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Erosion-driven uplift in the Gamburtsev Subglacial Mountains of East Antarctica

G.J.G. Paxman [a,b,*], A.B. Watts [a], F. Ferraccioli [c], T.A. Jordan [c], R.E. Bell [d], S.S.R. Jamieson [b], C.A. Finn [e]

[a] *Department of Earth Sciences, University of Oxford, South Parks Road, Oxford, OX1 3AN, UK*
[b] *Department of Geography, Durham University, Lower Mountjoy, South Road, Durham, DH1 3LE, UK*
[c] *British Antarctic Survey, High Cross, Madingley Road, Cambridge, CB3 0ET, UK*
[d] *Lamont Doherty Earth Observatory of Columbia University, Palisades, NY 10964, USA*
[e] *US Geological Survey, Denver, CO 80225, USA*

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ABSTRACT

The relative roles of climate and tectonics in mountain building have been widely debated. Central to this debate is the process of flexural uplift in response to valley incision. Here we quantify this process in the Gamburtsev Subglacial Mountains, a paradoxical tectonic feature in cratonic East Antarctica. Previous studies indicate that rifting and strike-slip tectonics may have provided a key trigger for the initial uplift of the Gamburtsevs, but the contribution of more recent valley incision remains to be quantified. Inverse spectral (free-air admittance and Bouguer coherence) methods indicate that, unusually for continents, the coherence between free-air gravity anomalies and bedrock topography is high (>0.5) and that the elastic thickness of the lithosphere is anomalously low (<15 km), in contrast to previously reported values of up to ∼70 km. The isostatic effects of two different styles of erosion are quantified: dendritic fluvial incision overprinted by Alpine-style glacial erosion in the Gamburtsevs and outlet glacier-type selective linear erosion in the Lambert Rift, part of the East Antarctic Rift System. 3D flexural models indicate that valley incision has contributed ca. 500 m of peak uplift in the Gamburtsevs and up to 1.2 km in the Lambert Rift, which is consistent with the present-day elevation of Oligocene–Miocene glaciomarine sediments. Overall, we find that 17–25% of Gamburtsev peak uplift can be explained by erosional unloading. These relatively low values are typical of temperate mountain ranges, suggesting that most of the valley incision in the Gamburtsevs occurred prior to widespread glaciation at 34 Ma. The pre-incision topography of the Gamburtsevs lies at 2–2.5 km above sea-level, confirming that they were a key inception point for the development of the East Antarctic Ice Sheet. Tectonic and/or dynamic processes were therefore responsible for ca. 80% of the elevation of the modern Gamburtsev Subglacial Mountains.

1. Introduction

The Gamburtsev Subglacial Mountains (GSM) are located beneath Dome A of the East Antarctic Ice Sheet (EAIS) (Fig. 1). Although the GSM cannot be directly observed, the subglacial landscape has recently been revealed by Antarctica's Gamburtsev Province (AGAP) radar, aerogravity and aeromagnetic data, collected during the International Polar Year (2008–2009) (Bell et al., 2011). The GSM exhibit 2–3 km of relief and a landscape heavily dissected by fluvial and glacial valleys that resembles the European Alps (Bo et al., 2009; Creyts et al., 2014; Rose et al., 2013). Flanking the Gamburtsevs are a series of north–south trending basins interpreted as comprising the East Antarctic Rift System (EARS) (Ferraccioli et al., 2011). When compared to other mountain ranges, the Alpine-style geomorphology of the GSM (Creyts et al., 2014) is paradoxical, since they are located atop Precambrian cratonic lithosphere (Heeszel et al., 2013). This problem is compounded because no in situ geological samples from the GSM exist; their lithology, age and structure remain unknown.

Unravelling the enigmatic topographic evolution of the GSM is particularly important, because (1) this mountain range is thought to have provided a key nucleation site for the development of the EAIS at the Eocene–Oligocene Boundary (DeConto and Pollard, 2003; Rose et al., 2013) and (2) the processes that build intraplate

* Corresponding author at: Department of Geography, Durham University, Lower Mountjoy, South Road, Durham, DH1 3LE, UK. Fax: +44 1913 341801.
E-mail address: guy.j.paxman@durham.ac.uk (G.J.G. Paxman).

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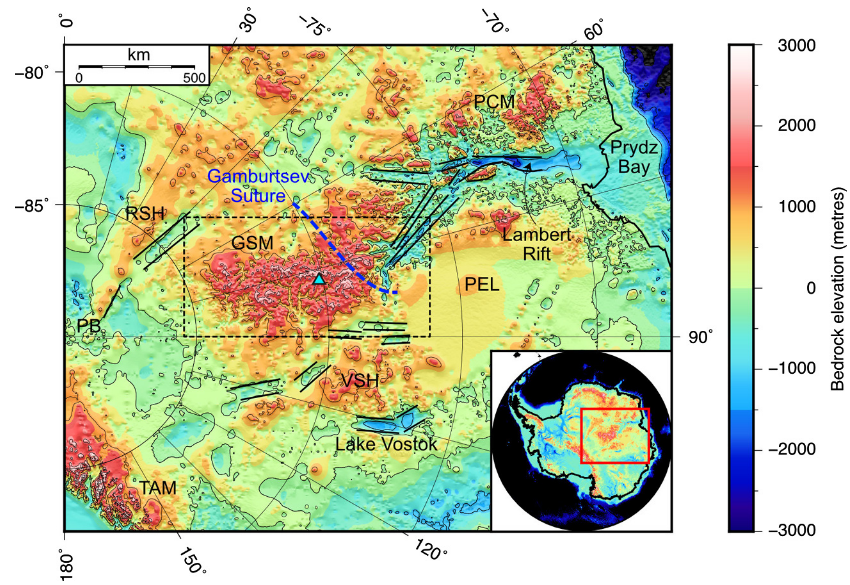

Fig. 1. Geographical and tectonic setting of the Gamburtsev Subglacial Mountains (GSM) within East Antarctica. Bedrock elevation data (above mean sea-level) are from the Bedmap2 compilation (Fretwell et al., 2013). Rift basins (bounded by black lines) comprise the recently defined East Antarctic Rift System (EARS), a proposed trigger for GSM uplift (Ferraccioli et al., 2011). The proposed location of the Gamburtsev Suture (Ferraccioli et al., 2011) is labelled with the blue dashed line. Black dashed box shows the area displayed in Figs. 2 and 5. Abbreviations: PB – Polar Basins; PCM – Prince Charles Mountains; PEL – Princess Elizabeth Land; RSH – Recovery Subglacial Highlands; TAM – Transantarctic Mountains; VSH – Vostok Subglacial Highlands. Blue triangle marks Dome A. True scale at 71°S. Inset shows the main study area (red box) within Antarctica. Much of East Antarctica is characterised by an elevated topographic plateau ∼1 km above sea-level. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

mountains remain poorly understood, and the Gamburtsevs are the most enigmatic intraplate mountain range on Earth.

Permian rifting and Cretaceous strike-slip faulting have been advanced as tectonic triggers for GSM uplift (Ferraccioli et al., 2011). However, the isostatic response to fluvial/glacial valley incision has been suggested to be responsible for the modern relief and geomorphology of the GSM (Ferraccioli et al., 2011), as has been demonstrated in other mountain ranges (e.g. Champagnac et al., 2007). This isostatic uplift has been quantified using simple 2D flexural models (Ferraccioli et al., 2011), but the 3D distribution of erosion and flexure, as well as the influence of the neighbouring Lambert Rift, have not previously been considered. The aim of this study is to quantify the spatial distribution of Cenozoic fluvial and glacial erosion and the associated isostatic response prior to and during the early stages of EAIS development in order to determine whether this effect was sufficient to drive a substantial part of the uplift of the GSM.

To address this question, the AGAP radar and aerogravity data were used to estimate the effective elastic thickness of the lithosphere (T_e) and the amount and distribution of eroded material in the Gamburtsev region. 3D flexural models were used to calculate the resulting flexural uplift induced by valley incision for different T_e scenarios, and thereby estimate the pre-incision elevation of the GSM. The age of fluvial incision in the GSM was constrained using a landscape evolution model. The main findings are that the processes of valley incision in the GSM predominantly occurred in a temperate climate, and that the Gamburtsevs were at 2–2.5 km elevation prior to the Eocene–Oligocene Boundary.

2. Aerogeophysical data acquisition and reduction

The acquisition of AGAP airborne geophysical data took place between 2nd December 2008 and 16th January 2009. Two de Havilland Canada Twin Otter aircraft successfully obtained 120,000 line-km of radio-echo sounding (RES), aeromagnetic and aerogravity data over the GSM and adjacent Lambert Rift. The survey comprised flight lines oriented north–south, with 5 km horizontal spacing. East–west tie lines intersected the main lines every 33 km.

2.1. Surface and bedrock topography

Mapping of surface and bedrock topography was carried out using a wing-mounted RES system. RES data were acquired using ice-penetrating radars with a 150 MHz carrier frequency and 15–20 MHz bandwidths, which sample the ice at 2 m intervals along the flight-track (Creyts et al., 2014). Kinematic GPS provided location and altitude data accurate to ∼5 cm.

The two-way travel time (TWTT) for the ice surface reflector was multiplied by the radar velocity in air (300 m/μs) to give the terrain clearance of the aircraft. The difference between the altitude of the aircraft and the terrain clearance is the surface elevation. The difference in TWTT between the bed and ice surface reflectors gives the TWTT in the ice, which is depth converted to an ice thickness using an ice radar velocity of 168 m/μs, with an additional 10 m correction for the firn layer. The difference between the surface elevation and the ice thickness gives the bed elevation. Bed elevations were measured relative to the WGS-84 ellipsoid. The root mean square (RMS) cross-over error was 64 m (Creyts et al., 2014).

The radar data were gridded using a 'nearest neighbour' griding routine (GMT's *nearneighbor* module, Wessel et al., 2013) with a grid spacing of 1 km and search radius of 5 km. To form a complete bedrock topography grid for the East Antarctica, data gaps in the grid were filled using the Bedmap2 compilation (Fretwell et al., 2013). This maintained the high resolution of the AGAP data while avoiding excessive computational demand. While griding causes some of the resolution to be lost, the grid picks out the sharp and high local relief observed in the radar data (Fig. 2). Radar-derived bedrock topography data are essential for the spectral analysis carried out in this study, as they guarantee independence of the gravity and topography grids.