Influence of Surface Processes on Strain Localization and Seismic Activity in the Longmen Shan Fold-and-Thrust Belt: Insights From Discrete-Element Modeling

Maomao Wang1 ©, Ming Wang1, Wang Feng1, Bing Yan1 ©, and Dong Jia2 ©

1Institute of Tectonics and Geophysics, College of Oceanography, Hohai University, Nanjing, China, 2School of Earth Sciences and Engineering, Nanjing University, Nanjing, China

Abstract We investigated interactions between structural deformation and surface processes in the Longmen Shan fold-and-thrust belt and the adjacent western Sichuan foreland basin (WSFB) in the eastern margin of the Tibetan Plateau. The discrete-element modeling (DEM) method was used to study the influences of the various mechanical properties of the detachments and syn-tectonic erosion/deposition on the structural evolution of the Longmen Shan and WSFB. DEM simulations demonstrated two stages of surface processes during the Late Cenozoic profoundly influenced thrusting sequences and strain localization in the hinterland and foreland portions of the Longmen Shan. Models indicate that the fold-and-thrust belt lacking surface processes propagate in a forward-breaking manner, whereas those with surface processes develop following an out-of-sequence thrusting pattern. We infer that large-scale erosion propagation from the Sichuan Basin westward to the Tibetan Plateau since Late Cenozoic caused the Longmen Shan hinterland to reach a subcritical wedge state. Tectonic activity retreats to the edge of Plateau, enhancing the rapid uplift of the Longmen Shan and inhibiting the propagation of substantial shortening deformation to the foreland basin. The foreland thrust belt slides stably along the shallow detachment, causing the initiation and growth of the Longquan fault in the leading front. These results explain why both the Longmen Shan hinterland and the western Sichuan foreland thrust belts are currently in a state of simultaneous seismic activity. Our findings offer important implications regarding the seismic potentials of other fold-and-thrust belts that interact with dynamic surface processes.

Plain Language Summary The Longmen Shan is located between the high-altitude Tibetan Plateau and the Sichuan Basin, the steepest topographic margin around the Tibetan Plateau. This region was the site of devastating earthquake events including the 2008 magnitude 7.9 Wenchuan earthquake and the 2013 magnitude 6.6 Lushan earthquake, which caused severe casualties. Geologists differ in opinion regarding how this high mountain range was uplifted during the Late Cenozoic, and the roles of surface processes are often ignored. To address this issue, we used a numerical sandbox-like simulation method to explore the effects of erosion and sedimentation on the uplift and lateral propagation of the Longmen Shan during the Late Cenozoic. Most fold-and-thrust belts models traditionally show a forward-breaking thrusting sequence, where the youngest and most active thrust fault is located at the toe of the fold-and-thrust belt. However, we found that surface processes significantly changed this thrusting sequence and that the fault activity of the Longmen Shan hinterland was reactivated. During the Late Cenozoic, large-scale erosion propagating from the Sichuan Basin toward the Tibetan Plateau destabilized the mountain front and increased the activities of the hinterland faults, leading to the rapid uplift of the Longmen Shan and inhibited shortening deformation of the foreland basin.

1. Introduction

The Longmen Shan fold-and-thrust belt is located between the highly elevated eastern Tibetan Plateau and the low-relief Sichuan Basin, defining the steepest margin around the Tibetan Plateau (Burchfiel et al., 1995; Clark & Royden, 2000; Clark et al., 2004; Kirby et al., 2002) (Figure 1). Unlike rivers draining the northern margin of the Tibetan Plateau, which flow north into Tarim Basin, the Yangtze River in the eastern margin flows into the southern Sichuan Basin and continues eastward into the East China Sea (Figures 1 and 2) (Zheng et al., 2013, 2021). During the Late Cenozoic, reorganization of the Yangtze drainage system may have led to large-scale erosion within the Sichuan Basin, with approximately 1–4 km of sediment being removed (Richardson et al., 2010). The Longmen Shan lacks evidence of a large foredeep flexure and syn-tectonic deposition during the Late Cenozoic, with a maximum Quaternary sedimentation thickness in the western Sichuan Basin of ~600 m (Guo et al., 1996).
However, the thicknesses of the Cenozoic syntectonic sedimentation in the northern and southern margins of the Tarim Basin reach 5 and 7 km, respectively, in some areas (Figure 1) (C. Li et al., 2020). The high and steep topographic gradient of the Longmen Shan does not correspond to a large crustal shortening rate, but instead exhibits a relatively low crustal shortening rate of <3 mm/yr (Z. Chen et al., 2000; Densmore et al., 2007; M. Wang et al., 2020; P.-Z. Zhang et al., 2004). In contrast, the present-day convergence rates across the northwestern margin of the Tibetan Plateau (from 75° to 80°E) range from 15 to 10 mm/yr (M. Wang et al., 2020). The devastating 2008 Wenchuan Mw 7.9 earthquake and the subsequent 2013 Lushan Mw 6.6 earthquake demonstrated ongoing crustal shortening in the Longmen Shan fold-and-thrust belt (Hubbard & Shaw, 2009; Liu-Zeng et al., 2009; M. Wang et al., 2014; Xu et al., 2009). These recent catastrophic earthquake events require us to reconsider the processes between crustal shortening, rapid uplift, syn-tectonic sedimentation, and erosion of Longmen Shan and Sichuan Basin in the eastern margin of the Tibetan Plateau, and their influences on fault activity and seismic hazards.

Over the past decade, the uplift timing, crustal structure, and structural evolution of the Longmen Shan in the eastern margin of the Tibetan Plateau have been studied extensively (Cui et al., 2020; Feng et al., 2016; Godard et al., 2009; Hubbard et al., 2010; Jia et al., 2010; Y. Li et al., 2010; Liu et al., 2020; Robert et al., 2010; Shen et al., 2019; Styrön & Hetland, 2015; Sun et al., 2016; Tian et al., 2013; E. Wang et al., 2012). The major geological questions regarding Cenozoic Longmen Shan fold-and-thrust belt presently include: (a) Why does the Longmen Shan lack syn-orogenic foreland deposition? (b) Why are both the Longmen Shan hinterland region and western Sichuan foreland basin (WSFB) seismically active today? (c) What roles did surface processes play in the structural deformation and evolution of the Longmen Shan and WSFB? And (4) How does the structural variability form along strike in the Longmen Shan?

Previous studies investigated the relationship between the detachment fault strength and topography relief in the Longmen Shan range fronts and adjacent foreland basin using critical wedge taper theory, sandbox physical modeling, and numerical simulation (Cui et al., 2020; Hubbard et al., 2010; Sun et al., 2016; Z. Zhang et al., 2018). These studies reveal that the mechanical strength differences of basal and shallow detachments control the crustal shortening and topography of the Longmen Shan range front and WSFB. However, these models do not explain the absence of syn-orogenic foreland deposition in the western Sichuan basin. The shallow detachment forming-material is gypsum rock deposited in Mid-Triassic salt lakes. It is important to assess whether the sedimentary facies variations in this stratigraphic unit influence thrust slip propagated from the hinterland to foreland basin. Furthermore, these models also lack sufficient constraints on how geologic slip propagated into foreland basin during the Late Cenozoic. Finally, whether the widespread surface processes in the eastern margin of the Tibetan Plateau pose important impacts on the structural evolution of the Longmen Shan fold-and-thrust belt remains unclear. In this study, we used discrete-element modeling (DEM) (Cundall & Strack, 1979; C. Li et al., 2018, 2021; Morgan, 2015) to investigate the role of surface processes and interactions during structural deformation of the Longmen Shan fold-and-thrust belt. The DEM was chosen as an optimal tool because it reproduces Coulomb failure and fracture, and can generate new faults in direct response to the applied stresses. Thus, it is a suitable technique for investigating structural deformation that allows us to quantitatively observe and analyze the stress and strain evolution process and to reveal the fault activity and mechanical evolution of fold-and-thrust belt. Based on the structural and mechanical properties of the detachments, we designed comparative DEM experiments to investigate the structural deformation and surface processes of the Longmen Shan fold-and-thrust belt in the Late Cenozoic. By comparing the thrust-faulting history and modern seismic activity, we constructed a new integrated model of the structural deformation and surface processes of the Longmen Shan fold-and-thrust belt. Our model furthers the understanding of the relationship between uplift and contractional deformation, syntectonic erosion/sedimentation, and earthquake activity of Longmen Shan and western Sichuan Basin in the eastern margin of the Tibetan Plateau.

2. Geological Setting

The Longmen Shan fold-and-thrust belt is located on the eastern margin of the Tibetan Plateau and is a natural laboratory for studying intracrustal deformation and tectonic geomorphology (Burchfiel et al., 2008). Unlike the arid environment of the northern margin of the Tibetan Plateau, the eastern margin has plenty of rainfall and is drained by large rivers. The Yangtze River is one of these and is the largest drainage system in Asia (Zheng et al., 2013). Large drainage systems are widely developed in the Sichuan Basin (such as the Jialin River, Fu
River, Tuo River, Min River, and Qingyi River), which eventually connect with the Jinsha River at the southern edge (Yibin at Figure 2) of the basin to merge with the Yangtze River and transport sediments to the East China Sea. Richardson et al. (2008) investigated the Cenozoic thermal history of the Sichuan Basin using apatite fission track and U-Th/He techniques in combination with stratigraphic and borehole data. They found widespread accelerated cooling in the Sichuan basin since 40 Ma, accompanied by 1–4 km thick sediments removed from the basin. This large-scale erosion is interpreted to be due to the connection of the middle and upper Yangtze River in the Three Gorges area (Yichang at Figure 2) at about 40–45 Ma. Subsequently, widespread erosion in the Sichuan basin started a gradual capture of the upper drainage system from east to west. Zheng et al., 2013 constrain the timing of the connection between the upper and middle streams of the Yangtze River to be between the Oligocene and Miocene, at about 23 Ma. This age is close to the age of the top of the Lushan Formation (Paleogene strata in Figure 1) that resides on the western margin of the Sichuan basin.

Figure 1. Geological map of the eastern Tibetan Plateau showing the focal mechanisms of the 2008 Mw 7.9 Wenchuan earthquake, the 2013 Mw 6.6 Lushan earthquake, and the 2020 Ms 5.1 Qingbaijiang earthquake. The red lines represent surface ruptures of the 2008 Wenchuan earthquake (Liu-Zeng et al., 2009; Xu et al., 2009). The gray rectangles represent the age of previous published low-temperature thermochronology data, from (E. Wang et al., 2012)[1] and (Richardson et al., 2008)[2]. The brown lines represent the structural profiles in the study area, where profile (a–c) is shown in Figures 5a–5c, respectively. LQF: Longquan Fault; PGT: Pengguan Thrust; RFBT: Range Front Blind Thrust; WLF, Wulong Thrust; WLT: Wenchuan–Maowen Fault; XPT: Xiongpo Thrust; YBT: Yingxiu–Beichuan Thrust.
The tectonic evolution of Longmen Shan and western Sichuan Basin can be divided into four stages. From Sinian to Mid-Triassic, the study area is a passive margin tectonic environment with the deposition of marine sedimentary strata (Figure 3). From Late Triassic to early Jurassic, the Longmen Shan fold-and-thrust belt and adjacent WSFB are formed due to intracontinental convergence that occurred in the western margin of the Yangtze block. In this stage, the WSFB was subjected to flexural subsidence, forming a wedge-shaped sedimentary basin underlain by Middle Triassic evaporite rocks (Figure 4), thickening westward to a maximum thickness of 4 km (Guo et al., 1996; Hubbard et al., 2010; Jia et al., 2006; M. Wang et al., 2020). From Mid-Jurassic to Cretaceous, the WSFB entered a phase of intracontinental subsidence. Since Cenozoic, the Longmen Shan fold-and-thrust belt was rejuvenated by the long-distance effect of the India-Tibetan continental collision. The
Figure 3. Stratigraphic column of Longmen Shan fold-and-thrust belt and western Sichuan Basin (modified from Jia et al., 2006). The regional detachments and unconformities are shown.
results of low-temperature thermochronology indicated that the central segment of the Longmen Shan underwent stable exhumation during the Early Cenozoic, followed by two periods of rapid exhumation, one beginning 25–30 Ma and a second beginning ∼10–15 Ma, which continued to the present (Figure 1) (Shen et al., 2019; E. Wang et al., 2012). The widespread erosion that started since 40–45 Ma from the eastern Sichuan Basin may have finally reached the western margin of the Sichuan Basin, which probably led to the first phase of rapid uplift during ∼30–20 Ma of the Longmen Shan. Interpretations of seismic reflection profiles demonstrate that crustal shortening of the Longmen Shan has propagated through the range front and into the interior of the WSFB (Hubbard et al., 2010; Jia et al., 2006, 2010; M. Wang et al., 2020).

The northeast-trending Longmen Shan consists of a series of parallel northwest-dipping thrust faults, from the hinterland to the foreland, the Wenchuan-Maowen Thrust (WMT), the Yingxiu-Beichuan Thrust (YBT), the Pengguan Thrust (PGT), and the Range Front Blind Thrust (RFBT) (Figures 1 and 5). The Longmen Shan consists of a two-level detachment system: a gently dipping basal detachment at a depth of 15–18 km and a shallow detachment located in the basin interior at a depth of 5–7 km, dipping toward the hinterland (Figures 5 and 6) (Hubbard et al., 2010; Hubbard & Shaw, 2009; Jia et al., 2010; M. Wang et al., 2014). Basement-involved thrust-related structures have developed in the hinterland region of the Longmen Shan. In the WSFB, an array of northeast-and north-northeast-striking thrust-related folds are formed above the Triassic evaporitic sequence detachment, which is consistent with the thin-skinned tectonic model. Based on balanced cross-sections, the total shortening of the southern segment of the Longmen Shan during the Cenozoic is 38.4 km (Z. Chen et al., 2005; Hubbard et al., 2010).

Figure 4. Sedimentary facie map of Section 4 of the Leikoupo Formation in the Sichuan Basin, modified from He et al. (2019).
3. Numerical Methods and Experimental Setup

3.1. Basic Principles

We used the discrete-element method (e.g., Cundall & Strack, 1979) to investigate the interactions between structural deformations and surface processes occurring in the Longmen Shan thrust belt and the WSFB in the...
Late Cenozoic. The numerical code utilized for DEM modeling in two-dimensions, VBOX or Virtual Sandbox, is accessed publicly and available on the website (https://geovbox.com/en/). This code was written in C language and the parallel design was completed using OpenMP (C. Li et al., 2021). This code was modified from RICE-BAL, developed at Rice University by Julia Morgan (Morgan, 2015), which was modified from the original open-source code TRUBAL, developed by Peter Cundall and Otto Strack (Cundall & Strack, 1979). The processing scripts used in VBOX were also developed which shared by Julia Morgan (Morgan, 2015), which used GMT (Wessel & Smith, 1995). DEM is a particle-based numerical approach that solves Newton’s equations of motion for each particle to study the mechanical behavior of a system (Cundall & Strack, 1979; Morgan, 2015). DEM can effectively simulate the structural evolution and fault activity in fold-and-thrust belts (Blank & Morgan, 2019; Burbidge & Braun, 2002; Dean et al., 2013; Finch et al., 2003; Hardy et al., 2009; Meng & Hodgetts, 2019; Morgan, 2015; Yamada et al., 2006). The DEM system consists of a series of elastic-frictional particles (Figure 7), where each particle moves independently, generating normal ($f_n$) and shear forces ($f_s$) in contact with neighboring particles (Figure 7). The normal forces ($f_n$) and shear forces ($f_s$) on particle interaction are calculated as:

$$f_n = k_n \delta_n,$$

$$f_s = k_s \delta_s,$$

where $k_n$ represents the normal interparticle stiffness, and $\delta_n$ denotes the amount of overlap between particles. In DEM, bonds are usually formed between particles to simulate the cohesion of natural rocks (Figure 7c). Bonds can deform under tensile and shear forces, and break when the forces exceed the tensile or shear strength of the particles (Guo & Morgan, 2004; C. Li et al., 2021; Morgan, 2015). The particles slide past each other, and faults begin to develop and grow when the following conditions are achieved:

$$f_s \leq \mu f_n,$$

where $\mu$ represents the friction on the particle surfaces. By calculating the combined forces on each particle, which mostly include gravity, interparticle contact forces, and the external forces exerted by the boundary wall, the displacement and velocity of each particle can be solved. In this study, we followed the concept of distortional strain defined by Morgan (2015) to illustrate strain and shear sense during structural deformation. In the output images from DEM, the distortional shear is displayed by color intensity, with red and blue indicating right and left sense of shear, respectively. The fault displacement is measured from certain marker layers in the model (Figure 7).

3.2. Experimental Design and Setup

3.2.1. Model Setup

The models are set up based on the interpretation of the seismic reflection profile L2 (Figure 5a) (Jia et al., 2010), and tectonic evolution of the Longmen Shan. Due to the intense erosion in the Late Cenozoic, the sedimentary

![Figure 7. Illustration of the discrete-element modeling (DEM) method used in the numerical simulation conducted in this study. (b) bond; $f_n$: normal stress; $f_s$: shear stress. This is the result of the model when the shortening amount is 15 km. Only the green layer is rheologically distinct.](image-url)
strata within hinterland of the Longmen Shan in the L2 profile are generally absent. Thus, structural recovery in this region is more uncertain. In contrast, the Pre-Jurassic strata are well-preserved in the Longmen Shan range front to foreland basin, including two detachments, that is, late Triassic evaporite sequence (Leikoupo Formation) and Precambrian metasedimentary rocks. Thus, we restored the structural profile from the Longmen Shan range front to foreland basin, and set the foreland basin to a total length of 120 km. Meanwhile, we set the dips angle of the basal and shallow detachments 3° to the west, based on the interpretation of the seismic profile L2.

The Precambrian Pengguan Complex rocks found in the central segment of the Longmen Shan, lack comparable sedimentary stratigraphy in the seismic reflection profile (Figures 1 and 6). For the hinterland of the central Longmen Shan, we referred to the estimated shortening of the balanced section of the southern segment, which is approximately 38.4 km (Z. Chen et al., 2005). We set the horizons of the hinterland to be horizontal with a total length of 60 km to ensure that it could completely absorb the structural shortening since the Late Triassic. The material properties (include the friction coefficient) used in the models were based on previous DEM simulation (C. Li et al., 2018, 2021; Morgan, 2015). The model was filled with particles that had grain sizes ranging between 60 and 80 m, a density of 2,500 kg/m³, a friction coefficient of 0.3, a shear modulus of 2.9 GPa, a Poisson ratio of 0.2, and a local damping coefficient of 0.4 (Table 1) (C. Li et al., 2018, 2021; Morgan, 2015). We used the nonlinear Hertz–Mindlin contact theory (Johnson, 1985) to calculate the interparticle contact forces. Gravity caused the particles to settle freely, and once they stabilized; they became bonded to one another. Young's modulus and the shear modulus for particle bonding were both set to 2.0 × 10^9 Pa. The tensile and shear strengths were set to 2.0 × 10^7 and 4.0 × 10^7 Pa, respectively.

### 3.2.2. Shortening Rate

Using the model, we set up a two-level detachment system with different mechanical strengths. The shallow detachment was set to a thickness of 500 m, which dips toward the hinterland at an angle of 3°, over a depth range of 6.7–1.4 km in the foreland region (Figure 8a; Table 1). The basal detachment, set at the bottom of the model, was horizontal in the hinterland, and dips 3° to the west in the foreland region. The particles representing the low-strength, shallow detachment within the basin were assigned a density of 2,200 kg/m³ and a friction coefficient of 0.2, with no interparticle bonding (Table 1) (C. Li et al., 2021; Maxwell, 2009; Morgan, 2015). After the particles were deposited and bonded, the left rigid wall moved to the right at a speed of 2 m/s, simulating tectonic forces that caused horizontal contractions and thrust faulting.

We set the compression rate to 2 m/s to ensure that the numerical simulation process was quasi-static and thus, suitable for modeling the evolution of tectonic deformation at a quasi-static process over geological scale in nature. The biaxial test results show that the peak stress of the specimen increased steeply when the compression rate was ≥2 m/s. However, the stress-strain curve did not change much when the rate was ≤2 m/s. The system's rate dependency is most likely caused by particle viscous damping, which supports a stable system by having no impact on particle behavior at adequate particle velocities (Morgan, 2015). Moreover, the strain rate has moderate effect on brittle frictional processes or strength, which is predominantly sensitive to pressure. Thus, even though the loading rate is significantly higher than the tectonic loading rates, the mechanical response should be valid. In addition, the calculation time will increase significantly when the compression rate is set at less than 2 m/s.

For the thin (average 200–300 m) detachment in the western Sichuan basin, the effect of compression rate on the structural style can be neglected. Due to the lack of well-preserved growth strata, it is difficult to constrain the change in structural shortening rate of Longmen Shan since 30 Ma. Thus, we set the compression rate to 2 m/s,

### Table 1

**Bulk Mechanical Properties Used for the DEM Simulations**

| Units                       | Particle properties | Interparticle bond properties | Macro parameters |
|-----------------------------|---------------------|-----------------------------|-----------------|
|                             | Friction coefficient| Density (kg/m³) | Young’s modulus (Pa) | Shear modulus (Pa) | Tensile strength (Pa) | Shear strength (Pa) | Cohesion C₀ (MPa) | Internal friction angle (φ) (°) |
| 1. Deep detachment          | 0.3                 | 2,500                      | 2.0E08           | 2.0E08            | 2.0E07               | 4.0E07               | 19.0           | 19.3                        |
| 2. Shallow detachment       | 0.0                 | 2,200                      | /               | /                | /                   | /                   | 2.5            | 5.8                         |
| 3. Cover and synkinematic sedimentation layer | 0.3             | 2,500                      | 2.0E08           | 2.0E08            | 2.0E07               | 4.0E07               | 19.0           | 19.3                        |

*Radii: 60/80 m, shear modulus: 2.9E09 Pa, Poisson's ratio: 0.2, and wall velocity: 2 m/s. *Morgan (2015).
which ensures that the simulation process is quasi-static. Moreover, the time and cost incurred are acceptable (C. Li et al., 2021; Morgan, 2015). The structural-deformation and distortional-strain results were recorded at a rate of one per 1 km of shortening during the experiment. We carried out two sets of comparative experiments, without and with surface processes (corresponding to Model I-1 and Model I-2, respectively), to investigate the interactions between structural deformations and surface processes in the central segment of Longmen Shan and WSFB.

3.2.3. Timing of Events

E. Wang et al. (2012) reported the exhumation history of the Pengguan Complex in the central segment of the Longmen Shan, revealing two phases of rapid uplift in Cenozoic. The first phase and second phase correspond between 30 and 20 Ma and from 15 to 10 Ma to the present day, respectively. We infer that widespread erosion may have started about 40–45 Ma from the eastern Sichuan Basin, which finally reached the western margin of the Sichuan Basin during ~30–20 Ma. This led to the first phase of rapid uplift of the Longmen Shan. The second phase of rapid uplift of Longmen Shan is inferred to be associated with the extensive erosion in the late Cenozoic (Godard et al., 2009; Liu-Zeng et al., 2009). Based on data from previous studies of low-temperature thermochronology (E. Wang et al., 2012) and tectonic evolution, we set up two stages of surface processes (syntectonic erosion and syntectonic sedimentation) in Model I-2 (Figures 5b and 5c). We thus, assigned the time ranges of the two-stage surface processes in Longmen Shan to 30–20 and 10–0 Ma.
We set the first phase of surface processes when Model I-2 was shortened to 15–20 km, corresponding to a geological time of ∼20–30 Ma. The materials in the hinterland were eroded and further deposited in the foreland portion following a prograding-sedimentation pattern (Fillon et al., 2013), with the average surface-slope angle of 1.4°. The second stage of surface processes that occurred during Model I-2 was shortened by 33–38 km, corresponding to a geological time of ∼10 Ma. During this stage, most of the Mesozoic sediments in the eastern Sichuan Basin were removed by the Yangtze River and gradually eroded westward toward the front of the Longmen Shan. The erosion rate varies at various locations in the Longmen Shan thrust belt to foreland basin, which reflects its enhanced erosion propagation from the basin to the orogenic belt. The model was subjected to syntectonic erosion and syntectonic deposition for every 1 km of shortening. The syn-kinematic erosion and sedimentation rates are provided in Figure S1 in Supporting Information S1.

3.2.4. Pre-Existing Shallow Detachment Geometry

The shallow detachment in the western Sichuan basin is composed of gypsiferous rocks of the Mid-Triassic Leikoupo Formation (Figure 3). The sedimentary facies map of this stratigraphic unit, which is constrained by limited drilling and exploration data, is illustrated in Figure 4 (He et al., 2019). The sedimentary facies transitions from marginal-platform shoal to inter-shoal to dolomitic flats to gypsiferous salt lakes from west to east (Figure 4). We set the trailing edge of the shallow detachment in the WSFB as the western boundary of the Mid-Triassic salt lake. The distance from the central and northern segments of the range front blind fault to the western boundary of the salt lake is approximately 5 and 10 km, respectively (Figure 4). In this study, we built a series of models (Model II), to examine the effect of the location of the trailing edge of the shallow detachment on the along-strike variation of thrusting propagation.

4. Experimental Results

We present in this section two series of DEM experiments, the first containing two comparative models with-surface and without-surface processes (Models I-1 and I-2), and the second serial of models (Model II) used to investigate the effect of the salt lake boundary on thrusting propagation. The distortional strain field is superimposed on the colored strata and the fault displacements for various faults during the progressive shortening of the models are also calculated (Figures 9 and 10; Movies S1 and S2).

4.1. Model I-1—No Surface Processes

Model I-1 (performed without surface processes) was characterized by a two-stage evolution, similar to other sandbox-analog modeling (Wu & McClay, 2011) of fold-and-thrust belts with two-level detachments. In the first stage, three fore-thrusts (T1–T3) formed above the basal brittle detachment and developed in a break-forward thrusting sequence (Figures 9a–9c; Movie S1). When the total shortening was 6 km, T1 started to form and continued to be active with a maximum displacement of approximately 4 km (Movie S1). T2 started to form when the shortening increased to 13 km and the displacement of T1 no longer increased (Figure 9b; Movie S1). T3 continued to absorb the fault displacement, reaching 11 km by the end of the experiment (Figure 9c; Movie S1). The onset of the second stage of tectonic-wedge evolution was indicated when the distortional strain propagated to the foreland basin along a shallow detachment (Figure 9c). We found that continued shortening produced four thrust faults above the shallow detachment, corresponding to T4–T7 from left to right (Figures 9d and 9e). These thrust faults formed sequentially in the foreland basin and exhibited distinct fault-related folding geometric patterns. T4 and T5 are back thrusts, whereas T6 and T7 form as pop-up structures. It is noteworthy that the evolutionary features of the thrust faults above the shallow detachment (T4–T7) differed from those above the basal detachment, even though they were found to generally follow the break-forward thrusting sequence. We found that several thrust faults exhibited simultaneous growth above shallow detachments (Figure 11). All fault displacements above the shallow detachments were < 4 km at the experimental end point, which was less than the T1–T3 displacements.

4.2. Model I-2—With Surface Processes

We found that Model I-2 (Figure 10) also exhibited a two-stage evolutionary process, similar to that of Model I-1. However, the quantity, geometry, and activity of the thrust faults formed in the thrust wedge differed significantly...
Figure 9. The progressive evolution observed in Model I-1 (conducted with five stages and no surface processes), with distortional strains superimposed on the colored strata. (a)–(e) The results of Model I-1 at total shortenings of 10 km (a), 15 km (b), 24 km (c), 30 km (d), or 35 km (e). T1–T7 denote thrust faults in the order of their formation. RFBT, Range Front blind thrust.
Figure 10. The progressive evolution observed in Model I-2 (conducted with five stages and surface processes), with distortional strains superimposed on the colored strata. (a)–(e) The results of Model I-2 at total shortenings of 15 km (a), 19 km (b), 31 km (c), 33 km (d), or 35 km (e). T1–T5 denote thrust faults in the order of their formation.
from those of Model I-1. T1 in Model I-2 shortened from 6 to 13 km and reached a steady state, similar to T1 in Model I-1. During this period, erosion occurred in the hinterland region, syn-kinematic sediments formed in a prograding pattern in the foreland basin region, and the toe of the sedimentary wedge expanded eastward (Figure 10a, Movie S2). Owing to the influence of erosion, T2 continues to be active and exhibits long-lived characteristics, reaching a fault displacement of approximately 8 km at a shortening of 25 km. RFBT T3 was formed much later than in Model I-1, occurring after shortening reached 26 km. Thereafter, the distortional strain was found to propagate along the shallow detachment into the foreland basin and form a back thrust fault (T4), located ~90 km from the range front (Figures 10c–10e). As the shortening increases to 32 km, widespread erosion processes occur in both the foreland basin and the hinterland region, and large volume of sediments was removed. We found that a thrust splay fault, T5, was formed at the range front (Figure 10d), whereas T1 and T2 in the interior were reactivated. In the second phase of the surface process, T1 and T2 in the hinterland increased the fault displacement by 0.3 and 1 km, respectively, and T3 and T5 in the range front increased the fault displacement by 1.1 and 1.6 km, respectively (Figure 11). At the experimental end point (s = 38 km), all faults were actively slipping (Figure 11) with total displacements of 4.2, 9.5, 6.8, 3.9, and 2.9 km for T1, T2, T3, T4, and T5, respectively (Figure 11b). Eventually, all faults in the fold-and-thrust belt system of Model I-2 were found to be simultaneously active. Notably, in contrast to Model I-1, we found that no internal shortening structures in foreland region between T5 and T4 are formed in Model I-2 (Figure 10e).
4.3. Model II

We conducted five groups of experiments to investigate the influence of the locations of the shallow detachment on the structural evolution of the Longmen Shan fold-and-thrust belt and WSFB. The starting position of the boundary of the shallow detachment is defined as $X_i$ and is located at the transverse coordinates $X_i = 0, 40, 60, 70$, and $80$ km (Figure 8). The detailed structural modeling results are shown in Figures 12 and 13, corresponding to shortening amounts of 15 and 25 km, respectively.

Overall, our modeling suggests that the boundary of the Mid-Triassic gypsiferous salt lake profoundly influences the rate of thrusting propagation from the hinterland region to the foreland basin (Figures 12 and 13). Specifically, the western boundary of the shallow detachment in the WSFB affects the initial location of the Range Front blind thrust of Longmen Shan. In addition, the western boundary of shallow detachment affects the structural style of thrusts in the hinterland region. If the shallow detachment extends up to the baffle boundary ($X_i = 0$ km), a thrust-duplex structure will eventually form in the hinterland (Figure 13a). In contrast, if the starting positions of the shallow detachment are set at $X_i = 40$ and $60$ km, the hinterland region will form an imbricate thrust structure with no roof thrust development (Figures 13b and 13c). When the $X_i$ is set at 70 and 80 km, an imbricate thrust structure formed in the hinterland, while a gently dipping shallow detachment developed in the foreland basin (Figures 13d and 13e). Notably, when the model was shortened to 25 km, there was no fault slip propagation from hinterland into the foreland basin (Figures 13d and 13e), but rather several back-thrust faults (T4 in Figure 13d) formed above the basal detachment in the range front. In the northern Longmen Shan (Figure 5b), the gypsiferous Salt Lake boundary is relatively distant (40 km) from the Range Front and total shortening in Cenozoic is low (<10 km) (Z. Chen et al., 2005). Furthermore, we observed that geological slip is not transported to the foreland basin. Instead, some back thrust faults are formed above the basal detachment in the northern Range front, which is consistent with interpretations of seismic reflection profiles (Figure 5b).

5. Discussions

We discuss three aspects of the main geological questions of the Longmen Shan fold-and-thrust belt summarized in Section 1. This involves the Longmen Shan: (a) thrusting sequence and deformation processes; (b) fault activity and seismic hazard; and (c) structural variability along strike.

5.1. Surface Processes and Thrusting Sequences

Previous studies investigated the effects of surface processes on critically tapered Coulomb wedges and analyzed their influences on thrusting propagation and geometries of thrust-related folds (Hoth et al., 2006; Konstantinovskaia & Malavieille, 2005; Upton et al., 2009; Wilcox et al., 2013; Wu & McClay, 2011). They found that syntectonic erosion and syntectonic sedimentation play important roles on the fault activities and thrusting sequences of critically tapered Coulomb wedges. With no surface processes, the fold-and-thrust belt follows a general forward-breaking sequence with synchronous thrust fault activity. While surface processes in general caused the model to experience differential erosion and sedimentation, which influenced the distribution of deformation in various parts of the tectonic system. For instance, syntectonic erosion in the hinterland enhanced the activity of thrust faults in this region while inhibiting forward propagation of thrusts in the foreland region. In contrast, syntectonic sedimentation in the foreland promoted the self-similar growth of the critically tapered Coulomb wedges, decreased the number of major forward-vergent thrusts, and inhibited the activity of thrusts in the foreland basin.

The results of our simulations showed that both Models I-1 and I-2 contain two individual critically tapered Coulomb wedges, one developed above the brittle detachment in the hinterland and the other formed above the ductile detachment in the foreland. These two detachments show different fault strength and basal detachment dips. In Model I-1 (with no surface processes), structural deformation exhibited characteristics of a forward-break thrusting sequence (Figure 9). The model results showed that the strain propagates along the weak and shallow detachment into the basin and thrust faults and their related folds are mainly formed in the range front. Model I-2 (with surface processes) generally exhibited out-of-sequence thrusting sequence features (Figure 10). In the first stage of syntectonic sedimentation, the surface slope angle of the foreland thrust belt in Model I-2 increased to 1.5° ($\alpha$), and the total angle of thrust-wedge system ($\alpha + \beta$, and $\beta = 3\degree$) increased to 4.5° (Figure 10). We found that the detachment slip rapidly propagated into the interior of the basin, forming the back thrust T4, located ~100 km...
Figure 12. Comparative deformation results of the DEM experiments (Model II) for the initial position ($X_i$) of the shallow detachment at the transverse coordinates 0, 40, 60, 70, and 80 km, respectively, at a shortening amount is 15 km. $X_i$, initial position of the western boundary of shallow detachment.
Figure 13. Comparative deformation results of the DEM experiments (Model-II) for the initial position ($X_i$) of the shallow detachment at the transverse coordinates 0, 40, 60, 70, and 80 km, respectively, at a shortening amount is 25 km.
away from the range front (Figures 10 and 14). These results indicate that the hinterland-tapered Coulomb wedge is in a supercritical state in the first stage and that the deformation propagates forward along the detachment into the foreland basin to reduce the wedge angle, thus achieving a critical state. Previous studies show that continued shortening of the supercritical wedge will cause rapid advance of the deformation front or extensional collapse in the hinterland, which will both lead to a decrease in the wedge angle ($\alpha + \beta$) and thus return to the critical state (Davis et al., 1983; Platt, 1986). This also indicates that the foreland region is in a subcritical state and favors thrusting, thus with the deposition of syntectonic sedimentation in the basin, detachment slip propagates forward along the shallow detachment, but is limited to the outer edge of the newly deposited sediments. Under the second stage of erosion in Model I-2, the surface slope angle of the wedge decreases dramatically and evolves into a subcritical state. Therefore, additional internal shortening must be accommodated within the hinterland-tapered Coulomb wedge to reach the critical state.

Combined with low-temperature thermochronological studies (e.g., Jia et al., 2020; Shen et al., 2019; E. Wang et al., 2012), our DEM models show the dynamic processes and interactions of fault activities, syntectonic erosion, and sedimentation of central segment of Longmen Shan in late Cenozoic. During the first stage, intensive exhumation occurred in the hinterland of the Longmen Shan, approximately 30–20 Ma. The YBT and PGT faults were highly active, and the exhumed material was subsequently transported to the foreland basin area and then deposited (Figure 10). During the second stage, ~20–10 Ma, surface processes were relatively quiescent, the hinterland thrust-wedge system gradually reached a critical or supercritical state, and the activities of the YBT and PGT Faults decreased. The structural strain propagated through the RFBT above the shallow detachment of the foreland thrust belt, forming a back thrust (the Longquan Fault) in the interior of the Sichuan Basin (Figure 10). In the third stage, from ~10 Ma to the present, under the widespread westward erosion trend of the
Sichuan Basin, massive sediments were removed from the WSFB and the hinterland of the Longmen Shan. The tectonic activity retreated to the hinterland of Longmen Shan, and the YBT and PGT Faults were reactivated (Figures 10 and 14). Meanwhile, in the WSFB, the RFBT and Longquan Faults continued to sustain simultaneous activities. These DEM results demonstrate that the present-day Longmen Shan fold-and-thrust belt develops in an out-of-sequence thrusting manner.

### 5.2. Fault Activity and Seismic Hazards

Based on our DEM modeling and Coulomb critical-wedge theory, we propose a new model that correlates the erosion/uplift rates, inter-seismic deformation rates, and tectonic activities of the Longmen Shan and WSFB. Figure 15a shows a composite cross-section that extends across the eastern margin of the Tibetan Plateau, including the erosion/uplift rates (A), inter-seismic deformation rate (B and C), structural profile (D) perpendicular to...
the strike of the faults in Longmen Shan (data collected from Godard et al., 2009; Du et al., 2009). As shown in Figure 11a, at the geologic scale (since 10 Ma), large-scale propagation of erosion from the Sichuan Basin toward the Plateau increases rapidly, with less than 0.5 mm/a in the range front and foreland basin, and greater than 1.0 mm/a in the Longmen Shan thrust belt (Godard et al., 2009). In our DEM experiment of surface processes, the imposed syn-tectonic erosion follows a similar distribution pattern in the WSFB and Longmen Shan thrust belt (Figure S1 in Supporting Information S1). We thus inferred that since the Late Cenozoic (~10 Ma), intensive denudation in the Longmen Shan hinterland caused a wedge in a subcritical state (Godard et al., 2009, 2010; Shen et al., 2019). The reactivation of faults within the Longmen Shan thrust belt enhanced the vertical uplift of the wedge and reduced its lateral propagation to the foreland. Global Positioning System (GPS) monitoring between 1997 and 2007 shows a steady downward trend in the shortening rate between the Longriba fault and the Longmen Shan range front, and a steady state on either side of it (Figure 15c) (Du et al., 2009). Combined with recent earthquakes (2020 Ms 5.1, 1967 Ms 5.5) (Wang & Lin, 2017; Zhao et al., 2021) occurred in the Longquan fault in the WSFB, these data also indicate that the northern part of the western Sichuan foreland thrust-wedge is active. In addition, vertical uplift rates across the Longmen Shan obtained using leveling surveys before the 2008 Wenchuan earthquake show rapid uplift in the Longmen Shan hinterland region located over 200 km west of the plateau margin, whereas extremely slow uplift is observed in the frontal-range fault and central fault of the Longmen Shan (Du et al., 2009) (Figure 15b). This indicates that these faults in the Longmen Shan were locked in several decades before the 2008 Wenchuan Mw 7.9 earthquake.

Previous findings related to recent geological periods of denudation and the distribution of landslides following the Wenchuan earthquake suggest that the Longmen Shan is now undergoing an accelerated erosion process. The 2008 Mw 7.9 Wenchuan earthquake produced nearly 56,000 landslides (Dai et al., 2011), and the subsequent aftershocks and the 2013 Mw 6.6 Lushan earthquake caused landslides, which also caused significant short-term mass loss and accelerated the denudation rate (Ouimet, 2010; Parker et al., 2011). In addition, enhanced denudation can also cause weak weatherable rocks to be exposed to the ground, leading to further rapid surface denudation (Koons et al., 2012; Zeitler et al., 2001). These factors contribute to accelerated surface processes in the Longmen Shan that affect the evolution of the critically tapered Coulomb wedge, as well as internal faults, on various time scales. At the geologic scale of 1–10 Ma, accelerated surface processes can localize structural deformation within the thrust-wedge system and affect strain localization among the hinterland and foreland portions (Beaumont et al., 2001; Cruz et al., 2010; Dahlen & Barr, 1989; Willett, 1999). At the 10 kyr to 1 Ma time scale, accelerated surface processes can initiate the slipping of individual faults within the thrust-wedge system (Cattin & Avouac, 2000; Maniatis et al., 2009; Vernant et al., 2013). At short time scales (0.1–1 kyr, accelerated surface processes can trigger rapid changes in stress states within the critical tapered Coulomb wedge, sufficient to cause seismic fault slip and generate surface ruptures (Steer et al., 2014). Therefore, it is important to consider the intensities and spatial-temporal distributions of the surface processes, as well as their roles in fault activities and structural evolution in fold-and-thrust belts.

5.3. Influence of Salt Lake Boundary on Thrusting Propagation

The along-strike structural variation of fold-and-thrust belts and its relation to the seismotectonic models has been a general interest. In particular, the over 200 km surface rupture generated by the 2008 Mw 7.9 Wenchuan earthquake also exhibits along-strike structural kinematics variability (Hubbard et al., 2010; Jia et al., 2010; Liu-Zeng et al., 2009; Xu et al., 2009). This illustrates the importance of exploring the relationship between preexisting thrusts structures and modern seismotectonic model in the Longmen Shan and adjacent WSFB. The structural deformation in the northern segment of Longmen Shan is mainly concentrated in the foothills and exists in the pattern of imbricate structures and structural wedges (Figure 5b). In contrast, in the central-southern Longmen Shan, structural shortening is propagated into the WSFB through shallow detachment, forming extensive thrust fault-related folds in the region (Figure 5c). In past studies, the northern and southern segmental variability in the Longmen Shan were mainly understood from the perspective of orogenic belts. For example, the rapid uplift of the Minshan (Figure 1) during the Late Cenozoic may have shielded the transfer of crustal shortening to the northern Longmen Shan, resulting in only limited (<10 km) shortening being absorbed in this segment (Burchfiel et al., 1995; S. F. Chen et al., 1994).

Here, we attempt to explain why geologic slip did not enter the northwest Sichuan Basin from the perspective of internal factors in the sedimentary basin. As shown in Figure 4, the distance between the western boundary of the
salt lake in the southwestern Sichuan basin and Longmen Shan range front is ∼5–10 km, while in the northern Longmen Shan, the boundary of the salt lake in the basin is farther from the range front, reaching ∼30 km. Our DEM simulations show that this salt lake boundary poses important influences on the rate of thrusting propagation and faults structure in the Longmen Shan foothills. In the southern Longmen Shan, it shows imbricate structures and duplex thrusts are formed in the hinterland and range front, and geologic slip has propagated into the foreland basin (Figures 13a–13c). In the northern segment, compressional deformation is concentrated in the hinterland and range front, and fault slip does not enter the foreland basin. Instead, it forms back thrust faults above the basal detachment in the range front (Figures 13d and 13e). These simulations reveal the correlation between the structural variation along the Longmen Shan and the Mesozoic salt lake boundary. This suggests that the internal factors (such as the distribution of evaporite sequence or rock strengths) within the sedimentary basins should not be ignored in the analysis of thrusting propagation from the orogenic hinterland to the foreland basin.

5.4. Model Limitations

In this study, we conducted DEM simulations to explore the influence of surface processes and preexisting shallow detachment on the thrusting sequence and fault structure of the Longmen Shan fold-and-thrust belt. However, as with general geological physical and numerical modeling, the rock strength and boundary conditions in the models are based on simplified assumptions. Because of the limitations of DEM modeling and the lack of quantitative constraints on the geological processes of the Longmen Shan, the following factors were not considered in our DEM simulation:

First, the effects of preexisting rock strength contrasts between the Proterozoic basement and young sedimentary rocks were not considered in the modeling. This is manifested in the contacted relationship between the Proterozoic basement Pengguan Complex in the central Longmen Shan and the sedimentary rocks in the WSFB. However, it is uncertain whether the Pengguan Complex involved a paleo-uplift or was formed by exhumation during the Cenozoic. In future studies, a high/low rock strength contrast between the basement and sedimentary cover needs to be modeled to simulate its effect on thrusting propagation. Second, we focused on the role of upper crustal-scale shortening and did not evaluate the contribution of lower-crustal flow or pure shear thickening models at the lithosphere level (e.g., Clark et al., 2000). In addition, we did not consider the effects of variations in shortening, sedimentation rates relative to the geologic timescale on the modeling results. This is because the availability of these geological parameters is limited owing to the lack of well-preserved Cenozoic syntectonic sedimentation records in the Longmen Shan range front (Burchfiel et al., 1995). Third, the effect of syntectonic deposition and erosion on the flexural isostatic of the lithosphere was not considered in this modeling. Although the current Longmen Shan lacks prominent foreland flexure, this does not imply that flexure isostatic and rebound of the lithosphere did not occur during the Cenozoic. In physical and numerical geological modeling, the flexural isostatic response of the lithosphere can be simulated using a flexible plate that allows a progressive basal tilt (Hoth et al., 2006; Simpson, 2006; Stockmal et al., 2007). In future studies, it is recommended to consider the role of these factors coupled with the structural deformation and geomorphic evolution of the Longmen Shan in the eastern margin of the Tibetan Plateau.

6. Conclusions

Based on DEM simulations, we reveal the interaction between thrusting propagation and surface processes, and its influence on modern seismicity in the Longmen Shan fold-and-thrust belt and its adjacent WSFB. Based on our study results, we obtain the following conclusions:

DEM simulations without surface processes indicated that the fold-and-thrust belt developed in an in-sequence thrusting manner. In contrast, DEM simulations with surface processes revealed that the Longmen Shan fold-and-thrust belt developed in an out-of-sequence manner during the late Cenozoic. Starting at ∼30–20 Ma, rapid denudation processes occurred in the Longmen Shan hinterland, and the YBT and PGT Faults continued to be active. From ∼10 Ma to the present, large-scale propagation of denudation occurred from the Sichuan Basin toward the Tibetan Plateau, and tectonic activity retreated to the hinterland of Longmen Shan. Surface processes were relatively quiescent between these two stages, structural shortening propagated forward through the RFBT, and formed the Longquan Fault in the Sichuan basin.
Instrumental and historical earthquakes indicate that the frontal faults in the WSFB and the imbricate faults in the Longmen Shan hinterland region are simultaneously seismically active. We interpret that the activity of the Coulomb wedge of the Longmen Shan is related to the latest stage of surface process. Since ~10 Ma, large and widespread propagation of erosion from the Sichuan Basin toward the eastern Tibet Plateau caused the Longmen Shan hinterland to enter a subcritical state. The reactivation of reverse faults in the hinterland enhanced the rapid uplift of the Longmen Shan and inhibited most of its slip lateral propagation to the foreland basin. The WSFB is currently in a critical state, with wedge slides occurring steadily along the shallow detachment, with the occurrence of frequent, small-moderate earthquakes in the frontal thrust.

The distribution of Mesozoic salt lakes in the interior of the Sichuan Basin influenced the location, rate, and structural style of thrust slip that propagated from the Longmen Shan hinterland to the foreland basin. Our simulations indicate that the front blind thrust of Longmen Shan range gradually connects the basal detachment and shallow detachment in foreland, and its position is controlled by the western boundary of the salt-leaf. Results of comparative experiments show that fault slips from the hinterland of Longmen Shan entered the southwestern Sichuan basin extensively to form several thrust fault-related folds above shallow detachment. However, slip in the northern Longmen Shan was confined to the range front and did not propagate into the northwest Sichuan basin. This suggests that the structural variability along the strike in the Longmen Shan can be explained from the perspective of the internal factors of the Sichuan basin.

Data Availability Statement

The authors used VBOX version 2.1 (C. Li et al., 2021; https://geovbox.com/en/) for the discrete-element method (DEM) numerical simulations. Numerical simulations were conducted at the High-Performance Computing Center (HPCC), Nanjing University. The code for our DEM experiments can be obtained from Open Science Framework (Model I-1, no surface processes, https://osf.io/tz2qq; Model I-2, with surface processes, https://osf.io/pa9sy).

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References

Beaumont, C., Jamieson, R. A., Nguyen, M. H., & Lee, B. (2001). Himalayan tectonics explained by extrusion of a low-viscosity crustal channel coupled to focused surface denudation. Nature, 414(6865), 738–742. https://doi.org/10.1038/414738a
Blank, D. G., & Morgan, J. K. (2019). Precursory stress changes and fault dilation lead to fault rupture: Insights from discrete element simulations. Geophysical Letters, 46(6), 3180–3188. https://doi.org/10.1029/2018GL081107
Burbidge, D. R., & Braun, J. (2002). Numerical models of the evolution of accretionary wedges and fold-and-thrust belts using the distinct-element method. Geophysical Journal International, 148, 542–561. https://doi.org/10.1046/j.1365-246x.2002.01579.x
Burchfiel, B. C., Royden, L. H., van der Hilst, R. D., Hager, B. H., Chen, Z., King, R. W., et al. (2008). A geological and geophysical context for the Wenchuan earthquake of 12 May 2008, Sichuan, People’s Republic of China. Geological Society of America Today, 18, 4–11. https://doi.org/10.1130/GSATG18A.1
Burchfiel, B. C., Zhihliang, C., Yuping, L., & Royden, L. H. (1995). Tectonics of the Longmen Shan and adjacent regions, Central China. International Geology Review, 37, 661–735. https://doi.org/10.1080/0020681950465424
Cattin, R., & Avouac, J. P. (2000). Modeling mountain building and the seismic cycle in the Himalaya of Nepal. Journal of Geophysical Research: Solid Earth, 105, 13389–13407. https://doi.org/10.1029/2000Jb900032
Chen, S. F., Wilson, C. J. L., Deng, Q. D., Zhao, X. L., & Zhi, L. L. (1994). Active faulting and block movement associated with large earthquakes in the Min Shan and Longmen Mountains, northeastern Tibetan Plateau. Journal of Geophysical Research: Solid Earth, 99(B12), 24025–24038. https://doi.org/10.1029/94JB02132
Chen, Z., Burchfiel, B. C., Liu, Y., King, R. W., Royden, L. H., Tang, W., et al. (2000). Global Positioning System measurements from eastern Tibet and their implications for India/Eurasia intercontinental deformation. Journal of Geophysical Research, 105, 16215–16227. https://doi.org/10.1029/2000Jb000992
Chen, Z., Jia, D., Zhang, Q., Wei, G., Li, B., Wei, D., & Shen, Y. (2005). Balanced cross-section analysis of the fold – Thrust belt of the Longmen Shan. Acta Geologica Sinica, 79, 38–45.
Clark, M. K., & Royden, L. H. (2000). Topographic oases: Building the eastern margin of Tibet by lower crustal flow. Geology, 28, 703. https://doi.org/10.1130/0091-7613(2000)200<0703:TOBEEM>2.0.CO;2
Clark, M. K., Schoenbohm, I. M., Royden, L. H., Whipple, K. X., Burchfiel, B. C., Zhang, X., et al. (2004). Surface uplift, tectonics, and erosion of eastern Tibet from large-scale drainage patterns. Tectonics, 23, 1–21. https://doi.org/10.1029/2002TC001402
Cruz, L., Malinski, J., Wilson, A., Take, W. A., & Hilley, G. (2010). Erosional control of the kinematics and geometry of fold-and-thrust belts imaged in a physical and numerical sandbox. Journal of Geophysical Research: Solid Earth, 115, B09404. https://doi.org/10.1029/2010JB007472
Cui, J., Jia, D., Yin, H., Chen, Z., Li, Y., Wang, M., et al. (2020). The influence of a weak upper ductile detachment on the Longmen Shan fold-and-thrust belt (eastern margin of the Tibetan Plateau): Insights from sandbox experiments. Journal of Asian Earth Sciences, 198, 104220. https://doi.org/10.1016/j.jseaes.2020.104220
Cundall, P. A., & Strack, O. D. L. (1979). A discrete numerical model for granular assemblages. Geotechnique, 29, 47–65. https://doi.org/10.1680/geo.1979.29.1.47
Dahlen, F. A., & Barr, T. D. (1989). Brittle frictional mountain building I. Deformation and mechanical energy budget. Journal of Geophysical Research, 94, 3906–3922. https://doi.org/10.1029/JB094iB04p03906
Meng, Q., & Hodggetts, D. (2019). Structural styles and decoupling in stratigraphic sequences with double décollements during thin-skinned contractional tectons: Insights from numerical modelling. *Journal of Structural Geology*, 127, 103862. https://doi.org/10.1016/j.jsg.2019.103862

Morgan, J. K. (2015). Effects of cohesion on the structural and mechanical evolution of fold and thrust belts and contractual wedges: Discrete element simulations. *Journal of Geophysical Research: Solid Earth*, 120, 3870–3896. https://doi.org/10.1002/2014JB011455

Ouimet, W. B. (2010). Landslides associated with the May 12, 2008 Wenchuan earthquake: Implications for the erosion and tectonic evolution of the Longmen Shan. *Tectonophysics*, 491, 244–252. https://doi.org/10.1016/j.tecto.2009.09.012

Parker, R. N., Densmore, A. L., Rossier, N. J., De Michele, M., Li, Y., Huang, R., et al. (2011). Mass wasting triggered by the 2008 Wenchuan earthquake is greater than orogenic growth. *Nature Geoscience*, 4, 449–452. https://doi.org/10.1038/ngeo1154

Platt, J. P. (1986). Dynamics of orogenic wedges and the uplift of high-pressure metamorphic rocks. *The Geological Society of America Bulletin*, 97(9), 1037–1053. https://doi.org/10.1130/0016-7606(1986)97<1037:doowat>2.0.co;2

Richardson, N. J., Densmore, A. L., Seward, D., Fowler, A., Wipf, M., Ellis, M. A., et al. (2008). Extraordinary denudation in the Sichuan Basin: Insights from low-temperature thermochronometry adjacent to the eastern margin of the Tibetan Plateau. *Journal of Geophysical Research*, 113, B04409. https://doi.org/10.1029/2006JB004739

Richardson, N. J., Densmore, A. L., Seward, D., Wipf, M., & Yong, L. (2010). Did incision of the Three Gorges begin in the Eocene? *Geology*, 38, 551–554. https://doi.org/10.1130/G30527.1

Robert, A., Pubellier, M., De Sigoyer, J., Vergne, J., Lahfid, A., Cattin, R., et al. (2010). Structural and thermal characters of the Longmen Shan (Sichuan, China). *Tectonophysics*, 491(1–4), 165–173. https://doi.org/10.1016/j.tecto.2010.03.018

Shen, X., Tian, Y., Zhang, G., Zhang, S., Carter, A., Kohm, B., et al. (2019). Late Miocene hinterland crustal shortening in the Longmen Shan thrust belt, the eastern margin of the Tibetan Plateau. *Journal of Geophysical Research: Solid Earth*, 124(11), 11972–11991. https://doi.org/10.1029/2019JB018358

Sun, C., Jia, D., Yin, H., Chen, Z., Li, Z., Shen, L., et al. (2016). Sandbox modeling of evolving thrust wedges with different preexisting topography: Implications for the Longmen Shan thrust belt, eastern Tibet. *Journal of Geophysical Research: Solid Earth*, 121, 4591–4614. https://doi.org/10.1002/2016JB013013

Tian, Y., Kohn, B. P., Gleadaw, A. J., & Hu, S. (2013). Constructing the Longmen Shan eastern Tibetan Plateau margin: Insights from low-temperature thermochronology. *Tectonics*, 32(3), 576–592. https://doi.org/10.1002/tect.20043

Upton, P., Mueller, K., & Chen, Y. G. (2009). Three-dimensional numerical models with varied material properties and erosion rates: Implications for the mechanics and kinematics of compressive wedges. *Journal of Geophysical Research: Solid Earth*, 114(B4), B04408. https://doi.org/10.1029/2008JB005708

Vernant, P., Hivert, F., Chéry, J., Steer, P., Cattin, R., & Rigo, A. (2010). Structural and thermal characters of the Longmen Shan mountain ranges. *Geology*, 38, 551–554. https://doi.org/10.1130/G33942.1

Wang, E., Kirby, E., Furlong, K. P., Van Soest, M., Xu, G., Shi, X., et al. (2012). Two-phase growth of high topography in eastern Tibet during the Cenozoic. *Geology*, 40, 915–918. https://doi.org/10.1130/G35809.1

Wang, M., & Lin, A. (2017). Active thrusting of the Longquan Fault in the central Sichuan basin, China, and the seismotectonic behavior in the Longmen Shan fold-and-thrust belt. *Journal of Geophysical Research: Solid Earth*, 122, 5639–5662. https://doi.org/10.1002/2016JB013391

Wessel, P., & Smith, W. H. (1995). The generic mapping tools, GMT, version 3: Technical reference and cookbook. School of Ocean and Earth Science and Technology, University of Hawaii at Manoa.

Wilcox, T., Mueller, K., Upton, P., Powell, L. K., Chen, Y. G., Huang, S. T., et al. (2013). Structural inheritance and erosional controls on thrust kinematics in Western Tibet. *Geosphere*, 9(4), 1091–1101. https://doi.org/10.1130/geo2013-0819.1

Willett, S. D. (1999). Orogey and orography: The effects of erosion on the structure of mountain belts. *Journal of Geophysical Research: Earth Moana*, 104, 28957–28981. https://doi.org/10.1029/1999jb900248

Wu, J. E., & McClay, K. R. (2011). Two-dimensional analog modeling of fold and thrust belts: Dynamic interactions with syncontractional sedimentation and erosion. *AAPG Memorial, 303–333*. https://doi.org/10.1130/12513133M9450

Xu, X., Wen, X., Yu, G., Chen, G., Klinger, Y., Hubbard, J., & Shaw, J. (2009). Coseismic reverse- and oblique-slip surface faulting generated by the 2008 Wwenschuan earthquake, China. *Geology*, 37, 515–518. https://doi.org/10.1130/G25462A.1

Yamada, Y., Babb, K., & Matsuoka, T. (2006). Analogue and numerical modelling of accretionary prisms with a décollement in sediments. *Geological Society, London, Special Publications*, 253, 169–183. https://doi.org/10.1144/GSL.SP.2006.253.01.09

Zeilier, P. K., Meltzer, A. S., Koons, P. O., Crawford, D., Hallet, B., Chamberlain, C. P., et al. (2001). Erosion, himalayan geodynamics, and the geomorphology of the himalaya. *Geological Society of America Today*, 11, 4. https://doi.org/10.1130/0252-5173(2001)011<0004:EHGATG>2.0.CO;2

Zhang, Z.-Z., Shen, Z., Wang, M., Gan, W., Bürgmann, R., Molnar, P., et al. (2004). Continuous deformation of the Tibetan Plateau from global positioning system data. *Geology*, 32, 809. https://doi.org/10.1130/G20554.1

Zhang, Z., Zhang, H., Wang, L., Cheng, H., Shi, Y., & Leroy, Y. M. (2018). Concurrent deformation in the Longmen Shan and the Sichuan Basin: A critical wedge captured by limit analysis. *Tectonics*, 37, 283–304. https://doi.org/10.1029/2017TC004791
Zhao, M., Long, F., Yi, G., Liang, M., Xie, J., & Wang, S. (2021). Focal mechanism and seismogenic structure of the MS5.1 Qingbaijiang Earthquake on February 3, 2020, Southwestern China. *Frontiers of Earth Science, 9*, 360. https://doi.org/10.3389/feart.2021.644142

Zheng, H., Clift, P. D., He, M., Bian, Z., Liu, G., Liu, X., et al. (2021). Formation of the first bend in the late Eocene gave birth to the modern Yangtze River, China. *Geology, 49*(1), 35–39. https://doi.org/10.1130/g48149.1

Zheng, H., Clift, P. D., Wang, F., Tada, R., Jia, J., He, M., & Jourdan, F. (2013). Pre-miocene birth of the Yangtze River. *Proceedings of the National Academy of Sciences of the United States of America, 110*(19), 7556–7561. https://doi.org/10.1073/pnas.1216241110