LETTERS

The Gamburtsev mountains and the origin and early evolution of the Antarctic Ice Sheet

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Ice-sheet development in Antarctica was a result of significant and rapid global climate change about 34 million years ago[1]. Ice-sheet and climate modelling suggest reductions in atmospheric carbon dioxide (less than three times the pre-industrial level of 280 parts per million by volume) that, in conjunction with the development of the Antarctic Circumpolar Current, led to cooling and glaciation paced by changes in Earth's orbit[2]. Based on the present subglacial topography, numerical models point to ice-sheet genesis on mountain massifs of Antarctica, including the Gamburtsev mountains at Dome A, the centre of the present ice sheet[2,3]. Our lack of knowledge of the present-day topography of the Gamburtsev mountains[4] means, however, that the nature of early glaciation and subsequent development of a continental-sized ice sheet are uncertain. Here we present radar information about the base of the ice at Dome A, revealing classic Alpine topography with pre-existing river valleys overdeepened by valley glaciers formed when the mean summer surface temperature was around 3 °C. This landscape is likely to have developed during the initial phases of Antarctic glaciation. According to Antarctic climate history (estimated from offshore sediment records) the Gamburtsev mountains are probably older than 34 million years and were the main centre for ice-sheet growth. Moreover, the landscape has most probably been preserved beneath the present ice sheet for around 14 million years.

Deep-sea oxygen isotope records show that the Eocene and Oligocene epochs represent times of global cooling culminating in the development of the first Antarctic Ice Sheet and an important expansion of Antarctic ice volume[1]. The Eocene (~52 to ~34 million years (Myr) ago) is characterized by a global cooling trend which continued during the remainder of the Cenozoic era. Subsequently there were two stepped changes in the rate of cooling. The first, at the Eocene–Oligocene boundary ~34 Myr ago, saw the onset of significant glaciation in Antarctica. The second, at ~14 Myr ago, is recorded by a 6–7 °C cooling in the marine isotope record[5,6] and in terrestrial evidence of cooling of at least 8 °C in the Transantarctic mountains[7].

Two approaches to modelling the initial growth of the Antarctic Ice Sheet show that glaciation begins in the upland mountain massifs of Antarctica, at coastal Dronning Maud Land, the Transantarctic mountains, and the Gamburtsev mountains beneath Dome A[2,8]. This central dome dominates glaciation because of its high altitude and consequent cold surface temperatures. Ice-sheet modelling, ocean cores and stratigraphic evidence suggest that for 20 million years, from 34 to 14 Myr ago, Antarctica experienced orbitally driven ice-volume fluctuations similar in scale to those of the Pleistocene ice sheets of the Northern Hemisphere and that these fluctuations were accompanied by marked changes in global sea level[2,9–11]. Tundra biota survived at high altitudes during this period[7]. After 14 Myr the ice sheet, at least in higher mountain peripheries in East Antarctica, maintained its presence and control over the cold polar climate of today, leading to extremely low rates of erosion[12], cold-based local glaciers[13] and even the preservation of buried Miocene ice[14].

Our knowledge of the subglacial topography at Dome A has been obtained during only one radar flight in the 1970s[4,15,16]. Consequently, the present form and evolution of the Gamburtsev mountains are poorly understood, making models of ice-sheet inception problematic. Indeed, the morphology of the mountains is less well known than the surface of Mars.

In seasons 2004/05 and 2007/08, Chinese glaciologists made the first detailed radar survey of the Gamburtsev mountains (as part of the International Polar Year programme Chinese Antarctic Research Expedition; CHINARE). The bed was detected in the majority of radar lines (Fig. 1), and by subtracting ice thickness from surface elevation (measured by GPS) the elevation of the bed could be found. The bed elevations were then interpolated[17] onto a regular grid with pixel resolution of 140.5 m (see Methods Summary and Supplementary Methods for interpolation details). The unprecedented density of radar transects in this region means that the resulting Digital Elevation Model (DEM) provides the first detailed depiction of the topography of the central Gamburtsev mountains (Fig. 2).

The topography revealed beneath the ice is striking (Fig. 2 and Supplementary Fig. 1). The region consists of a south-facing elongated valley head, cutting over a kilometre into flanking mountains. The whole region is covered by ice 1,649–3,135 m thick. The maximum elevation of the topography is 2,434 m above sea level at 80° 18′ S, 76° 10′ E. The valley geometry is dendritic. We highlight this geometry by extracting a drainage network using standard methods[18] (Fig. 2, Supplementary Discussion 1). Recent numerical modelling, backed by empirical observations, has shown that ice cannot create such networks alone; subglacial topography takes this form only when ice exploits pre-existing fluvial topography (Supplementary Fig. 2)[8,19]. This fluvial landscape has subsequently been subject to intense valley glaciation, as demonstrated by overdeepening in the valley floors of up to 432 m and the presence of steep trough sides. It is also shown by details such as the location of overdeepened basins at points of valley convergence, staircases of intervening riegels or valley steps, hanging tributary valleys, and corries with steep arcuate cliffs and flat floors at the head of some tributary valleys (Fig. 3); such features are characteristic of landscapes shaped by valley glaciers[20,21]. Hanging valleys are formed when ice ponds in tributary glaciers as they enter the trunk glacier; this ponding leads to reduced ice surface slopes, which in turn reduces shear stress and sliding velocities at the glacier bed, ultimately reducing erosive capacity in the tributary glacier[20,21]. Another effect of

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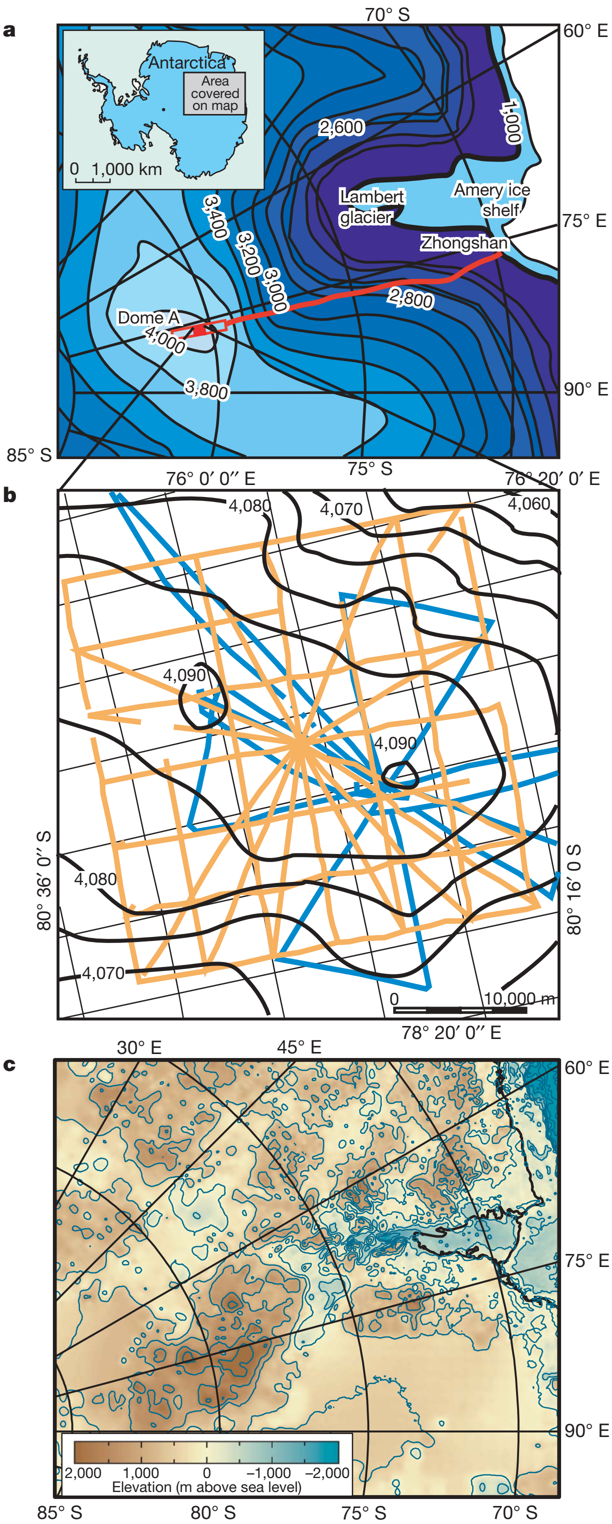

Figure 1 | Location of Dome A and orientation of radar transects. **a**, Location of the 30 km × 30 km radar network. Ice sheet surface contours are provided at intervals of 200 m above 2,000 m, and at 1000 m. **b**, Radar data acquired in 2004/5 are shown in blue and from 2007/8 in orange. The area covered in the map is the same as in Fig. 2b. Ice sheet surface contours are provided in metres above sea level. Ice flow is perpendicular to these contours. **c**, Existing bed depiction of the Dome A region[4]. Elevation (metres above sea level) is provided in the scale bar.

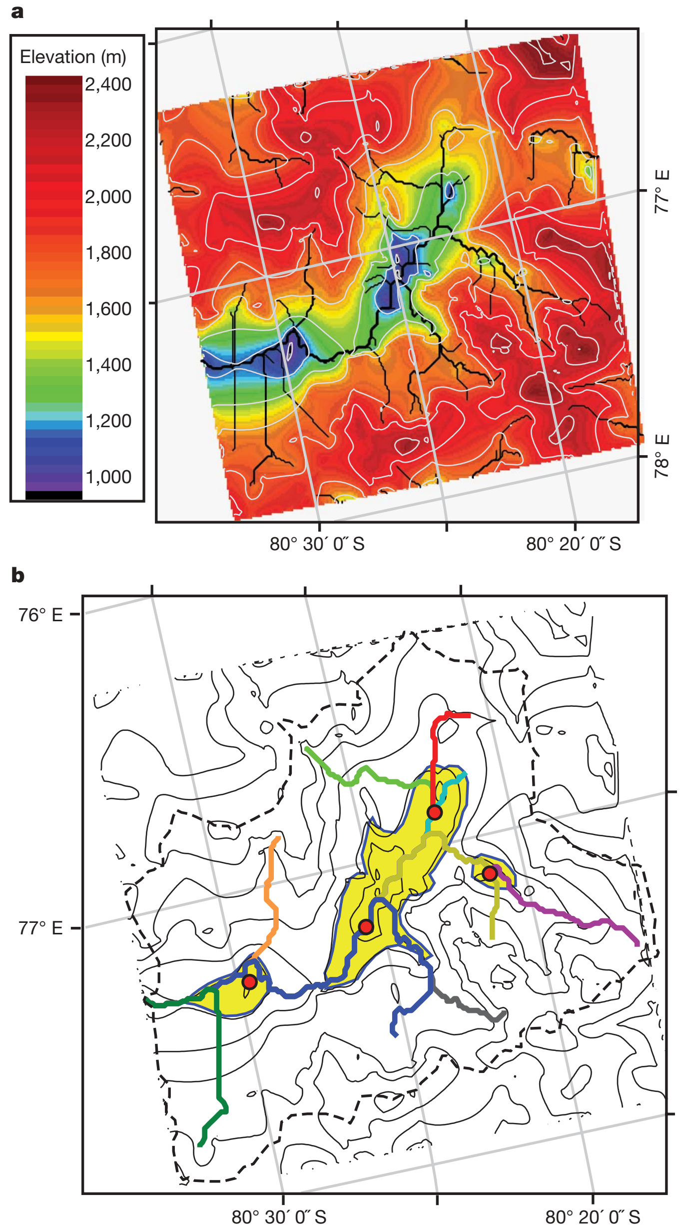

Figure 2 | Subglacial topography of the central Gamburtsev mountains. **a**, Topography of the surveyed section of the Gamburtsev mountains. Topographic contours (spaced at 200 m, lowest contour at 1,000 m) in grey; extracted valley network in black. Local elevation minima (red dots in **b**) are those which lie more than 150 m below the nearest down-valley saddle; this elevation change is well in excess of the vertical error (see main text). **b**, Selected features of the topography. Overdeepened areas are shown in yellow. Coloured channels are those selected for longitudinal profile analysis (Fig. 3). Main basin (562 km^2) delimited with black dotted line. Contours provided as in **a**. Present day ice flow is to the North.

a tributary entering a trunk glacier is an increase in ice discharge in the trunk glacier, which increases the sliding rate and causes overdeepening[20,21]. The landscape has relief similar to the European Alps, yet the largest valley revealed by our survey is broader than valleys of similar drainage area in the Alps and other glaciated terrains such as the Olympic peninsula in Washington and central Idaho, both in the United States[22,23] (Supplementary Discussion 2). We note that the landscape identified beneath Dome A is different to that measured beneath other East Antarctic ice-sheet divides, such as at Dome C where the relief is far more subdued and low-lying[24].

Three phases of glaciation are apparent. First, small mountain-top glaciers occupied the corries, causing the development of discrete cliffed basins. Second, an expanded valley glacier occupied the central trough, fed by ice accumulating either on the surrounding mountains or on ice caps centred over the mountains. This glacier flowed south,

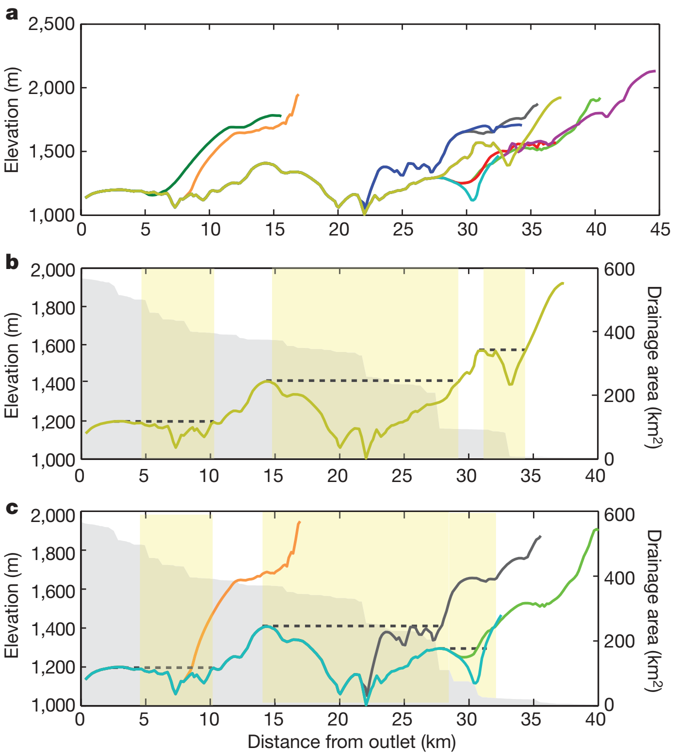

Figure 3 | Longitudinal profiles and drainage area–distance plots of Dome A tributary valleys. a, Profiles of selected valleys (colouring as in Fig. 2b). Several tributaries have steep headwaters indicative of corrie excavation. Hanging valleys and overdeepenings downstream of confluences are also visible. Overdeepenings are more than 150 m below the closest down valley bar. **b**, Profile (yellow) and drainage area (grey) of an individual valley, highlighting overdeepenings (dashed lines) corresponding to sections of valley where drainage area increases sharply (owing to tributary confluences). **c**, Further tributary profiles and drainage areas. The grey drainage area–distance plot is for the tributary marked in green.

and eroded the valley floor and sidewalls to their present shape, leading to a series of hanging valleys. Third, there is the modern ice sheet, which subsumes the entire region with cold slow-flowing ice. None of the landforms are conformable with present-day ice flow (Fig. 1b).

The three glacial phases have very different climatic needs. Today's ice-surface climate involves hyper-cold conditions (likely to be the coldest on the planet's surface) and no melting. Under such conditions, glaciological theory shows that the basal ice remains below the pressure melting point and is frozen to the bed, thus preventing significant glacial erosion and preserving the topography beneath[25]. For the two smaller-scale glacial phases, the climate must have been different. Both require an equilibrium line altitude separating glacier accumulation and ablation zones that is higher than the surrounding lowlands. Allowing for isostatic recovery of 500–1,000 m in view of the absence of the ~3-km-thick East Antarctic Ice Sheet at the onset of glaciation[8,24] (see Supplementary Discussion 3), the landscape would have been at an altitude of 1,500–3,500 m in pre-glacial times. This must imply an equilibrium line altitude of ~1,500–2,000 m above present sea level. Clearly, the larger valley glaciers would exist in colder periods, while corrie glaciers would exist when the climate was warmer. Thermomechanical glaciological models show that local Antarctic glaciers in the Transantarctic mountains would need maximum summer temperatures of the order of 3 °C or above if they are to have warm basal ice[7]. The implication is that summer temperatures in central East Antarctica at altitudes above 1,500–2,000 m in the early stages of mountain glaciation would have been no lower than about 3 °C.

The scale of the warming represented by the glacial landforms in the Gamburtsev mountains is unlikely to have occurred in Antarctica for the past 14 Myr (refs 5 and 8). Hence, we believe it is likely that the glacial topography observed predates this time. The dendritic valley networks probably date back to the topography of Antarctica achieved in the Eocene when there were beech trees in coastal Antarctica and soils containing the clay mineral smectite typical of forests[26,27]. Alpine glaciation of the Gamburtsev mountains must have began at least by 34 Myr ago and may have continued during several intervals during the next 20 million years. One implication is that the Gamburtsev mountains predate 34 Myr ago, although at this stage we cannot rule out synchronous uplift and glaciation around this time. If the orbitally forced glacial changes were on the scale of the Northern Hemisphere fluctuations of the Pleistocene epoch, then there would also have been many occasions when the mountains lay buried beneath larger and colder ice sheets that protected the mountains beneath cold-based ice. In such a case the Alpine glaciation could have marked warmer periods. What seems more certain is that the mountains and their record of early warm-based glaciation have remained buried and preserved by the present cold-based ice sheet, which nucleated at the Gamburtsev mountains and grew to continental size[28], for the past 14 Myr. The alternative view, that the upland glacial landforms could have been formed in the Pliocene epoch[29], requires the loss of the bulk of the Antarctic Ice Sheet, with significant implications for global temperature and sea level that are not observed in proxy records at this time[1].

METHODS SUMMARY

Radar information, collected by overland traversing at a frequency of 179 MHz, was gathered across a 30 × 30 km section of Dome A (Fig. 1). The two-way travel times of radio reflections from the ice-sheet base were converted to ice thickness, thus revealing information about the subglacial relief. The accuracy of the radar was assessed in 111 transect crossover points, revealing errors of <50 m in 64% of them, which in high-relief terrain is excellent (Supplementary Fig. 2). Around the centre of the survey region the transect separation is less than 5 km. To build a surface DEM from a series of transects requires us to interpolate between data points. Several interpolation procedures are commonly available, but we chose a technique called 'natural neighbour' interpolation, because it is designed to be used with distributed data confined to discrete transects[17]. For such data arrangements, this technique has been shown to give better results than interpolation algorithms designed for use on randomly distributed data[30], which can lead to artefacts introduced in the DEM. To examine how alternative data interpolation procedures may yield differences in DEMs, we processed the radar data using a variety of algorithms (see Supplementary Methods). Although the DEM results did differ slightly, the main topographic features discussed in this paper were consistently reproduced by all the interpolation techniques used. Importantly, the main valleys and depressions discussed are each covered by radar transects and, therefore, several data points (given the along-track data point separation of ~125 m). We are therefore confident that the DEM presented in Fig. 2a is not subject to artefacts that adversely affect the conclusions of this paper.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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Author Contributions S.B., C.X., J.Y., T.X. and L.Y. collected and processed radar data. S.F. prepared and provided a radar system in the 2004/2005 season, and gave support and advice on the radar technique, data collection and data processing. M.J.S. and D.S. provided knowledge of Antarctic glacial history and glacial dynamics. S.M.M. analysed the DEM for quantitative information on the dendritic network and landform features. M.J.S., D.S., S.M.M. and S.B. wrote the paper. All authors discussed the results and commented on the manuscript.

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