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Bulk crustal properties in NE Tibet and their implications for deformation model

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ABSTRACT

The crust beneath the northeastern (NE) Tibetan Plateau records far field effects of collision and convergence occurring between the Indian and Eurasian plates. A better structural understanding of the crust beneath NE Tibet can improve our understanding of Cenozoic deformation resulting from the India–Eurasia collision. Taking advantage of the relatively dense coverage in most areas in NE Tibet except for the Qaidam basin by regional seismic networks of Gansu and Qinghai Provinces, we isolate receiver functions from the teleseismic P wave data recorded from 2007 to 2009 and resolve the spatial distribution of crustal thickness and Vp/Vs ratio beneath NE Tibet from H–κ scanning. Our results can be summarized as: (1) NE Tibet is characterized by ~60-km-thick crust beneath the Nan Shan, Qilian Shan thrust belts and the Anyemaqen Shan, and 45–50 km-thick crust beneath the Tarim basin, the Alashan depression and the Ordos basin; the crust thins gradually from west to east in addition to the previously observed pronounced thinning from south to north; (2) the crust of NE Tibet exhibits a relatively lower Vp/Vs ratio of 1.72 than the north China block and a decrease in average crustal Vp/Vs ratio with increasing crustal thickness; and (3) the crustal thicknesses are less than the values predicted by the simple isostatic model of the whole Tibetan plateau wherein the elevation is larger than 3.0 km. Our observations can be explained by the hypothesis that deformation occurring in NE Tibet is predominated by upper-crustal thickening or lower-crust extrusion.

1. Introduction

Uplift of the Tibetan Plateau began during the Cenozoic collision of India and Eurasia, and offers a classic example of the geodynamic processes associated with large-scale continental deformation as well as feedback mechanisms operating between lithospheric deformation, atmospheric circulation and biological evolution (England and Houseman, 1986; Molnar et al., 1993; Yin and Harrison, 2000; Tapponnier et al., 2001; Li et al., 2012). Several key parameters concerning the structure, growth mechanisms and history of the Tibetan plateau are still matters of debate. Fundamental questions persist concerning the initiation of convergence (Aitchison et al., 2007; Chen et al., 2010a; Aitchison et al., 2011; Guan et al., 2012), the extent of shortening (Dewey et al., 1989; Johnson, 2002; Sun et al., 2012) and the model of crustal thickening (e.g., Zhao and Morgan, 1987; Houseman and England, 1996; Royden et al., 1997; Meyer et al., 1998; Clark and Royden, 2000).

Many studies have focused on structural aspects of the crust and upper mantle beneath the central and southern regions of the Tibetan plateau, areas which have an average altitude of 5000 m, and show little variation in surface topography (Molnar and Tapponnier, 1975; Nelson et al., 1996; Yuan et al., 1997; Kind et al., 2002; Tilmann et al., 2003; Chen and Yang, 2004; Zhang and Klemperer, 2010; Zhao et al., 2010; Zhang et al., 2011a). As the northern terminus of contiguous deformation, the NE Tibetan Plateau is an important area for investigating the far field effects of the India–Eurasia collision (Yin et al., 2007, 2008a,b; Dayem et al., 2009). NE Tibet is bounded to the south by an easterly arm of the Kunlun fault (KF in Fig. 1), to the north and west by the Altyn Tagh fault (ALT), and to the north and east by the Haiyuan fault (HF). GPS measurements, structural analysis and studies of sedimentation rates indicate that NE Tibet is still in the early stages of uplift and deformation (Fang et al., 2003; Zheng et al., 2006; Gan et al., 2007; Lease et al., 2007; Lu and Xiong, 2009; Zheng et al., 2010a). Yin et al. (2007, 2008a,b) conducted detailed field mapping and systematically analyzed drill-hole data and seismic-reflection profiles across the Qaidam basin and surrounding areas. Their results indicate a progressive shift in crustal shortening mechanisms across the Qaidam basin, from a predominance of upper-crustal shortening in the west to a predominance of lower-crustal shortening in the east (Yin et al., 2008b). Their results also showed that the magnitude of Cenozoic crustal shortening strain across the southern Qilian Shan–Nan Shan thrust belt and northern Qaidam basin is sufficient to explain the current elevation and crustal thickness of these areas without invoking lower-crustal flow and/or a thermal event in the mantle (Yin et al., 2008a). Lower-crustal flow or mantle thermal events could be additional causes of plateau uplift across the southwestern Qaidam basin and the Eastern Kunlun Range if the deformation between the upper- and lower-crust decoupled during the Cenozoic India–Eurasia collision (Yin et al., 2007). This decoupling mechanism might include southward

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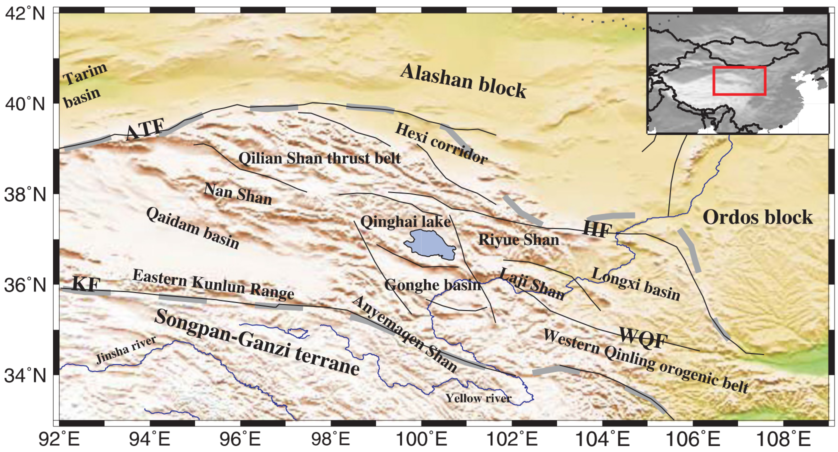

Fig. 1. Map of the study area showing topography and major tectonic features. Inset map shows the location of the study area. Thick dashed gray lines indicate the south and north boundaries of NE Tibet. Solid lines denote major faults and abbreviations are as follows: Altyn Tagh fault, ATF; Haiyuan fault, HF; Kunlun fault, KF; and Western Qinling fault, WQF.

underthrusting of the Qaidam basin in the lower-crust, and southward overthrusting of the Qaidam basin in the upper-crust above the Eastern Kunlun Range (Yin et al., 2007). It is still unclear whether this hypothesis about Cenozoic deformation mechanism in the southern part of NE Tibet can be generalized into the whole NE Tibet because of the natural conditions and difficulty in deep seismic sounding even though there are some seismic profiles conducted in the study area (e.g., Vergne et al., 2002; Jiang et al., 2006; Liu et al., 2006; Karplus et al., 2011; Wang et al., 2011; Zhang et al., 2011b). Obviously, more studies in NE Tibet are needed to resolve responses of crustal shortening in both the upper- and lower-crust of areas impacted by the India–Eurasia collision. Areal studies of crustal thickness, density and Poisson's ratio (Vp/Vs ratio) beneath NE Tibet can provide robust constraints on the lithospheric deformation mechanism that accommodates the shortening between East Kunlun at its south and North China Craton at the north.

In this study, we use the teleseismic P wave data recorded by a regional seismic network in NE Tibet to isolate the receiver functions, and then calculate the crustal thickness and Vp/Vs ratio. The increase in data over previous studies provides the opportunity to obtain a more reliable model of spatial variations in bulk crustal properties. Tectonic implications of our results are discussed in the context of crustal deformation models of NE Tibet.

2. Geological setting and previous geophysical studies

2.1. Geologic setting

As the contiguous region between the Tibetan Plateau and the North China Craton, NE Tibet is surrounded by the Alashan block to the north, the Tarim basin to the northwest, the Ordos block to the east, and Songpan–Ganzi terrane to the south (Fig. 1). NE Tibet itself consists of a series of basins, thrust faults and orogenic belts which include the Qaidam, Gonghe and Longxi basins, Qinghai lake; the Nan Shan and Qilian Shan thrust belts; the Anyemaqen Shan, Riyue Shan, Laji Shan and the Western Qinling orogenic belts. The Hexi corridor may also behave as a contiguous component of NE Tibet.

Previous tectonic studies indicate that the Qilian Shan thrust belt collided with the Qaidam basin during the Early Paleozoic (Yang et al., 2002; Song et al., 2006; Yu et al., 2012) and later with the Alashan block in the Late Devonian (Xiao et al., 2009). The Qaidam basin collided with the Songpan–Ganzi terrane in the Early Jurassic (Dewey et al., 1988; Yin and Harrison, 2000). NE Tibet itself is a collage of island arcs, as well as deep marine and shallow marine assemblages, formed by a protracted series of Early to Middle Paleozoic subduction- and collision-related events (Gehrels et al., 2003). As such, NE Tibet consists of island arc and accretionary prism material, ophiolites, seamounts and high- to ultrahigh-pressure metamorphic rocks (Yin and Harrison, 2000; Gehrels et al., 2003; Xiao et al., 2009). Following Mid-Paleozoic accretion, NE Tibet experienced additional phases of deformation, metamorphism and uplift from Late Paleozoic to Late Jurassic time (Delville et al., 2001; Sobel et al., 2001; Zhu et al., 2012).

As a response to the India–Eurasia collision, crustal deformation in NE Tibet has occurred in the Cenozoic (Dayem et al., 2009). Offsets of strike-slip faults, and basin sedimentation rates suggest that the deformation began in NE Tibet shortly after collision (Tapponnier et al., 1981; Yin et al., 2002; Fang et al., 2003; Ritts et al., 2004; Yue et al., 2005; Wang et al., 2008). Increased exhumation of high terrain suggests that crustal thickening accelerated in NE Tibet during Middle- to Late-Miocene (Garzione et al., 2005; Zheng et al., 2006; Lease et al., 2007; Zheng et al., 2010a). Surface structure of NE Tibet is featured by regular, large-scale disposition of mountain ranges separated by piggyback basins and south-dipping thrusts (Métivier et al., 1998; Meyer et al., 1998). Fieldwork and SPOT image analysis studies (Meyer et al., 1998) suggest that NE Tibet has experienced at least 150 km of cumulative regional shortening perpendicular to its major faults (~N30°E), the Kunlun and Haiyuan faults in the last 10 million years. Geological investigations (Chung et al., 2005; Xia et al., 2011) indicate that the Tibetan plateau preserves evidence for widespread volcanism as a consequence of the collision of India with Asia; Cenozoic volcanic rocks are however absent in NE Tibet. Although surface heat flow measurements are relatively sparse, the crust beneath NE Tibet appears to be cool (Pollack et al., 1993; Hu et al., 2000).

2.2. Previous geophysical studies

Over the past two decades, several passive and active source seismic profiles have been conducted in NE Tibet. A major review of the issue was recently published by Zhang et al. (2011a). Although spatial distribution is very sparse, these seismic profiles showed some basic characters of the crust in NE Tibet and the surrounding regions. Crustal thickness increases from 42 km beneath the Ordos block (Liu et al., 2006) and 45 km beneath the Alashan block (Li et al., 2006b) to 60–70 km beneath the Qilian Shan thrust belt (Cui et al., 1995). Crustal thickness reduces to 50–53 km beneath the Qaidam basin (Cui et al., 1995), and then increases again to 60–70 km near the Kunlun fault (Vergne et al., 2002; Jiang et al., 2006; Li et al., 2006a; Karplus et al., 2011; Zhang et al., 2011b). To study the lateral variation in the crustal structure across the boundaries of NE Tibet and considering the difficulties in fieldwork, most of these profiles are located in