Tectonophysics 627 (2014) 122–134

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

Seismically constrained thermo-rheological structure of the eastern Tibetan margin: Implication for lithospheric delamination

Lin Chen [a,*], Fredrik Berntsson [b], Zhongjie Zhang [a], Peng Wang [c,d], Jing Wu [a], Tao Xu [a]

[a] State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China
[b] Linköping University, Linköping S 581 83, Sweden
[c] Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou 510640, China
[d] University of Chinese Academy of Sciences, Beijing 100049, China

ARTICLE INFO

Article history:
Received 27 April 2013
Received in revised form 5 October 2013
Accepted 3 November 2013
Available online 12 November 2013

Keywords:
Lithosphere rheology
Temperature
Seismic velocity
Eastern Tibetan margin
Delamination

ABSTRACT

The eastern Tibetan margin bordered by the Longmen Shan range exhibits significant lateral differences in the lithospheric structure and thermal state. To investigate the roles of these differences in mountain building, we construct a thermo-rheological model along a wide-angle seismic profile across the eastern Tibetan margin based on recent seismic and thermal observations. The thermal modeling is constrained by the surface heat flow data and crustal P wave velocity model. The construction of the rheological envelopes is based on rock mechanics results, and involves two types of rheology: a weak case where the lower crust is felsic granulite and the lithospheric mantle is wet peridotite, and a strong case where the lower crust is mafic granulite and the lithospheric mantle is dry peridotite. The results demonstrate: (1) one high-temperature anomaly exists within the uppermost mantle beneath eastern Tibet, indicating that the crust in eastern Tibet is remarkably warmer than that in the Sichuan basin, and (2) the rheological strength of the lithospheric mantle beneath eastern Tibet is considerably weaker than that beneath the Sichuan basin. The rheological profiles are in accord with seismicity distribution. By combining these results with the observed crustal/lithospheric architecture, Pn velocity distribution and magmatism in the eastern Tibetan margin, we suggest that the delamination of a thickened lithospheric mantle root beneath eastern Tibet is responsible for the growth of the eastern Tibetan margin.

1. Introduction

The lateral rheological contrast in the continental lithosphere is a key factor controlling the behavior of continental deformation (Ranalli and Adams, 2013). Thus, knowledge of lithospheric rheological structure is fundamental to understanding the geodynamic process at the conjunct zone of different tectonic units, especially the interaction zone between mountain and basin. Both observation and modeling show that the rheology of the continental lithosphere varies with depth, characterized by alternating brittle and ductile layers with one or more brittle–ductile transitions (Ranalli and Murphy, 1987). There are two primary competing rheological models for the long-term strength of continental lithosphere, which have been termed "jelly sandwich" and "crème brulée" (Burov, 2010; Burov and Watts, 2006; Jackson, 2002). The former argues that a relatively strong and brittle upper crust is separated from a strong uppermost mantle by a weak ductile lower crust (Chen and Molnar, 1983). The latter suggests that the strength of continental lithosphere resides only in the upper part of the lithosphere, which overlies a ductile lithospheric mantle (Jackson, 2002; Jackson et al., 2008; Maggi et al., 2000a, 2000b). The lower crust may or may not have rheological strength, which depends on the geological age of the study area (Maggi et al., 2000a, 2000b). Recent studies show that these two models most likely represent two end members of a continuous spectrum of rheological behaviors, depending on the composition and temperature (Afonso and Ranalli, 2004; Pauselli et al., 2010). In fact, the rheology of the continental lithosphere not only varies with depth, but also significant lateral variations in the rheological properties can arise from different lithospheric structures, compositions and thermal regimes. Such lateral rheological variation of the continental lithosphere may play an important role in the behavior of the lithosphere deformation (Cloetingh and Burov, 1996; Pauselli et al., 2010; Tejero and Ruiz, 2002; Wang, 2001).

The eastern Tibetan margin adjacent to the Sichuan basin (see Fig. 1) is an ideal place for studying the lateral variation in the lithospheric rheology due to the lateral differences of the lithospheric structure and thermal state (Hu et al., 2011; Z. Li et al., 2012; Robert et al., 2010; Wang et al., 2007; Xu et al., 2011a; Zhang et al., 2009; Z. Zhang et al., 2010). During past decades, various observations, such as surface heat flow, gravity, seismicity and crustal velocity structure, have been accumulated in this region (Hu et al., 2000; Jiang and Jin, 2005; Wang et al., 2007; Xu et al., 2011b; J.S. Zhang et al., 2010). These data make such a study become possible. In this paper, we first briefly review the geological setting and geophysical observations on the

* Corresponding author. Tel.: +86 10 82998345; fax: +86 10 82998229.
E-mail address: sinica.lin@gmail.com (L. Chen).

0040-1951/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.tecto.2013.11.005

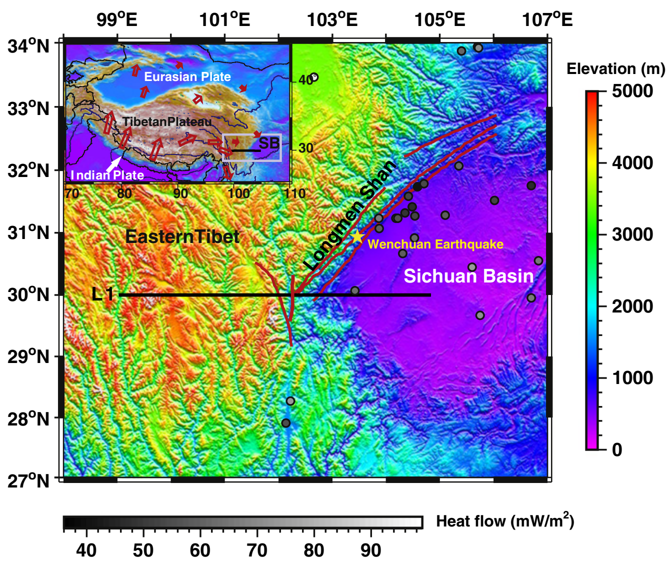

Fig. 1. Topographic map of the eastern Tibetan margin adjacent to the Sichuan basin. The solid black line, labeled as L1, shows the location of the wide-angle seismic profile reported by Wang et al. (2007). The gray-scaled points show the available heat flow observations in this region (Hu et al., 2000; Xu et al., 2011a). The red lines denote the main faults in the area. The yellow star indicates the epicenter of the 2008 Wenchuan earthquake. The inset image in the top left corner is a map of the Tibetan Plateau and its surrounding area. The white arrow shows the movement direction of Indian plate relative to Eurasian plate, which causes the southeastern extrusion of the Tibetan lithosphere. The red arrows indicate GPS vectors (Gan et al., 2007).

crustal/lithospheric structure and thermal state in the eastern Tibetan margin. Next, we describe the data set used in the study, which provide the compositional, structural and thermal information of the study region and form the basis of the construction of the 2D lithospheric thermo-rheological model. The approaches and parameters used for 2D thermo-rheological modeling are presented in the next section. Finally, the results and their possible implication are discussed.

2. Geological setting

The eastern margin of the Tibetan Plateau adjacent to the Sichuan basin is a transitional zone between the Tibetan Plateau and Yangtze craton. This margin is bordered by the NE–SW trending Longmen Shan (LMS) range with the Songpan–Ganze terrane to the west and the Sichuan basin (part of the Yangtze craton) to the east (Fig. 1). It is characterized by a sharp topography gradient from ~500 m in the Sichuan basin to more than 5000 m in the plateau over a horizontal distance less than 50 km. The eastern Tibetan margin has experienced a prolonged and complex tectonic evolution history (Burchfiel et al., 1995; Chen et al., 1995; Li et al., 2003). Its deformation was initiated in the Middle to Late Triassic in response to the amalgamation of the North China, South China and Qiangtang continental blocks (Burchfiel et al., 1995; Chen and Wilson, 1996; Li et al., 2003; Z.-W. Li et al., 2012; Liu et al., 2009). The Cenozoic deformation of the Longmen Shan was superimposed on the preexisting Mesozoic orogen (Burchfiel et al., 2008), which was reactivated by the far-field effect of the Indian–Asian collision (Harrison et al., 1992; Royden et al., 2008). The opinions concerning the timing of the Indian–Asian collision vary (Aitchison et al., 2007; Molnar and Stock, 2009; Xia et al., 2011; Zhu et al., 2013), but most researchers agree that it occurred between 55 and 45 Ma, conspicuously evidenced by a slow-down of convergence rate from over 100 mm/yr to about 50 mm/yr around 50 Myr ago (Zahirovic et al., 2012). As Indian–Asian convergence continued, the eastward growth of the Tibetan Plateau was strongly resisted by the cratonic Sichuan basin, contributing a further uplift of the eastern Tibetan margin. Although the formation mechanism of the eastern Tibetan margin is still controversial (Chen et al., 2013a, 2013b; Clark and Royden, 2000; Hubbard and Shaw, 2009; Royden et al., 2008), it is generally believed that the present high topography of the Longmen Shan and the eastern Tibetan Plateau was probably not developed until the Late Cenozoic (Arne et al., 1997; Burchfiel et al., 2008; Godard et al., 2009; Kirby et al., 2002; Z.-W. Li et al., 2012; Wang et al., 2012). However, both geological survey and GPS measurements indicate that active shortening rate across the Longmen Shan is less than 3 mm/yr (Burchfiel et al., 2008; Densmore et al., 2007; Gan et al., 2007). In addition, the Longmen Shan lacks a significant Late Cenozoic foreland basin in the Sichuan basin (Burchfiel et al., 1995). These observations suggest that the crustal shortening in the eastern Tibetan margin mainly occurred at depth and the crust here is Airy-compensated (Burchfiel et al., 2008).

Recent seismic studies reveal that great differences in crustal and lithospheric structure and property exist between the eastern Tibet and the Sichuan basin (Y. Chen et al., 2013; Hu et al., 2012; Robert et al., 2010; Wang et al., 2007; Zhang et al., 2009; Z. Zhang et al., 2010). The crustal thickness decreases from ~60 km beneath eastern Tibet to ~40 km beneath the Sichuan basin. There is an abrupt Moho offset as large as 15–20 km over a horizontal distance of ~70 km beneath the LMS (Robert et al., 2010; Zhang et al., 2009). The Moho offset may have a deep origin. Receiver function results demonstrate that the lithosphere–asthenosphere boundary (LAB) beneath eastern Tibet is remarkably shallower than that beneath the Sichuan basin with a sudden change also occurring at the LMS, although the results reported by different authors show some diversity (Hu et al., 2011, 2012; Z. Zhang et al., 2010). Moreover, P-wave tomography shows a seismically fast structure beneath the Sichuan basin up to ~250 km depth (Li et al., 2006), which suggests that the lithosphere beneath the Sichuan basin is probably cold and mechanically strong compared to surrounding regions (Burchfiel et al., 2008). Above ~250 km depth, the eastern Tibetan plateau region is seismically slow, probably indicating lower mechanical strength and elevated temperatures in the lithosphere (Li et al., 2006). The distribution of heat flow in the continental China also demonstrates that the heat flow in eastern Tibet is remarkably higher than that in the Sichuan basin (Hu et al., 2000; Tao and Shen, 2008). Such significant lateral variations in seismic and thermal structures can place important constraints on the rheological properties of the lithosphere and thus may provide insight into the formation mechanism of the eastern Tibetan margin.

3. Data set

Our study mainly involves three types of data: (1) surface heat flow, (2) crustal P-wave velocity distribution from wide-angle seismic profiling, and (3) seismicity data recorded during 1970 to 2012.

The distribution of the available heat flow data is quite uneven in the continental China with a dense coverage in eastern China and poor coverage in western China (Hu et al., 2000). In the eastern Tibetan Plateau, the heat flow data are especially sparse. In order to make our geothermal study reasonable, we adopt a new heat flow map produced by Tao and Shen (2008), which was developed with an objective and integrated interpolating method, taking account of the uniformity within tectonic units and the coherency of regional heat flow, on the basis of a compilation of 6980 heat flow measurements in the Chinese continent and its adjacent areas. In general, the overall heat flow data exhibits high values in eastern China and the Tibetan Plateau, and low in the central and northwestern China (Fig. 2). In contrast to the hot eastern Tibet, the heat flow in the Sichuan basin ranges from 35.2 to 68.8 mW/m^2 with an average of 53.2 mW/m^2, which is typical of a cratonic basin (Xu et al., 2011b; Yuan et al., 2006). This pattern is further confirmed by a recent new release of heat flow data, which showed the local heat flow in the Songpan–Ganze terrane can be as high as