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Dynamic support of the Tien Shan lithosphere based on flexural and rheological modeling

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ABSTRACT

The Tien Shan is a high, young and seismically active intracontinental mountain belt in central Asia that has been uplifted approximately 3 km over the past 10 Ma. A flexural analysis using Bouguer gravity and topographic data was used to determine the dynamic lithospheric mechanisms that are responsible for the topographic uplift and crustal thickening of the range. Bouguer gravity anomalies were used to constrain flexural models for isostatic compensation associated with the large relief of the Tien Shan. This is explained by significant underthrusting of a continuous elastic plate below the Tien Shan, with an effective elastic thicknesses (T_e) that gradually changes from 40 to 50 km in the Tarim and Junggar basins and the Kazakh plate to 20–23 km beneath the Tien Shan. Horizontal shortening due to folding and thrusting of the upper–middle crust causes uplift and crustal thickening of the margin of the Tien Shan. The regional and local compensation occur at the eastern and western parts of the Tien Shan respectively.

Rheological modeling using a simple geothermal structure for the Tien Shan reveals that the base of the strong upper crust of Tibet is at a depth of 30–35 km, which is consistent with the depths of 7776 earthquakes between 1970 and 2011, which serve as constraints on the brittle failure domain of the area. The Moho depths are used to determine the thickness of the lower crust (17–25 km) and to understand the mobility of the lower-crustal flow of the Tien Shan. The tendency for the strong upper crust to flow over the weak, ductile lower crust (or middle–lower crust) depends on the thickness of the lower crust. In other words, its strength depends on the depths of the base of the upper crust and the Moho. The larger the difference, the easier it is for the upper crust to flow relative to the strong upper-mantle lithosphere. The crustal deformation is decoupled from deformation of the upper-mantle lithosphere by the weak, ductile lower crust of the Tien Shan.

1. Introduction

Many aspects of intracontinental deformation are poorly understood. The Tien Shan is a young and very active intracontinental range in central Asia and is bounded by the Kazakh Plate to the northwest, the Junggar Basin to the northeast and the Tarim Basin to the south (Fig. 1). More than 1500 km to the north of the Indian–Eurasian collision zone, the Tien Shan currently absorbs approximately 30% of the total relative plate convergence of ~20–23 mm/yr (e.g., Abdraknmatov et al., 1996; Holt et al., 2000; Wang et al., 2001; Bullen et al., 2003; Zhang et al., 2004; Zubovich et al., 2010). Rapid shortening in the Tien Shan has created the highest elevations in Asia outside of the Himalayas. With such large amounts of deformation, the Tien Shan is a good laboratory for studying intracontinental mountain building. The tectonics of the Tien Shan, such as the timing of uplift, slip rates on the thrust fault systems that bound the margins, and the Quaternary shortening in the interior of the fold belt, have been investigated in previous studies (e.g., Avouac et al., 1993; Brown et al., 1998; Yin et al., 1998; Burchfiel et al., 1999; Thompson et al., 2002; Sun et al., 2004; Pirajno et al., 2008; Ji et al., 2008; Jolivet et al., 2010). However, the geodynamic mechanisms responsible for the topographic uplift and crustal thickening of the Tien Shan remain controversial. It is generally accepted that since the late Cenozoic Period, the remote effect induced by the convergence of India and Eurasia caused the tectonic activity of Central Asia inland along the Tien Shan orogen. Some scholars (e.g., Makarov et al., 2010) believe that the south Tien Shan piedmont buried a great continental plate subduction zone, beneath which the Tarim plate subducted the Tien Shan along it, leading to the Tien Shan uplifting. Thus, the uplift mechanism of the Tien Shan Mountains is the crustal thickening caused by the horizontal compression. Crustal shortening, crustal thickening, movements caused by large thrust faults, and foreland basins formed by the compression on both sides of the Tien Shan

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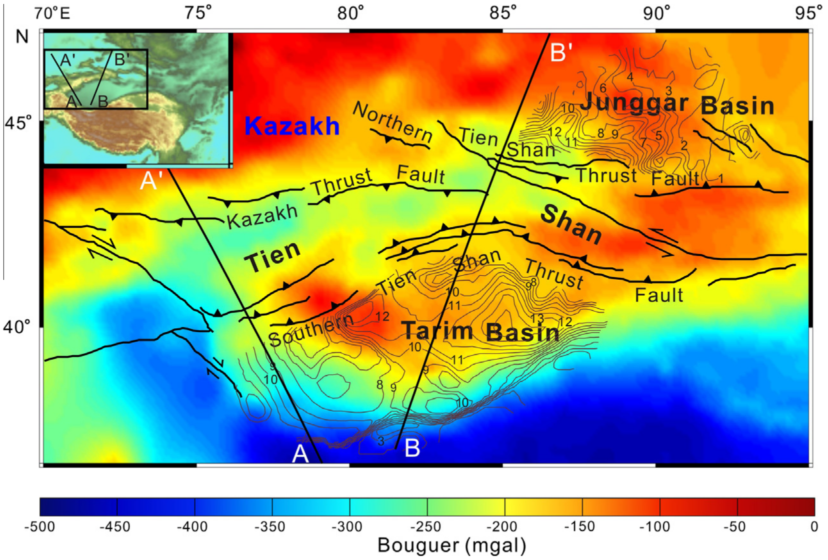

Fig. 1. Map of Bouguer gravity anomalies in mGal. The data are digitized from the 1:500,000 Regional Bouguer Gravity Map of the Tarim and Junggar basins and the 1:4,000,000 Regional Bouguer Gravity Map of China for other areas within China. The data outside China are from Kogan and McNutt (1993) and are in the public domain. The contours of the Tarim and Junggar basins indicate sediment thickness (XPB, 1998; Li, 2002) in kilometers, with a contour interval of 1 km, and are derived from industrial seismic reflection profiles. Solid lines with teeth or arrows indicate major faults in the study area (Zhang et al., 2003). The lines in the box indicate the locations of the 2D profiles modeled in this paper.

Mountains support the idea that the overthrust of the upper crust causes the uplift of the mountains. And some scientists suggest that the strong seismic heterogeneities of low-velocity and high VP/VS anomaly exist within the mantle of the Tien Shan area as a result of small-scale convection. Small-scale mantle convection in the upper mantle beneath the Tien Shan are supported by the broadband seismic data (Vinnik et al., 2004, 2006; Makeyeva et al., 1992; Wolfe and Vernon, 1998), the seismic tomography (Roecker et al., 1993; Roecker, 2001; Li et al., 2009; Guo et al., 2010), and the Receiver Functions analysis (Oreshin et al., 2002). The Tien Shan has nearly double amount of the heat flow in comparison with the Kazakh plate, indicating that the uplift of the Mountains is corresponding to small-scale convection in mantle (Kosarev et al., 1993; Roecker et al., 1993; Roecker, 2001; Curtis and Woodhouse, 1997; Vinnik et al., 2004; Li et al., 2009; Wang, 2011). Also, Wilson (1990) proposes that the uplift of the Tien Shan Mountains is the result of the normal force similar to that of the Botswana plateau in Africa.

Using gravity and a thin elastic-plate model, lithospheric folding with wavelengths of 50 and 300–360 km have been found for the crust and mantle lithosphere (Lyon-Caen and Molnar, 1984; Burov et al., 1990, 1993; Kogan and McNutt, 1993; Caporali, 1998; Braitenberg et al., 2003; Steffen et al., 2011). In this paper, the lateral heterogeneities of the lithospheric deformation are studied using flexural modeling and high-resolution Bouguer gravity and topographic data to elucidate the dynamic processes involved in deformation. We also used earthquake locations to constrain the lithospheric model.

The Tien Shan is formed from the Upper Paleozoic to Lower Mesozoic suture between the Tarim and the Kazakh (Junggar) plate, and it is bounded in the north and south by Cenozoic thrust faults (Carroll et al., 1995; Yin and Nie, 1996; Heermance et al., 2007; Hubert-Ferrari et al., 2007; Ji et al., 2008; Hinsbergen et al., 2011). The Kazakh Plate and the Tarim and Junggar basins are stable Precambrian features that have undergone little deformation overall during the Cenozoic convergence of India and Asia, with deformation localized along their margins (Yang and Liu, 2002). The marine basins of the Tien Shan were closed in the Early Permian and the fold belt developed during the Middle Permian as a consequence of the collision and suturing of the Tarim Basin and Kazakh plate (Hendrix et al., 1994). The change from marine sedimentation to a continental setting and the marked angular unconformity separating the Paleogene and Neogene strata are consistent with reactivation in the Tien Shan, which occurred in the Cenozoic in response to the India–Asia collision (Sobel and Dumitru, 1997; Me′ tivier and Gaudemer, 1997; Charreau et al., 2006; Rowley and Currie, 2006; Sobel et al., 2006; Jolivet et al., 2010). The tectonics of the Tien Shan appear to be dominated by thrusting on roughly E–W striking faults and folding of Cenozoic sediments (Avouac et al., 1993; Molnar et al., 1994; Thompson et al., 2002; Bullen et al., 2003). The range increases elevation and becomes wider to the west, where it connects to the dextral Talas-Ferghana strike-slip fault (Li and Chen, 2006; Korjenkov et al., 2010). The N–S Cenozoic shortening of the Tien Shan increases from near zero in the east to 200 km in the west (Kosarev et al., 1993).

The crustal thickness throughout the Tien Shan is approximately 50–65 km (Burbank et al., 1999; Oreshin et al., 2002; Vinnik et al., 2004; Wang et al., 2004; Kumar et al., 2005). However, GPS measurements indicate that the crustal shortening rate is not uniform, varying from ~20 to 12 to 4 mm/yr in the western, central and eastern parts of the Tien Shan, respectively (Abdraknmatov et al., 1996; Wang et al., 2001; Zhang et al., 2004; Yang et al., 2006). Geological field studies also show that shortening across the Tien Shan is spatially heterogeneous (Burchfiel et al., 1999; Buslov et al., 2007). It is unclear if the surface thrust faults are directly related to the structure of the lithosphere because the deformational properties of continental rocks are heterogeneous and the crust is extremely thick.

Gravity and topographic data can provide information on the crust and upper-mantle structure independently of other geophysical information. In this paper, two gravity transects across the Tien Shan are presented (Fig. 1). Our mechanical model allows for either one continuous plate with a laterally varying lithospheric strength or for two separate plates, allowing us to discern between the rigid lithosphere of the mountains and its neighboring areas. Flexural modeling enables the study of the sensitivity of Bouguer gravity anomalies to the bending of the Moho, and the degree of bending