Earth and Planetary Science Letters 480 (2017) 33–41

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

New images of the crustal structure beneath eastern Tibet from a high-density seismic array

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ARTICLE INFO

Article history:
Received 30 May 2017
Received in revised form 21 September 2017
Accepted 27 September 2017
Available online xxxx
Editor: A. Yin

Keywords:
east margin of Tibetan Plateau
receiver function
crustal structure
crustal thickening
seismic array

ABSTRACT

An east–west trending, high-density seismic array was deployed along the eastern margin of the Tibetan Plateau to investigate its eastward expansion. The 160 km long array spans the Ruoergai basin, Minjiang fault, Minshan Mountains, Tazang fault, and West Qinling. The array included 330 short-period seismographs spaced at 500 m intervals, which recorded teleseismic 3-component waveforms over a one month period. P-wave receiver functions calculated from 35 teleseismic events provided an image of crustal structure. The results show a massive thrust nappe structure around the Minshan Mountains and beneath the Minjiang fault. We suggest that this nappe formed after the closure of the Paleo-Tethyan ocean. The resultant Triassic thrusting contributed to partial uplift of the eastern Ruoergai basin and the Minshan Mountains in middle-to-late Miocene time. Receiver function images show that the Tazang fault is a crustal-scale rupture cutting across the Moho. The western Tazang fault appears as a nearly vertical strike-slip fault accommodating left lateral shear at the terminus of the eastern Kunlun fault. After clockwise rotation from an approximate east–west orientation to a nearly north–south orientation, the eastern Tazang fault became a west-dipping thrust fault, which caused crustal thickening beneath the Minshan Mountains and the West Qinling. Our results suggest that late Cenozoic uplift of the eastern margin of the plateau is produced by eastward overthrusting and crustal shortening, processes that absorbed slip along the Tazang and Kunlun faults.

1. Introduction

The Tibetan Plateau formed primarily due to the continental collision between India and Eurasia occurring over the last 60 Ma (Molnar et al., 1993; Tapponnier et al., 2001; Yin and Harrison, 2000), but the prominent uplift of southeastern and northeastern Tibet did not occur until 13–4 Ma (e.g., Clark et al., 2005b; Enkelmann et al., 2006; Zheng et al., 2010). Several models have been proposed to explain lateral expansion and uplift of the eastern Tibetan Plateau but limited coverage and resolution of subsurface structural images prevent consistent validation (or rejection) of any particular mechanism. These models include the lower crustal flow model (Royden et al., 1997), the upper-crustal deformation model (Hubbard and Shaw, 2009), and the crustal-scale deformation model (Guo et al., 2013).

For the northeastern Tibetan Plateau and to the north of the Sichuan Basin, topography decreases smoothly from the Songpan-Ganzi block to areas south of the western Qinling orogenic belt to form a broad, gentle plateau margin (Fig. 1). Clark et al. (2005a) described one branch of lower crustal flow as passing through the northeastern Songpan-Ganzi terrane where it was diverted eastward into the West Qinling. This process has been proposed as a primary mechanism for transferring plateau crustal material to eastern China. Seismic studies (e.g., Jiang et al., 2014; Li et al., 2014) have identified a middle to lower crustal low velocity zone (LVZ), and magnetotelluric measurements have also recognized a high conductive zone in middle to lower crust (e.g., Zhang et al., 2012; Zhao et al., 2012) in this region, which have been interpreted as evidence for lower crustal flow.

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https://doi.org/10.1016/j.epsl.2017.09.048

In the lower crustal flow model, elevated topography along the plateau margin results directly from thickening of the deep crust without significant shortening of the upper crust (Royden et al., 1997). A high-resolution seismic-reflection survey of the eastern Songpan-Ganzi however reveals high strain in both the lower and upper crust (Gao et al., 2014; Wang et al., 2011). Dip reflectors throughout the middle crust and thrust features in the lower crust are not consistent with interpreted channel flow through the middle and/or lower crust necessary to produce sub-horizontal shear foliations and flat reflections (Wang et al., 2011). Although featured by low seismic velocity in seismic tomography, the weak middle crust may not be activated everywhere during the Indo-Asian collision due to the laterally varying rheology. Thus, determination of continental rheology such as seismic-tomography methods alone is insufficient to establish the mode of continental deformation (Wang et al., 2011).

Most seismic surveys of the eastern Tibetan Plateau (Guo et al., 2013; Jia et al., 2014; Zhang et al., 2009) focus on uplift of the Longmenshan range. The crustal structure beneath the Ruoergai basin, the Minshan Mountains and the West Qinling are not well understood due to the lack of east–west trending seismic lines and associated high-resolution subsurface images. To better understand eastward plateau expansion and uplift in the Ruoergai basin, the Minshan Mountains and the West Qinling, we deployed a dense, short-period seismic array from the eastern Songpan-Ganzi block to the southern West Qinling orogenic belt. A high resolution image of lateral crustal structure between these blocks was obtained from receiver functions (RFs) based on teleseismic waveforms. Because RFs can image the deep crust using higher signal-to-noise ratios relative to those generated by regular seismic-reflection surveys, our results can reveal more subsurface detail in this critical area where the Tibetan Plateau expands eastward into the southern West Qinling.

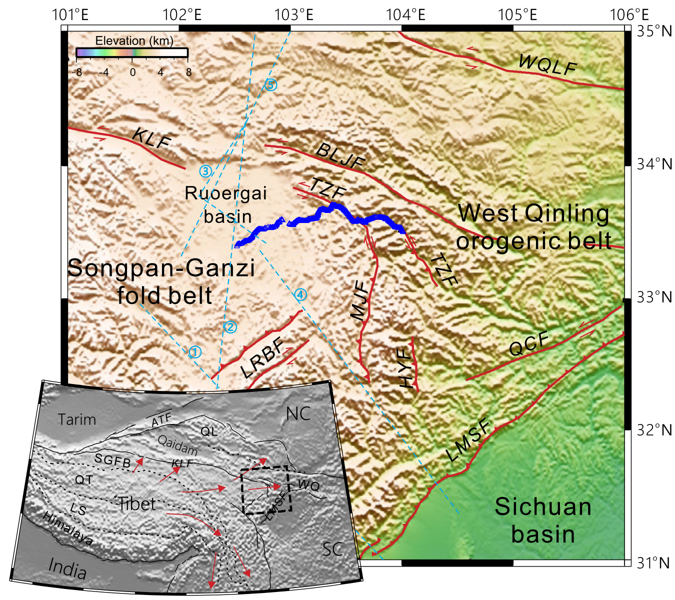

Fig. 1. Topographic map of the eastern Tibetan Plateau, the West Qinling orogenic belt, and the western Sichuan basin, showing the location of the 160 km long seismic array (blue open triangles). The inset show the research area (bold dashed box) and red arrows represent the inferred direction of lower crustal flow (Clark et al., 2005a; Clark and Royden, 2000). SPGZ: Songpan-Ganzi fold belt; QT: Qiangtang Terrane; LS: Lhasa Terrane; SC: South China block; NC: North China block; QL: Qilian fold belt; WQ: West Qinling orogenic belt; ATF: Altyn-Tagh fault; KLF: Kunlun fault; LMSF: Longmenshan fault; TZF: Tazang fault; MJF: Minjiang fault; HYF: Huya fault; BLJF: Bailongjiang fault; WQLF: West Qinling fault; LRBF: Longriba fault; QCF: Qingchuan fault. Light blue lines mark the locations of previous seismic profiles: ① Broadband seismic array (Zhang et al., 2009); ② Wide-angle reflection profile (Jia et al., 2010); ③ Deep seismic-reflection profile (Wang et al., 2011); ④ Deep seismic-reflection profile (Guo et al., 2013); ⑤ Broadband seismic array (Ye et al., 2015).

2. Tectonic setting

The Songpan-Ganzi fold belt (SGFB) is located in the eastern part of the Tibetan plateau and west of the Sichuan basin (Fig. 1). It is bounded by the Qaidam basin and the West Qinling orogenic belt to north and northeast, and by the south China block and the Qiangtang Terrane of central Tibet to the southeast and southwest. As a major component of the Tibetan plateau, the SGFB is generally interpreted as forming from interactions between the South China, North China, and Qiangtang blocks during the Triassic closure of the Paleo-Tethys ocean (Roger et al., 2010). The SGFB is dominated by a thick (locally >10 km) supracrustal, Triassic flysch complex (Burchfiel et al., 1995; Nie et al., 1994). Roger et al. (2010) interpreted the SGFB as an atypical collisional belt due to the triangular plan of oceanic basin closure and because its relatively large volume of accreted sediments hindered typical continent–continent collisional interaction. Triassic lithospheric delamination occurred (Zhang et al., 2007) after the crust had reached thicknesses of $\sim$50 km (Lease et al., 2012). As a result, Triassic syn-tectonic adakitic-type granitoids are widely distributed in the eastern SGFB (Zhang et al., 2006). Located in the northeastern corner of the SGFB, the Ruoergai basin is bound by the Kunlun fault to the north, the Tazang fault to the northeast, and Minjiang fault to the east (Fig. 1).

The Qinling orogenic belt was formed as a result of the closure of the Paleo-Tethys ocean and subsequent collision between the North and South China blocks in the Triassic (Meng and Zhang, 1999). The West Qinling represents a Paleozoic–Mesozoic orogenic collage to the north of the Sichuan basin. It now lies northeast of the Tibetan Plateau (Fig. 1).

The Kunlun fault system terminates in the Ruoergai basin (Kirby and Harkins, 2013) (Fig. 1). The Bailongjiang fault or Tazang fault was originally interpreted to have connected with the eastern Kunlun fault to the west (Chen et al., 1994; Kirby et al., 2000; Ren et al., 2013). The slip amount along the Kunlun fault probably drove internal deformation of adjacent fault zone domains in eastern Tibet (Kirby et al., 2007). Global Position System (GPS) measurements (Gan et al., 2007; Shen et al., 2005, 2009) also show a dramatic decrease in eastward extrusion velocity after crossing the Longriba and Minjiang faults, as well as the Bailongjiang fault further to the east. The north-striking Minjiang fault system appears to connect with the Tazang fault (Chen et al., 1994). Observations reported in Kirby et al. (2007) suggest that slip rates along the Tazang fault are quite low (less than $\sim$1 mm/yr), consistent with relatively low rates of shortening inferred for the Minjiang fault system ($\sim$1 mm/yr) since the late Pleistocene (Kirby et al., 2000). The Minshan mountains are a Cenozoic uplift zone bounded by the Minjiang fault to the west and the Huya and Tazang faults to the east and northeast, respectively. Uplift and block movement of the Minshan Mountains probably relate to compression along the eastern end of the Kunlun fault (Chen et al., 1994).

Apatite fission-track thermochronology data (Enkelmann et al., 2006) indicate that rapid uplift of the West Qinling commenced around 9–4 Ma, a few million years later than it began in the eastern Tibetan Plateau. Active sinistral and dextral strike-slip faults recorded rapid late Cenozoic cooling and eastward lower crustal flow.

3. Data and methods

From 20 July to 20 August, 2015, a linear seismic array collected earthquake waveforms along a 160-km long transect spanning the