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Late Cenozoic denudation by large-magnitude landslides in the eastern edge of Tibetan Plateau

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Abstract

Eastern edge of the Tibetan Plateau is marked by the Longmen Shan, which experienced pronounced denudation in late Cenozoic and was previously attributed to river erosion. Our recent work, however, demonstrated that the landsliding must have played an important integral role in the surface processes. Various-scale landslides are present in the peripheral zone of the southern Longmen Shan, which were interpreted as overthrust-related klippen in previous works. We revisited these exotic blocks, and demonstrated that they were actually gravity-driven landslides in origin. The landslides are composed mostly of thick-bedded marine limestone and sandstone of Paleozoic–Early Triassic ages, and were detached along some weak zones like Lower Silurian phyllite and unconformities. Three types of landslides can be categorized, distributed, stacked, and coherent, and their differential occurrence is considered to bear upon both uplift rates of the Longmen Shan and foreland topography. Outward flow of lower-crustal materials from the Tibetan Plateau interior provides a feasible mechanism for initiating the uplift of its eastern flank in Cenozoic. Positive feedbacks are believed to have existed between extrusion of lower-crustal channel flow and surface denudation processes. Rapid denudation by large-magnitude landslides in conjunction with coeval river erosion in the southern Longmen Shan might have led to predominant sub-vertical extrusion of lower-crustal flow channel, as evidenced by nearly symmetric exhumation of the Pengguan massif. The northern Longmen Shan was comparatively less denuded, with few basement rocks cropping out, and landslides are absent in its front as well. Differential denudation between the southern and northern Longmen Shan might have in large part resulted from the lower-crustal flow that presumably moved to the southeast and had less impact on the northern Longmen Shan.

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Keywords: Tibetan Plateau; Longmen Shan; Cenozoic; denudation; landslide

1. Introduction

The Tibetan Plateau is considered to have expanded by lateral growth in the Cenozoic [1–3], and its present margins therefore serves as one of the ideal regions for studying how the plateau develops. Eastern flank of the Tibetan Plateau is marked by the Longmen Shan, which

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is now topographically expressed as a steep escarpment adjacent to the Sichuan basin on the east (Fig. 1). It is shown that, following a slow cooling process from late Mesozoic to early Tertiary, the eastern margin of the Tibetan Plateau commenced an accelerating uplift since ~23 Ma [4,5]. Recent investigation further indicates that inception of rapid cooling (>30–50 °C/my) occurred no older than late Miocene or early Pliocene along the Longmen Shan, with high denudation rates up to 2 mm/yr [6]. Erosional denudation is estimated to have led to the removal of ~8–10 km of sediments and resulted in deep exhumation of middle-crustal rocks [6]. Late Cenozoic denudation was demonstrated to have been heterogeneous across the eastern margin of the Tibetan Plateau, with high rates along its present narrow flank or the Longmen Shan [4]. In reality, the denudation was also differential along the strike of the Longmen Shan, as manifested by high elevation and pronounced exhumation of the Pengguan and Baoxing metamorphic massifs in its southern segment, and low elevation and few exposures of crystalline basement rocks in the north (Figs. 1 and 2).

Late Triassic crustal shortening of the Songpan–Ganzi terrane and transpressional deformation in the Longmen Shan have been investigated [7–10], and relevant granitoid magmatism and Barrovian-type metamorphism have also been documented [11,12]. Another two metamorphic events were recently recognized in the Danba dome ~100 km west of the Baoxing massif, one occurring at circa 168–158 Ma [11] and the other at circa 65 Ma [13]. By restoring sedimentary history of the northwest Sichuan basin, Meng

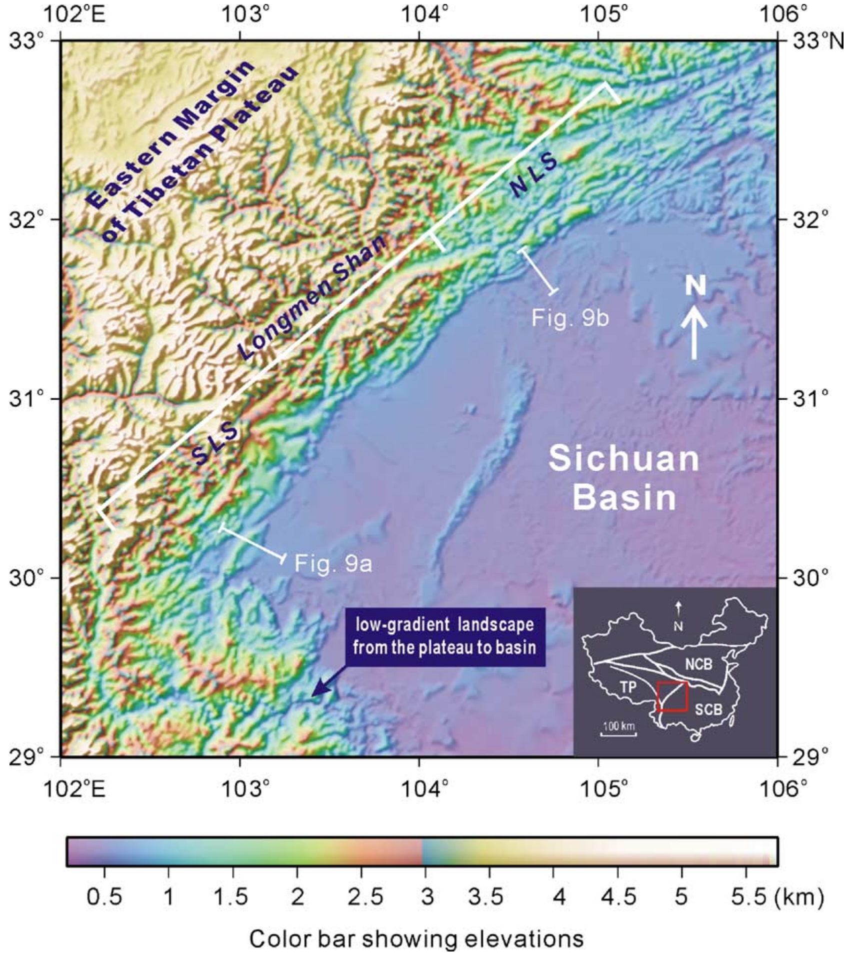

Fig. 1. Image of topography of the eastern margin of the Tibetan plateau and adjacent Sichuan basin. Note sharp change in elevations from the Sichuan basin and eastern edge of the plateau or the Longmen Shan, as well as differential elevation between the southern Longmen Shan (SLS) and northern Longmen Shan (NLS). Abbreviations in inset map: NCB—North China block; SCB—South China block; TP—Tibetan plateau. Also noticeable is gradual transition from southeastern margin of the plateau to the Sichuan basin.

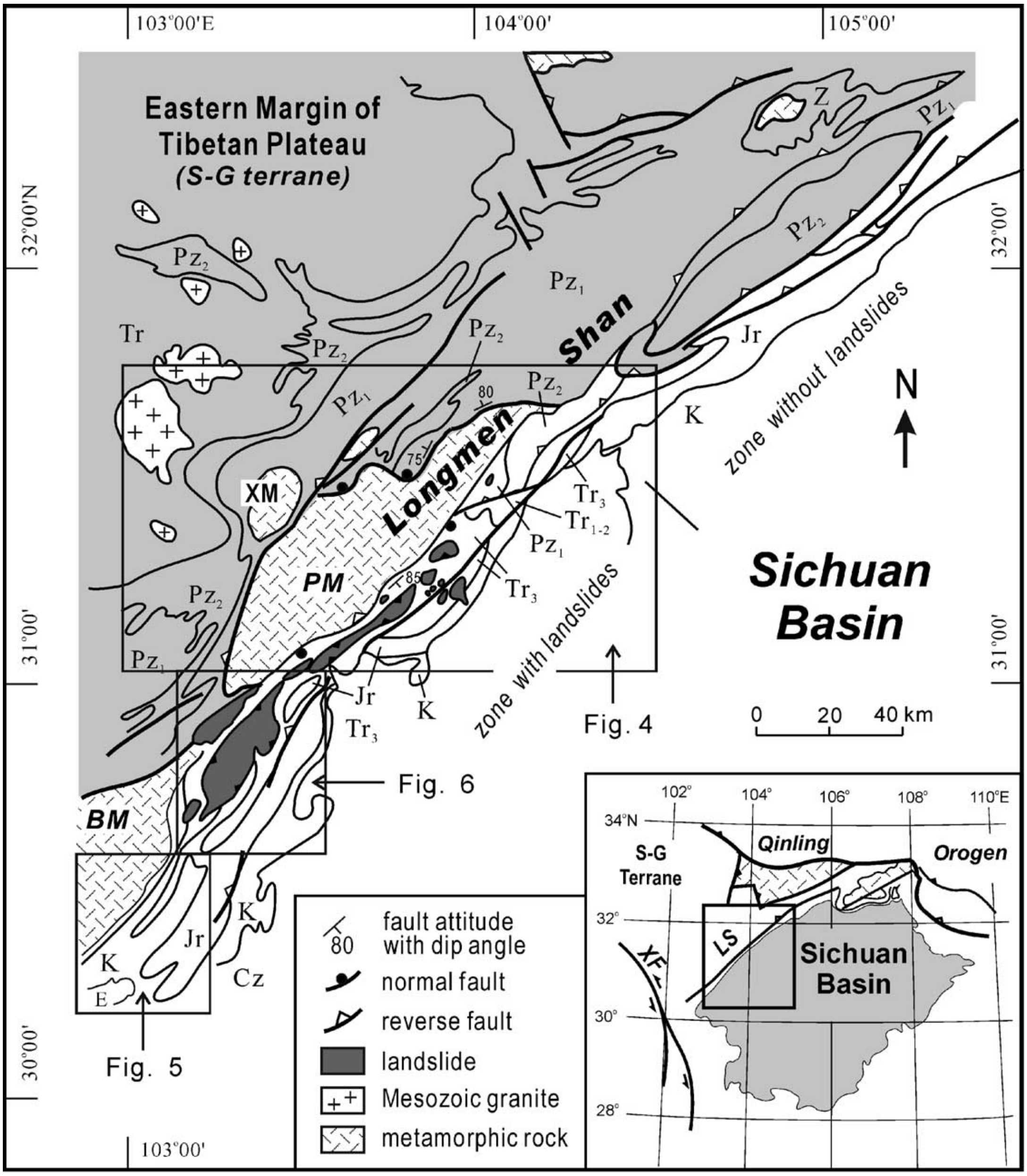

Fig. 2. Simplified geologic map of the Longmen Shan and adjacent regions. Note that the basement metamorphic rocks crop out only in the southern Longmen Shan with various-scale landslides present in its peripheral zone. In contrast, the northern Longmen Shan is devoid of basement exposures and free of landslide in its front. Abbreviations: PM—Pengguan massif; BM—Baoxing massif; XY—Xuelongbao massif; S-G—Songpan–Ganzi; XF—Xianshuihe fault; Z—Sinian (Upper Neoproterozoic); Pz_1—lower Paleozoic; Pz_2—upper Paleozoic; Tr—Triassic (Tr_1, Tr_2, Tr_3, representing Lower, Middle, and Upper Triassic), Jr—Jurassic (Jr_1, Jr_2, Jr_3, representing Lower, Middle, and Upper Jurassic); K—Cretaceous (K_1, K_2, representing Lower and Upper Cretaceous); E—Paleocene to Eocene; Cz—Cenozoic.

et al. [14] stated that active transpressional deformation might have been renewed along the Longmen Shan since the Middle Jurassic after a period of tectonic quiescence in the Early Jurassic, and was active throughout late Mesozoic. Late Mesozoic sinistral shearing along the Wenchuan-Maowen fault zone of the Longmen Shan was constrained by $^{40}Ar/^{39}Ar$ dating of muscovites, yielding ages of 131 ± 0.5 Ma and 119 ± 1.1 Ma [4], and the synchronous deformation also developed in the eastern Sichuan basin, as manifested by thin-skinned fold–thrust systems involving strata as young as the Upper Jurassic [15]. Magnitude of Mesozoic uplift and pristine topography remain uncertain of the eastern margin of Tibet, though the recorded Barrovian metamorphic events imply that the crust had become considerably thick prior to the rapid uplift in late Cenozoic [13].

Present-day topography of the Longmen Shan was mainly established during late Cenozoic [6], but accompanied with no large-magnitude crustal shortening [8,16–18]. Lower-crustal ductile flow is assumed to move from the Tibetan Plateau interior to its flank in response to topographically induced differential pressure and was diverted upward as meeting adjacent rigid basement of the Sichuan basin [19,20]. The lower-crustal flow has been invoked to account for the growth of conspicuous steep landscape of the Longmen Shan [19,20]. Focused denudation by river erosion was considered responsible for exhumation of the middle crust there [21,22]. Late Oligocene normal faulting was identified on the western side of the elongate Pengguan massif [23], and thought to have presumably played a part in promoting the massif uplifting [8]. In this contribution, we show that the large-magnitude landsliding must have played an important integral role in exhuming the middle crust at the eastern flank of the Tibetan Plateau in conjunction with simultaneous river erosion. We also suggest that there existed positive feedbacks between the rapid denudation by the coupled landsliding and river erosion and the lower-crustal ductile flow in the structural and topographic development of the Longmen Shan.

2. Reassessing the exotic blocks

To the east of the southern Longmen Shan exists a zone of exotic blocks of varying scales (Fig. 2), which are composed of Paleozoic–Lower Triassic units and a few crystalline basement rocks (Fig. 3). These exotic blocks were previously assumed to have resulted from sporadic eastward overthrusting during Late Triassic to Miocene times [7,9]. Late Triassic crustal shortening was obvious in the eastern margin of the Tibetan Plateau, as evidenced by emplacement of fold–thrust

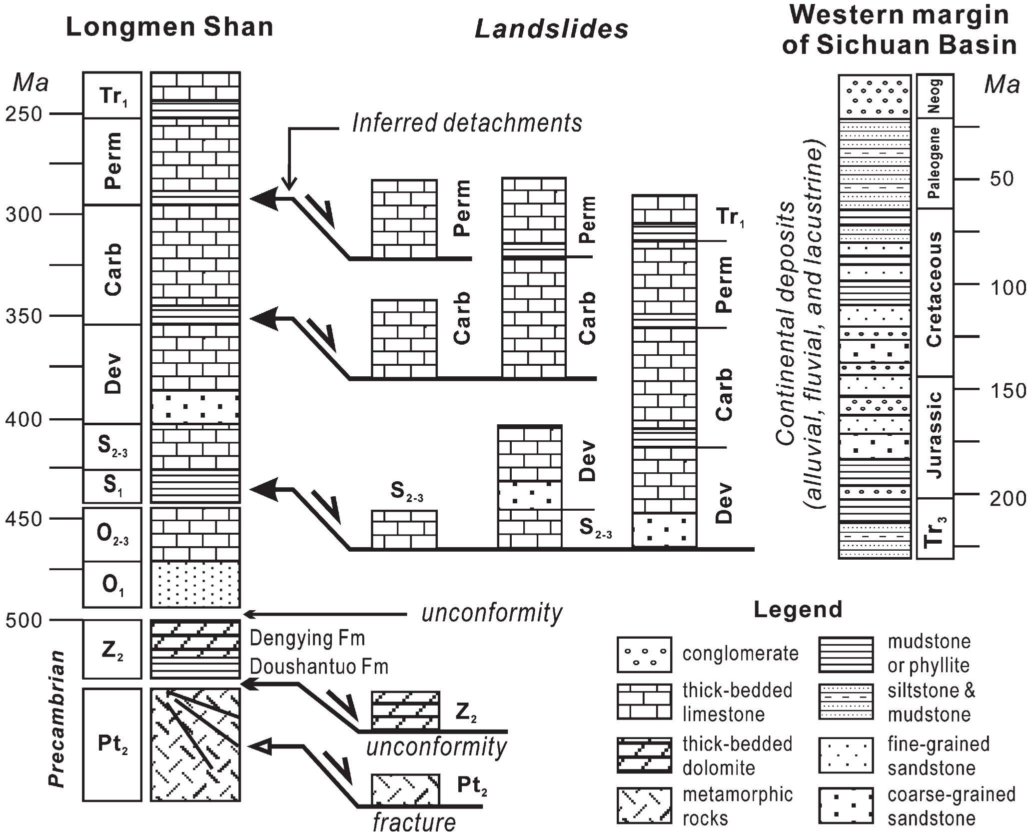

Fig. 3. Stratigraphy of the Longmen Shan, the western Sichuan basin, and the landslides. Abbreviations: Pt_2—Mesoproterozoic; Z_2—Upper Sinian; O—Ordovician (O_1, O_{2-3}, representing Lower and Mid-Upper Ordovician); S—Silurian (S_1, S_{2-3}, representing Lower and Mid-Upper Silurian); Dev—Devonian; Carb—Carboniferous; Perm—Permian. Refer to Fig. 2 for explanations of other abbreviations.

system in both the Songpan–Ganzi terrane [24,25] and the Longmen Shan [7,8] as well as synchronous flexural subsidence of western Sichuan basin [14,26,27]. Late Mesozoic–Cenozoic overthrusting event, however, has been a matter of controversy. The exotic blocks was speculated to have resulted from the Cenozoic overthrusting, but this speculation conflicts with the following facts: (1) there is no geologic evidence in support of Cenozoic large-scale overthrusting in the eastern flank of Tibet, though early Tertiary folding did occurred in front of the southernmost Longmen Shan [8]; (2) geodetic measurements indicate that active shortening across the Longmen Shan is insignificant [16–18]; (3) the exotic blocks consist exclusively of pre-Upper Triassic rocks, with no involvement of younger units, which should have been present if the strong over-thrust had occurred in late Cenozoic; and (4) there developed no Cenozoic peripheral foreland basins east of the Longmen Shan, which should normally form in response to tectonic loads imposed by the postulated thrust sheets. All these facts are at odds with previous interpretations that ascribed the exotic blocks to the

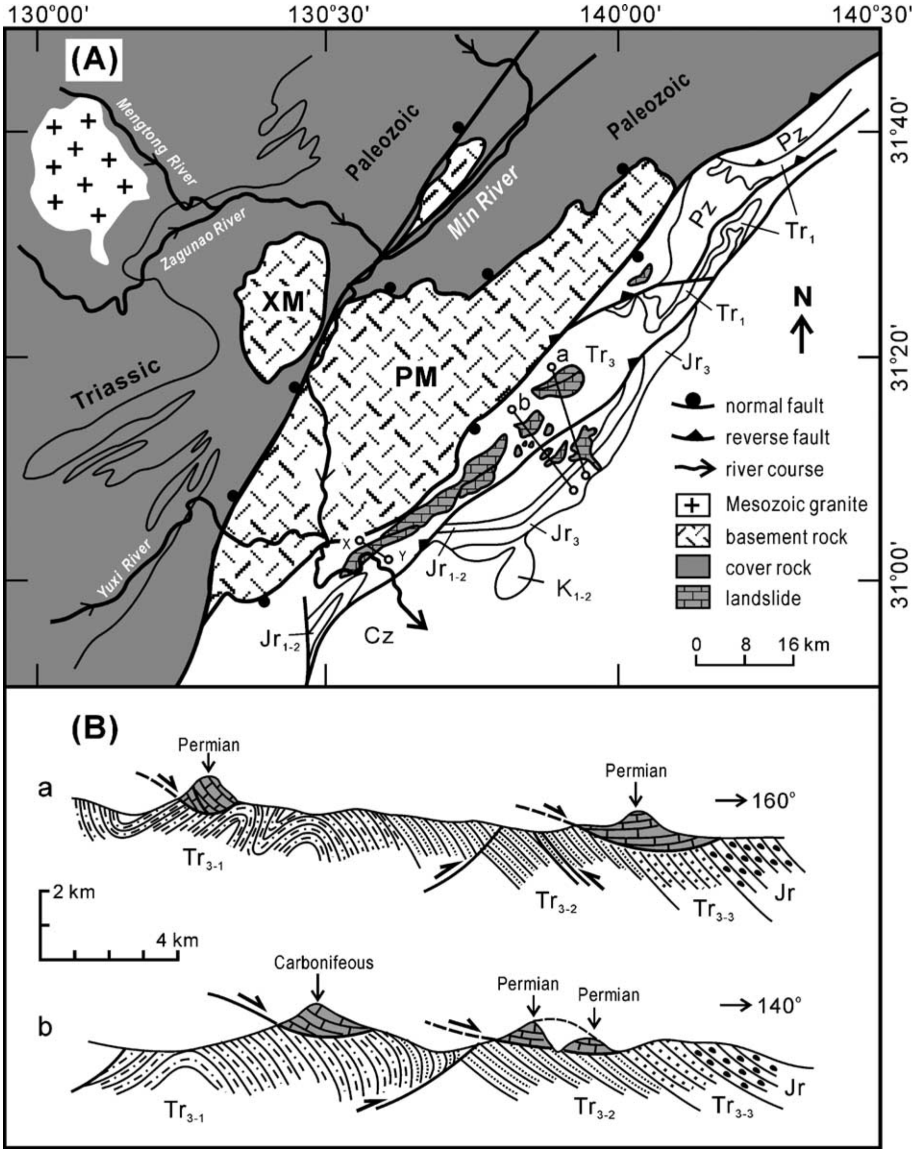

Fig. 4. Diagram showing spatial distribution of landslides in front of the Pengguan massif (A) and sections illustrating relationships between landslides and underlying deformed Mesozoic units (B). Noting that some individual landslides occur as independent ones (section a), while others presumably resulted from post-landslide channelization (section b). Refer to Figs. 2 and 3 for explanations of abbreviations.

Cenozoic eastward overthrusting. Some blocks were once attributed to gravitational instability, but the sliding processes were not explored in detail [28,29].

We recently carried out an investigation of these exotic blocks in an attempt to unravel their origin. Our observations further invalidate previous interpretation that the exotic blocks were the products of sporadic Cenozoic eastward overthrusts. Our rationales are as follows: (1) All the blocks occur in topographic lows rather than atop hills, contrasting with the common occurrence of thrust-related klippen; and (2) Various-scale normal brittle faults and related deformations develop in the rear and middle potions of some large blocks, though reverse faults typify their leading edges. This kind of internal strains is hardly explained by overthrust processes but well compatible with gravity-induced landsliding processes [30]. As a result, we argue that all the exotic blocks were best explained as the consequence of gravitational landsliding rather than the products of overthrusting. We will deal with the landslides in detail in the following sections.

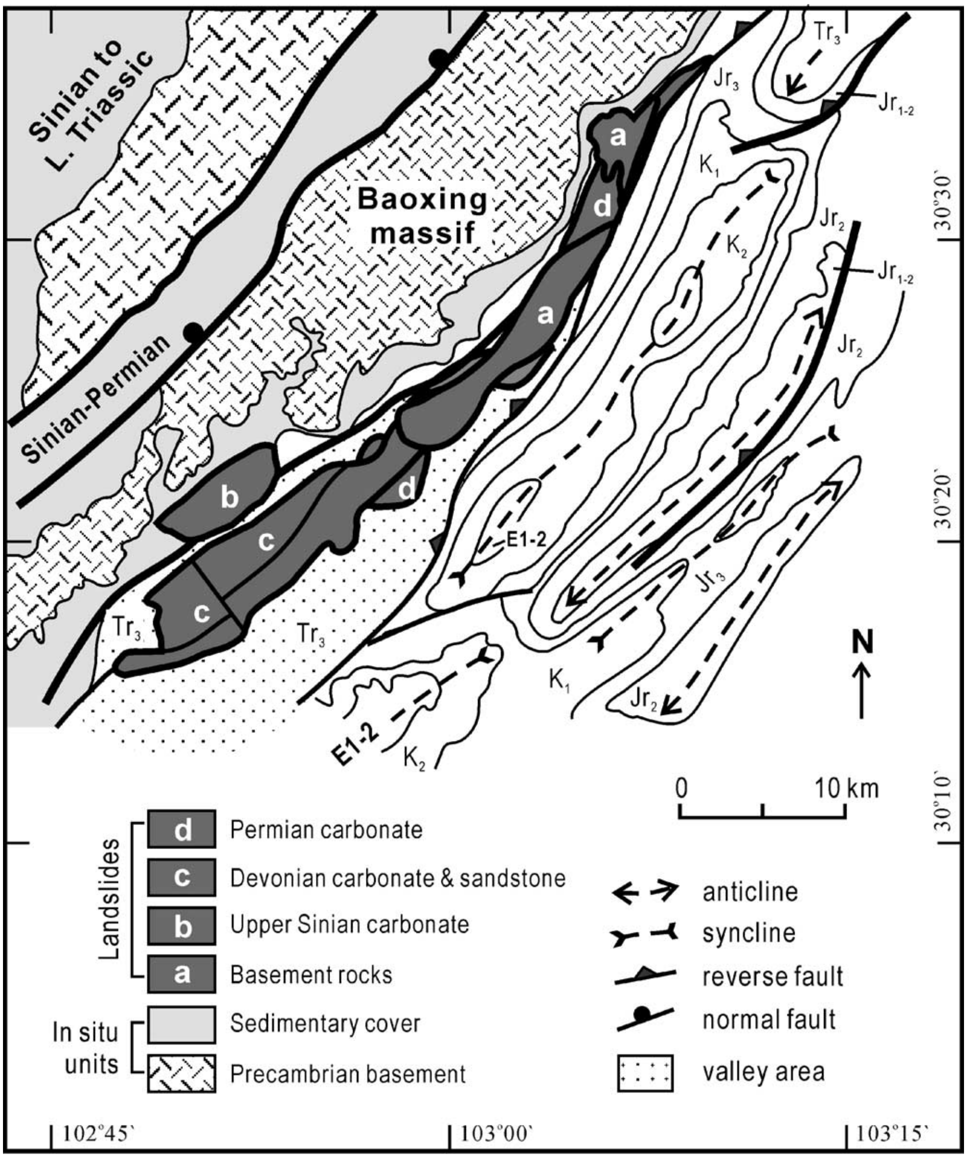

Fig. 5. Diagram illustrating occurrence of stacked landladies east of the Baoxing massif. The stacking is quite evident in the northern narrow segment of the valley. On the east exists a topographic high constructed by folded Jurassic–Eocene strata (also see Fig. 1). Refer to Figs. 2 and 3 for explanations of abbreviations.

3. Occurrence of landslides

3.1. Components of landslides

The landslides are composed of a variety of rocks, most of which are marine sedimentary units ranging from the late Neoproterozoic to Early Triassic in age. Landslides in front of the Pengguan massif consist exclusively of Devonian to Lower Triassic marine strata, with Lower Devonian unit composed mostly of quartz arenites and the Middle Devonian to Lower Triassic consisting of thick-bedded limestone (Figs. 3 and 4). The sedimentary facies associations and sequences can be well correlated with their counterparts in the Longmen Shan (Fig. 3). The landslides east of the Baoxing massif, in comparison, show relatively diverse rock types, made up of Mesoproterozoic metamorphic rocks, Upper Sinian (latest Neoproterozoic) dolomite, and Middle Silurian to Permian sandstone and limestone (Fig. 5). The metamorphic rocks are comparable with the Baoxing complex, and the sedimentary units are well correlated with coeval strata atop and around the Baoxing massif in both sedimentary facies and sequences (Fig. 3). On account of their spatial relationships, the landslides can be in general categorized into three main types: coherent, distributed, and stacked.

3.2. Coherent landslide

Some individual landslides are gigantic and relatively less fragmented, with the largest up to ~150 km^2 in area (Fig. 6). The giant coherent landslides normally occur in the region where few Mesoproterozoic

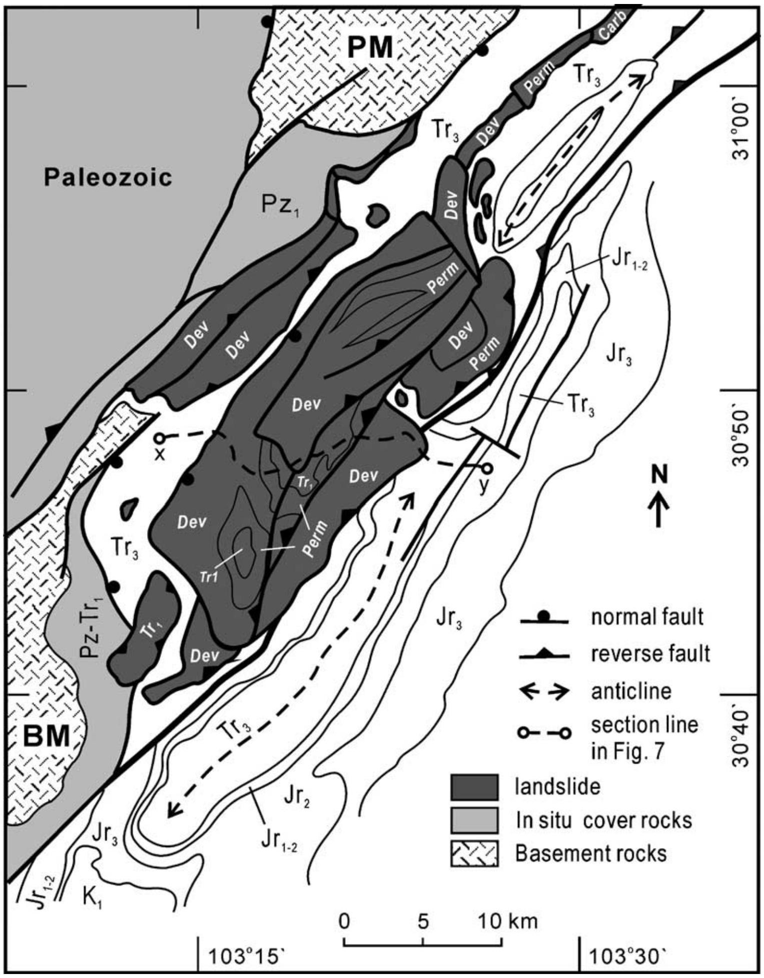

Fig. 6. Diagram showing coherent large-scale landslides that occur in front of the segment of the southern Longmen Shan where basement rocks are less exhumed in comparison with adjacent Pengguan and Baoxing massifs. Refer to Figs. 2 and 3 for explanations of abbreviations.

metamorphic rocks are exposed in the adjacent Longmen Shan. The landslides are composed of differing successions from the Upper Sinian to Silurian, or from the Middle Silurian to Devonian, or from the Permian to Lower Triassic units, with no weak units involved, such as Lower Silurian phyllites. Some giant landslides internally manifest themselves as synclines as a whole, and are often sliced by both along-strike and transcurrent faults. Fig. 7 represents a section across one of the landslides to show internal variation of strains. Extensional and contractional deformations typify the trailing and leading portions of the landslide, respectively, as convincingly indicated by normal faults or resultant Z-shaped drag folds (Fig. 7A,B) in the rear and reverse fault zone in the front (Fig. 7C).

3.3. Distributed landslides

There occur various-scale landslides that are scattered widely in front of the Pengguan massif, showing a variety of shapes in plain view, elongated, ellipsoid, or quite irregular (Fig. 4). The landslides range in size from ~80 km^2 to <1 km^2. Most of the landslides are near the Pengguan massif, overlying deformed Upper Triassic Xujiahe Formation, but some are located relatively far away, sitting on the folded Jurassic sequence (Fig. 4). Larger landslides proximal to the Pengguan massif manifest themselves as synclines or broken synclines, whereas distal ones display few synclinal structures (Fig. 4). Similar to the landslides of coherent group, some larger landslides display spatial variations

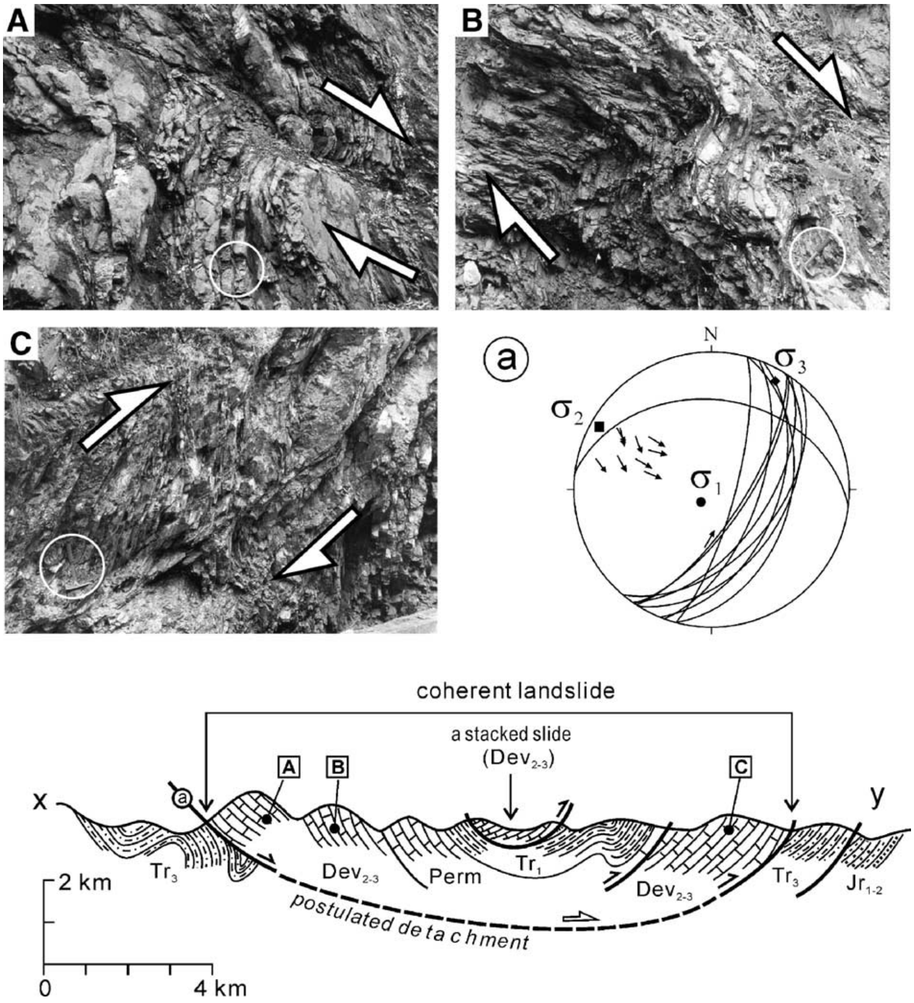

Fig. 7. Diagram showing cross-sectional structures of a gigantic coherent landslide. Of significance is internal strain variation from extension in the rear to contraction in leading edge. Extension is verified by normal fault (A) and drag fold (B), while contraction is evidenced by reverse fault zone (C). Basal detachment fault is analyzed (circled a), indicating a normal-sense movement. Hammer in photos (circled, 35 cm long) for scale. Refer to Fig. 6 for location of the section, and Figs. 2 and 3 for abbreviations of stratigraphic units.

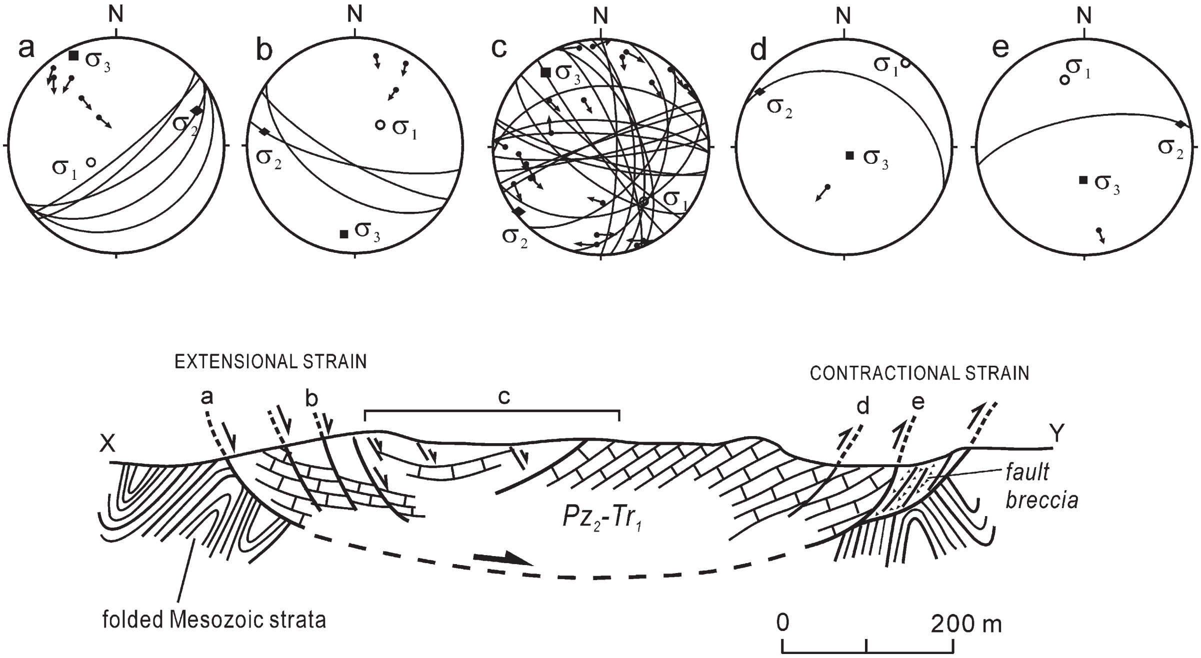

Fig. 8. Cross section of a landslide showing strain variation from extension in rear to contraction in leading edge. Strain analysis is carried out, as represented by Lower Hemisphere, equal-area stereographic projections of faults at different localities. Noting that σ_3 (least principal stress) in a, b and c are sub-horizontal, indicating dominance of extensional regime in the rear, whereas σ_1 (greatest principal stress) is orientated sub-horizontally in d and e, suggesting a state of compression in the frontal part. Arrow indicates displacement vector, with dot ends being poles of corresponding fault planes. Refer to Fig. 4 for location of the section.

of strains from extension in the rear and middle portions to contraction in their leading edges (Fig. 8).

3.4. Stacked landslides

East of the Baoxing massif exist a number of landslides that are superposed over one another and confined within a valley (Fig. 5). The superposition is quite evident in the northern narrow portion of the valley, with individual landslides being relatively smaller. The landslides become larger and coherent toward the southeast as the valley gets wider in that direction, and the superposition rarely occurs there (Fig. 5). In some cases, the stacked landslides show a vertical succession with the lower units composed of younger rocks and the upper consisting of older rocks. For instance, the lower landslides are usually Permian and Lower Triassic units, whereas the overlying units are the Devonian, or even Proterozoic metamorphic rocks (Fig. 5).

4. Landslide development

4.1. Original positions of landslides

In situ successions from Upper Sinian to Lower Triassic strata are well preserved in the Longmen Shan (Figs. 2 and 3), and their stratigraphy and sedimentary facies have been well studied [31,32]. The depositional sequences are built up primarily of shallow-marine siliciclastics and carbonates, except for the Lower Silurian unit that are dominated by dark-gray phyllite and thin-bedded limestone (the Maoxian Group), representing deep-marine deposition. Middle and Upper Silurian units are present in the southern Longmen Shan and characterized by thick-bedded limestone, contrasting with Lower Silurian fine-grained facies. Stratigraphic correlations of the landslides with the in situ units demonstrate that the landslides were undoubtedly derived from different parts of the Upper Sinian to Lower Triassic successions of the Longmen Shan (Fig. 3).

It is appreciable that, if a landslide is composed of a stratigraphic succession, there is no Lower Silurian phyllite involved that is, however, well preserved in the Longmen Shan (Fig. 3). It is rationalized that the Lower Silurian phyllite might have functioned as a lubricating zone for the slipping-off of overlying thick-bedded sandstone or limestone. Another plausible sliding surface is the unconformity between metamorphic basement and Sinian cover units that consist dominantly of thick-bedded dolomite (the Dengying Fm) in the upper and phyllite and thin-bedded limestone at its lower portions (the Doushantuo Fm). The contrasting lithologies would permit Upper Sinian dolomite to be easily detached from underlying metamorphic basement, in particular, on the presence of phyllite in between. Pre-existing fractures within the Pengguan and Baoxing massifs were also probably utilized as sliding surfaces and led to the stripping-off of the metamorphic blocks.

4.2. Controls on development of diverse landslides

As described above, the landslides can be divided into three types. The distributed landslides come about in a relatively wider zone east of the Pengguan massif, where there exist no striking topographic highs (Fig. 1). In contrast, the stacked landslides took place in a narrow zone that is confined by the southern Longmen Shan on the west and a prominent topographic high on the east (Fig. 1). The topographic high is constructed by the folded Jurassic–Eocene succession. The coherent landslides develop in the areas where some topographic highs do exist on the east, but stand some distance away from the Longmen Shan (Fig. 5).

It is interpreted that the distributed landslides were the result of unrestrained translation of the various-scale detached blocks. Two factors probably allow the detached blocks to travel a relatively long distance: high-rate uplifting of the Longmen Shan so as rapidly to create a great hillslope gradient, and no barriers in the way to stop the landslides from traveling basinwards. Profound uplift and marked denudation of the Longmen Shan have been demonstrated [6] and can be also readily inferred by the exhumation of metamorphic complex to the west of the region where distributed landslides occur (Fig. 4). Smaller landslides scattering in distal area are thought to have multiple origins. They might have come about as individual landslides, or resulted from dismemberment of the moving landslides, or arisen from segmentation by post-landslide channelization of large landslides (Fig. 4B).

Strikingly, the landslides are stacked on the floor of a narrow valley to the east of the Baoxing massif, and bounded on the east by a topographic high (Figs. 5 and 9a). Occurrence of metamorphic landslides indicates that the Baoxing massif underwent marked denudation as well. Superposition of the older over the younger slides implies an unroofing process by virtue of sequential detachment of in situ sequences. It is considered that the stacking bears primarily upon two factors: the existence of a topographic high on the east that impeded translation of the landslides, and the continued uplift of the Baoxing massif that sustained a steep hillslope and thus facilitated repetitive detachment of overlying units.

Large-scale landslides usually display relatively coherent internal structures and appear proximal to the southern Longmen Shan, indicating a short-distance translation. Less displacement of coherent landslides might be in part pertinent to the existence of topographic highs on the east that hampered the traveling of landslides. However, the topographic highs ahead of coherent landslides usually appear some distant away, and thus seems to have not exert a direct influence of landslide movement. Fig. 6 shows that the southern Longmen Shan adjacent to a gigantic coherent landslide did not experience marked uplift and strong denudation, as indicated by relatively low elevation (Fig. 1) and limited exhumation of metamorphic basement (Figs. 2

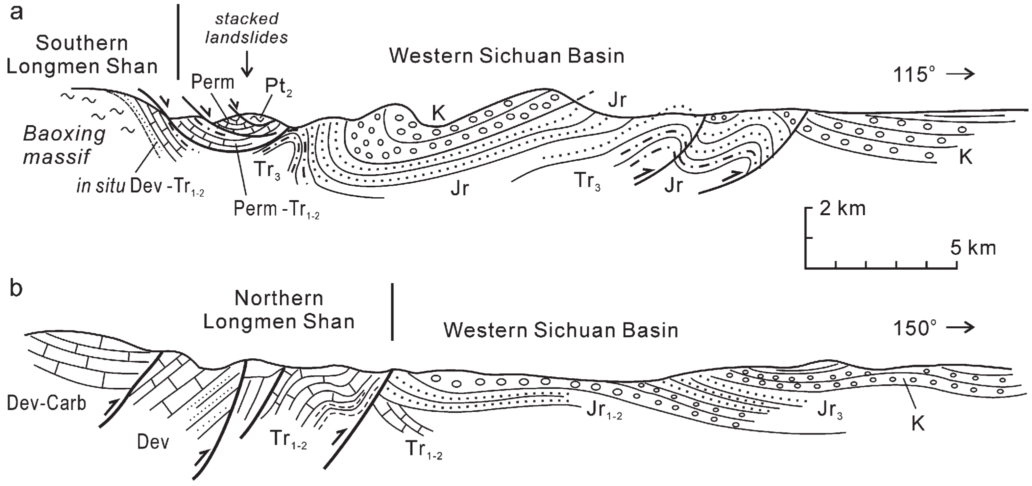

Fig. 9. Cross sections showing relatively strong folding in front of the southern Longmen Shan (a), contrasting to the gentle folds in front of the northern Longmen Shan (b). Refer to Fig. 1 for locations of the two sections.

and 6). It is accordingly regarded that large coherent landslides were unable to travel a long distance by virtue of their less potential energy and comparatively low-gradient hillslope. The synclinal structures of some larger landslides are thought to be the relics of Mesozoic deformation because they are quite similar to the in situ synclines formed in the Mesozoic in the northern Longmen Shan [8,9].

4.3. Timing of the landsliding

The timing of landsliding has not been precisely constrained, but it should not have happened until late Tertiary in general. The rationale is based on the following two observations: (1) Upper Jurassic strata and overlying continuous Cretaceous–Eocene sequences are folded concordantly (Fig. 4). The fact that some landslides rest over the Upper Jurassic unit therefore implies that the folding must have taken place prior to the landsliding, or the landsliding should occur after the post-Eocene folding event. (2) The topographic highs, which are constructed by folded sequences as young as the Eocene in the zone east of the Baoxing massif (Fig. 5), apparently retarded landslide movement, thereby suggesting a post-Eocene age of the landsliding. (3) In addition, it is conceivable that the landsliding should have come along roughly synchronous with rapid uplifting of the Longmen Shan. Denudation and exhumation of the Longmen Shan have been shown to take place in the Oligocene [4] and accelerate since late Miocene–Pliocene times [5,6], and implicitly the landslides were prone to take place in this time interval.

5. Denudation processes

It was documented recently that the Longmen Shan has been experiencing large-magnitude exhumation from depths of ~8–10 km at high rates of 1–2 mm/yr since the late Miocene or early Pliocene, as recorded by rapid denudation event in that region [6]. The pronounced denudation was considered to be primarily the result of river erosion [6,21]. Our study show that, coupled with river erosion, gravity-driven landsliding must have played an integral role in the exhumation of the Longmen Shan.

Given that it was coincident with rapid cooling event of the Longmen Shan, the landsliding might be in part responsible for rapid removal of the supra-crustal materials originally atop the Pengguan and Baoxing massifs. Considering that some landslides can be as large as up to 150 km^2 in area, large portions of mountainsides must have been stripped from the Longmen Shan by massive landslides. Being a process of delivering materials en masse and much more effective in exhuming deep-seated crustal rocks to the surface [33], the landsliding thus provides a feasible explanation for high-rate exhumation of the Longmen Shan since the Miocene. In comparison, denudation by river erosion is incremental and therefore leads to relatively steady exhumation.

Interestingly, landslides are only present in the peripheral zone of the southern Longmen Shan, and absent in front of the northern segment where basement rocks are rarely exposed (Fig. 2). This spatial distribution of landslides hints at a genetic link between the landsliding of supra-crustal materials and the exhumation of deep-seated basement rocks. Differential exhumation rates in eastern margin of Tibet have been revealed by the studies of apatite fission track and ^{40}Ar/^{39}Ar and (U–Th)/He thermochronology [4,6], clearly demonstrating that denudation was more rapid in the south than in the north [6]. This phenomenon further suggests that denudation by landsliding must have played a crucial role in exhuming the southern Longmen Shan, and permits us to hold that the southern Longmen Shan was denudated by a coupled action of landslide and river erosion, whereas the denudation in the northern Longmen Shan might have only arisen from river erosion.

Denudation by rivers might be overwhelming prior to the initiation of the landsliding, though it was still vigorous synchronous with the landsliding. In addition, river erosion could become more significant after the episodes of landslides, since isostatically induced uplift can intensify continuous incision of rivers and the erosional fluxes out of the Longmen Shan. The Min River, draining along the western side of the Longmen Shan in its upper and middle reaches and running across the Pengguan massif in its lower reach, should have contributed considerably to the erosional denudation. The river valley is as deep as 300 m in its middle and lower reaches, thereby indicating the significance of river erosion. Another case of denudation by river erosion can be exemplified by exhumation of the Xuelongbao massif (Fig. 4), in that the edges of this dome-shaped massif is drained by some rivers including the Zagunao River and Min River, and no landslides are observed around it. Kirby et al. [21,22] explicated the erosional processes by rivers and their role in accentuating uplift of the Longmen Shan. In general, though the calibration of relative importance of river erosion and landslide can be difficult in long-term denudation processes, their coupled action should be robust and readily bring about the rapid denudation and exhumation of the Longmen Shan in late Cenozoic times.

6. Possible feedbacks between lower-crustal flow and surface erosion

As described above, the Longmen Shan underwent rapid uplift during late Cenozoic, but it remains uncertain why the pronounced exhumation has been occurring there in no association with strong crustal shortening. The crust of Tibetan Plateau was thickened up to 80 km in its interiors due to continued penetration of India into Eurasia, and the over-thickened crust tends to collapse and thin. The thinning can be achieved by means of upper-crustal extension [34,35] or middle- and lower-crustal lateral flows [19,36,37]. Crustal flows are considered to be viable beneath the Tibetan Plateau, inasmuch as the middle to lower crust is proved hot and therefore very weak [38,39]. Recent study further shows that the crustal materials are able to flow at temperatures as low as ~400 °C [40]. The eastern edge of Tibetan Plateau is noticeably marked by prominent steep escarpment, contrasting with other margins with a regional low-gradient slope, like southeastern margin of the Tibetan Plateau (Fig. 1). The distinctiveness in morphologic expressions was thought to be the result of distinct strength of the crust between the plateau and adjacent blocks [19]. When the lower-crustal ductile flow from plateau interior encounters rigid crustal blocks at its margin, the flow will attempt to move upwards so as to raise overlying supra-crustal materials and create a steep landscape. In contrast, if the strength of adjacent crustal block is similar to that of the crustal flow, the flow is capable of penetrating into the surrounding block and will not produce an abrupt boundary as expressed by a prominent landscape [20]. Large-magnitude river incision has increasingly been recognized to have a profound influence on structural deformation and exhumation in orogens [41–43]. Coupled thermal-mechanical-erosion models have been advanced to show that deep and rapid river incision can lead to uplift of hot rocks from below and consequently bring about the weakening of the crust and attendant metamorphism [44,45]. Beaumont et al. [46] recently developed a sophisticated thermo-mechanical model for crustal channel flow, and applied it to tectonic development of the Himalayan-Tibetan orogen. Merits of the model are that the surface denudation rate and upper-crustal strength can exert a strong effect on deformation styles above the crustal flow channel and at exhumation fronts. One of the modeling results is that rapid denudation at plateau flanks will lead to nearly vertical extrusion of crustal-flow channel or near-symmetric exhumation of the channel if the upper crust above the channel remains stable or does not move with the underlying channel flow [46]. In contrast, asymmetric thrust extrusion of crustal-flow channel will result if unstable outward flow of the upper crust occurs simultaneously [46], as manifested by the Himalayan tectonics [47].

Lower-crustal flow has been invoked to account for late Cenozoic uplift of the Longmen Shan [6,20]. We concur with this idea and further develop a model that not only appeals to the lower-crustal flow but also combines the large-magnitude landsliding with river erosion to explain the high-rate denudation (Fig. 10). It is postulated that, when encountering rigid basement of the Sichuan basin to the east, the lower-crustal flow from the plateau interior was forced to move upward and tended to drive the overlying crust upwards at the eastern flank or the Longmen Shan. With continuous attempt of upward diversion of the crustal flow, the slopes of the Longmen Shan gradually became gravitationally unstable and the supra-crustal materials were prone to collapse. Landslides took place catastrophically and were able to deliver large volume of materials en masse. River erosion was simultaneously amplified and became more vigorous in the Longmen Shan, and thus played a more important role in surface denudation and even became more prevalent after landsliding episodes. For instance, the Min River runs parallel to and across the southern Longmen Shan (Fig. 4), and has led to an obvious excavation of deep gorges and major erosional fluxes out of the mountain [6,22]. As a result, surface processes characterized by the coupled landsliding and river erosion could certainly bring about high-rate denudation of the Longmen Shan, as represented by exhumation of the Pengguan and Baoxing massifs.

Our observations further show that the Pengguan massif was primarily uplifted sub-vertically, in that it is bounded on the east and north by linked high-angle (65–90°) faults, though the faults exhibit lateral switch from reverse to normal senses of dip-slip movements. Generation of the high-angle bounding faults is thought as the result of subvertical extrusion of the lower-crustal flow (Fig. 10). Beaumont et al. [46] illustrated that the nearly symmetric exhumation of the flow channel require not only rapid surface denudation but also no association of the unstable outward flow above the channel. The upper crust west of the Longmen Shan is characterized by folded Triassic unit (the Songpan–Ganzi terrane), and there developed no late Mesozoic to Cenozoic extensional basins. This fact suggests that the upper crust did not extend or move with the underlying channel. Stable upper crust west of the Longmen Shan, high-rate surface denudation, and sub-vertical

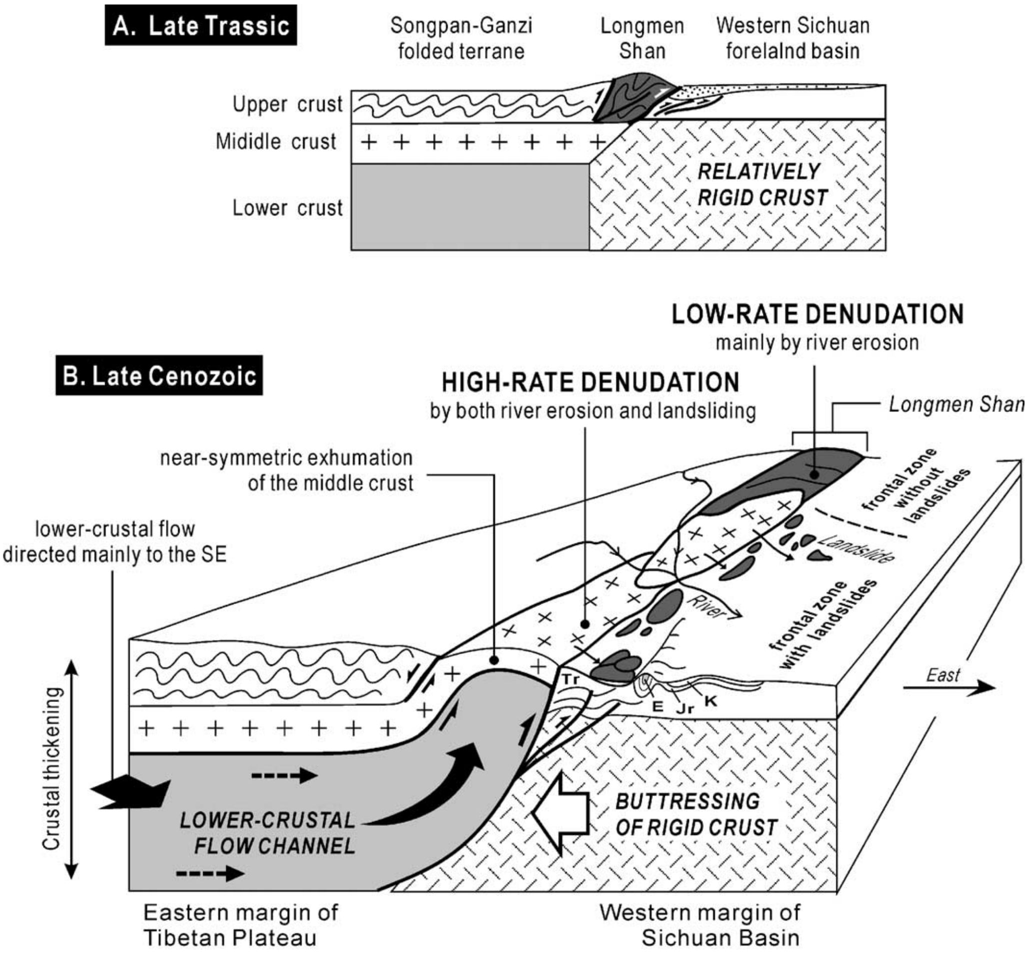

Fig. 10. (A) The folded Songpan–Ganzi terrane and the Longmen Shan fold–thrust system were established in Late Triassic, and accompanied by development of west Sichuan foreland basin. (B) A model to illustrate possible links between surface processes and upward extrusion of lower-crustal flow channel at the eastern flank of the Tibetan plateau. It is suggested that a positive feedback existed between nearly symmetric exhumation and high-rate denudation by a coupled action of landslide and river erosion in the southern Longmen Shan. The lower-crustal flow is directed mainly to the southeast, and has exerted less influence on the northern Longmen Shan, which thus underwent neither marked denudation nor exhumation of crystalline basement rocks. See text for explanation of the model and refer to Fig. 2 for abbreviations of strata.

exhumation of the Pengguan massif appear quite compatible with the mode of near-symmetric exhumation of crustal flow channel [46]. In addition, as shown by the seismic and magnetotelluric sounding across the Longmen Shan [48], both the frontal and rear faults of the Pengguan massif dip steeply to the west and penetrate to the depth of at least 20 km deep, thus also supporting upward extrusion of deep-seated material through the channel.

Also noticeable is the occurrence of folds involving late Mesozoic to Eocene units in the peripheral zone of the southern Longmen Shan, as displayed by a series of synclines and anticlines east of the Baoxing massif (Figs. 5 and 9a). The folding should have occurred prior to the landsliding since the folded strata are either overlain directly by some landslides or served as obstacles retarding displacement of some landslides. We suggest that the folds originated from the crustal flow because outward extrusion of the flow channel could readily give rise to a contractional regime in its front when meeting the western boundary of the Sichuan basin. Contraction might have well developed in the initial stage since strong horizontal compression can be induced as crustal-flow channel attempted to extrude outwards in this time interval. Compression then considerably declined when the landsliding occurred, inasmuch as rapid removal of supra-crustal materials could readily lead the crustal flow to go upwards, thereby considerably decreasing horizontal compression in the peripheral zone.

The crust ranges from 45 to 60 km in thickness in the eastern margin of Tibet, and the lower-crustal temperatures are estimated from 600 to 800 °C and about 25–35 km thick [49]. As a consequence, the lower crust should have been in a state of low viscosity and tends to flow from the interior to the eastern edge of the plateau in response to topographically induced differential pressure. Feasibility of crustal flow can also gain some supports from Cenozoic metamorphism and granite emplacement in the eastern margin of Tibetan Plateau. For instance, early Cenozoic Barrovian-type metamorphism in the Danba dome suggests that the crust might have been either thickened significantly [13] or experienced the heating that can be sourced from hot lower-crustal advection, as modeled by Jamieson et al. [50]. Emplacement of ~12 Ma granites beside the Xianshuihe fault [51] provides another clue that the crust must have become considerably hot in the Miocene. The melting can be related to a combined effect of the outward flow of hot lower crust from plateau interior and decompression caused by rapid surface denudation and faulting at plateau flank, as advocated by Zeitler et al. [45].

There occurred no landslides in the peripheral zone of the northern Longmen Shan (Fig. 2). The absence of landslides, however, is not at variance with our model, and rather implicates that the northern Longmen Shan has not been rising high enough to reach the threshold for hillslope collapse, as indicated by its present-day low elevation (Fig. 1). In addition, structural deformation in the peripheral zone of the northern Longmen Shan is insignificant (Fig. 9b), contrasting with relatively intense folds in the south (Fig. 9a). Considering that exhumation of the metamorphic massifs occurred in the southern Longmen Shan and arose presumably from lower-crustal flow, we conjecture that the flow was mainly directed to the southeast in the eastern margin of the Tibetan Plateau, and thus left the northern Longmen Shan unaffected by the flow. Positive feedbacks should have existed between the rapid denudation and lower-crustal flow, and the high-rate unroofing of the southern Longmen Shan might reinforce the lower-crustal flow to the southeast (Fig. 10).

7. Conclusions

The eastern margin of the Tibetan Plateau is demonstrated to have been experiencing rapid denudation and uplift since late Cenozoic, as manifested by exhumation of metamorphic basement rocks in the southern Longmen Shan. It is shown that gravitational landsliding must have played a very important part in removing supra-crustal materials en masse, though river erosion was persistently vigorous in excavating bedrocks and delivering sediments out of the Longmen Shan. The high-rate exhumation in the eastern edge of Tibet is therefore considered as the consequence of a coupled action of landslides and river erosion. Lower-crustal flow is plausible in the eastern margin of the Tibetan plateau on account of present-day crustal thickness and thermal state, and therefore thought to be responsible for initiating the Longmen Shan to move upward. A positive feedback should have existed between upward extrusion of the lower-crustal flow channel and surface processes at the plateau flank. The Longmen Shan might be initially uplifted by advection of the lower-crustal flow from below, and thus enhanced surface erosion. The resulting high-rate denudation by river erosion and landslide then simultaneously led to nearly symmetric exhumation of the crustal-flow channel, as revealed by sub-vertical uplifting of the Pengguan massif. Focused rapid and large-magnitude denudation in the southern Longmen Shan might have led the lower-crustal materials preferably to flow toward the southeast, and as a result, the northern Longmen Shan was less influenced, as implied by the absence of landslides and low elevation.

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