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Seismic velocity variations beneath central Mongolia: Evidence for upper mantle plumes?

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A B S T R A C T

Central Mongolia is marked by wide spread recent volcanism as well as significant topographic relief even though it is far from any plate tectonic boundaries. The cause of the recent magmatism and topography remains uncertain partially because little is known of the underlying mantle seismic structure due to the lack of seismic instrumentation in the region. From August 2011 through August 2013, 69 broadband seismic stations were deployed in central Mongolia. Teleseismic traveltime residuals were measured using waveform correlation and were inverted to image upper mantle P and S velocity variations. Significant lateral variations in seismic velocity are imaged in the deep upper mantle (100 to 800 km depth). Most significant are two continuous slow anomalies from the deep upper mantle to near the surface. One slow feature has been imaged previously and may be a zone of deep upwelling bringing warm mantle to beneath the Hangay Dome resulting in uplift and magmatism including the active Khanuy Gol and Middle Gobi volcanoes. The second, deep low velocity anomaly is seen in the east from 800 to 150 km depth. The anomaly ends beneath the Gobi Desert that is found to have fast shallow mantle indicating a relatively thick lithosphere. We interpret the second deep slow anomaly as a mantle upwelling that is deflected by the thick Gobi Desert lithosphere to surrounding regions such as the Hentay Mountains to the north. The upwellings are a means of feeding warmer than normal asthenospheric mantle over a widely distributed region beneath Mongolia resulting in distributed volcanic activity and uplift. There is no indication that the upwellings are rooted in the deep lower mantle i.e. classic plumes. We speculate the upwellings may be related to deep subduction of the Pacific and Indian plates and are thus plumes anchored in the upper mantle.

1. Introduction

Although far from any plate boundary, the Mongolian Plateau exhibits large topographic relief as well as extensive recent volcanic activity. The average elevation of the Plateau is 1500 m while in central Mongolia the Hangay Dome rises to near 4000 m and the Hentay Mountains to the northeast reach elevations near 3000 m above sea level (Fig. 1). The age of uplift of the Hangay and Hentay ranges is uncertain although Hangay likely began uplift 25–30 Ma (Walker et al., 2007, and references therein) with the most active phase between 3–4 Ma and today (Barry and Kent, 1998). The Hentay Mountains and Hangay Dome are found to have high heat flow (60–70 mW/m^2) relative to the surrounding regions (Khutorskoy and Yarmoluk, 1989). A large region of Cenozoic intra-plate volcanism stretches across central Asia from the Baikal Rift through central Mongolia to China. In Mongolia the volcanism consists of numerous, small-volume, alkali-basalt cones and lavas erupted since ∼30 Ma (Hunt et al., 2012). Most of the recent volcanism is concentrated around the Hangay Dome and to the north towards the Baikal Rift although the largest lava flows are to the east in Dariganga. Seven late Cenozoic volcanic eruption sites are shown in Fig. 1, Taryatu Chulutu (TC), Khanuy Gol (KG), Bus Obo (BO), Middle Gobi (MG), Dariganga (DG), Honggeertu (HG) and Datong (DT). Finally, central Asia and Mongolia in particular, is also seismically active with a range of strike-slip and normal earthquakes occurring over a broad area (Bayasgalan et al., 2005).

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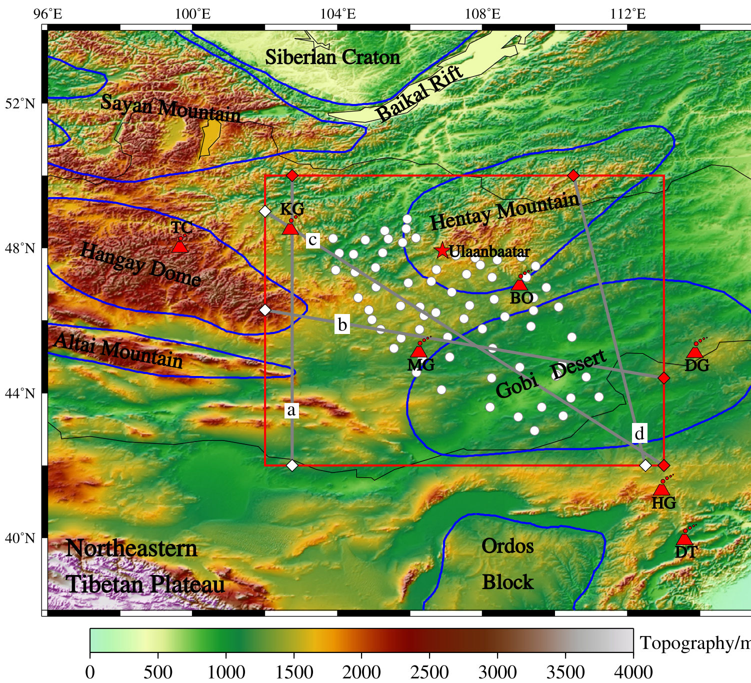

Fig. 1. Topographic map of the study area and its surrounding regions. The red triangles denote volcanoes, red star is city, blue lines represent outline tectonic provinces, the red frame represents the study area, the white hollow circles denote seismic stations, and the gray lines labeled a, b and so on, represent the location of sections with red/white diamond endpoints shown in Fig. 7. Abbreviations for the volcanic sites are: TC – Taryatu Chulutu, KG – Khanuy Gol, BO – Bus Obo, MG – Middle Gobi, DG – Dariganga, HG – Honggeertu, DT – Datong. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The cause of the tectonic activity in Mongolia is still a matter of debate. Two end member models are 1) that the Mongolia tectonic activity is due to a hot plume or plumes from depth impinging on the base of the lithosphere causing uplift of the entire plateau, or more localized regions, as well as widespread volcanism (Windley and Allen, 1993; Zorin et al., 2003, 2006; Zhao et al., 2006; Mordvinova et al., 2015) and 2) that the activity is due to lithospheric processes that are likely due to the India–Asia collision far to the south (Molnar and Tapponnier, 1975; Khain, 1990; Bayasgalan et al., 2005; Hunt et al., 2012). Although the studies cited above differ in detail, the question of whether a deep upwelling is affecting Mongolia or not remains an open fundamental question.

Several geophysical studies have been undertaken in Mongolia although much remains to be done. Tiberi et al. (2008), Petit et al. (2008), and Mordvinova et al. (2015) used data from a north south temporary seismic deployment (the MOBAL seismic experiment) along with gravity data to image the crust and mantle beneath a profile including the Hangay Dome. They conclude that most of the buoyancy for the dome topography is located in the asthenosphere from depths of 60 to 225 km. A second seismic experiment consisted of a linear array focused on the Baikal Rift but extended to the Hentay Mountain range (Gao et al., 2003). This study found slow seismic velocities in the shallow mantle beneath the Hentay Mountains (Gao et al., 2003; Zorin et al., 2003). A recent deployment of seismic stations around the Hentay Mountains (discussed below) used receiver functions and gravity to determine that the buoyancy supporting the Hentay Mountains was also located in the shallow mantle, presumably an upwarped asthenosphere (He et al., 2016). Seismic travel time tomography using regional and global data has also supported the idea that Hangay and Hentay overlie slow mantle anomalies near 100 km depth (Kulakov, 2008) but deep structure is ambiguous in these studies. Recently, Chen et al. (2015a) developed an East Asia regional model of upper mantle P and S velocities using waveform inversion. They find strong slow seismic anomalies beneath Hangay and Hentay near 100 km depth but also found an eastward dipping slow cylindrical anomaly in the transition zone that they interpret as upwelling from the deep mantle that is contributing to the buoyancy beneath the Hangay Dome. It should be noted, however, that station coverage in the Chen et al. (2015a) study is limited in Mongolia. Zorin et al. (2003) used Bouguer gravity anomalies to postulate that there are several deep mantle upwellings (plumes) beneath Mongolia, including beneath the Hangay Dome and the Hentay Mountains.

Cenozoic basalts in Mongolia have been studied by numerous authors. Since 30 Ma the volcanism in Mongolia has been focused in a north–south swath through the center of Mongolia including around the Hangay Dome (Barry and Kent, 1998). Barry et al. (2007) find no evidence of high He^3/He^4 ratios in olivine phenocrysts in Mongolian basalts. This does not rule out a lower mantle plume giving rise to Mongolian activity but certainly does not support the idea. Hunt et al. (2012) and Barry et al. (2003) find that Mongolian magmatism results from asthenospheric and deep lithosphere melting due to a higher than normal potential temperature at those depths. They rule out that the high temperature and volumes of melt observed could be due solely to extension and consequent shallowing of the asthenosphere. Hunt et al. (2012) note that there is no indication of subduction related fluids being responsible for lower lithosphere melting under Hangay and conclude that either lithosphere delamination or some mild plumes have increased the temperature at depths near 100 km to cause the observed volcanism. Barry et al. (2007) agree with this conclusion but also propose that the warm mantle may come from lateral flow.

Currently it is well established that the high topography of the Hentay and Hangay regions is largely due to mantle buoyancy in the shallow mantle. The magmatic activity is largely explained by heating of the mantle at these depths as well. What caused the mantle temperature anomalies, however, is less well understood. Part of the uncertainty is due to the lack of high resolution seismic images of the region which is due to a lack of seismic data from Mongolia. Here we present the results of a finite-frequency traveltime tomography inversion to develop a 3-D P and S veloc-