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Role of pre-existing structures in controlling the Cenozoic tectonic evolution of the eastern Tibetan plateau: New insights from analogue experiments

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A B S T R A C T

Pre-existing weakness due to repeated tectonic, metamorphic, and magmatic events is a fundamental feature of the continental lithosphere on Earth. Because of this, continental deformation results from a combined effect of boundary conditions imposed by plate tectonic processes and heterogeneous and anisotropic mechanical strength inherited from protracted continental evolution. In this study, we assess how this interaction may have controlled the Cenozoic evolution of the eastern Tibetan plateau during the India–Asia collision. Specifically, we use analogue models to evaluate how the pre-Cenozoic structures may have controlled the location, orientation, and kinematics of the northwest-striking Xianshuihe and northeast-striking Longmen Shan fault zones, the two most dominant Cenozoic structures in eastern Tibet. Our best model indicates that the correct location, trend, and kinematics of the two fault systems can only be generated and maintained if the following conditions are met: (1) the northern part of the Songpan–Ganzi terrane in eastern Tibet has a strong basement whereas its southern part has a weak basement, (2) the northern strong basement consists of two pieces bounded by a crustal-scale weak zone that is expressed by the Triassic development of a northwest-trending antiform exposing middle and lower crustal rocks, and (3) the region was under persistent northeast–southwest compression since ~35 Ma. Our model makes correct prediction on the sequence of deformation in eastern Tibet; the Longmen Shan right-slip transpressional zone was initiated first as an instantaneous response to the northeast–southwest compression, which is followed by the formation of the Xianshuihe fault about a half way after the exertion of northeast–southwest shortening in the model. The success of our model highlights the importance of pre-existing weakness, a key factor that has been largely neglected in the current geodynamic models of continental deformation.

1. Introduction

Formation of continental lithosphere results from multi-phase magmatic differentiation, terrane accretion/collision, metamorphism, and tectonic activities (e.g., Hawkesworth et al., 2017). As a result of its protracted evolution, the rheological properties of continental lithosphere vary strongly in time and space, contrasting sharply to those of oceanic lithosphere (e.g., McKenzie et al., 2005). The spatiotemporally variable mechanical strength of the continental lithosphere can be expressed either as crustal-scale weak zones or storage of gravitational potential energy (e.g., Kluth and Coney, 1981; England and Houseman, 1989). Hence, continental deformation is ultimately a combined result of (1) boundary conditions imposed by plate tectonic processes and (2) the interaction of its induced stress fields with pre-existing distribution of heterogeneity and anisotropy inherited from protracted early continental evolution.

The eastern margin of the Tibetan plateau was created by the Cenozoic development of the Longmen Shan thrust belt/right-slip transpressional system during the India–Asia collision. The Longmen Shan thrust belt is located at the site where intense Triassic deformation took place during the closure of the Paleo-Tethys (e.g., Burchfiel and Chen, 2012). Despite this well-established geologic

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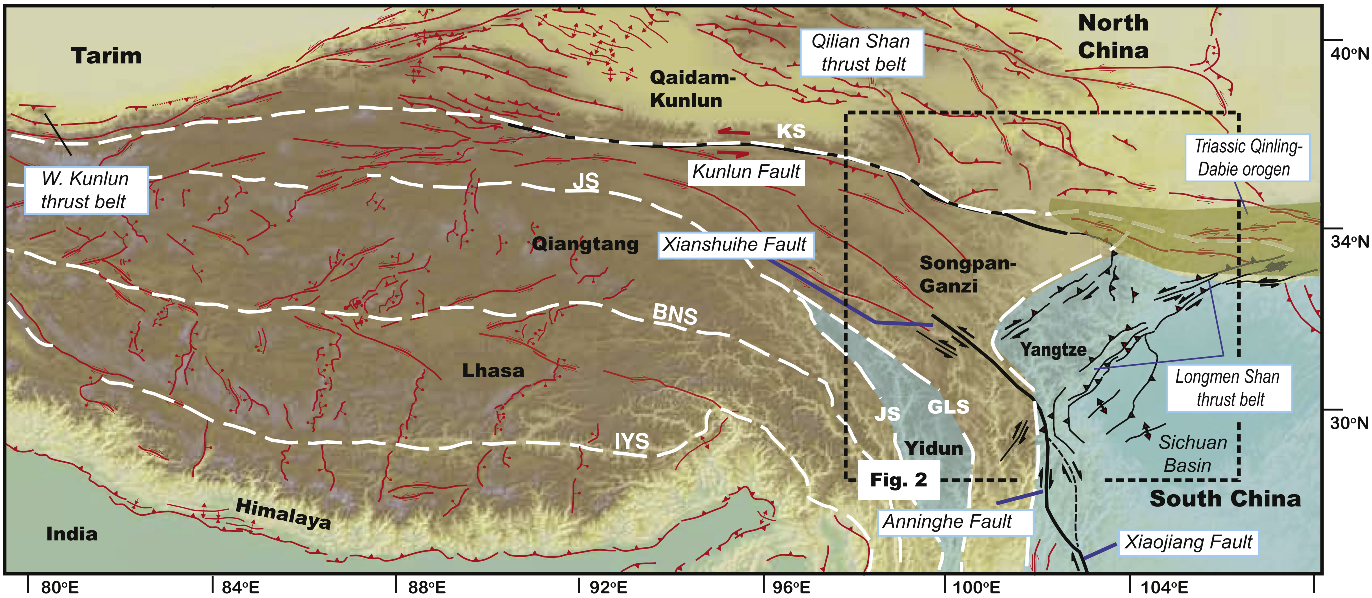

Fig. 1. Cenozoic fault map of the Himalayan–Tibetan orogen and location of major pre-Cenozoic terrane boundaries after Taylor and Yin (2009). IYS: Indus–Yarlung suture; BNS: Bangong–Nujiang suture; JS: Jinsha suture; GLS: Garze–Litang suture; KS: Kunlun suture. Note that the boundary between the Yangtze terrane of South China and the Songpan–Ganzi terrane is transitional and complex due to Triassic and Cenozoic deformation. Also shown is the approximate location of Fig. 2B.

relationship, the dynamic role of Triassic structures in controlling Cenozoic tectonic evolution of the eastern Tibetan plateau has not been investigated. Current research on the Cenozoic development of the eastern Tibetan plateau focuses mainly on testing two end-member models in cross-section view, with one emphasizing the role of lower-crustal channel flow (e.g., Clark and Royden, 2000; Bendick and Flesch, 2007) and another the development of a thrust wedge (e.g., Hubbard and Shaw, 2009). Not only that the above two end-member models do not involve pre-existing weakness, their two-dimensionality makes them inadequate to evaluate the impact of the well-established Cenozoic transpressional and strike-slip faulting on the tectonic development of the eastern Tibetan plateau (Fig. 1).

Although the role of pre-existing weakness in controlling intra-plate deformation at a continental scale has been evaluated through numerical modeling (e.g., Neil and Houseman, 1997; Kong et al., 1997) and the application of rock-mechanics principles (e.g., Cooke and Underwood, 2001; Tong and Yin, 2011), these approaches are unable to simulate coeval nucleation of new faults and reactivation of pre-existing weak zones in the continental lithosphere. This problem can be overcome by analogue modeling that is capable of simulating fault creation and reactivation under proper model setups (e.g., Haq and Davis, 1997; Viola et al., 2004; Yan et al., 2016). In this study we use analogue-model experiments to determine the mechanical origins of the left-slip Xianshuihe fault zone and the right-slip transpressional Longmen Shan belt, the two most dominant Cenozoic fault systems in eastern Tibet. Specifically, we would like to answer the following questions. (1) Was the Xianshuihe fault nucleated as a new structure or reactivated from an older weakness zone? (2) Does the Songpan–Ganzi terrane have a coherent or fragmented basement in eastern Tibet? (3) What has been the dominant shortening direction in eastern Tibet during the development of the Cenozoic Xianshuihe and Longmen Shan fault zones?

2. Geologic setting of eastern Tibet

2.1. Triassic structures

Eastern Tibet exposes the Songpan–Ganzi terrane, the Yidun terrane, and the western margin of the Yangtze terrane/craton (Fig. 1) (Yin and Nie, 1996; Yin and Harrison, 2000; Roger et al., 2010). The Songpan–Ganzi terrane is composed of a thick (locally >15 km) Triassic turbidite sequence that is strongly folded and intruded by earliest Jurassic plutons (Nie et al., 1994; Burchfiel and Chen, 2012; de Sigoyer et al., 2014). The easternmost Songpan–Ganzi terrane and the Yangtze craton share the same continental basement, which is characterized by the presence of 825–750 Ma felsic rocks (Zhou et al., 2002) covered by Neoproterozoic to Triassic strata (Fig. 2) (Roger et al., 2010). The Yidun terrane is bounded by the Garze–Litang and Jinsha suture zones between the Qiangtang and Songpan–Ganzi terranes (Fig. 1) and consists of a Cambrian–Carboniferous continental-shelf sequence overlain by a Permo-Triassic arc sequence (e.g., Reid et al., 2005; Roger et al., 2010). Geochemistry and Hf model ages of Triassic and Cretaceous plutonic rocks require the Yidun terrane to have a thinned continental basement, which may have resulted from rifting from the Yangtze terrane during the postulated Permian backarc extension (Reid et al., 2005) (Fig. 2A). Deformation of the Yidun terrane was induced by the Early Triassic closure of the Jinsha Ocean in the west side and the Late Triassic closure of the Garze–Litang Ocean on the east side, respectively (Reid et al., 2005; Burchfiel and Chen, 2012) (Fig. 2B).

2.2. Cenozoic structures

The first-order Cenozoic structures in eastern Tibet are the Longmen Shan thrust belt and the Xianshuihe left-slip fault. The northeast-striking Longmen Shan thrust belt defines the eastern margin of the Tibetan plateau (Fig. 1) (Burchfiel et al., 1995), which has experienced slow exhumation during the early Cenozoic followed by two pulses of rapid exhumation at 30–25 and 10–15 Ma, respectively (Wang et al., 2014). The northern segment of the thrust belt accommodates both thrusting and right-slip shear deformation (Fig. 1), whereas the southern segment terminates at the left-slip Xianshuihe fault (Burchfiel et al., 1995; Liu-Zeng et al., 2010; Yan et al., 2011; Burchfiel and Chen, 2012). The Xianshuihe fault has accommodated ∼60 km left-slip offset and has been active since ∼10 Ma (Roger et al., 1995; Burchfiel et al., 1995). This age is significantly younger than the initiation age of the Longmen Shan thrust belt to the north at ∼35 Ma (Wang