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Antarctica's hypsometry and crustal thickness: Implications for the origin of anomalous topography in East Antarctica

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ABSTRACT

The hypsometry of Antarctica revealed by BEDMAP2 data is characterised by deglaciated modal elevations of ∼−450 m and ∼650 m for West and East Antarctica, respectively, and an East Antarctic plateau that is topographically anomalous by ∼400–600 m with respect to global continental modal elevation estimates. Superimposed on the East Antarctic plateau are the Gamburtsev Subglacial Mountains, the Dronning Maud Land Mountains and the Vostok Highlands with modal elevations ∼400 m in excess of the East Antarctic mode. To ascertain whether East Antarctica's anomalous topography can be attributed to Airy-type crustal compensation, a continental-scale crustal thickness model was derived from the inversion of GOCO03S satellite gravity data constrained by seismic crustal thickness estimates. The average crustal thickness of East Antarctica is ∼40 km (for West Antarctica ∼24 km), a value typical of continental shields, and while crustal thicknesses of >50 km locally beneath the Gamburtsev Subglacial Mountains and Dronning Maud Land can account for their differential modal elevation above the plateau, crustal thicknesses elsewhere across East Antarctica offer no suggestion of crustal-level continental-scale support for the broader plateau. Enderby Land, for example, resides on the plateau and is characterised by a modal elevation of ∼750 m and crust ∼40 km thick, whereas off the plateau in East Antarctica, the Aurora and Wilkes Subglacial Basins have modal elevations of ∼−50 m and ∼50 m, respectively, yet similarly thick crust. The lack of crustal support for the elevated broader East Antarctic plateau, coupled with seismic images showing fast upper mantle velocities beneath the plateau, suggest a mid-to-lower mantle source for East Antarctica's anomalous topography.

1. Introduction

Antarctica is a continent of contrasts, with stark geological and hypsographic differences manifest between East and West Antarctica. The anomalously high elevation of East Antarctica, in particular, has long been recognised (e.g., Southam and Hay, 1981), although it was typically excluded from early global hypsometric analyses due to a paucity of data (e.g., Bond, 1979; Harrison et al., 1981). A first focused study by Cogley (1984a) confirmed the geological dichotomy of Antarctica through the continent's markedly bimodal hypsometric curve, with deglaciated modal elevations of 950 m and −450 m with respect to sea level reported for East and West Antarctica, respectively. The modal height documented by Cogley (1984a) for East Antarctica significantly exceeds the corresponding measurements of 87 m (Harrison et al., 1983) and 250 m (Cogley, 1984b, 1985) for the global ensemble of continents, affirming East Antarctica's anomalous topography.

Southam and Hay (1981) proposed that East Antarctica's modal height anomaly might be explained by a very low erosion rate through glacial protection of the surface during the time Antarctica has been covered by ice, while Cogley (1984a) speculated that the anomalous topography might reflect hotspot epeirogeny. The origin of the modal height anomaly, which is the focus of this study, is still unknown. Seismic data from experiments conducted across Antarctica in the interim since the Cogley (1984a) study offer the opportunity to probe the source of the anomalous topography. In this paper, we (1) re-examine the hypsometry of Antarctica using the recently released BEDMAP2 data (Fretwell et al., 2013) in order to obtain refined estimates of anomalous topography across the continent and (2) subsequently assess whether East Antarctica's anomalous topography can be attributed to isostatic support from crustal thickness variations. We accomplish the second objective by deriving a continental-scale crustal thickness model from the inversion of GOCO03S satellite gravity data constrained by seismic crustal thickness estimates. In contrast to preceding Antarctic studies of continental-scale crustal structure, the joint gravity-seismic analysis lessens the uncertainty which can arise in modelling gravity or seismic data separately for continental-scale Moho topography.

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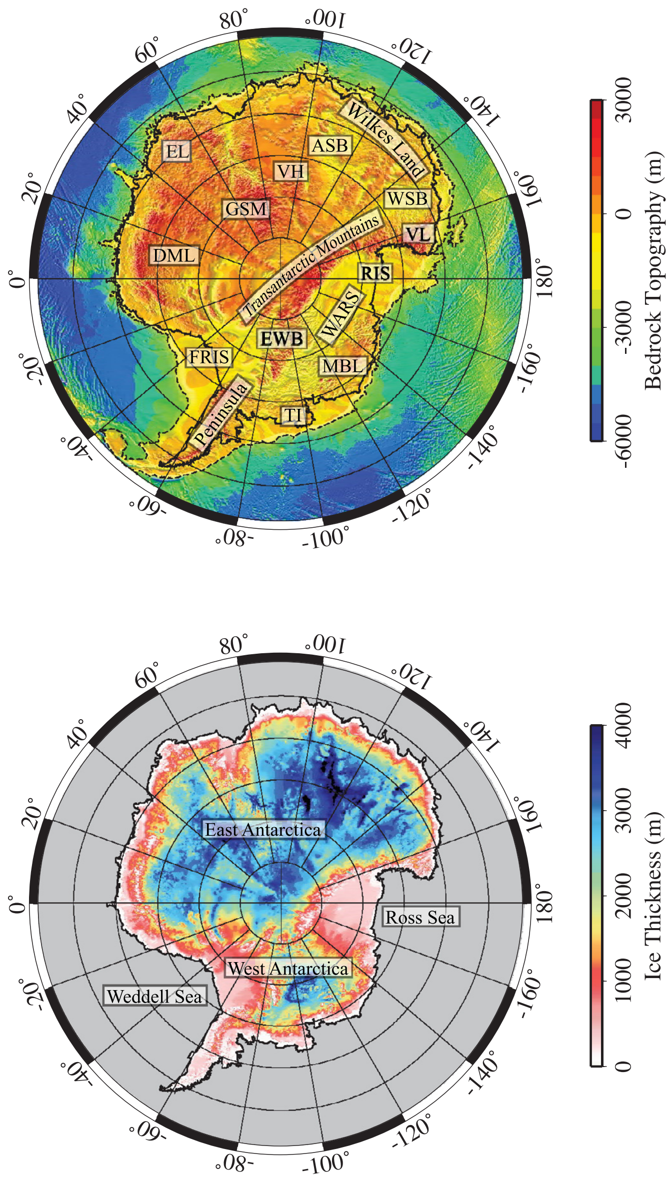

Fig. 1. BEDMAP2 Antarctic subglacial bedrock topography (top) and ice thickness (bottom). The −2500 m bathymetric contour (dashed line, top) is adopted as the continental boundary for the hypsometry analysis. ASB, Aurora Subglacial Basin; DML, Dronning Maud Land; EL, Enderby Land; EWB, Ellsmore–Whitmore Block; FRIS, Filchner–Ronne Ice Shelf; GSM, Gamburtsev Subglacial Mountains; MBL, Marie Byrd Land; RIS, Ross Ice Shelf; TI, Thurston Island; VH, Vostok Highlands; VL, Victoria Land; WSB, Wilkes Subglacial Basin.

2. Tectonic setting

The Antarctic continent constitutes two distinct and contrasting geological provinces (e.g., Adie, 1962) (Fig. 1). East Antarctica has been interpreted as a Precambrian shield which was amalgamated from Archean nuclei in the Mesoproterozoic, eventually forming an integral part of Gondwana prior to breakup in the Mesozoic (e.g., Dalziel, 1992; Boger, 2011). Geological correlations between the exposed marginal cratons along the coast of East Antarctica and counterparts in Africa, India and Australia are the basis for this interpretation (e.g., Dalziel, 1992).

Toward the interior of East Antarctica, geophysical data reveal a subglacial landscape of basins and orogens, the most prominent of which include the Aurora and Wilkes Subglacial Basins, the mountains of Dronning Maud Land and the Gamburtsev Subglacial Mountains. However, the thick, obscuring East Antarctic Ice Sheet has rendered deciphering formative mechanisms difficult.

West Antarctica is regarded as an assemblage of discrete or semidiscrete geological terranes separated by subglacial depressions. Three of the main four blocks – the Antarctic Peninsula, Thurston Island and Marie Byrd Land – are Palaeozoic to Mesozoic fore-arc and magmatic-arc terranes associated with the paleo-Pacific margin of Gondwana between South America and eastern Australia. The Ellsworth–Whitmore Block, meanwhile, is considered a displaced segment of the East Antarctic craton margin (Dalziel and Elliot, 1982; Dalziel, 1992; Boger, 2011). Extending through the interior of West Antarctica is the West Antarctica Rift System, a largely aseismic rift system characterised by late Cretaceous and Cenozoic extension initiated by the break-up of Australia and Antarctica (e.g., Behrendt et al., 1991; Wörner, 1999).

3. Previous studies

The fundamental difference in gross crustal structure between East and West Antarctica was first inferred in a series of pioneering surface wave dispersion studies carried out in the late 1950s and early 1960s (e.g., Evison et al., 1960; Kovach and Press, 1961; Bentley and Ostenso, 1962). These early investigations estimated mean crustal thicknesses of ∼35–40 km and ∼25–30 km for East and West Antarctica, respectively, with a 10 km differential consistently emerging. A handful of ensuing dispersion studies restricted to East Antarctica essentially reinforced the preceding 35–40 km mean crustal thickness estimates (Dewart and Toksöz, 1965; Knopoff and Vane, 1978; Neunhöfer et al., 1983). Early gravity analyses confirmed the distinction between East and West Antarctica, but disagreed on actual Moho depths. For example, Groushinsky and Sazhina (1982) estimated crustal thicknesses generally between 30–35 km for West Antarctica, contrasting with Segawa et al. (1986), who estimated Moho depths of 28–29 km and 15–23 km for East and West Antarctica, respectively.

Inaugural two-dimensional continental-scale models of crustal thickness based on interpolated deep seismic soundings (DSS) and gravity data (Bentley, 1991; Groushinsky et al., 1992) revealed broad details of Moho geometry within East and West Antarctica, such as crustal thickening to 50 km beneath the Gamburtsev Subglacial Mountains. However, while the DSS studies (see Baranov and Morelli, 2013, for a review) adequately constrain crustal structure locally in Antarctica, the confinement of the soundings to accessible coastal regions meant that the derived continental-scale models had little resolution in regions constrained solely by interpolation across wide data gaps.

The first surface wave tomographic images of the crust and upper mantle confirmed the gross distinction between the cratonic structure of East Antarctica and the accreted terranes of West Antarctica (e.g., Roult et al., 1994; Danesi and Morelli, 2000, 2001; Ritzwoller et al., 2001; Kobayashi and Zhao, 2004). Ritzwoller et al. (2001), for example, inferred average crustal thicknesses of ∼40 km and ∼27 km for East and West Antarctica, respectively, with a clear distinction between the regions, marked by contrasting wave speeds, persisting well into the upper mantle. The progressive improvement in gravity data coverage and quality has similarly facilitated the development of more accurate regional and continental-scale Moho models (e.g., von Frese et al., 1999; Ferraccioli et al., 2001, 2011; Llubes et al., 2003; Block et al., 2009; Jordan et al., 2013). Block et al. (2009), for instance, took advantage of the advent of high resolution satellite gravimetry to model pan-Antarctic crustal thickness by inverting GRACE data. They predicted thick crust (∼40 km) beneath the Transantarctic Mountains increasing to a maximum of 46 km near the pole, crust thicker than 40 km beneath the Gamburtsev Subglacial Mountains in East