Earth and Planetary Science Letters 497 (2018) 69–79

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Crustal structure and deformation beneath eastern and northeastern Tibet revealed by P-wave receiver functions

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ARTICLE INFO

Article history:
Received 31 January 2018
Received in revised form 1 June 2018
Accepted 6 June 2018
Available online xxxx
Editor: A. Yin

Keywords:
receiver function imaging
eastern Tibet
northeastern Tibet
crustal structure
crustal channel flow
wedging tectonics

ABSTRACT

The present-day Tibetan crust records the shallow response of the Cenozoic continental collision between the Indian and Eurasian plates. An analysis of the deep crustal structure beneath eastern and northeastern Tibet is of vital significance for studying the geodynamic processes of crustal thickening and expansion of the Tibetan Plateau. We herein provide detailed images of the crustal structure of eastern and northeastern Tibet and the adjacent Sichuan Basin using teleseismic P-wave receiver function (P-RF) data from a NW–SE-trending linear seismic array. Our P-RF imaging result reveals distinct structural features of the study region, including marked lateral variations in the depth to basement beneath the Songpan–Ganzi block and the Sichuan Basin, a seismically slow mid-lower crust beneath the Songpan–Ganzi block and a low-velocity anomaly just above the Moho around the easternmost Kunlun fault area, and obvious Moho offsets near the boundaries of tectonics blocks. These structural features may reflect various crustal responses within the continental interior to the India–Eurasia collision at the plate margin. The rigid crust of the Sichuan Basin might have wedged into the Tibetan crust in the Longmenshan area, which probably facilitated crustal thickening and enabled channelized mid-lower crustal flow in the Songpan–Ganzi block to the west. Being a pre-existing tectonic boundary, the Kunlun fault could have acted as a focus of heating and hot mantle upwelling associated with the deep processes of the Indian plate underthrusting and subduction, possibly resulting in localized weakening and modification of the lower crust around this fault area. The observed significant differences in the crustal structure of eastern and northeastern Tibet suggest that crustal shortening in this region may have been absorbed by not only vertical thickening in the interiors of the tectonic blocks but also complex local deformation along the boundary zones.

1. Introduction

The significant crustal thickening and high topography of Tibet were generated in response to the Indian–Eurasian continental collision that began during the Early Cenozoic (e.g., Yin and Harrison, 2000). However, to date, no consensus has been reached regarding the style of crustal deformation. Some models, including crustal channel flow and rigid block model, have been proposed to explain the tectonic deformation and high topography throughout the Tibeatan Plateau. The crustal channel flow model proposes that the lower crustal material beneath central Tibet is moving eastward, before being diverted towards the northeast and southeast around the Sichuan Basin (e.g., Royden et al., 1997); meanwhile, the rigid block model suggests that the India–Eurasia convergence is accommodated largely by the extrusion of material along strike-slip faults (Tapponnier et al., 2001). A recent study suggested that rigid block motion and crustal flow constitute two reconcilable modes of crustal deformation in eastern and southeastern Tibet, as both of these mechanisms significantly contribute to the eastward expansion of the Tibetan Plateau (Liu et al., 2014). In the eastern and northeastern areas of Tibet, however, it is unclear which mechanism is primarily responsible for the regional crustal deformation.

Detailed information of the crustal properties and structure in eastern and northeastern Tibet are crucial for reconstructing the processes of crustal deformation and regional orogenesis, which is however still lacking. In the eastern and northeastern Tibetan re-

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https://doi.org/10.1016/j.epsl.2018.06.007

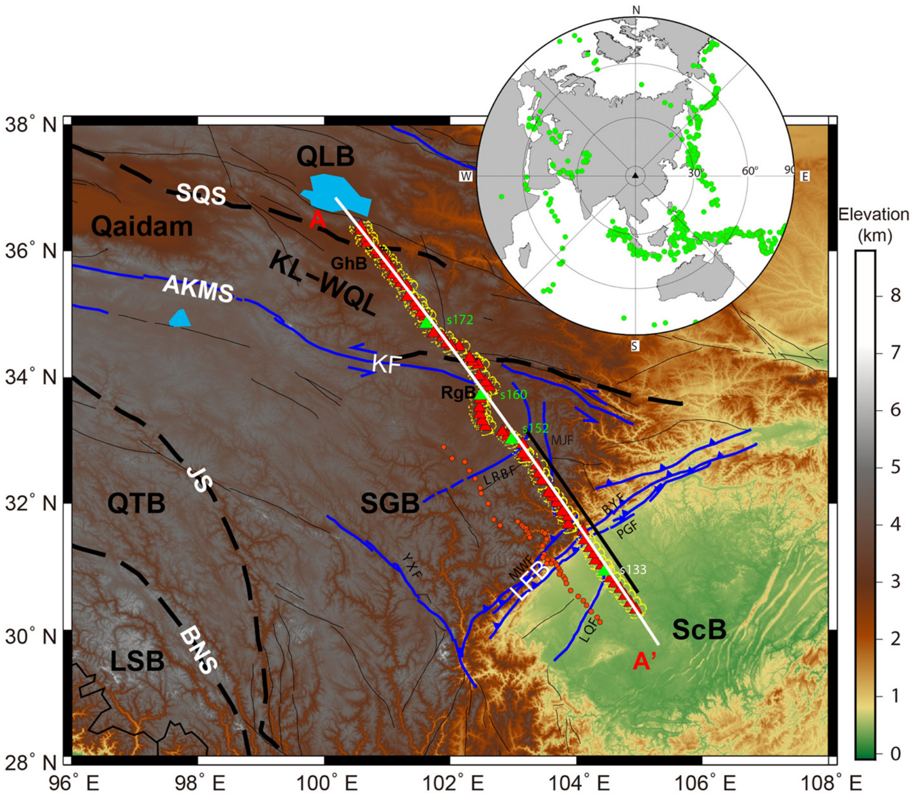

Fig. 1. Topographic map of eastern and northeastern Tibet and the Sichuan Basin, showing the locations of the broadband seismic stations (red and green triangles) and imaging profile (white straight line A–A′). Black dashed lines mark main sutures and blue solid lines represent main faults. Yellow dots show the piercing points at 50-km depth for *Ps* conversions. Red circles are the MT stations from Zhao et al. (2012). The black solid line delineates the tomographic imaging section from Wang et al. (2014). The inset map shows the distribution of teleseismic events used in this study. LSB: Lhasa block; QTB: Qiangtang block; SGB: Songpan–Ganzi block; Qaidam: Qaidam Basin; KL–WQL: Kunlun–West Qinling block; QLB: Qilian block; ScB: Sichuan Basin; GhB: Gonghe Basin; RgB: Ruoergai Basin; BNS: Bangong–Nujiang suture; JS: Jinsha river suture; AKMS: Anyimaqen–Kunlun–Muztagh suture; SQS: South Qilian suture; KF: Kunlun fault; LFB: Longmenshan fault belt; PGF: Pengxian–Guanxian fault; BYF: Beichuan–Yingxiu fault; MWF: Maoxian–Wenchuan fault; LRBF: Longriba fault; MJF: Minjiang fault; YXF: Yushu–Xianshuihe fault; LQF: Longquan fault. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

gion that we are focusing on in this study, there are two major fault or fault systems (Fig. 1). One is the Kunlun fault within the Tibetan Plateau, which separates the Songpan–Ganzi block from the Kunlun–Qinling orogenic system to the north. The other is the Longmenshan (LMS) fault belt, the boundary zone between the Songpan–Ganzi block (Tibetan Plateau) in the west and the Yangtze Craton in the east. The LMS area, which is the site of the devastating Wenchuan earthquake, exhibits greater topographic relief than anywhere else in the marginal areas of the Tibetan Plateau. Numerous studies have been conducted across the LMS fault belt and several distinctive models have been proposed for the uplift of this area (see review by Yin, 2010), including upper crustal detachments (Hubbard and Shaw, 2009), mid-lower crustal channel flow (Royden et al., 1997) and wedging tectonics (Cai et al., 1996). The fundamental reason for the coexistence of these models is the uncertainties in the crustal structure of the eastern Songpan–Ganzi block, which is covered by a thick Triassic flysch complex (5–15 km; Nie et al., 1994). The nearly E-W-trending Kunlun fault represents a long transition from the flat, high-altitude central plateau in the south to the active tectonic domain characterized by ranges and intramontane basins in the north (Kirby et al., 2007). However, as indicated by the geophysical, geodetic and tectonic-geomorphological investigations (Kirby et al., 2007; Shen et al., 2005; Vergne et al., 2002; Wang et al., 2011; Xu et al., 2014; Zhang et al., 2011), the easternmost part of the Kunlun fault exhibits not only weaker variations in the crustal geometry but also reduced surface kinematics relative to the central-western part of the fault zone. Surface wave tomographic studies also observed a low-velocity anomaly with negative radial anisotropy ($V_{SH} < V_{SV}$) throughout the entire lithosphere and significant low-velocity characteristics with positive radial anisotropy in the asthenosphere right beneath the eastern section of the Kunlun fault (Li et al., 2016). A recent geomorphic analysis of longitudinal stream profiles in this area indicated a broad zone of rapid rock uplift (Kirby and Harkins, 2013). Moreover, in spite of the scarcity of heat flow sites, the measured heat fluxes near the easternmost part of the Kunlun fault and the Gonghe Basin are nearly twice as high as the average for the mainland of China (Jiang et al., 2016). The features, including seismically slow lithosphere–asthenosphere and high heat fluxes, support the scenario of an asthenosphere upwelling related to localized lithospheric delamination (Li et al., 2016). Such a process may locally induce the isostatic uplift of the surface, leading to local rapid rock uplift above (Kirby and Harkins, 2013; Li et al., 2016). Additionally, the result from a joint inversion of receiver function and Rayleigh wave dispersion data (Wu et al., 2017) suggests that the mid-lower crustal low-velocity zones (LVZs) beneath the Songpan–Ganzi block thin out around the transition zone between the Songpan–Ganzi block and the Kunlun–Qinling orogenic system. However, the results of ambient noise tomography conducted by Jiang et al. (2014) and magnetotelluric (MT) data from Pape et al. (2012) support the hypothesis that the crustal low-velocity and high-conductivity zones penetrate northward from the Songpan–Ganzi block into the Kunlun–Qinling orogen. Whether these LVZs are stopped by the Kunlun fault or have extruded to the north into the Kunlun–Qinling orogenic system remains obscure, as does the mechanism that contributes to the