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How does crustal shortening contribute to the uplift of the eastern margin of the Tibetan Plateau?

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ABSTRACT

The eastern margin of the Tibetan Plateau, the Longmen Shan, has triggered a vigorous debate to explain the uplift and maintaining of its steep and high topography. Several mechanical and kinematic models have been previously developed in order to investigate the tectonic and erosional control on the formation mechanism of the Longmen Shan. But the contribution of crustal shortening has never been taken into account due to the lack of significant surface convergence rate (about 3 mm/a) across the Longmen Shan range. We investigate this question through 2D finite element modelling assuming visco-elasticity rheology. The numerical results are constrained with geological and geophysical observations across the Longmen Shan range. We find that even low rate of crustal shortening contributes significantly to the uplift of the Longmen Shan. This contribution has been greatly underestimated in previous studies. The viscosity contrast between the Tibetan Plateau lower crust and the Yangtze crust crucially controls the uplift of the Longmen Shan due to crustal shortening. The ductile Tibetan lower crust thickens to accommodate most of crust shortening, as the eastward movement of the Tibetan Plateau is obstructed by the mechanical strong and stable Yangtze craton. The uplift rate contrast between the Tibetan Plateau and the Sichuan causes a steep uplift rate gradient to produce and maintain the Longmen Shan steep and high topography in the time scale of several million years. Our results support a possible explanation for the paradox of the high topography and low convergence rate at the Longmen Shan range.

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1. Introduction

The ongoing collision between Eurasian and Indian plate lasts for about 50 million years and has created the largest and highest Plateau on Earth known as the Tibetan Plateau (Yin and Harrison, 2000; Royden et al., 2008). The borders of this continental plateau, as well as the Altiplano or the Colorado Plateau, are among the most important topographic structures on Earth (Godard et al., 2009). They mark the transition between the high elevation low-relief surface of the plateaus and the low elevated foreland basins.

In the eastern margin of the Tibetan Plateau, the Longmen Shan, the site of the 2008 Mw7.9 Wenchuan earthquake and the 2013 Mw6.6 Lushan earthquake, marks the dividing range between the eastern Tibetan Plateau and the Yangtze craton beneath the Sichuan Basin (Fig. 1a). It is known as one of the steepest topographic gradient in the Tibetan Plateau, separating the high elevation Tibetan Plateau and low elevation Sichuan Basin. The elevation decreases from nearly 5 km in the eastern Tibetan Plateau to about 500 m in the Sichuan Basin over a horizontal distance less than 50 km (Fig. 1b). However, the horizontal surface convergence rate across this range inferred by GPS measurements is low (about 3 mm/a) (Chen et al., 2000; Zhang et al., 2004; Shen et al., 2005; Gan et al., 2007). This intriguing feature, which is high topographic gradient and low surface shortening across the Longmen Shan range, has triggered a vigorous debate on explaining the formation of the Longmen Shan high and steep topography. Several proposed models and mechanisms in previous research are competing to comprehend the evolution process of the Longmen Shan.

By studying the fault zones in the Tibetan Plateau, Tapponnier et al. (2001) argued that brittle crustal thickening, in which thrust faults with large amounts of slip are probably rooted in the lithosphere, are the primary driver for the uplift of the Plateau margin.

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However, the whole brittle Tibetan crust model has been challenged by several recent studies, which postulated a different Tibetan crustal rheology (Royden et al., 1997; Clark and Royden, 2000; Beaumont et al., 2001; Clark et al., 2005; Burchfiel et al., 2008). Royden et al. (1997) used a thin viscous sheet model with depth-dependent Newtonian viscosity to investigate the surface deformation of the eastern Tibetan margin. They proposed that the upper crustal deformation was decoupled from the motion of the lithospheric mantle by a weak lower crust. In this research it was suggested that the crust thickening mainly happened in the lower crust level instead of the upper crust. Clark and Royden (2000) designed a simplified Newtonian fluid crust model with uniform thickness to compare calculated topographies with observations in Tibetan margins. Their results showed that the lower crust flow in a 15 km-thick layer, with a viscosity of 10^{21} Pa s, could produce a steep topography fitting with the slope of the Longmen Shan. In this research the viscosity between Tibetan lower crust and Yangtze crust are assumed to be uniform. This model was refined by Clark et al. (2005) by introducing viscosity contrast between the Tibetan Plateau lower crust and Yangtze crust. It was suggested that dynamic stresses, developed from the gravitational driven flow of the Tibetan ductile lower crust obstructed by the strong stable Yangtze craton, may explain anomalously high topography of the Longmen Shan.

While Hubbard and Shaw (2009) argued that lower crust flow is not necessary to explain the evolution of the Longmen Shan. By studying substantial amounts of petroleum industry seismic reflection data, they proposed that the upper crustal shortening decoupled from the lower crust by a series of detachments is the primary contribution for the Longmen Shan topography building.

Godard et al. (2009) proposed that isostatic rebound induced by rapid surface erosion-related unloading is the mechanism to remain the steep and stable margin in time scale of million years. In their numerical experiments, crustal shortening rate is set to zero.

These previous studies are based on the assumption that the contribution to the uplift of the Longmen Shan by low rate crustal shortening is very limited. However, a precise description and qualification of the uplift process induced by crustal shortening has yet been provided. The aim of this research focuses on this problem through numerical experiments assuming visco-elasticity rheology. Low crustal shortening rate inferred from GPS is introduced as the velocity boundary conditions in finite element calculations. Numerical results are constrained with geological and geophysical observations across the Longmen Shan range.

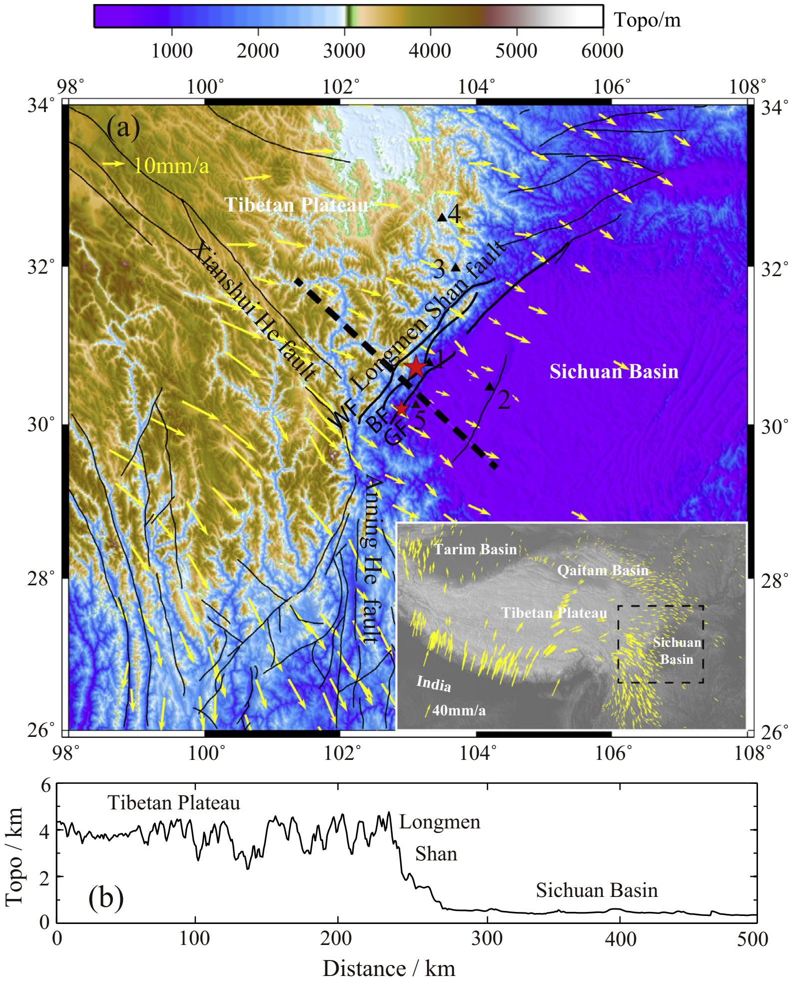

Fig. 1. (a) Relief map of the eastern Tibetan Plateau and the Sichuan Basin. Black curve lines indicate the faults. Black bold curve lines indicate the three main faults located in the Longmen Shan area, WF: Wenchuan fault, BF: Beichuan fault, GF: Guanxian fault. The red stars indicate the epicenters of the 2008 Wenchuan earthquake and the 2013 Lushan earthquake, correspondingly. Back straight dash line indicates the cross section presented in Fig. 2. The numbers mark the city names: 1, Wenchuan; 2, Chengdu; 3, Diexi; 4, Songpan; 5, Lushan. The inset image in the down right corner is the map of the Tibetan Plateau and its surrounding area, in which yellow arrows indicate the surface movement inferred from GPS observations (Shen et al., 2005). (b) Elevation along the cross section. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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