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Crustal rheology control on earthquake activity across the eastern margin of the Tibetan Plateau: Insights from numerical modelling

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ABSTRACT

The devastating 2008 Mw7.9 Wenchuan and 2013 Mw6.6 Lushan earthquakes occurred in the Longmen Shan (LMS) fault zone, the eastern margin of the Tibetan Plateau. Seismology investigation reveals that earthquakes of Ms > 5.0 are frequently recorded in the eastern Tibetan Plateau, however rare earthquake of Ms > 5.0 and only a few earthquakes of 3.0 < Ms < 5.0 have been recorded in the Sichuan Basin. This study investigates the relation between the crustal rheology and the earthquake activity across the eastern margin of the Tibetan Plateau through 3D numerical experiments assuming visco-elasticity rheology. We setup several finite element lithospheric models based on different rheological structure. The interseismic stress accumulation processes in the models are simulated with boundary conditions of steady compressional deformation rate constrained by GPS observations. The results show that the crustal stress accumulation process across the eastern margin of the Tibetan Plateau is significantly controlled by the regional crustal rheology, which presents large horizontal viscosity variation in the lower crusts between the Tibetan Plateau and the Sichuan Basin. The stress accumulation rate in the upper crust of the eastern Tibetan Plateau is much higher than the Sichuan Basin. This stress spatial distribution explains the seismology observation that earthquakes are densely recorded in the eastern Tibetan Plateau, whereas rarely in the Sichuan Basin. The stress concentration nearly at the bottom of the entire LMS fault zone is thought to be responsible for the generation of the 2008 Mw7.9 Wenchuan and 2013 Mw6.6 Lushan earthquakes. There is a high possibility of future earthquakes in the seismic gaps at the southwest segment of the LMS fault zone, where it was stress accumulated but did not rupture during the last two events of the 2008 Wenchuan and 2013 Lushan earthquakes.

1. Introduction

The eastern margin of the Tibetan Plateau is a seismically active area. It is known as the collision zone between the two plates of the eastern Tibetan Plateau and the Yangtze craton beneath the Sichuan Basin (Chen et al., 2013a). The devastating 2008 Mw7.9 Wenchuan earthquake (30.986°N, 103.364°E) occurred in the LMS fault zone (Fig. 1a). Five years later, another destroying Mw6.6 Lushan earthquake (30.284°N, 102.956°E) was activated in the southwest segment of the LMS fault zone on April 20, 2013. This segment did not rupture in the 2008 Wenchuan earthquake (Fig. 1a). Seismology investigation also reveals that earthquakes (Ms > 5.0) are frequently recorded in the eastern Tibetan Plateau, even large shocks such as the 1933 M7.9 Diexi earthquake and the 1976 Mw7.2 Songpan earthquake (Fig. 1a) (Teng et al., 2008; Toda et al., 2008). However, rare earthquake of Ms > 5.0 and only a few earthquakes of 3.0 < Ms < 5.0 have been recorded in the Sichuan Basin (Teng et al., 2008; Toda et al., 2008).

Several conceptional seismotectonic models have been proposed to investigate the earthquake generation mechanism in the LMS fault zone. Hubbard and Shaw (2009) suggested that the 2008 Wenchuan earthquake was a direct manifestation of the active upper-crustal shortening that produced and supports the LMS range front. By studying the lithosphere rheological structure of the LMS, many researchers proposed that materials of the Tibetan ductile lower crust accumulated in the LMS fault zone causing energy accumulation, as the eastern movement of the Tibetan

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Plateau was obstructed at the LMS fault zone by the strong and stable Yangtze craton (Teng et al., 2008; Royden et al., 2008; Stone 2008; Burchfiel et al., 2008). These studies advocated the ductile behavior of the Tibetan lower crust. Zhu and Zhang (2012) used 2D visco-elastic finite element models to simulate the inter-seismic straining process in the LMS fault zone, and found that the elastic strain energy accumulates rapidly in and around the LMS fault zone. Their models were based on a simplified crustal rheological structure by assuming a quite weak Tibetan lower crust with the viscosity of 4.5×10^{18} Pa s, and a whole elastic crust beneath the Sichuan Basin. However, Tapponnier et al. (2001) argued that the Tibetan deep crust is not especially that soft, and large scale thrusts along the Tibetan margin may penetrate through the whole Tibetan crust and root in the lithosphere by studying the uplift of the Tibetan Plateau. These proposals describe different rheological structures of the eastern Tibetan Plateau.

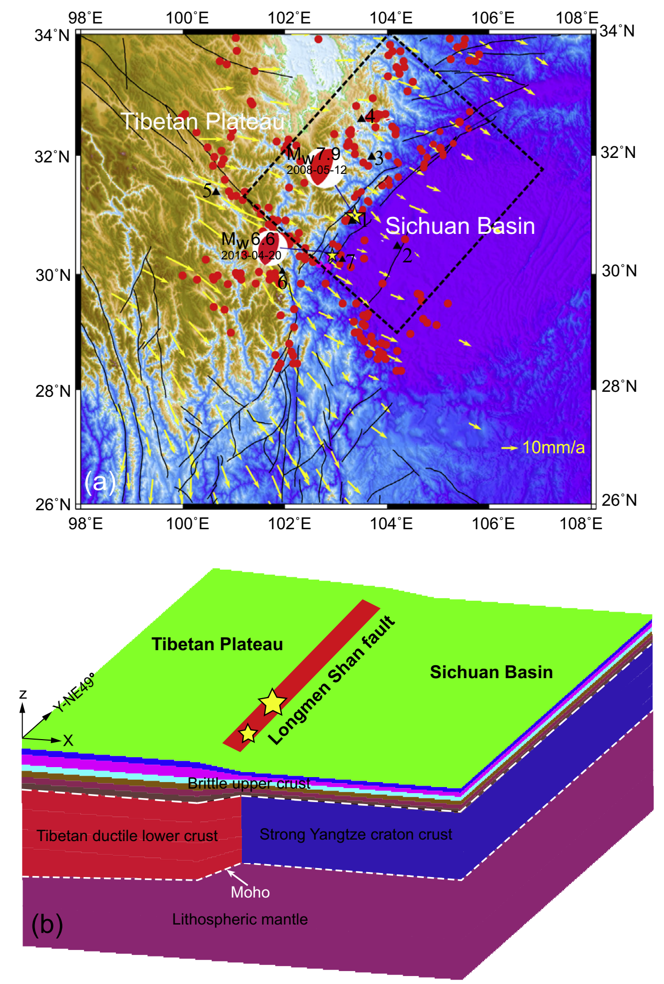

Fig. 1. (a) Map of the eastern Tibetan Plateau and the Sichuan Basin showing the LMS fault zone. Yellow stars indicate the epicenters of the 2008 Wenchuan and 2013 Lushan earthquakes. Red dots indicate the aftershocks of Ms > 5.0 (http://www.seismology.harvard.edu/, in the area of 100–106°E, 28–24°N between Dec. 1920 and Jan. 2014). The beach balls indicate the focal mechanism solution of the Wenchuan and Lushan earthquakes (Chen et al., 2013c). The yellow arrows indicate the GPS velocity (Shen et al., 2005). The black triangles indicate the locations of cities. The numbers mark the city names: 1, Wenchuan; 2, Chengdu; 3, Diexi; 4, Songpan; 5, Luhuo; 6, Kangding; 7, Lushan. The black solid lines indicate the faults. The black dashed lines forming a rectangle mark the area where the model is built up. (b) Lithosphere model across the eastern margin of the Tibetan Plateau. The size of this model is 500 × 500 × 100 km ($X \times Y \times Z$). The Y axis is parallel to the strike of the LMS fault zone. The yellow stars indicate the epicenters of the 2008 Wenchuan earthquake and 2013 Lushan earthquakes. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

What is the influence of the stress accumulation process by different crustal rheology across the eastern margin of the Tibetan Plateau, has not been investigated. Furthermore, to investigate earthquake activity in the LMS fault zone a precise description and qualification of stress accumulation distribution along the strike of the LMS fault zone is yet provided. The controlling factor of the earthquake spatial distribution that earthquakes are densely recorded in the eastern Tibetan Plateau but rarely in the adjacent Sichuan Basin, still keeps uncertain.

The intraplate earthquake activity is related to the long period of interseismic stress build-up and release in the crust. To investigate the mechanism for earthquake activity across the eastern margin of the Tibetan Plateau, we simulate the crustal stress accumulation process in this area using 3D numerical experiments with different crustal rheology. We aim to investigate how the stress accumulation process is affected by the regional crustal rheology, and demonstrate the relation between the crustal stress accumulation and the earthquake special distribution in this area.

2. Geological background

The eastern margin of the Tibetan Plateau, the LMS, is characterized by a steep topographic gradient of decreasing averagely 5 km in a horizontal distance of about 50 km from the Tibetan Plateau to the Sichuan Basin. The LMS fault zone striking NE is about 470-km long and 50-km wide. It contains several thrust faults because of the compression between the Tibetan Plateau and the Yangtze craton. Three sub-parallel main thrust faults, the Wenchuan fault, the Beichuan fault, the Guanxian fault, and some blind thrusts are located in the fault zone. The primary rupture of the 2008 Wenchuan earthquake occurred on the Beichuan fault (Shen et al., 2009).

To decipher the crustal structure in the LMS area, decades of seismology exploration have been documented using tomography (Huang et al., 2002; Wang et al., 2003, 2008, 2009, 2011; Lei and Zhao, 2009; Wei et al., 2013; Lei et al., 2014; Liu et al., 2014), receiver function data analysis (Xu et al., 2007; Zhang et al., 2009; Robert et al., 2010), wide-angle reflection seismological imaging (Wang et al., 2005; Wang et al., 2007a,b); and structural mapping (Burchfiel et al., 1995, 2008). It is suggested that Moho depth is about 60 km at the eastern Tibetan Plateau and about 45 km at the Sichuan Basin (Wang et al., 2007a,b; Xu et al., 2007; Zhang et al., 2009; Robert et al., 2010). This indicates a steep Moho ramp of about 15 km in an approximate horizontal distance of less than 50 km.

Evidence from geological study, and geophysical observations using tomography, GPS measurement, and magnetotellurics observation, together with numerical modelling research, is in favor of weak ductile Tibetan lower crust (Bird, 1991; Beaumont et al., 2001, 2004; Clark et al., 2005; Wang et al., 2007a,b, 2009, 2011, 2014b; Bai et al., 2010; Wei et al., 2013; Huang et al., 2014; Liu et al., 2015). According to recent seismic (Wang et al., 2007a,b, 2009; Bai et al., 2010; Wei et al., 2013; Liu et al., 2014) and magnetotelluric studies (Bai et al., 2010; Zhao et al., 2012) in this region, there are low seismic velocity and high electrical conductivity zones at the middle/lower crustal level in the eastern Tibet. These observations are considered as strong evidences of the ductile weak lower crust existing beneath the eastern Tibet. It is also inferred that the low velocity and high conductivity zones discovered in the middle/lower crust are composed of partially molten material with low viscosity (Royden et al., 1997; Burchfiel et al., 2008). Thus, the mechanical strength of the deep crust beneath the eastern Tibet is supposed to be weak.

However, the low-viscosity zones in the deep Tibetan Plateau crust terminate against the steeply sloping plateau margin