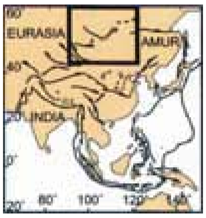

Topography, geoid and gravity anomalies in Western Mongolia

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Introduction: mantle plumes, topography and gravity anomalies

One of the proposed manifestations of mantle plumes is uplift of the Earth's surface that cannot be explained by other mechanisms such as tectonic crustal thickening. Mantle plumes are thought to generate uplift because they:

- are made of hot, light mantle material which is more buoyant than the surrounding mantle,
- heat the lithosphere, and
- comprise ascending mantle which dynamically lifts the surface.

In reality, the effect of a mantle plume on the surface topography is complex and depends on various factors such as the rheological stratification of the lithosphere (see Lithospheric Uplift webpage) One cannot, therefore, conclude from surface topography alone that a mantle plume beneath is required. The support of gravity and geoid data is of great help because they enable us to investigate density anomalies. Bouguer gravity anomalies are sensitive to shallow-seated anomalies, and the geoid can detect deeper ones. In addition, gravity can be combined with topography to calculate isostatic anomalies and investigate the depth of compensation of the topography.

The Hangai dome of Western Mongolia: general setting

The Hangai dome (HD) of western Mongolia is a 500 km-long topographic bulge topped by a relatively flat, young plateau culminating at ~4000 m (Figure 1). Active tectonics in this region are mainly localised in the Altai and Gobi-Altai ranges (west and south of HD) where numerous active wrench and reverse faults have been found (*e.g.*, *Bayasgalan et al.*,1999) . On the other hand, the HD is almost devoid of active faults, and only a few normal faults bound its southern flank. Thus, tectonic thickening of the crust is unlikely to be the origin of its elevated topography. Besides this, volcanic activity has occurred there during the past 30 Myr, suggesting the presence of a thermal anomaly in the upper mantle (*Windley & Allen*, 1993).

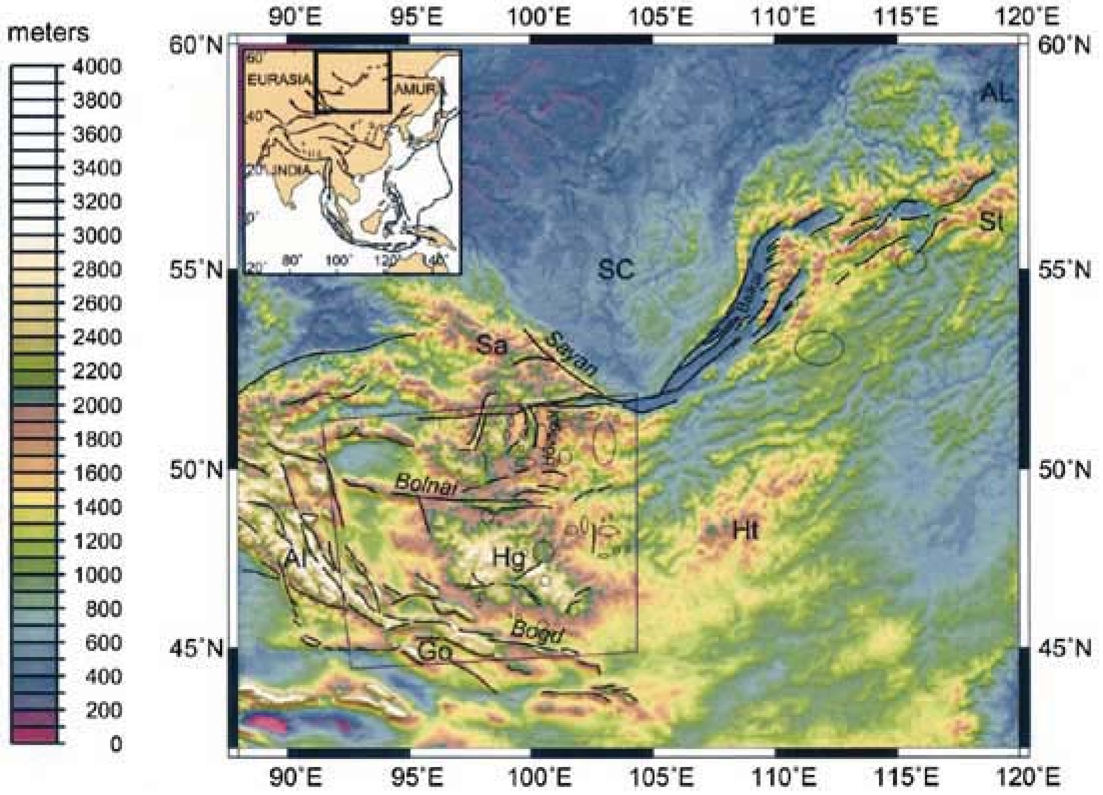


Figure 1. Topography of the Baikal-Mongolia region (after Petit et al., 2002). Abbreviations refer to the main topographic ranges: Al = Altai; Go = Gobi-Altai; Hg = Hangai; Ht = Hentai; Sa = Sayan; St = Stanovoy). SC = Siberian craton; AL = Aldan shield. Ellipses indicate outcrops of recent (Cenozoic) volcanism. Solid lines correspond to active faults.

Up to now, the best-constrained information on the vertical structure of the lithosphere comes from thermobarometric and petrologic analyses of young xenoliths from the Tariat (Hangai) region (see the Mongolia webpage of *Barry et al.*, 2005; *Ionov et al.*, 1998; *Kopylova et al.*, 1995) and can be summarised as follows:

1. the average crustal thickness is ~ 45 km in western Mongolia;
2. the maximum crustal thickness (50 ± 3 km) occurs beneath the northern Hangai area, where pressure equilibration conditions deduced from the shallowest ultramafic rocks are ~ 1.4 x 10^3 MPa;
3. the lithosphere – asthenosphere transition is likely to occur at depths greater than 70 km, as indicated by an upper mantle xenolith geotherm (*Ionov*, 1998);
4. around 40-50 km depth, xenolith equilibration temperatures suggest a steep geotherm which cannot result from heat conduction alone, and could suggest heat advection from basaltic intrusions and underplated cumulates near the Moho. Except in some places such as the Hovsgol graben, the average heat flow in Mongolia is moderate (~60 mW m^{-2}), which does not support the hypothesis of large-scale thinning and heating of the lithosphere.

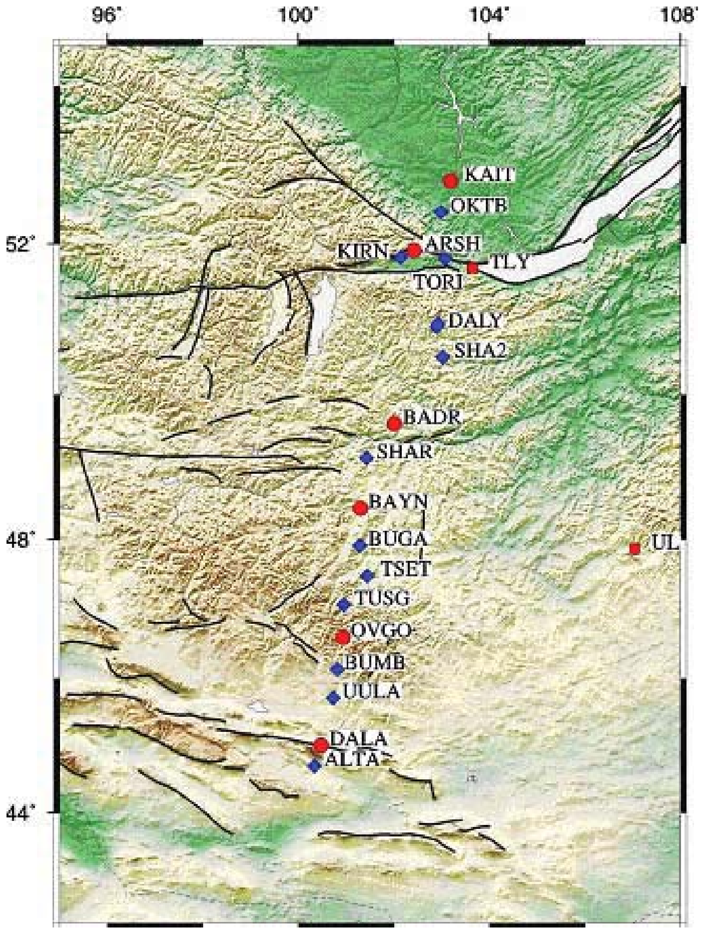


Figure 2. Location of the 20 seismic stations of the 2003 MOBAL seismic experiment.

Until recently, crustal seismic data were lacking in Mongolia. However, a seismic experiment was conducted in 2003 with 20 stations crossing Western Mongolia in a NS direction from the Gobi-Altay range to the Siberian craton (Figure 2). The results will provide crucial constraints on crust and upper mantle structure and are expected in 2006 (see http://www-sdt.univ-brest.fr/~jacdev/mobal.htm for more information). Global and regional tomography models in Asia have consistently imaged a deep-seated (around and below 100 km) low-velocity anomaly beneath central Mongolia (*e.g., Curtis et al.*, 1998; *Petit et al.*, 1998; *Ritzwoller & Levshin*, 1998). The shear-wave velocity model obtained by *Villasenor et al.* (2001) from inversion of surface wave velocities further strengthens this view: it depicts a large low-velocity anomaly beneath the Hangai-Hovsgol region at about 100 km depth, with a –4% contour line fitting approximately the broad uplands of Hangai and Hovsgol, whereas no anomaly is found below Lake Baikal. The surface projection of the Hangai-Hovsgol shear-wave velocity anomaly correlates quite well with widespread volcanic emissions dated between Paleogene and Quaternary.

Gravity, isostatic anomalies and the geoid

The Bouguer gravity anomaly is, on average, much lower in Western Mongolia than in the Baikal region (Figure 3). A greater crustal thickness and/or a thinner lithosphere are possible explanations for this observation. Isostatic anomalies show large minima over western Mongolia, indicating mass deficits with respect to a local, Airy-type compenstated situation (Figure 4). Some of these minima, for instance along the Altai and Gobi-Altai ranges, closely follow the pattern of active faults and could reflect tectonic crustal thickening, which is consistent with field observations (Figure 4a). However, the Hangai dome and its northern prolongation, the Hovsgol dome, are associated with a wide, oval-shaped negative anomaly of much larger wavelength (Figure 4b). This anomaly correlates well with the region of low velocity imaged by seismic tomography models (Figure 5), and also with higher-than-average (70-80 mW/m^2) surface heat flow (*Khutorskoy & Yarmoluk*, 1989).

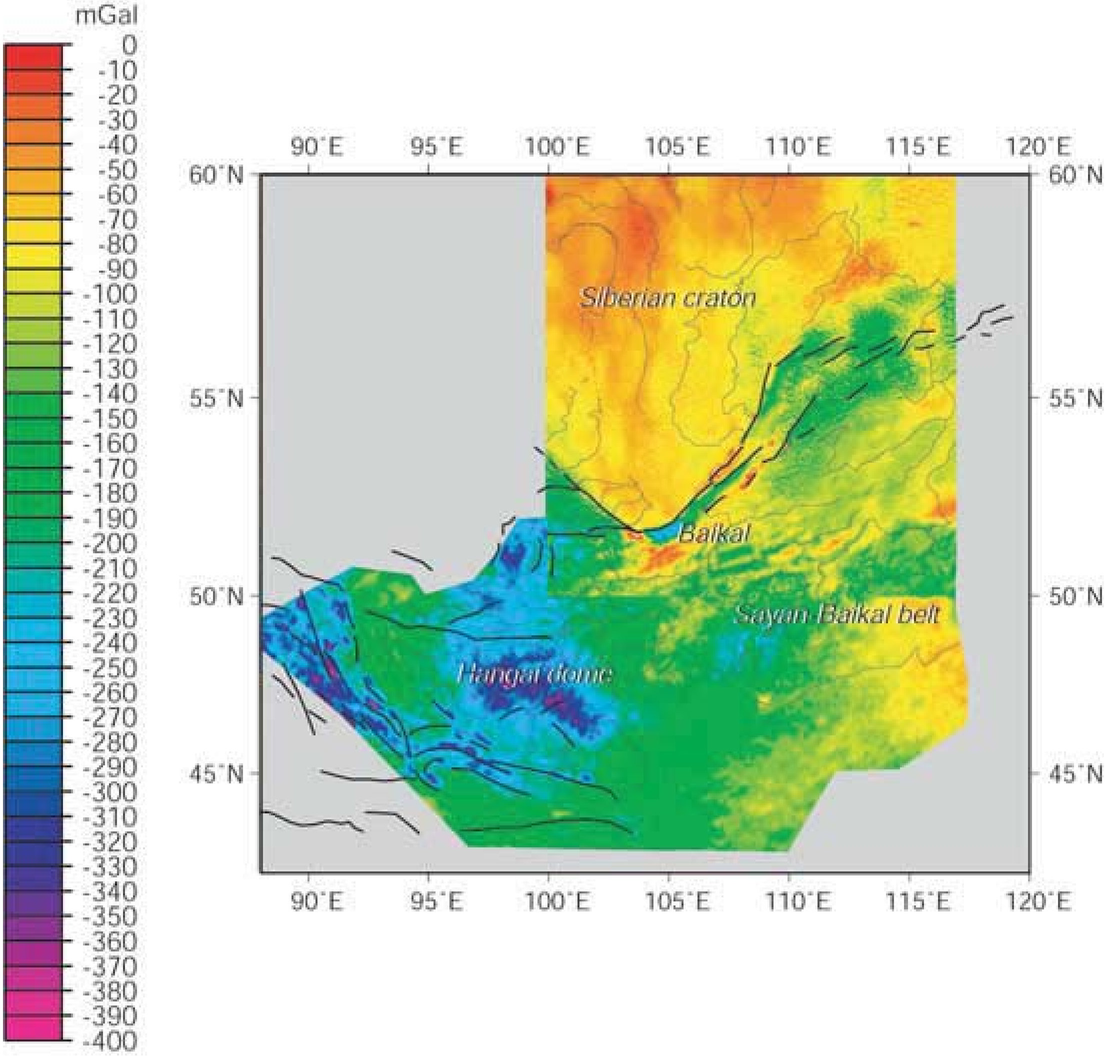


Figure 3. Bouguer gravity

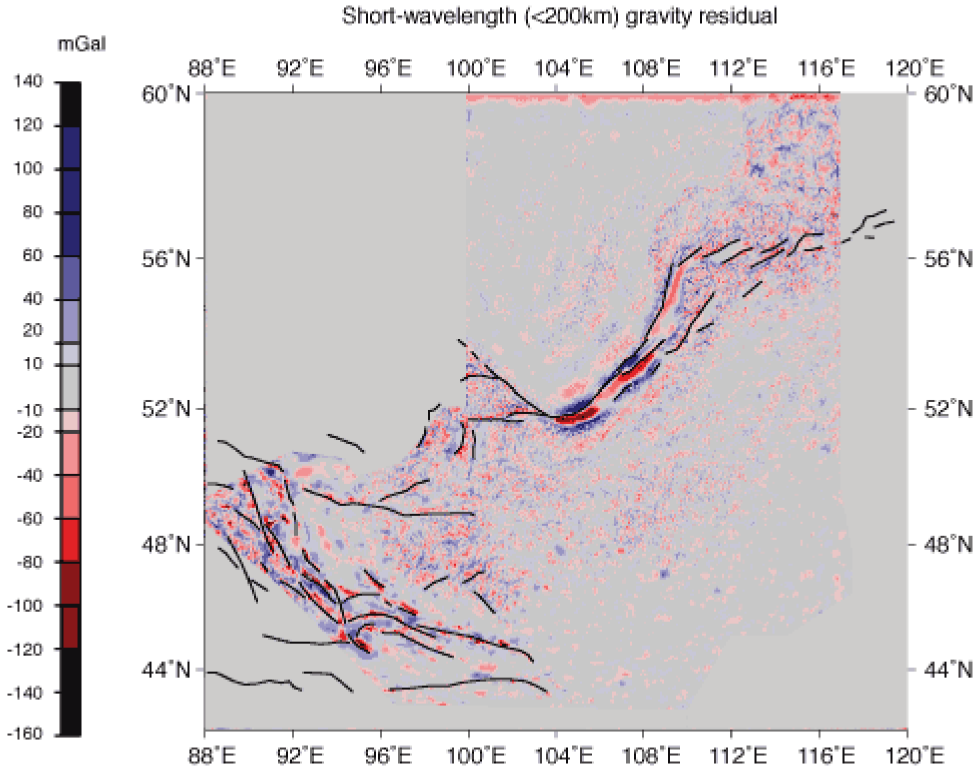


Figure 4a. Short-wavelength isostatic anomalies

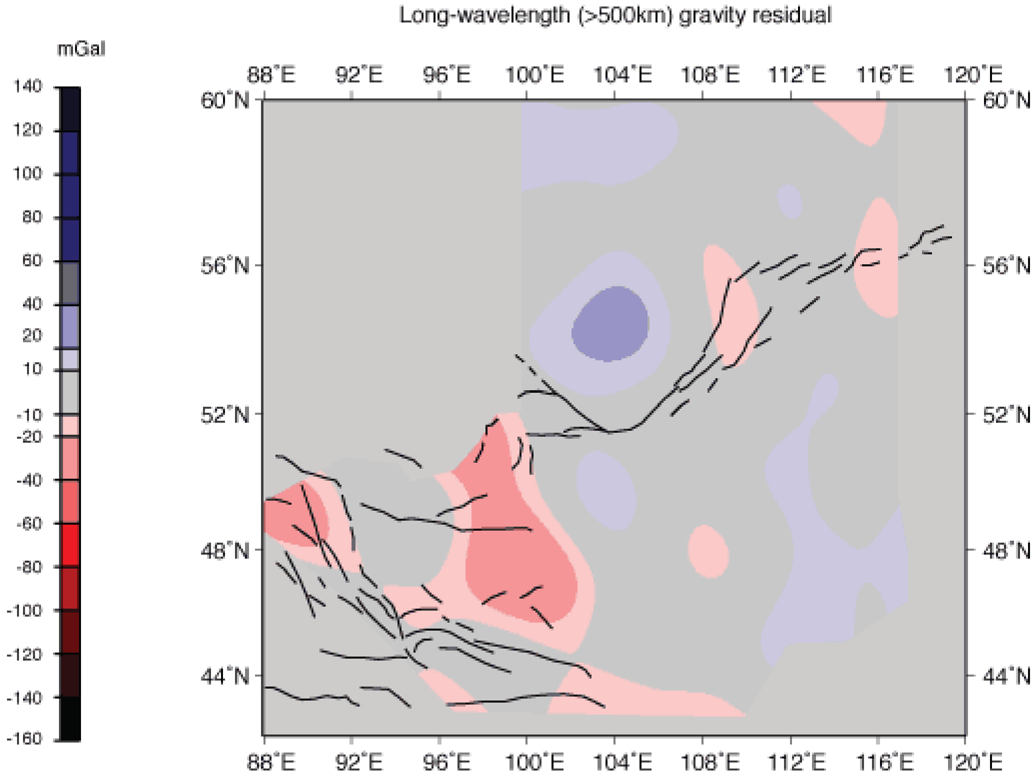


Figure 4b. Long-wavelength isostatic anomalies

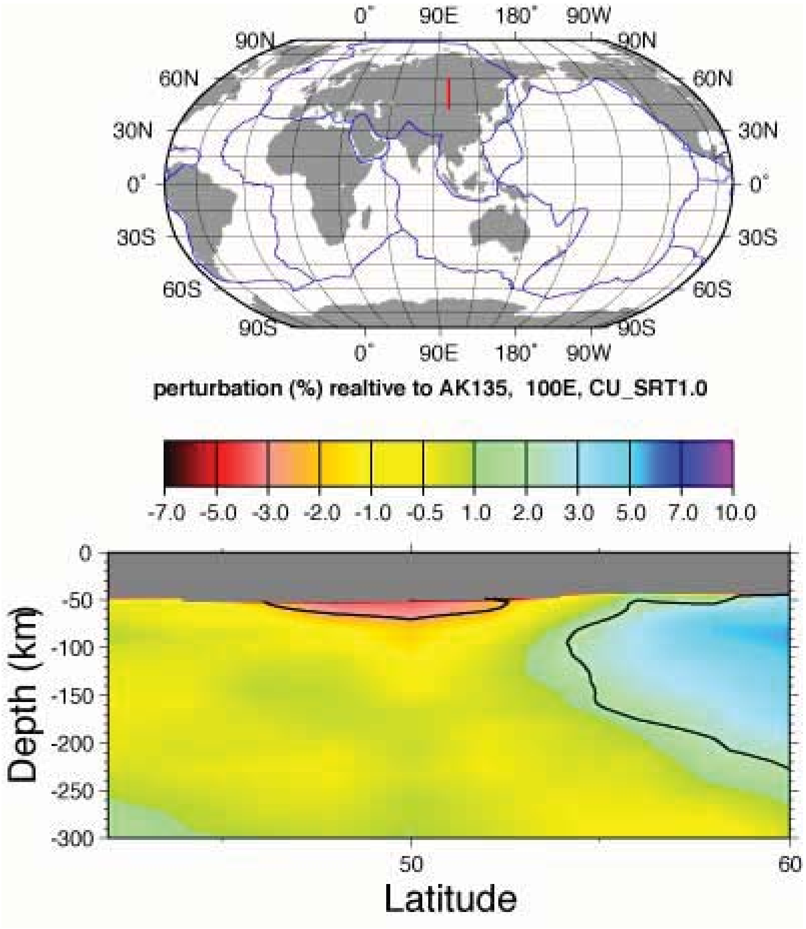
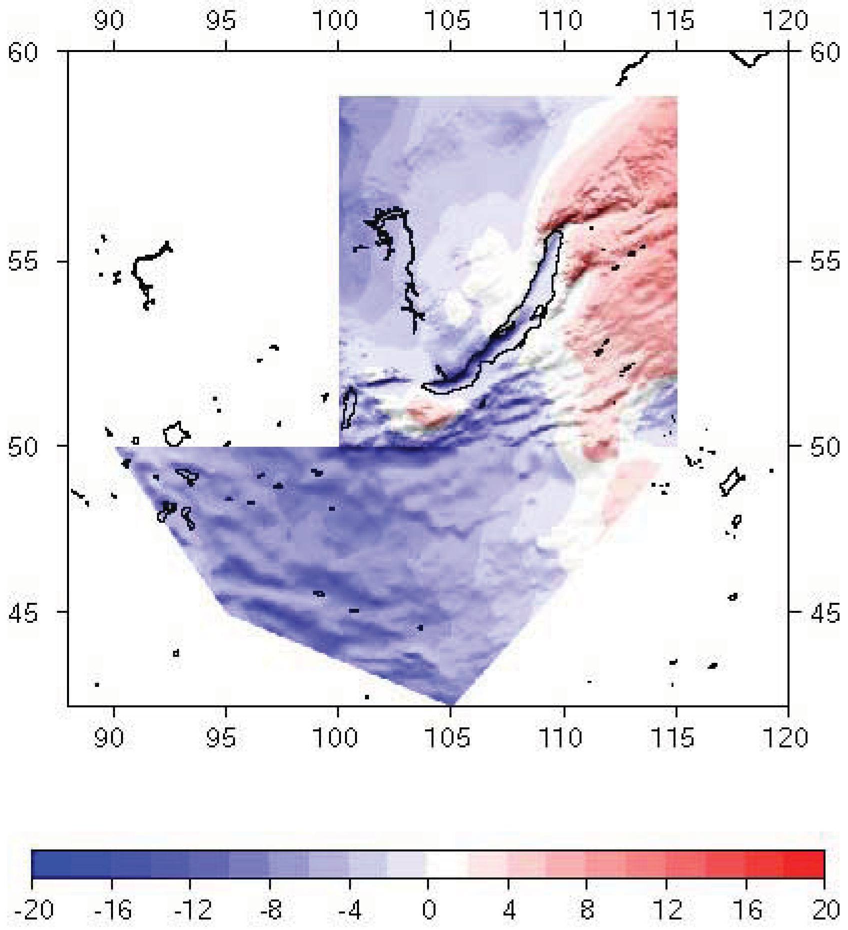
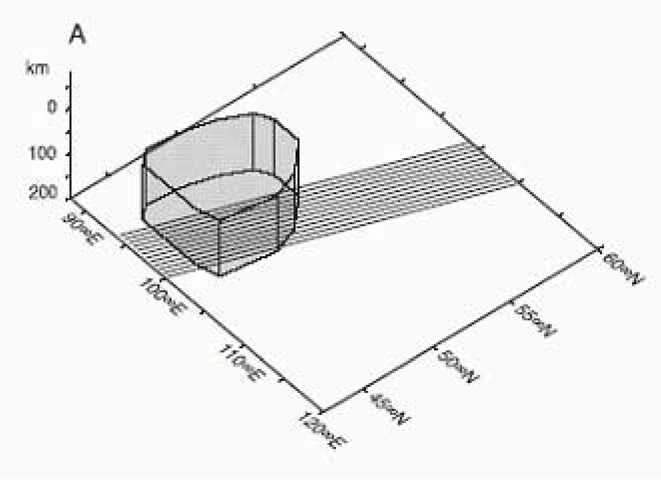


Figure 5. N-S tomographic cross-section at longitude 100°E extracted from the global CUB model of Nikolai Shapiro.

Geoid anomalies over Mongolia are negative, indicating a mass deficit in the lithosphere or upper asthenosphere (Figure 6). In the "classical" mantle plume model, dynamic effects overcome the density deficit expected from rising, low-density material, such that positive geoid anomalies are expected (the Iceland region is an often-quote example of this. See also webpages on Iceland). This is clearly not the case here, and instead the evidence is more consistent with a low-flux plume or simple "static" thermal anomaly in the lithosphere as advocated by Barry et al., 2005.

Figure 6. Geoid height in meters

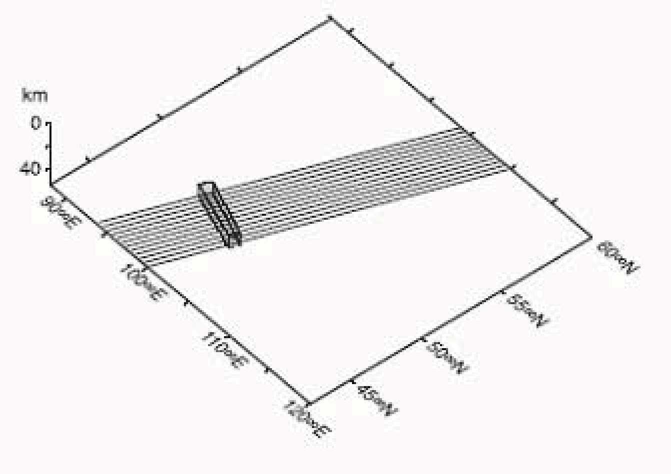




(a) Three-dimensional forward modelling of the gravity and topography provides additional information on the mass deficit and may be compared with other, independent data *e.g.,* from mantle xenoliths and seismic tomography. A slightly lighter (–10 kg/m^3) upper mantle extending from 100 to 200 km can explain the long-wavelength gravity and isostatic anomaly extending from Hangai to Hovsgol. A deeply-rooted plume is not required (Figure 7a).

Locally, magmatic underplating beneath the crust could explain the larger mass deficit beneath the apex of the dome (Figures 7b and 8). We modelled the “excess” topography (with respect to the mean altitude related to the average crustal thickness) resulting from isostatic compensation of these anomalies using the Paravoz finite-element code (Figure 9, and Lithospheric Uplift webpage). Whereas the deep lithospheric anomaly can explain the long-wavelength, ~500 m-high topography excess encountered over Hangai and Hovsgol, the lower crustal anomaly can account for the additional 700 m found at the top of the Hangai dome itself.

North and south of the profile, the high mountains of Sayan and Bogd (Figure 1) are not reproduced by this model, but are likely to result from tectonic thickening of the crust, which is consistent with field observations of strike-slip and thrust faulting (*e.g., Bayasgalan et al.*, 1999).



(b)

Figure 7. 3D shape of the polygons representing (a) the deep-seated and (b) the lower crustal density anomalies, of –10 kg/m^3 and –200 kg/m^3, respectively.

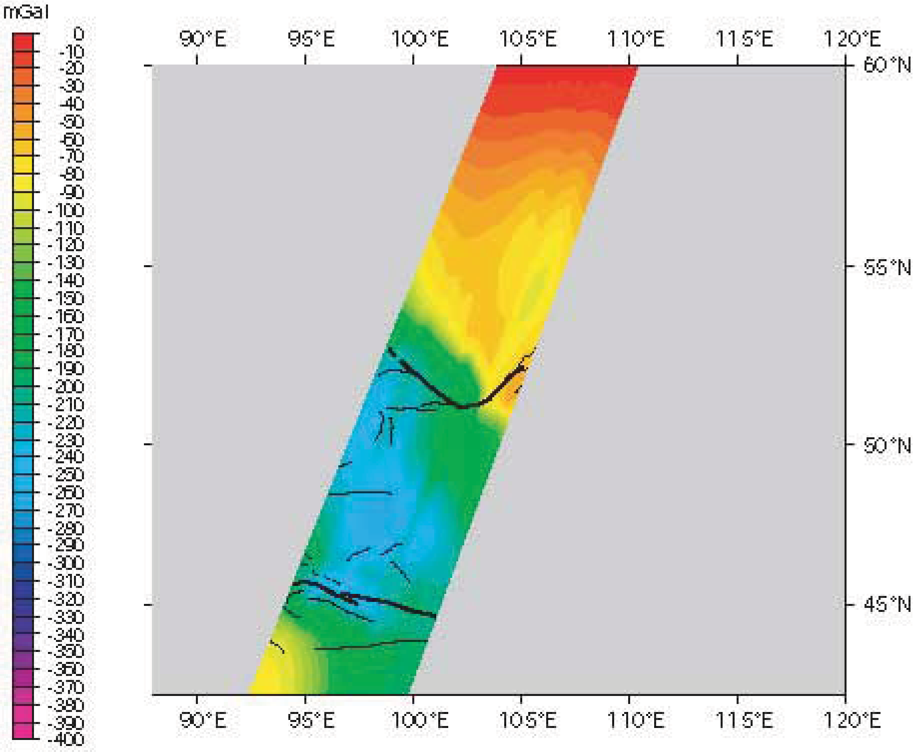


Figure 8. Synthetic Bouguer gravity produced by the two modelled density anomalies and localised fault flexure (north and south of the dome).

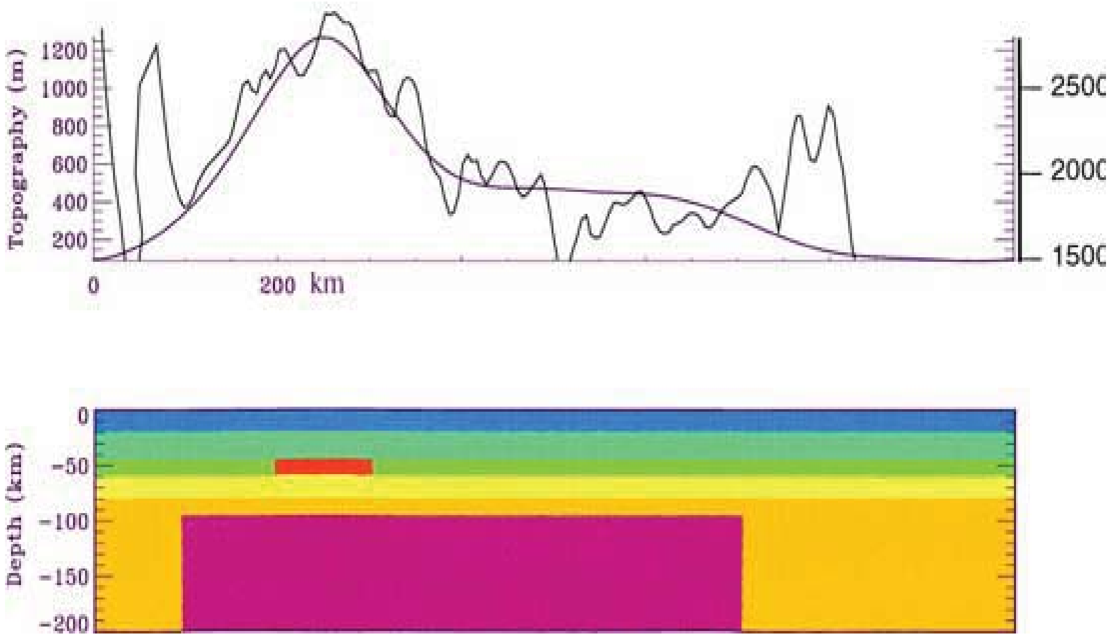


Figure 9. Isostatic topography (top, smooth, purple line) due to the 2 modelled density anomalies (bottom, in red and purple) compared to the observed (top, irregular, solid line) sampled along a S-N profile. Topography is computed using the Paravoz finite element code (see Lithospheric Uplift webpage and references therein)

Conclusion

Gravity and topographic data, combined with other constraints on crustal and mantle structure such as seismic tomography and analyses of mantle xenoliths, do not provide evidence for a high-flux plume (or "hot spot") beneath Mongolia. A model that fits the observations better is one involving a shallow (100-200 km) density deficit which isostatically supports part of the excess topography (with respect to the average crustal thickness) encountered there. This is in agreement with the petrology and geochemistry of the basalts which suggest a low-flux thermal anomaly located in the lower lithosphere or upper asthenosphere, as suggested by Barry et al. (2005). These authors point out that long-lived, scattered volcanism has occurred in Asia for ~30 Ma with similar chemical characteristics, suggesting a common origin for Mongolian, Chinese, and Baikal basalts. Its cause is still enigmatic, but could reside in large thermal perturbations in the Asian mantle that result from Pacific and Indian subduction (see also the Plate Tectonic Processes webpage).

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