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Early East Antarctic Ice Sheet growth recorded in the landscape of the Gamburtsev Subglacial Mountains

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ABSTRACT

The Gamburtsev Subglacial Mountains are regarded as a key nucleation site for the Antarctic Ice Sheet and they retain a unique long-term record of pre-glacial and early glacial landscape evolution. Here, we use a range of morphometric analyses to constrain the nature of early glaciation and subsequent ice sheet evolution in the interior of East Antarctica, using a new digital elevation model of the Gamburtsev Subglacial Mountains, derived from an extensive airborne radar survey. We find that an inherited fluvial landscape confirms the existence of the Gamburtsev Subglacial Mountains prior to the onset of glaciation at the Eocene–Oligocene climate boundary (ca. 34 Ma). Features characteristic of glaciation, at a range of scales, are evident across the mountains. High elevation alpine valley heads, akin to cirques, identified throughout the mountains, are interpreted as evidence for early phases of glaciation in East Antarctica. The equilibrium line altitudes associated with these features, combined with information from fossil plant assemblages, suggest that they formed at, or prior to, 34 Ma. It cannot be ruled out that they may have been eroded by ephemeral ice between the Late Cretaceous and the Eocene (100–34 Ma). Hanging valleys, overdeepenings, truncated spurs and steep-sided, linear valley networks are indicative of a more widespread alpine glaciation in this region. These features represent ice growth at, or before, 33.7 Ma and provide a minimum estimate for the scale of the East Antarctic Ice Sheet between ca. 34 and 14 Ma, when dynamic fluctuations in ice extent are recorded at the coast of Antarctica. The implications are that the early East Antarctic Ice Sheet grew rapidly and developed a cold-based core that preserved the alpine landscape. The patterns of landscape evolution identified provide the earliest evidence for the development of the East Antarctic Ice Sheet and can be used to test coupled ice–climate evolution models.

1. Introduction

East Antarctica hosts the largest and longest-lived ice sheet on Earth. Despite the importance of the East Antarctic Ice Sheet (EAIS) as both a responder to, and potential driver of global environmental and sea-level change, there are significant uncertainties about its early history and the scale and duration of its subsequent fluctuations (Barrett, 1996, 1999; Denton et al., 1984; Miller et al., 2008; Naish et al., 2008; Siegert and Florindo, 2009; Wise et al., 1991; Zachos et al., 1992, 2001). The EAIS is thought to have grown rapidly (Coxall et al., 2005) in response to a major decline in CO_2 levels at ca. 34 Ma (DeConto and Pollard, 2003) and nucleated around the major highlands of East Antarctica, including the Gamburtsev Subglacial Mountains (hereafter, Gamburtsevs). Efforts to constrain the nature of early ice sheet growth in central East Antarctica have relied upon largely coastal records of EAIS behaviour, because of the paucity of data from the continental interior. However, geophysical and geological data from the interior are precisely what is required if the early patterns of glaciation in East Antarctica are to be constrained. Evidence of past EAIS behaviour is most likely to be preserved at sites where long-term erosion rates are extremely low and/or where cold-based ice preserves the landscape at the base of the ice sheet (Fabel et al., 2002; Naslund, 1997; Sugden et al., 1993, 1999; Summerfield et al., 1999). These conditions are found in central East Antarctica, where low ice velocities at Dome A (Rignot et al., 2011) are coupled with extensive areas of cold-based ice (Llubes et al., 2006), thus hindering subglacial erosion, as revealed in offshore deposits (Cox et al., 2010). Located in this region, the Gamburtsevs therefore

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represent a key site where a long-term record of both pre-glacial and glacial landscape evolution is likely to be found (Bo et al., 2009; Jamieson and Sugden, 2008; Jamieson et al., 2010).

Our aim is to understand the long-term landscape evolution of the Gamburtsevs, and in doing so to elucidate the dynamics of the early EAIS. In order to achieve this, we analyse the geomorphology of the Gamburtsevs at a regional-scale, using a new detailed and extensive airborne radar dataset, collected during the International Polar Year, as part of the *A*ntarctica's *Ga*mburtsev *P*rovince (AGAP) project (Bell et al., 2011; Ferraccioli et al., 2011). The AGAP survey provided a high resolution, regional, digital elevation model (DEM) of subglacial topography that greatly improves on the detail of previous continental-scale bedrock topography compilations (Le Brocq et al., 2010; Lythe et al., 2001) and the coverage of local surveys (Bo et al., 2009). We employ a series of morphometric techniques to quantify the geometry of the landscape and thereby map geomorphic features indicative of specific erosion processes, including fluvial erosion, warm-based glacial erosion and subglacial preservation. Our results are used to interpret the processes and patterns of landscape evolution in the Gamburtsevs, and to discuss their implications for the nature and timing of Antarctic Ice Sheet evolution.

2. Physiographic setting and origin of the Gamburtsev Subglacial Mountains

The Gamburtsevs lie beneath Dome A in the interior of East Antarctica (Fig. 1). They are bounded by the Pensacola Pole Basin to the south, Lake Vostok to the east and the Lambert Rift to the north. First discovered in 1958 by a Russian gravity and seismic survey (Sorokhtin et al., 1959), the Gamburtsevs are thought to be located in the middle of a Precambrian craton (Boger, 2011) and yet, unexpectedly, they retain a high elevation and significant relief. Prior to the AGAP project, the morphology, subglacial geology and deeper crustal structure of the Gamburtsevs were all poorly constrained, so that several contrasting models describing their origin remained largely untested (Cox et al., 2010; Fitzsimons, 2003; Sleep, 2006; van de Flierdt et al., 2008; Veevers, 1994). These models invoke ages for the Gamburtsevs' formation from the Cambrian (ca. 500 Ma) to the Cenozoic (30 Ma). However, based on analysis of the AGAP data, Ferraccioli et al. (2011) suggested that continental rifting processes provided the tectonic trigger for uplift of the Gamburtsevs at ca. 100 Ma. This was followed by fluvial (65.5–34 Ma) and then glacial erosion (34–14 Ma), causing renewed peak uplift.

3. Climate and ice sheet evolution

Past EAIS behaviour and key phases in Antarctic climate, ice sheet and surface process evolution over the last 100 Myr are derived from a mix of stratigraphic, geomorphological, geophysical and proxy data, combined with numerical modelling approaches (Supplementary Fig. S1). In the near-tropical climate conditions of the Early Eocene ‘Greenhouse World’, fluvial surface processes dominated (Baroni et al., 2005; Cooper et al., 2001; Francis et al., 2008; Pross et al., 2012). During these warmer periods, small, dynamic, ephemeral ice sheets may have formed on high elevation areas in the interior of East Antarctica (Birkenmajer et al., 2005; Cramer et al., 2011; Miller et al., 2005, 2008; Tripati et al., 2005). At the Eocene–Oligocene (E–O) boundary (ca. 34 Ma) a shift to a cool-temperate climate marked the onset of widespread East Antarctic glaciation (Liu et al., 2009; Zachos et al., 2001, 2008). On- and off-shore sedimentary sequences indicate that between ca. 34 and 14 Ma (Supplementary Fig. S1, grey box) the ice masses on East Antarctica were warm-based and dynamic (Baroni et al., 2008), fluctuating in pace with the Earth's orbital cycles (Escutia et al., 2005; Naish et al., 2001; Zachos et al., 1997, 2001). Glacial erosion was therefore a dominant agent of landscape modification, until a further decline in temperatures at ca. 14 Ma (Anderson et al., 2011; Lewis et al., 2007) resulted in a polar desert climate (Miller et al., 2008; Sugden and Denton, 2004; Zachos et al., 2001). This established a more stable continental-scale ice sheet and caused a switch from largely warm-based glaciation to a polythermal system (Anderson et al., 2011), where cold-based ice covered significant portions of the continent, reducing erosion rates across these areas (Armienti and Baroni, 1999; Ehrmann, 2001; Lewis et al., 2007; Miller et al., 2008).

4. Methodology

To understand the long-term patterns of landscape evolution in the Gamburtsevs, we analysed the geometry of an isostatically corrected DEM of subglacial topography generated from the AGAP airborne radar data. We then interpreted the morphometry in the context of former processes of landscape evolution and ice sheet dynamics. Our specific objectives were to

- generate a higher resolution DEM of the subglacial landscape of the Gamburtsevs;
- identify features that are representative of surface processes, which operate at local, regional and continental scales under warm and cold climates; and
- interpret patterns of long-term landscape evolution in the Gamburtsevs in the context of the interactions between topography, climate and ice sheet behaviour.

4.1. Data collection and DEM

The AGAP project completed a major aerogeophysical survey of the Gamburtsev Province during the 2008/09 field season, using two Twin Otter aircraft. 120,000 line-km of ice-penetrating radar, magnetic, gravity and laser measurements were collected in a detailed survey grid, with a line spacing of 5 km and tie lines 33 km apart (Bell et al., 2011; Ferraccioli et al., 2011). The study area covers 182,000 km^2, encompassing most of the Gamburtsevs and extending into the southernmost margin of the eastern branch of the Lambert rift system (Fig. 1). Following earlier work (Siegert et al., 2005; Young et al., 2011), the airborne radar data are used as the basis from which subglacial landscapes and past ice sheet dynamics can be interpreted.

Cross-over analysis of the AGAP radar flight-line data indicates RMS errors in bedrock elevation of 64 m with a mean of 74 m. The bedrock elevation data were gridded onto a 1 km grid mesh using an iterative finite difference interpolation technique that employs a nested grid strategy to calculate successively finer grids until the user specified resolution is obtained (Hutchinson, 1988, 1989). Our grid was compared against previous DEMs of the Gamburtsevs area generated from the same data, using minimum curvature (Bell et al., 2011) and kriging algorithms (Ferraccioli et al., 2011). All three methods generate landscapes whose detailed structure is closely comparable. The gridded DEM was isostatically corrected to compensate for the removal of the modern ice sheet load (Ferraccioli et al., 2011) and to produce a topography that is hydrologically sensible (Fig. 1). The correction grid assumes a continuous plate with a uniform rigidity (average uplift of 500 m) and ignores the isostatic component of subsequent uplift related to erosion by incision (Wilson et al., 2012). The rebounded DEM was used as the basis for subsequent morphometric analyses, enabling us