ and the x-axis.

The normal stress in Z direction $_z$ is assumed to be solely that due to the lithostatic overburden:

$$\sigma_z = \rho g (H - z) \qquad \text{Eq.4.14}$$

Combining Eq.4.12 ~ 3.14, we have:

$$\sigma_x = \rho g \frac{1 + sin\varphi cos2\gamma}{1 - \sin\ cos2\gamma}(H - z) \qquad \text{Eq.4.15}$$

Chapple (1978) suggested that the maximum normal stress $_1$ is parallel to the x-axis when the friction coefficient of basal decollement is small. Davis (1983) proposed that the local angle between the axis of the maximum normal stress $_1$ and the x-axis is close to 0. Therefore, we assume that equals to 0. Taking $cos2\gamma = 1$ into Eq.4.15 and performing a derivative with respect to x, we have:

$$\frac{1 + sin\varphi}{1 - \sin} \cdot \frac{\partial H}{\partial x} + \mu = 0 \qquad \text{Eq.4.16}$$

Now we obtain the critical conditions for lateral dynamic stability when material is located on x-axis. Assuming that represents the maximum topographic slope on which the material located on x-axis can still hold its lateral dynamic stability and invoking the small-angle approximation, we have:

$$\eta = \left|\frac{\partial H}{\partial x}\right| = \frac{\mu}{F} \quad where\ F = \frac{1 + sin\varphi}{1 - \sin} \qquad \text{Eq.4.17}$$

Eq.4.17 suggests that the maximum topographic slope on which the material located on x-axis can still hold its lateral dynamic stability is governed the friction coefficient of basal decollement and the physical properties (internal friction angle). Although it is difficult to compute the maximum topographic slope for lateral dynamic stability *(,)* at an arbitrary point in three-dimensional space, we infer that *(,)* has the same determinants.

Based on the topographic gradient in X and Y direction (and , respectively), and the small-angle approximation, we can compute the slope of any point within the compressional zone:

$$arctan(\sqrt{\alpha^2 + \beta^2}) \approx \sqrt{\alpha^2 + \beta^2} \qquad \text{Eq.4.18}$$

Therefore, the critical condition for lateral dynamic stability can be described as:

$$\sqrt{\alpha^2 + \beta^2} \le \eta(\mu,\ \varphi) \qquad \text{Eq.4.19}$$

Eq.4.19 suggests that *(,)* limits the maximum topographic slope during differential shortening and uplift. When the X-direction topographic gradient resulted from differential shortening and uplift, and the Y-direction topographic gradient do not satisfy the critical condition suggested by Eq.4.19. The material, driven by gravity, will move along the topographic slope. This movement can be decomposed into further shortening in Y direction and lateral extrusion in X direction. The lateral extrusion in X direction will probably result in shortening and thrusting at the leading edge of lateral side of compressional zone (e.g., the Longmenshan area).

4.3. Analysis of key factors of the lateral extrusion model

Whether material will be laterally extruded is governed by the lateral topographic gradient resulted from differential shortening and uplift, and the maximum topographic slope *(,)* on which material within compressional zone can still hold its lateral dynamic stability. If the lateral topographic gradient is larger while the maximum topographic slope *(,)* is smaller, the lateral extrusion is more likely to happen. Therefore, the key factors of lateral extrusion dynamics include the original sedimentary thickness h_0, the shortening factor in the first stage k (the ratio between the movement distance Δy and half the width of the blocking block, $\Delta y/w$), the rotation angle of compressional blocks , the friction coefficient of basal decollement and the physical properties (internal friction angle).

Figure 11 here

Combining Eq.4.2 and Eq.4.7, we are able to eliminate h_0 and k from Eq.4.7:

$$= \frac{w \tan\varphi}{(w + xtan\varphi)^2} h_1(x, 0) \qquad \text{Eq.4.20}$$

Therefore, we can use the thickness of material located on the x-axis when two compressional blocks encounter the blocking block $h_1(x,\ 0)$ to cover the effect of both h_0 and k. Fig.11a displays the effect of $h_1(x,\ 0)$ on the lateral topographic gradient when the rotation angle of compressional blocks is 15°. It is clear that the lateral topographic gradient is larger as $h_1(x,\ 0)$ increases. Eq.4.20 also displays the effect of the rotation angle of compressional blocks on the lateral topographic gradient .

Fig.11b-c display the regular change of as the rotation angle increases. When the rotation angle is small, there is no significant difference on lateral topographic gradient between points with different x-coordinates. As the rotation angle increases, the lateral topographic gradient gets larger and larger. Meanwhile, the further away from the blocking block (smaller x-coordinate), the faster the lateral topographic gradient increases. When the rotation angle reaches 20°, the lateral topographic gradient exceeds 10° and lateral extrusion is likely to occur. Meanwhile, the thickness of material $h_1(x,\ 0)$ has smaller effect on the lateral topographic gradient (Fig.11a), compared with the rotation angle of compressional blocks (Fig.11b, c).

The maximum topographic slope *(,)* in critical condition for lateral dynamic stability is governed by the friction coefficient of basal decollement and the physical properties (internal friction angle). Fig.11d displays the effects of basal friction coefficient and internal friction angle on the maximum topographic slope of points located on the x-axis. It is clear that when basal friction coefficient increases, the maximum topographic slope increases as well. However, when internal friction angle increases, the maximum topographic slope decreases. Therefore, lateral extrusion is more likely to occur with smaller basal friction coefficient and larger internal friction angle . Meanwhile, we notice that the effect of internal friction angle works only when basal friction coefficient is large (e.g. = 0.2 or 0.3 in Fig.11d). When basal friction coefficient is small (e.g. = 0.05 in Fig.11d), the curve is almost horizontal as internal friction angle changes. Therefore, we infer that basal friction coefficient has much larger impact on the maximum topographic slope than internal friction angle in real geological environment.

Fig.11d displays that the maximum topographic slope is usually smaller than 10° while the lateral topographic gradient will exceed 10° under certain circumstances. Therefore, lateral extrusion is highly possible to occur as the differential shortening and uplift going on. It should be noted that we did not take weathering and denudation into consideration, which are able to reduce the lateral topographic gradient and make lateral extrusion slightly difficult.

5 Discrete element simulation of the lateral extrusion model

5.1. Method

Above mathematical modeling provides several equations to describes the lateral extrusion model, but little information about the deformation process during lateral extrusion. Therefore, we for the first time conducted 3D discrete element simulations to reveal the evolutionary process of the compressional zone and verify the effects of key factors on lateral extrusion dynamics.

The 3D discrete element method, models the movement and interaction of stressed assemblies of rigid spherical particles, was first proposed by Cundall (1971) to promote the analysis of rock-mechanics problems. A thorough description of the method is given in the two-part paper by Cundall (1988) and Hart (1988). The 3D discrete element method uses simple particle interactions, governed by contact forces and force-displacement law, to observe the dynamic evolution of a system. It is well-suited to studying problems in which discontinuities are important as it allows large relative motion and does not require complex re-meshing at high strains.

Figure 12 here

We developed a 3D discrete element model using *PFC3D 5.0.* we treat the compressional zone as an assemblage of spherical particles that interact in pairs as if connected by elastic springs and that undergo motion relative to one another. These particles interact with their neighbor through a 'linear contact model' in which the resultant force between particle i, $\boldsymbol{F_i}$, is given by (Fig.12):

$$\mathbf{F_i} = -F_{n,i}\mathbf{n_{c,i}} + \mathbf{F_{s,i}} \qquad \text{Eq.5.1}$$

where $F_{n,i}$ and $\boldsymbol{F_{s,i}}$ are the normal and shear components of the linear force, respectively. $\boldsymbol{n_{c,i}}$ represents the normal direction. Both normal and shear components of the contact force is produced by linear springs with constant normal and shear stiffnesses, k_n and k_s. The shear component of the contact force is also limited by the maximum static friction between particles:

$$F_{n,i} = \begin{cases} k_n g_i, & g_i \leq 0 \\ 0, & g_i > 0 \end{cases} \qquad \text{Eq.5.2}$$

$$\mathbf{F_{s,i}} = min(k_s |\ \mathbf{s_i}|,\ -\mu_p F_{n,i})(\ \mathbf{s_i}/ \parallel\ \mathbf{s_i} \parallel) \qquad \text{Eq.5.3}$$

where g_i and $\boldsymbol{\Delta s_i}$ is the surface gap and the relative sliding distance between particles, is the internal friction coefficient between particles. Eq.5.2 suggests that the contact force exists only when the surface gap of two particles g_i is less than 0.

The total contact force, $\boldsymbol{F}$, exerted on a particle is obtained by summing the forces on each contact that links the particle to its N neighbors and gravity:

$$\mathbf{F} = \sum_{i=1}^{N} \mathbf{F_i} + m\mathbf{g} \qquad \text{Eq.5.4}$$

Newton's second law is used to determine the motion of each particle arising from the contact and body forces acting upon it. Therefore, the equation for translational motion can be written in the form:

$$\mathbf{F} = m(\ddot{x} - \mathbf{g}) \qquad \text{Eq.5.5}$$

The dynamic behavior is represented numerically by a time stepping algorithm, which automatically executed by *PFC3D 5.0*, in which it is assumed that the velocities and accelerations are constant within each timestep. The timestep chosen is so small that the final results are consistent with the actual situation.

5.2. Boundary and initial conditions

The discrete element model is shown in Fig.13 with its coordinate system the same as that used in mathematical modeling. In the models presented here, we assume that one model unit corresponds to 10km in the real world. The blocking block (the green block) is 50 model units wide, corresponding to the 500km wide Longmenshan belt. We choose 500km of the eastern margin of the Songpan-Ganze terrane and 150km of the western margin of the Sichuan Basin to be the simulation area. Therefore, the blocking block and compressional blocks (the red blocks) are 15 and 50 model units long, respectively. The gray plane among three blocks represents the basement of the Songpan-Ganze basin and its friction coefficient represents the friction coefficient of basal decollement

. Yellow particles represent sediments within the Songpan-Ganze basin, while blue particles represent the cover of Sichuan Basin.

Figure 13 here

As discussed above, the closure of basin can be divided into two different stages. In the first stage, two compressional blocks move towards each other symmetrically, which leads to homogeneous shortening in the Y direction. Meanwhile, we can use the thickness of material located on the x-axis $h_1(x, 0)$ when two compressional blocks encounter the blocking block to cover the effect of both the original sedimentary thickness h_0 and the shortening factor in the first stage k. By simplify the topographic gradient in Y direction to be 0, Eq.4.2 can be written as:

$$h_1(x,0) = (1+k)h_0 \qquad \text{Eq.5.6}$$

Eq.5.6 suggests that there is some non-linear trade-off relationship between the original sedimentary thickness h_0 and the shortening factor in the first stage k. Therefore, by setting larger original sedimentary thickness h_0, we can reduce the shortening amount in the first stage to reach the same $h_1(x, 0)$, enhance the efficiency of simulation calculation and focus on the rotation and the resultant differential shortening in the second stage. The shortening amount chosen in simulations in the first stage is 10 model units and the corresponding shortening factor k is 0.4.

Figure 14 here

The top view of initial model is shown in Fig.14. Enough particles are generated within the geometric boundary described above, with their radius ranging from 0.225 to 0.275. Both normal and shear stiffnesses, k_n and k_s, of material within basin are set to be 5×10^6. The normal and shear stiffnesses, k_n and k_s, of foreland deposits are set to be 1×10^7. By choosing different values of the material thickness $h_1(x, 0)$, the friction coefficient of basal decollement and the internal friction angle , we can reveal the effect of these factors on simulation results. The friction coefficient of basal decollement is set to the basement directly. The material thickness $h_1(x, 0)$ is translated to the equivalent original thickness h_0 as input parameter through Eq.5.6 (the shortening factor k is 0.4). However, the internal friction angle , the macro physical parameters, cannot be set to micro particles directly. It was proposed that for material without internal cohesion, the internal friction angle is linear with the interparticle friction coefficient $_p$ (Chen et al., 2013 and reference within):

$$(\mu_p) = 37.3\mu_p + 3.9 \qquad \text{Eq.5.7}$$

Therefore, based on Eq.5.7, the internal friction angle is translated to the equivalent interparticle friction coefficient $_p$ as input parameter.

Table 1 here

Different parameters of different models are shown in Table 1. Model M1, M4 and M7 have different material thickness $h_1(x, 0)$. Model M2, M4 and M6 have different friction coefficient of basal decollement . Model M3, M4 and M5 have different internal friction angle . The friction coefficient of basal decollement in Model M8 is set to be 0.71 to simulate the situation without basal decollement. During the simulation, the compressional blocks in all models move 10 model units towards each other in the first stage, and then rotate certain angles in the second stage. The rotation angles of compressional blocks on both side in model M1 ~ M8 are 20°. The rotation angles of compressional blocks on both side in model M9 are 10° and 30° respectively to simulate the situation where the movements of two compressional blocks are asymmetrical. Red circles are used to monitor the strain during deformation.

5.3. General simulation results

The simulation results of model M1 ~ M8 have similar characteristics. Fig.15 and 16 display the top view and the cross-sectional view (X-Z plane) of the deformation process of model M4, respectively.

Figure 15 here

At the end of homogeneous shortening stage (Fig.15b and 16b), the material is mainly compressed in the Y-direction as shown by strain monitoring circles, and the shortening is the same along the X-direction. When the rotation angles of compressional blocks are 10°, the effects of differential shortening can be observed obviously. The farther away from the blocking block, the more the strain monitoring circles are squashed (Fig.15c) and the thicker the thickness of material (Fig.16c). When the rotation angles of compressional blocks reaches 20° (Fig.15d and 16d), it is quite clear that the material within basin is laterally extruded towards the blocking block. Accordingly, the deposits above the blocking block (blue particles) are compressed in the X-direction as shown by strain monitoring circles. This result suggests that the highly deformed material within basin can be laterally extruded during differential shortening and uplift, and cause shortening and thrusting at the leading edge of the laterally extruded material, as described by the lateral extrusion dynamics. The differential shortening in the Y-direction will be accommodated by the limited uplift in the Z-direction and the lateral extrusion in the X-direction.

Figure 16 here

The black dotted box in Fig.15d denotes the special stress-strain condition predicted by the lateral extrusion model. The longer axes of strain monitoring circles inside the shortened basin are perpendicular to the moving direction of the compressional blocks, while those at the leading edge of the laterally extruded material are parallel to the blocking block. This stress-strain distribution displays a good agreement between theoretical prediction by the lateral extrusion dynamics and corresponding real geological data obtained from the

Longmenshan thrust belt and the Xiaojin Arcuate Zone, where the orientation of the major principal stress ($_1$) changes gradually from NE-SW in the west to NW-SE in the east (Fig.5).

Figure 17 here

Fig.17 displays the average lateral displacement and normal strain in the X direction of landmarks (black dots in Fig.15a) with different X coordinates when the rotation angles of compressional blocks are 20°. It is clear that the lateral displacement is different with different X coordinate. The lateral displacement increases first and then reduces with increasing of the X coordinate. The maximum lateral displacement appears between X = -27 and X = -21, suggesting that the part of basin is extended in the X-direction. This phenomenon is more obvious in Fig.17b. The yellow area is the extension zone where the normal strain in the X direction is positive, while the green area is the compression zone where the normal strain in the X direction is negative. The minimum value appears between X = 0 and X = 6. This suggests that the strongest shortening occurs at the margin of the blocking block, where happens to be the Longmenshan thrust belt in the real world. The result strongly demonstrates that the laterally extruded material from the interior Songpan-Ganze terrane caused by differential shortening can result in shortening and thrusting around the Longmenshan area, just as predicted by the later extrusion dynamics.

5.4. Comparison of simulation results

The simulation results suggest that the different thickness of material $h_1(x, 0)$ and internal friction angle have little effect on the lateral extrusion (see Figures S2, S3 and S4 in Supporting Information S1), which is in agreement with the numerical analysis discussed above (Fig.11a, d). Therefore, here we focus on the effects of the rotation angle of compressional blocks and the basal friction coefficient .

Figure 18 here

The deformation of material within basin as the rotation angle increases reveals the effects of the rotation angles of compressional blocks on simulation results. Fig.18 displays the average lateral displacement and normal strain in the X direction of landmarks (the same position as those in Fig.15a) with different X coordinates in model M1 as the rotation angles of compressional blocks increases from 0° to 20°. It is clear that the lateral displacement increases at an ever-accelerating pace with increasing of the rotation angle (Fig.18a). Meanwhile, the increment of lateral displacement shows different patterns at different locations. The lateral displacements of landmarks far away from the blocking block increase more rapidly compared with those of landmarks around the blocking block. It can be observed that the division between the extension zone and the compression zone moves away from the blocking block and the compression zone gets bigger and bigger as the rotation angle increases (Fig.18b). The shortening in the compression zone increases at an ever-accelerating pace, which is similar to the change law of lateral displacement. However, the position where the minimum normal strain appears (between X = 0 and X = 6) does not change apparently, suggesting that the margin of the blocking block (the Longmenshan area in the real world) is always the position where the strongest shortening and thrusting occurs. The effect of rotation angle on the lateral extrusion dynamics revealed by simulation results agrees with the numerical analysis discussed above.

Figure 19, 20 here

Fig.19 and 20 display the lateral topographic gradient , and the average lateral displacement and normal strain of landmarks with different friction coefficients of basal decollement when the rotation angles are 20°, respectively. It is clear that the topographic gradient increases and the lateral displacement decreases as the basal friction coefficient increases, which suggests that the lateral extrusion gets more difficult. The effect of basal friction coefficient on division between the extension zone and the compression zone is uncertain. However, the position where the minimum normal strain appears does not change apparently, which is still located at the margin of the blocking block (between X = 0 and X = 6 in Fig.21b). The lateral displacement and shortening amount get larger as the basal friction coefficient gets smaller. When the basal decollement does not exist, the topographic gradient is very large and the material represented by yellow particles at the leading edge does not move laterally into the foreland (Fig.19d). Both the shortening amount and normal strain are close to 0 where around the basin-foreland division (X=0) when the basal decollement is missing (Fig.20), suggesting that shortening and thrusting do not occur at the margin of the blocking block. Therefore, the basal decollement underneath the highly deformed cover in the Songpan-Ganze terrane is essential to the Longmenshan southeastern thrusting.

Figure 21 here

Model M9 has the same key parameters as model M4 except the rotation angles of two compressional blocks, which are 10° and 30°, respectively. Fig. 21 displays the simulation results of model M4 and M9 when the total rotation angle is 40°. There are several similarities in both models. The material within basin is laterally extruded towards the blocking block. Accordingly, the deposits above the blocking block (blue particles) are compressed in the X-direction as shown by strain monitoring circles. The black dotted box in Fig.21b denotes the similar special stress-strain condition displayed in Fig.15d. The longer axes of strain monitoring circles inside the shortened basin are perpendicular to the moving direction of the compressional blocks, while those at the leading edge of the laterally extruded material are parallel to the blocking block. This stress-strain distribution displays a good agreement between theoretical prediction by the lateral extrusion dynamics and corresponding real geological data obtained from the Longmenshan thrust belt and the Xiaojin Arcuate Zone.

Figure 22 here

Due to the asymmetrical rotation, the simulation result of model M9 is also asymmetrical. Material near the compressional block with larger rotation angle undergoes more intense deformation. The shortening in the Y-direction, the lateral displacement in the X-direction and the shortening amount at the leading edge are larger than those on the other side (Fig.21 and 22), which donates the effects of asymmetrical rotation on the geological deformation. These differences disappear in the foreland between X = 0 and 15, suggesting that the deformation at the leading edge of laterally extruded material is scarcely influenced by the asymmetrical rotation of two compressional blocks.

Based on the comparison above, two key factors facilitate the lateral foreland thrusting, which are the wedge-shaped collisional zone resulted from rotation that produces differential shortening, and the low-strength decollement that decouples sedimentary sequences from basement. Both necessary conditions were fulfilled around the Longmenshan area, and generated the special Late Triassic Longmenshan lateral foreland thrusting. The original thickness and physical properties of sediments, and the asymmetrical rotation also have influence on the lateral extrusion dynamics.

6. Tectonic implications of the lateral extrusion model

As simulated by the 3D discrete element model, simultaneous bidirectional subductions led to the closure of the wide Songpan-Ganze basin, which resulted in differential shortening and produced southeastward inclined topographic gradient due to the special geometry of the Songpan-Ganze terrane. The bottom Silurian-Devonian weak strata served as the decollement (Xu et al., 1992; Roger et al., 2004, 2008, 2010; Harrowfield and Wilson, 2005), which decoupled the thick sedimentary pile from the subducting basement. Driven by topographic gradient and gravity, the sedimentary pile was laterally extruded and transported southeastward along the decollement, which resulted in the lateral foreland thrusting in the Longmenshan area (Fig.23b). The gradual change of the stress field from internal Songpan-Ganze terrane to Longmenshan thrust belt produced the Xiaojin Arcuate Zone. No arcuate zone was observed in the northeast corner of the Songpan-Ganze terrane, which was probably erased by the tectonic movement of the Bikou terrane (Fig.1a) (Yan et al., 2011, 2018).

In general, the continent-continent collision results in linear or arcuate orogenic belts (e.g., the Alps). The foreland thrust belts and the corresponding foreland basins resulting from regional isostatic compensation by lithospheric flexure can be grouped in two categories, which are the pro-foreland system lies above the subducting slab and the retro-foreland system lies above the over-riding slab (Johnson and Beaumont, 1995; Naylor and Sinclair, 2008). Although kinematic and dynamic evolution of these foreland systems are diverse (Johnson and Beaumont, 1995; Naylor and Sinclair, 2008), there are some common characteristics shared by foreland thrust belts in both pro- and retro-foreland system: (1) they are perpendicular to the collision direction and (2) they are driven by subducting slab. However, based on the lateral extrusion dynamic model, the Late Triassic Longmenshan thrusting has several specializations: (1) the Longmenshan thrusting, located at the lateral side of the Songpan-Ganze terrane and connected by the Xiaojin Arcuate Zone, is parallel to the collision direction of the Qiangtang Block, and (2) it is driven by the lateral topographic gradient resulted from the differential shortening of the wedge-shaped Songpan-Ganze terrane, rather than the subducting slab. Therefore, the Longmenshan thrusting, which has specializations in its tectonic location, stress condition and dynamic behavior, is a new kind of foreland thrust belt after pro-foreland thrust belt and retro-foreland thrust belt. We introduce the lateral foreland thrust belt to name the Late Triassic Longmenshan thrusting.

The tectonic geometry of lateral foreland thrust belt is characterized by wedge-shaped collisional zone (the Songpan-Ganze terrane in this study) and this special geometry is one of the key factors in lateral extrusion dynamics. The strike direction of foliations within the compressional zone is perpendicular to the collision direction. The thrusting resulted from lateral extrusion (the Longmenshan thrusting in this study) occurs at the lateral side of the compressional zone, with its strike direction of foliations parallel to the collision direction. The arcuate zone (the Xiaojin Arcuate Zone in this study) is produced by the gradual change of the stress field from internal compressional zone to lateral foreland thrust belt.

The tectonic kinematic and dynamic process is characterized by lateral extrusion resulted from the differential shortening within compressional zone, which produces lateral topographic gradient. When the lateral topographic gradient exceeded the critical conditions for lateral dynamic stability, the material within compressional zone will be driven by gravity and extruded along topographic gradient, leading to lateral thrusting. The basal decollement decouples sedimentary sequences from basement, which is one of the key factors in lateral extrusion dynamics. Without low-strength decollement, the coupling force between the sedimentary pile and the basement is hard to overcome, which probably results in diachronous collision rather than lateral extrusion.

As discussion above, two key factors facilitate the lateral foreland thrusting, which are the wedge-shaped collisional zone that produces differential shortening, and the low-strength decollement that decouples sedimentary sequences from basement. Both necessary conditions were fulfilled around the Songpan-Ganze-Longmenshan area during the Late Triassic, and resulted in the special Longmenshan lateral foreland thrusting. Meanwhile, the thick sedimentary pile led to crustal thickening and the subsidence of the western Sichuan foreland basin, and we introduce the lateral foreland basin to name it. The front of the Longmenshan thrust belt was pushed further southeastward and overlay the Xujiahe Formation as nappes, which were turned into widespread klippes by later weathering, denudation and tectonic events. The basic geological framework in the Longmenshan area was probably established during the Late Triassic and overprinted in some degree by the Cenozoic superimposition during the India-Asian collision (Xu et al., 1992; Worley and Wilson, 1996; Yan et al., 2011, 2018) (Fig.23c).

7. Conclusions

In this research, we explore the Late Triassic evolution of the Longmenshan thrust belt and its possible tectonic dynamics based on geological evidence, mathematical modeling and discrete element simulations. Our conclusions can be summarized as follows:

1. A new lateral extrusion model was proposed to explain the Late Triassic Longmenshan thrusting, which was a lateral foreland thrust belt during the Late Triassic. The western Sichuan basin was a lateral foreland basin. The new model also well predicted the Xiaojin Arcuate Zone.

2. The new lateral extrusion model suggests that the differential shortening within the wedge-shaped Songpan-Ganze terrane produced lateral topographic gradient. When the lateral topographic gradient exceeded the critical conditions for lateral dynamic stability, the material within collisional zone, decoupled from basement by weak basal decollement, was driven by gravity and extruded along topographic gradient, leading to lateral thrusting.

3. The results of mathematical modeling and 3D discrete element simulation first time used for the study of the Longmenshan area reveal that two key factors facilitate the lateral foreland thrusting, which are the wedge-shaped collisional zone that produces differential shortening, and the low-strength decollement that decouples sedimentary sequences from basement. The original thickness and physical properties of sediments also have influence on the lateral extrusion dynamics.

4. The lateral foreland thrust belt is a new kind of foreland thrust belt after pro-foreland thrust belt and retro-foreland thrust belt, which provides a new insight into the evolution of the Songpan-Ganze-Longmenshan system.

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Data Availability Statement

Codes for the simulation of the lateral extrusion dynamic model created for this study using *PFC3D 5.0* and the simulation results (Zhao et al., 2022) are available at: https://doi.org/10.18170/DVN/D84NQX.

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Figure captions

Fig.1 Geographical position and Geological map of the Longmenshan thrust belt and the adjacent Songpan-Ganze Terrane, Sichuan Basin. WMF: Wenchuan-Maowen fault, BYF: Beichuan-Yingxiu fault, GAF: Guanxian-Anxian fault, XLB: Xuelongbao complex, PG: Pengguan complex. Main sutures of Paleotethys: : Kunlun-Anyenaqen, : Jinsha-Yushu-Batang, : Bangonghu-Nujiang.

Fig.2 (a) Geological map of the Longmenshan nappes in the middle segment of the Longmenshan thrust belt. (b) Geological map and sample location near the Huaiyuan Town. See location in Fig.1.

Fig.3 Photographs showing field characters of the sampling location of the calcite veins (see location in Fig.2b). (a) The fault fracture zone with fault breccia, fault gouge and cataclastic rocks. (b) Contact between the fault fracture zone and the Upper Permian carbonate rock. (c) The well-exposed secondary fault rupture planes and calcite veins.

Fig.4 Tera-Wasserburg Concordia plots for LA-ICP-MS U-Pb dating results, with calculated lower intercept ages representing the formation time of calcite veins, from sample CV1 (a) and sample CV2-1 (b).

Fig.5 Schematic cross-sections through the Xiaojin Arcuate Zone. Section lines are marked on Fig.1b. All stereonets are lower hemisphere equal area projections.

Fig.6 Geological model of the lateral foreland thrust belt. The thick sedimentary pile, which is decoupled from the subducting basement by low-strength decollement, is laterally extruded and results in the lateral foreland thrusting and arcuate zone.

Fig.7 The coordinate system used in numerical modeling of the lateral extrusion model.

Fig.8 The cross-sectional view (Y-Z plane) of the homogeneous shortening in the first stage.

Fig.9 Schematic diagram of a wedge of material in X-Z plane. The force balance on an arbitrary column of width dx is shown.

Fig.10 Mohr diagram illustrating the state of stress at some point within the wedge.

Fig.11 The lateral topographic gradient in the X-direction with (a) different thickness of material located on the x-axis $h_1(x, 0)$, (b-c) different rotation angle of compressional blocks . (d) Critical topographic slope for lateral dynamic stability with different friction coefficient of basal decollment and the internal friction angle .

Fig.12 Contact of particles in *PFC3D 5.0* and the their interaction force component.

Fig.13 Discrete element model of the lateral extrusion model. The coordinate system is the same as that used in numerical modeling shown in Fig.7.

Fig.14 The top view of initial model.

Fig.15 The top view of the simulation result in model M4. The black dots represent landmarks used to monitor the displacement in different places. The black dotted box denotes the special stress-strain condition predicted by the lateral extrusion model.

Fig.16 The cross-sectional view (X-Z plane) of the simulation result in model M4.

Fig.17 The (a) average lateral displacement and (b) normal strain in the X direction of landmarks with different X coordinates when the rotation angles of compressional blocks are 20°.

Fig.18 The average lateral displacement and normal strain in the X direction of landmarks with different X coordinates and rotation angles in model M1.

Fig.19 The cross-sectional view (X-Z plane) of the simulation results with different friction coefficients of basal decollment   when the rotation angles are 20°.

Fig.20 The average lateral displacement and normal strain in the X direction of landmarks with different X coordinates with different friction coefficients of basal decollment   when the rotation angles are 20°.

Fig.21 The top view of the simulation result in model (a) M4 and (b) M9 when the total rotation angle is 40°. The black dotted box denotes the special stress-strain condition predicted by the lateral extrusion model. The black dotted line marks the leading edge of the laterally extruded material.

Fig.22 The average lateral displacement and normal strain in the X direction of landmarks with different X coordinates in model (a) M4 and (b) M9 when the total rotation angle is 40°.

Fig.23 Sketch of the tectonic evolution of the Songpan-Ganze-Longmenshan orogen (a) before Late Triassic, (b) from Late Triassic to Early Jurassic and (c) since Cenozoic.