The Glacial Geomorphology of the Antarctic Ice-Sheet Bed

Stewart S.R. Jamieson[1*], Chris R. Stokes[1], Neil Ross[2], David M. Rippin[3], Robert G. Bingham[4], Douglas S. Wilson[5], Martin Margold[1] and Michael J. Bentley[1]

[*] Corresponding author: Stewart. Jamieson@durham.ac.uk

[1] Department of Geography, Durham University, South Road, Durham, DH1 3LE, UK.

[2] Department of Geography, Newcastle University, Daysh Building, Claremont Road, Newcastle Upon Tyne, NE1 7RU, UK.

[3] Environment Department, University of York, Heslington, York, YO10 5DD, UK.

[4] School of Geosciences, University of Edinburgh, Drummond St., Edinburgh, EH8 9XP, UK.

[5] Department of Earth Science and Marine Science Institute, University of California Santa Barbara, California, USA.

Abstract

In 1976 David Sugden and Brian John developed a classification of Antarctic landscapes of glacial erosion based upon exposed and eroded coastal topography, providing insight into the past glacial dynamics of the Antarctic Ice Sheets. We extend this classification to cover the continental interior of Antarctica by analysing the hypsometry of the subglacial landscape using a recently released dataset of bed topography (BEDMAP2). We use the existing classification as a basis for first developing a low-resolution description of landscape evolution under the ice sheet before using this to build a more detailed classification of patterns of glacial erosion. Our key findings are that a more widespread distribution of ancient, preserved alpine landscapes may survive beneath the Antarctic ice sheets than has been previously recognised. Furthermore, landscapes of selective erosion are suggested to exist further inland than might be expected, and may reflect the presence of thinner, less extensive ice in the past. Much of the selective nature of erosion may be controlled by pre-glacial topography, and especially by the large-scale tectonic structure and fluvial valley network. The hypotheses of landscape evolution presented here can be tested by future surveys of the Antarctic Ice Sheet bed.

Keywords

Antarctica, landscape evolution, glacial erosion, ice-sheet history, morphometry, Cenozoic.

Introduction and Aim

The past behaviour of the Antarctic Ice Sheets is poorly understood because their presence obscures much of the subglacial environment. In contrast, the beds of former mid-latitude ice sheets now lie exposed (e.g. in North America, Patagonia and NW Europe), and investigations of glacial geomorphology have provided significant insight into past ice sheet extents, their fluctuations, and, via an understanding of patterns of glacial erosion, their former thermal regime and flow structure. This paradigm of process-based geomorphology, developed by David Sugden and colleagues (Sugden & John 1976, Sugden 1978, 1989, Sugden *et al.* 2005, Sugden *et al.* 2006), remains at the forefront of glaciological studies. Recently, a new compilation of bed topography beneath Antarctica has been released (Fretwell *et al.* 2013 and see Fig. 1), which adds significant morphological detail to parts of this generally inaccessible landscape. The availability of these data opens the possibility of exploring the growth and past behaviour of the Antarctic Ice Sheet and, in particular, the comparatively less-well studied East Antarctic Ice Sheet (EAIS). Unlike West Antarctica, the much more expansive East Antarctic landscape is tectonically relatively 'stable' and largely unmodified by Cenozoic tectonic activity, with potential to preserve a very ancient glacial history. In this paper, we aim to extend the process-based geomorphological classification of Antarctic glacial landscape (Sugden & John 1976) to include the previously ignored region currently buried beneath the Antarctic Ice Sheets. In addressing this aim, we hope to develop a better understanding of the past behaviour of the ice sheets and the flow regimes associated with their evolution. Our objectives are to:

- Extract regional measurements of landscape geometry (morphometry and hypsometry) from BEDMAP2 within the areas originally classified by Sugden and John (1976; Fig. 2) to identify whether distinct erosion process signals can be distinguished within BEDMAP2 using their topographic characteristics.
- Subdivide the bed dataset into equal areal units and extract hypsometry across the previously unclassified region of Sugden and John (1976).
- Extend the glacio-geomorphological classification to cover subglacial Antarctica by using the regional hypsometries (objective 1) as a training set to classify the subdivided areas (objective 2) based on their morphometric characteristics.

Background and Previous Work

Antarctic Ice Sheets and Climate Evolution

The EAIS grew in a stepwise fashion, initiating at ca. 33.7 Ma in response to a reduction in atmospheric CO_2 (DeConto & Pollard 2003), and then expanding further as the surrounding ocean cooled (Liu *et al.* 2009, Pusz *et al.* 2011). Its growth reflects the transition of the Earth from a 'Greenhouse' to an 'Icehouse' state at the Eocene-Oligocene (EO) Climate Transition, which spanned ca. 300-400 kyrs and is reflected in deep-sea benthic foraminiferal records (Katz *et al.* 2008, Miller *et al.* 2008, Pusz *et al.* 2011). The ice sheet initiated upon the highland topographies of Antarctica and expanded to cover the entire continent (DeConto & Pollard 2003). Given our previous knowledge of the bed, based largely on broadly-spaced radio-echo sounding surveys, it has long been assumed that important East Antarctic inception points were the Gamburtsev Subglacial Mountains (GSM), Dronning Maud Land (DML) and the Transantarctic Mountains (TAM; Fig. 1). However, it is possible that other, yet to be discovered subglacial mountain blocks may also have acted as minor nucleation points for East Antarctic ice.

Between 33.7 and 14 Ma, local offshore sediment cores and the global benthic oxygen isotope record suggest that the EAIS margin waxed and waned on a scale similar to Pleistocene Northern Hemisphere ice-sheet fluctuations (Naish *et al.* 2001, Miller *et al.* 2008) before a potentially more stable continental EAIS was established under a colder climate. Along with modelling studies (DeConto & Pollard 2003, Jamieson & Sugden 2008), these records suggest that the contractions and expansions in ice volume were significant (10's of meters of sea-level equivalent; Cramer *et al.* 2011) and the implication is that the ice margin, at least in East Antarctica, fluctuated considerably in scale (Siegert 2008) and may have retreated significantly inland from the coast on numerous occasions. There is, as yet, no direct record of the scale of these intermediate ice sheets, or any indication of whether the EAIS remained as a single ice mass, or separated into regional ice sheets or alpine glacier systems that covered the topographic highlands.

In West Antarctica, numerical models of ice growth based on modern subglacial topography suggested glaciation at the EO transition was limited in extent (DeConto & Pollard 2003) and that the West Antarctic Ice Sheet (WAIS) only grew when further significant cooling occurred at around 14 Ma (Miller *et al.* 2008). However, a recent modelling study (Wilson *et al.* 2013), which is in accordance with limited field data (Ivany *et al.* 2006), suggests that a full-scale WAIS may have expanded in tandem with the EAIS because the topography, which is largely below sea level today, was once significantly higher and thus more susceptible to accumulation of snow and ice than previously realised (Wilson *et al.* 2012).

Geomorphological Domains and Inferences Regarding Ice Sheet Behaviour

Given the lack of direct records for the extent of the EAIS and WAIS over such large periods of time the scale and nature of these ice-sheet fluctuations is not well known. However, an understanding of the behaviour of the former Laurentide Ice Sheet gained through process-based geomorphological interpretation (Sugden 1978), for example, shows the potential for developing new knowledge of past ice behaviour by interpreting ‘newly surveyed’ ice sheet beds (Fig. 1). Indeed, the modern Antarctic Ice Sheet bed should record the time-transgressive behaviour of the ice sheets in this region because of the erosional fingerprint imposed on the bed (Jamieson & Sugden 2008, Jamieson *et al.* 2010).

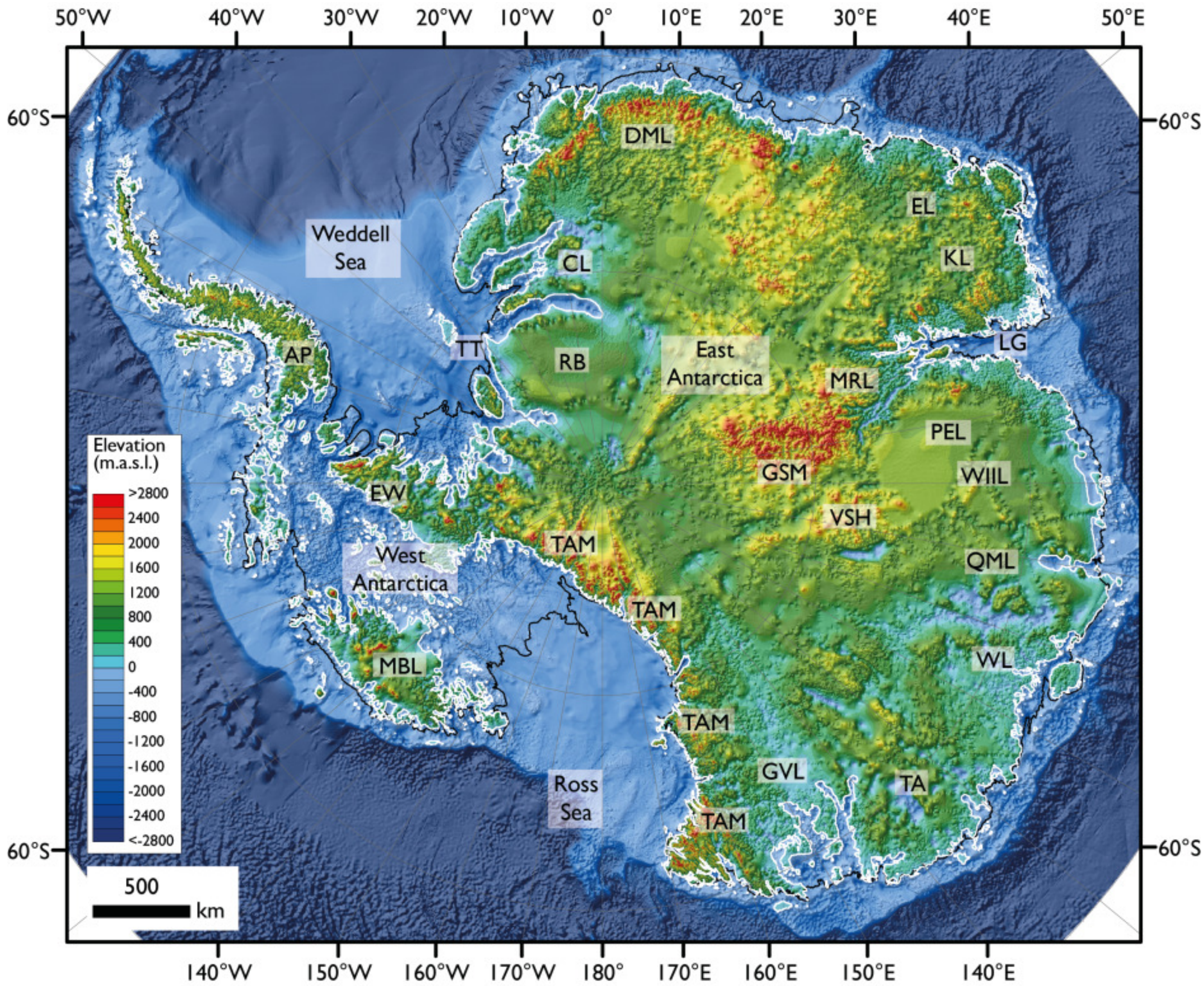

Figure 1: Antarctic BEDMAP2 topography (Fretwell *et al.* 2013) rebounded after the removal of present-day ice load. The black line indicates the modern grounding line (Scambos *et al.* 2007) and the white line indicates sea level under rebounded topographic conditions. AP: Antarctic Peninsula, CL: Coats Land, DML: Dronning Maud Land, EL: Enderby Land, EW: Ellsworth-Whitmore block, GSM: Gamburtsev Subglacial Mountains, GVL: George V Land, KL: Kemp Land, LG: Lambert Graben, MBL: Marie Byrd Land, MRL: Mac Robertson Land, PEL: Princess Elizabeth Land, QML: Queen Maud Land, RB: Recovery Basin, TA: Terre Adélie, TAM: Transantarctic Mountains, TT: Thiel Trough, VSH: Vostok Subglacial Highlands, WIIL: Wilhelm II Land, WL: Wilkes Land.

Despite the challenges of deciphering the erosional and ice dynamical regime in the interior of Antarctica, a number of studies have made advances, particularly with respect to the EAIS. For example, Perkins (1984) proposed that the GSM may retain a much older, 'sharper', alpine morphology which, it was later suggested, would have been protected beneath cold-based ice (Jamieson & Sugden 2008). Indeed, Van de Flierdt et al (2008) found that there was only very limited depositional evidence offshore for the erosion of these mountains, indicating that erosion of the GSM is likely to have been minimal since at least 14 Ma. Bo et al (2009) and Rose et al (2013) provide more recent support for this hypothesis using high resolution radar data and concluded that the geometry of the landscape reflects localised ice flow and erosion under restricted glacial conditions dated to at least 14 Ma, and possibly 33.7 Ma or earlier. Similarly, the buried topography of DML is identified as being eroded by localised ice flow to generate cirques and selective overdeepenings that are inconsistent with continental-scale ice-sheet flow and thus probably date from the mid-Cenozoic (Näslund 1997). Further afield, Young et al (2011) identified the presence of fjord-like features incised through an upland massif in Wilkes Land (WL) that reflected a dynamic EAIS during an earlier phase of its flow. Furthermore, Cook et al (2013) suggested that the Wilkes subglacial basin was subject to fluctuating ice margins during the Pliocene indicating that East Antarctica may have been less stable than previously thought (Sugden 1996).

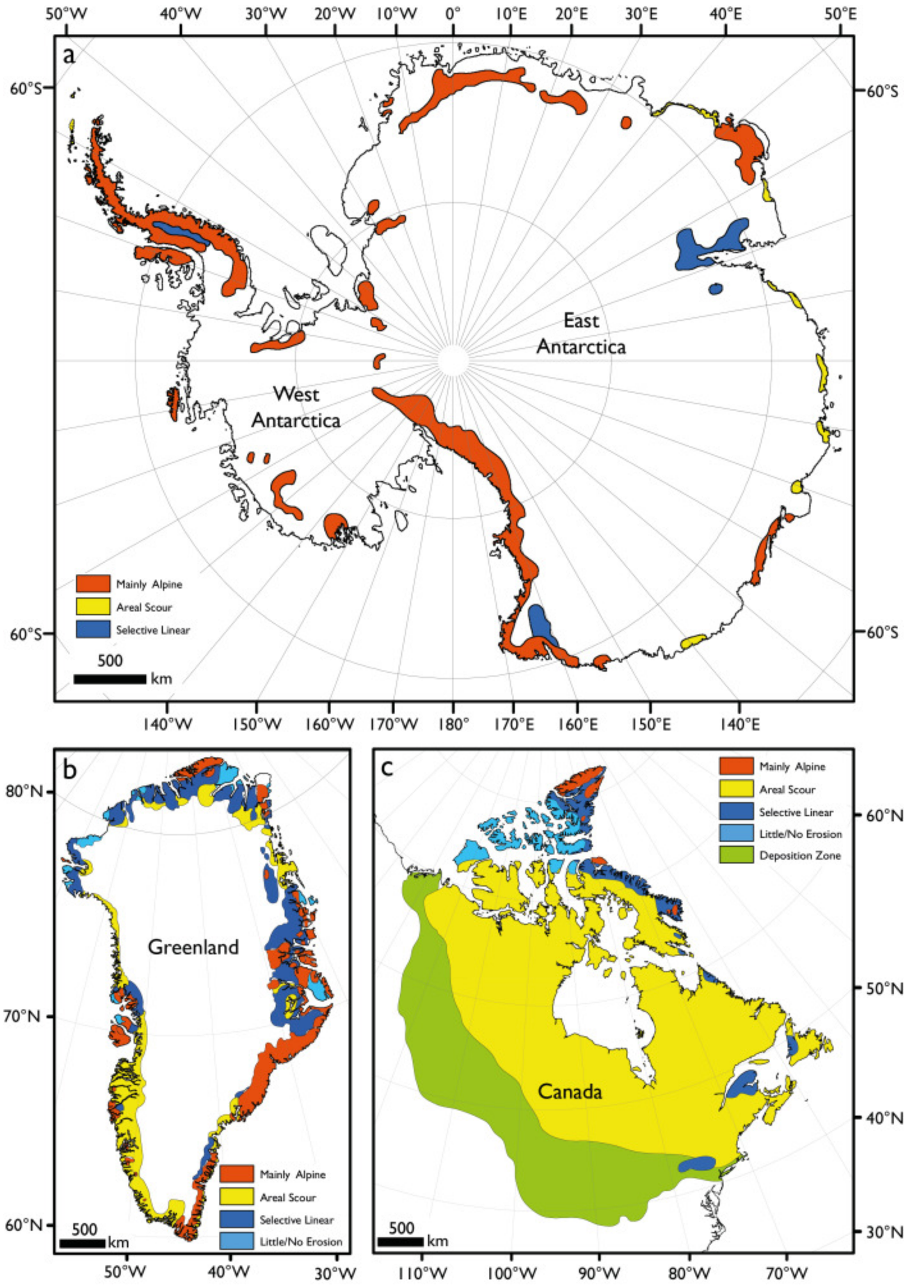

Figure 2: previous classifications of glacial landscape character for past and present glaciated beds (Re-drafted from Sugden 1974, Sugden & John 1976, Sugden 1978). a) Antarctica, with the MOA grounding line (Scambos *et al.* 2007) shown in black. Note that 90% of the landscape could not be characterised (white). b) Greenland. c) Laurentide.

Landscapes of Glacial Erosion

The pattern or mode of glacial landscape evolution is controlled by the size of the overlying ice mass, the long-term direction of flow and the temperature at the base of the ice. These are also modulated by pre-glacial topography and the underlying geology. Using these principles, Sugden (1974, 1978) and Sugden and John (1976) made process-based interpretations of ice-sheet beds in the Northern Hemisphere whereby the geomorphology was interpreted in terms of regimes of alpine glacial erosion, widespread areal scour, and selective linear erosion. Glaciologically, these differentiate between (i) small-scale valley and ice-cap glaciation (alpine landscapes), (ii) warm-based topographically-unconstrained ice-sheet flow (areal scour) and (iii) cold-based ice cover with fast-flowing warm-based outlets (selective linear erosion). A classification of landscapes of glacial erosion has been attempted for Antarctica (Sugden & John 1976) but was restricted to the coast by the limited exposure of the previously eroded ice sheet bed (Fig. 2). The majority of the bed of the modern ice sheet, therefore, has not been interpreted geomorphologically or in terms of palaeo ice dynamics.

Alpine landscapes have sharp peaks and deep, often closely-spaced valleys. They indicate that ice was constrained by topography and erosion was focused within existing valleys underneath valley glaciers. The glaciers would most likely be polythermal or warm-based and evidence for these former glacial conditions are common in mountain terrains but are also found in the TAM (Fig. 2), DML (Holmlund & Näslund 1994, Näslund 1997), Ellsworth-Whitmore mountains (EW) (Ross *et al.* 2014), MBL (Andrews & LeMasurier 1973) and more recently in the GSM in the interior of East Antarctica (Bo *et al.* 2009, Rose *et al.* 2013). Focussed erosion can be rapid at the valley floors and can generate characteristic cirque and valley overdeepenings whereby the valley profile is deepened to the extent that a downflow lip is generated.

Landscapes of areal scour are smoothed, low-relief landscapes formed by ice flow that is not focussed significantly by topography. On a large scale they are most commonly associated with landscapes buried under thick ice in central zones of ice sheets (Fig. 2) but on smaller scales they are also associated with ice flow convergence and streaming ice (Sugden & John 1976). Large parts of the bed of the former Laurentide Ice Sheet is scoured, with low-relief streamlined bedforms, some of which indicate the locations of former ice streams (Stokes & Clark 1999). The magnitude of hard-bed erosion under areal scour conditions in Antarctica is likely to be low (Sugden 1976, van de Flierdt *et al.* 2008, Jamieson *et al.* 2010). If the bed is underlain by soft sediment, it can often appear similar in morphology to either scoured or selectively eroded landscapes (Bingham & Siegert 2009) although the rates of sediment transport can be orders of magnitude higher, particularly under streaming ice (Smith *et al.* 2007).

Landscapes of selective linear erosion are identified by the presence of significant incisions into a landscape such as glacial troughs. These landscapes are generated where focussed and often rapid erosion under warm-based thick ice occurs adjacent to areas of minimal topographic modification under cold-based thin ice (Sugden 1974, Sugden & John 1976). This is often considered to be a function of the existing topography steering ice flow in upland landscapes (Kessler *et al.* 2008), with the fjord landscapes of Scandinavia or the NW coast of Scotland being a characteristic product. It is heavily dependent upon the topographic wavelength, and therefore pre-glacial topography, which enables rapid spatial changes in ice thickness and thus sharp boundaries between warm-based erosive and cold-based protective ice. Erosion can be rapid in the base of the characteristic overdeepened troughs but very low to non-existent on adjacent upland plateaus where ice flow is slower, ice is thinner and basal melting is less likely (Stroeven *et al.* 2002). In Antarctica, the landscapes of the Lambert region are selectively eroded, as are parts of DML (Näslund 2001), The Ellsworth Subglacial Highlands (Ross *et al.* 2014) Marie Byrd Land (MBL) in West Antarctica (Sugden *et al.* 2005) and parts of the TAM (Sugden & Denton 2004, Stern *et al.* 2005).

Approach and Methods

In order to identify the geomorphic and dynamic signal of past Antarctic ice-sheet behaviour that is recorded in the BEDMAP2 (BM2) bed elevation dataset, we analyse its geometry and interpret the potential modes of landscape evolution with respect to ice-sheet dynamics. We acknowledge that although the spatial resolution of the dataset is 1 km, in reality the bed data are interpolated from 5 km spaced data and therefore cannot resolve bed features smaller than 5 km in size. Indeed, 64 % of the 5 km cells contain no direct measurement. A full discussion of data coverage and limitations can be found in Fretwell at al (2013).

We isostatically adjust the BM2 dataset to account for the removal of the modern ice-sheet load and provide a basis for comparison to beds of former ice sheets in the Northern Hemisphere. Following Wilson et al (2012) the isostatic model calculates flexural load assuming a thin elastic plate with a uniform effective elastic thickness of 35 km overlying a non-viscous fluid. The load of water that replaces ice in areas that lie below sea level is iteratively calculated and applied to the ice-free landscape until, for reasons of computational efficiency, the load change drops below ca. 2 meters in magnitude. The water loading incorporates a uniform eustatic sea-level rise of 60 m that represents the addition of Antarctic ice to the ocean but that ignores spherical earth or gravitational effects. The relaxed topography, hereafter referred to as BEDMAP2r (BM2r), is shown in Figure 1 and is available in the supplementary material.

Morphometric Analysis and Modes of Glacial Landscape Evolution

Morphometric analysis characterises the topography of a digital elevation model and can enable the identification of particular landscape types. Thus it is a method that allows the link to be made between landscape and its genesis and evolution. In terms of ice-sheet beds, this is a natural extension of the process-based geomorphological approach pioneered by Sugden and his co-authors. We use the hydrology and surface toolboxes from the ArcGIS spatial analyst extension (ESRI 2012) and the peak classification tool from Landserf (Wood 2005) to extract a series of morphometric measurements from BM2r including hypsometry, relief, peak characteristics, basins and drainage form.

Hypsometry describes the distribution of area within a landscape and is extracted in the form of histograms. The form of the histogram describes the percentage distribution of landscape area against elevation, which can be linked to the process of landscape evolution, and which has been applied to parts of the bed of Antarctica (Rose *et al.* 2013). It records the shape of the land surface but different processes may result in similar histograms within low resolution data. It is therefore most useful when applied in conjunction with other physical measures of landscape. Descriptive statistics for the histograms, including measures of skewness and kurtosis are also extracted. If a histogram is not bimodal, negative skewness indicates that the lower elevation tail is either longer or fatter than the higher elevation tail, and positive values indicate the higher elevation tail is longer or fatter. Thus, negative skew indicates that the mode of the areal distribution lies at higher relative elevation, but that the mean of its distribution lies below this value. Therefore, negative skewness is indicative of enhanced area at higher elevation. Kurtosis describes the peakedness of the histogram. A normal distribution has a kurtosis of 3, with values below this indicating a lower, but flatter peak to the area-elevation distribution, such as in a landscape with uniform slope angles. High kurtosis indicates a significant percentage of the landscape area lies in a narrow elevation band.

We extract the locations of individual 'peaks' of at least 1000, 2000, 3000 or 4000 m elevation that rise 250 m clear of any adjacent peaks. We note that these peaks are simply high-points in the BM2r dataset, and describe average elevations over a 5 km grid area. As a consequence they provide minimum estimates for the density of actual peaks. We suggest that the density of individual peaks is higher in a landscape dominated by alpine glacial erosion, compared to one where topography is submerged beneath an ice sheet over a much greater area and where peaks can therefore be potentially subjected to modification. We also measure peak heights which indicate the scale of mountainous terrain. Furthermore, it has often been noted that pre-glacial landscapes and saprolites that become incised under ice sheets can be partly preserved as remnants in glaciated landscapes (Sugden 1989, Hättestrand & Stroeven 2002, Goodfellow 2007). Therefore, consistency in peak heights may evince the presence of remnants of pre-glacial landsurfaces that have subsequently been incised by surface processes.

The elevation range (relief) and slopes within each unit of the landscape are calculated and may help identify whether the topography has been selectively eroded or whether it has been smoothed. Relief may also help identify whether the landscape has been subjected to long-term flow that has not significantly changed direction and has therefore had longer to incise the landscape. Within this context, and at a kilometre scale, relatively low slopes with little variation may be expected in zones of areal scour whereas a bi-modal distribution of very low and very high slopes might indicate a selectively eroded fjord-like landscape.

The large-scale valley drainage network is also extracted because this has previously been used as an indicator of processes related to long-term Antarctic landscape evolution (Baroni *et al.* 2005, Jamieson *et al.* 2005). For example, a dendritic network may be an indicator of an unperturbed drainage system whereas deviation from this may indicate structural control or modification of valley spacing by erosion processes operating on a different scale to the fluvial system. We extract the network by assuming that the rivers would be routed down the steepest slope within the landscape. Drainage is deliberately extracted to the edge of the modern grounded ice in order to understand the potential impact of glacial processes upon the bed, but we note that the coastline would have lain inland of this position during ice-free conditions. Where internal basins were present, these are filled to enable drainage to the coast from all basins. The valley network and the associated internal basins are an indicator not only of water flow, but of sediment transport pathways and depo-centres during periods when parts of the bed topography lie exposed.

Morphometric Analysis of BEDMAP2r

In addition to the measurement of the ice sheet-wide bed topography (described above), and in order to conduct a process-based geomorphological classification of the Antarctic subglacial landscape, we also characterise specific regions of the BM2r database that relate to Sugden and John's (1976) original classification (Fig. 2). We do this in two phases. First, we analyse the characteristics of the sub-aerial regions previously-classified by Sugden and John (1976; Figure 2) to establish whether the morphometric analysis enables discrimination of distinct morphological characteristics for each landscape type. Crucially, the density of point measurements within BM2 is high in these areas. Secondly, using the same methods, we analyse the entirety of BM2r, applying the analysis in a grid of equally divided regions. Normally, hypsometry and other morphometric parameters would be determined using individual drainage basins as the areal unit of interrogation. However, the scale of the basins in Antarctica is such that some encompass regions where the ice margin might be expected to have fluctuated and therefore might show a mixed signal of landscape evolution. Consequently, BM2r is divided into a regular 250 x 250 km grid to provide standardised units for comparison across the bed. The use of this areal division allows direct comparison to regions in the earlier classification and provides a higher resolution analysis than is possible using drainage basin extents.

Following the extraction of these data, we use the morphometry of the original classifications (Fig. 2; Sugden & John 1976) as training data to characterise the glaciological processes that generated the landscapes of the previously unclassified regions. Two extended classifications are produced. The first relies strictly upon the previously classified 'training set', and follows a simple decision pathway to expand the classification into the centre of East and West Antarctica. The second is more tentative, using the first classification to direct a higher-resolution categorisation. In generating the latter classification, we let our understanding of the long-term thermal structure drive the decisions. In particular, we know that it is possible that rapid expansion from alpine-scale to ice-sheet scale glaciation occurred in Antarctica and that a protective cold-based ice-sheet core could therefore be established over the alpine landscape and then preserve it under continental-scale ice flow conditions (Jamieson *et al.* 2008, Bo *et al.* 2009, Jamieson *et al.* 2010, Rose *et al.* 2013). We transfer the assumption that this scale of selectivity may have been possible where steep topography and thus thermal gradient enabled cold-based ice to encase whole alpine landscapes rather than just upland plateaus. Thus, alpine landscapes can be nested within selectively eroded landscapes, as seen in the Ellsworth Subglacial Highlands (Ross *et al.* 2014), and we delineate these based upon the identification of regions of high elevation that also have a 'rough' appearance. Our intention is that this new classification be treated as a working hypothesis for the modes of landscape evolution in Antarctica.

Results

The drainage network of Antarctica

The drainage network, drainage divides and the likely internal sediment depo-centres are shown in Figure 3. The numerous numerically-filled basins partially mask channel morphology by generating multiple parallel channels across the erroneously flattened topography. This makes detailed network analysis, such as calculation of bifurcation ratios, drainage density and Horton numbers, which can all identify divergence from a dendritic morphology, subject to significant potential error. Therefore, we note that in East Antarctica the river network is largely dendritic in appearance and drains radially from the GSM and Vostok Subglacial Highlands (VSH) in East Antarctica. Indeed, the six largest drainage basins in East Antarctica are all similar in length (1,400 - 1,780 km), radiating from their relatively confined headwater region. Behind the TAM, drainage is directed towards the interior before draining longitudinally for up to 1,500 km towards the coast of George V Land (GVL) or through the Thiel Trough into the Weddell Sea.

The presence of coastal highlands between 100° E and 15° W results in the development of small, locally-draining basins indicating that short-scale (100-300 km distance) fluvial sediment delivery would be likely. On the inland flanks of these highlands, drainage is oriented towards the continental interior before draining longitudinally towards the coast. Valley spacing in the TAM is similar to that in the remaining coastal highlands. However, in WL, Terre Adéle (TA) and GVL, such small-scale drainage is less dominant, with longer drainage pathways extending from the interior out to the coast in a radial, dendritic manner. The potential depo-centres (and thus lakes during ice-free periods) are largely located inland of the coastal mountain ranges and are all interconnected via the drainage network. In Coats Land (CL), WL and GVL, the depo-centres are relatively larger, less frequent and appear to be aligned to present-day ice-sheet flow. However, in the remainder of East Antarctica the alignment is less obvious, with larger numbers of smaller basins. In West Antarctica, the largest depo-centres and much of the drainage are aligned along the path of ice-sheet flow but would lie below sea level whether ice-free or not (Figs. 1 and 3). In the Antarctic Peninsula (AP), the drainage basins are short with the longitudinal drainage divide located approximately equidistant from the West and East coasts.

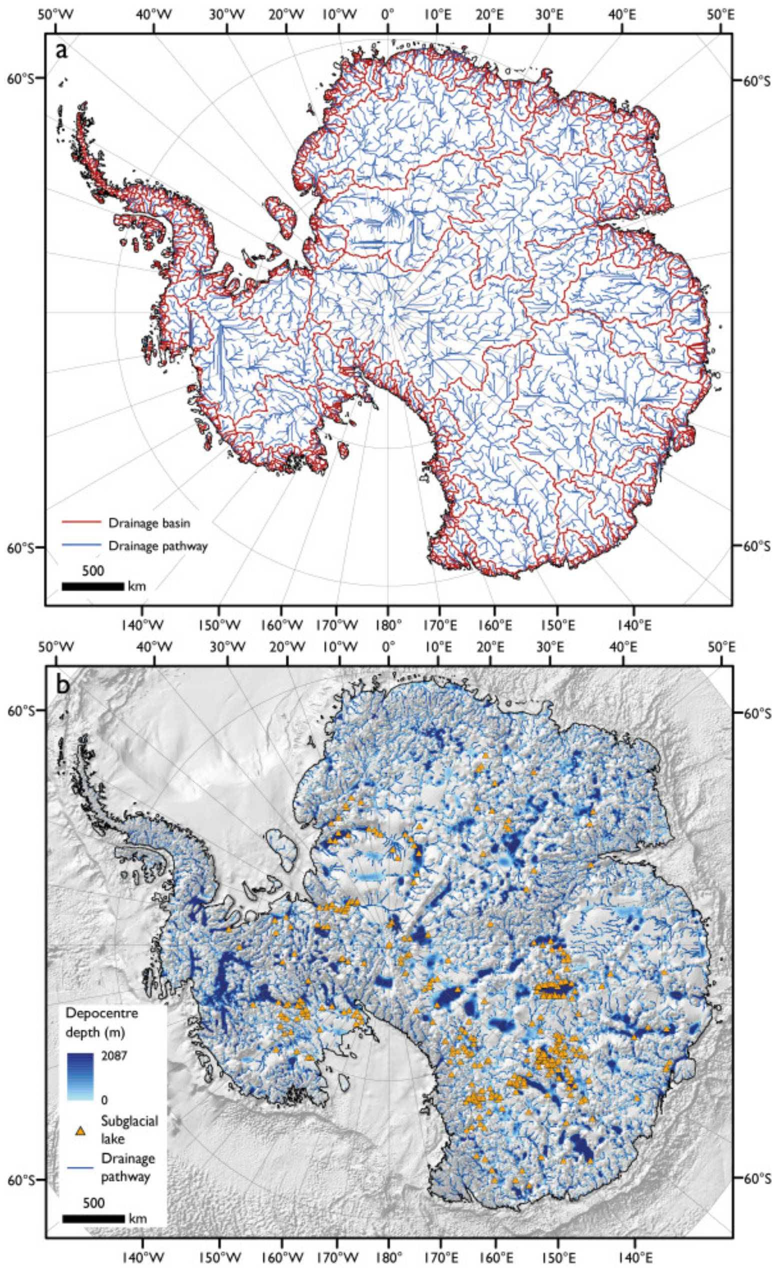

Figure 3: Drainage network on the BM2r landscape. a) deglacial hydrological and sediment transport pathways. The drainage pattern is dendritic in appearance and drains radially. b) The depth of potential depo-centre in the deglaciated BM2r and the location of modern subglacial lakes. Topography is shown using a hillshade of BM2r. The MOA grounding line (Scambos *et al.* 2007) is shown in black in both panels.

The distribution of mountainous terrain in Antarctica

Following from the identification of the low-points in the landscape and the ice-sheet wide drainage networks, the distribution of independent 1000 m 'peaks' in the BM2r dataset is shown in Figure 4. They are located most commonly in the alpine regions of the TAM, MBL and the AP. They are also found along coastal regions of East Antarctica stretching from DML to the Lambert region. In the interior, only the GSM show significant 'peak' densities, although other smaller clusters of 1000 m 'peaks' are found in the interior of East Antarctica. These latter groups may hint at sharp, mountainous landscapes, like the GSM, that are, as yet, poorly resolved beneath the ice.

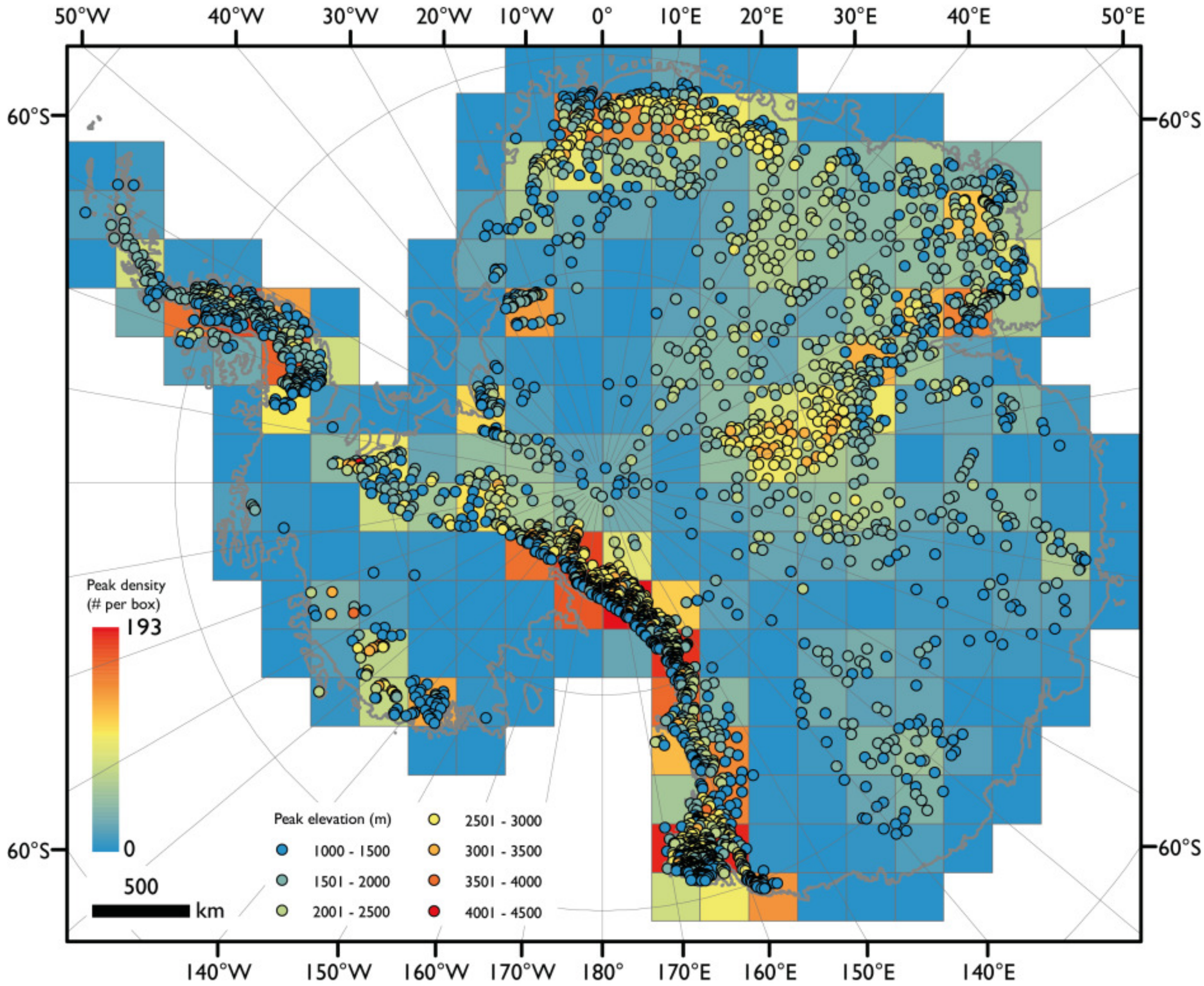

Figure 4: Distribution of 1000 m 'peaks' (which describe an area of high elevation averaged over a 5 x 5 km region) and their density in BM2r. 'Peaks' that are greater than 1000 m in elevation and that lie 250 m proud of surrounding topography are indicated by a point. 'Peak' densities are also shown for each analysis box. The MOA grounding line (Scambos *et al.* 2007) is shown in grey.

The morphometry of Antarctica's eroded landscapes

The topographic data for the three subsets of landscape classification and for BM2r as a whole are shown in Table 1.

Morphometric Parameter	Entire BEDMAP2r	Mainly Alpine	Areal Scour	Selective Linear
Relief (m under grounded ice)	6756	6756	1951	5090
Elevation mean (m)	679	902.9	-18.5	873.6
# 1000m peaks	2816	1346	0	159
# 2000m peaks	1109	552	0	68
# 3000m peaks	125	94	0	1
# 4000m peaks	1	1	0	0
Highest peak height (m)	4193	4193	498	3196
Lowest basin under grounded ice (m)	-2563	-2563	-1453	-1894
Hypsometric integral	0.48	0.51	0.74	0.54

Table 1: Key morphometric parameters extracted from BM2r across previously classified parts of the landscape and across the entire currently grounded portion of the dataset.

Hypsometries for the classified regions are shown in Figure 5 alongside similar data for portions of exposed ice-sheet beds in the Northern Hemisphere. The mainly alpine region displays a broad elevation distribution and unimodal, near-normal distribution similar to the European Alps (Fig. 5). The region of areal scour has a narrow elevation range within which the majority of the landsurface is distributed at relatively low altitude. The selective linearly eroded landscape displays a bimodal distribution indicating incision of flat-bottomed troughs into upland plateau topography. The spacing between peaks in the bimodal distribution suggest an average trough depth of ca. 1 km.

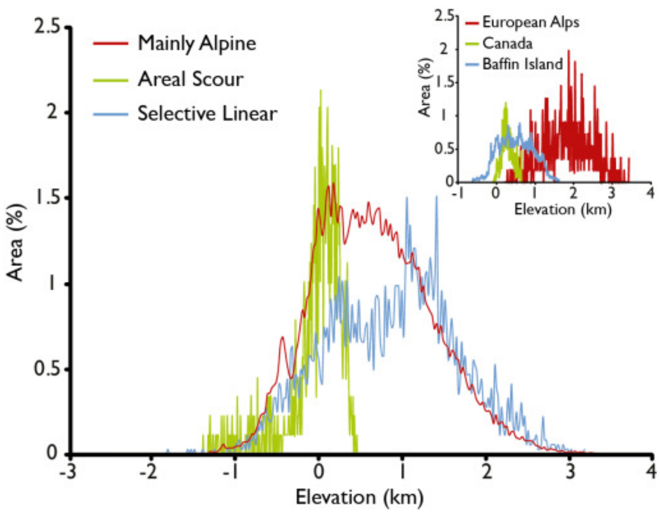

Figure 5: Hypsometric (area-elevation) relationships of the rebounded Antarctic bed within previously identified landscapes of erosion. Inset: hypsometric curves for parts of former ice sheet beds extracted from GMTED 15 arc-second resolution data (USGS 2010): alpine topography in the European Alps; glacially scoured topography to the west of Hudson Bay, Canada; and selectively eroded topography in the NW draining part of Baffin Island.

The classified regions (Fig. 2) have distinctive morphologies, in particular in the hypsometric distributions. The 'mostly alpine' region has a high regional relief of 6,756 m, with a near-normal area-elevation distribution (Fig. 5). The drainage network, and thus valley network, in this region is closely-spaced across flow, and the drainage areas are small with short trunk rivers whose headwaters are enclosed by the region. The density of peaks over 1000 m in relief is eight times higher than in any other region (Fig. 4) although we recognise that due to restricted data coverage it would be unlikely that comparably high densities could be picked out in the subglacial region of Antarctica if alpine landscapes do exist.

The selective linear erosion region (Fig. 2) has a high relief (5,090 m) and mean elevation of 874 m, but also a bimodal hypsometric distribution indicating the dominance of upland plateaus and glacially eroded valley floors in the landscape. Significant independent peaks are less common than in alpine regions (Fig. 4) and drainage appears to be routed through the valley floors from areas further inland (Figure 3).

The regions of areal scour (Fig. 2), though limited in coverage, show that relief is less than 2000 m with a mean elevation closer to sea level. The scoured landscapes do not contain significant independent peaks and have not had deep valleys carved into them. The drainage network (Figure 3) indicates that the headwaters of the rivers lie inland and cross the scoured topography en-route to the coast. We note, however, that regions of extensive deposition may have similar landscape geometries to those of areal scour. For example, we suggest that areas outboard of the 0 m contour (Fig. 1), where marine sedimentation is most likely, are the regions where deposition may mask earlier patterns of glacial erosion.

Expanding the Sugden and John classification of glacial landscape evolution

The hypsometries for each boxed region of the BM2r dataset (Fig. S1) are extracted and the morphometric parameters are outlined in Table S1. In order to show how the 'boxed' morphometric analysis would extend the Sugden and John (1976) classification (Fig. 2), we apply a simple decision pathway (Figure 6) based on the regional morphometric analysis and assign each box to one of the original classes. We classify by applying criteria in order of significance, building the assessment of each region by applying additional criteria one at a time until the area fits only a single category. We apply the minimum discriminators of hypsometric distribution and then relief because these encompass the form and scale of the topography in single measurements. Thereafter, mean slope, peak density and drainage density are applied if the classification remains ambiguous. The values chosen do overlap for some of the criteria, but a unique answer is reached when all are applied. Figure 7 shows the hypsometries extracted and then coloured according to this decision pathway.

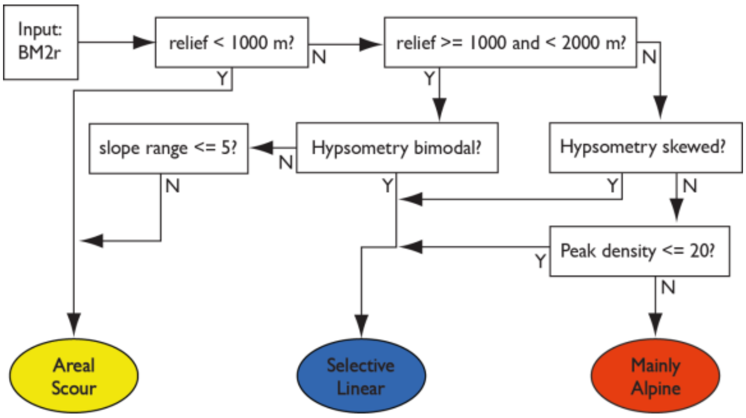

Figure 6: Decision pathway (Y=Yes, N=No) used to determine landscape classification within box regions of BM2r.

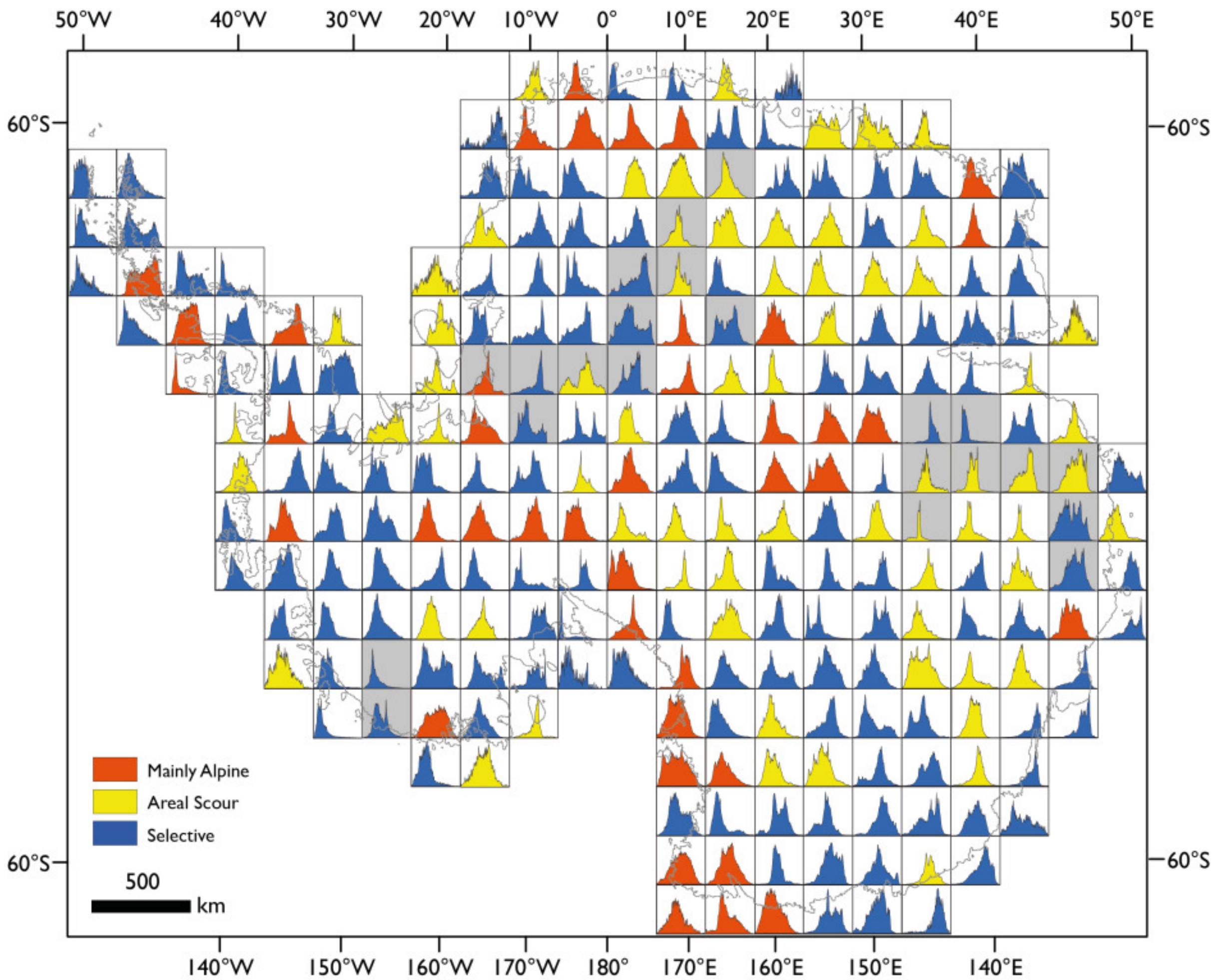

Figure 7: Antarctic hypsometry within each box region (Figure S1). For each histogram, area is on the y-axis and elevation is on the x-axis. The maximum and minimum elevations shown in each graph are presented in Table S1. The histograms are coloured following the application of the 'training data' to the morphometry (Table S1) and hypsometry of each square region. Greyed boxes highlight regions within BEDMAP2 where more than 50% of the area of the bed is classed as being generated from data that is over 200 km distant (see Fig. 3 in Fretwell *et al.* 2013). The MOA grounding line (Scambos *et al.* 2007) is shown in grey.

As Figure 7 illustrates, there is significant variability in the signal of glacial landscape evolution. In general, landscapes of selective erosion tend to be found in pathways leading from the interior to the coast or as a more localised signal in the coastal mountains. Landscapes of selective erosion, including areas where sedimentary drapes are likely to have been eroded, seem to underlie much of the present-day WAIS. Zones of alpine morphology are often narrow in width and occur, as might be expected, along the TAM, in DML, MBL, in the GSM and along the AP. Small areas of alpine morphology are also picked out corresponding to the Ellsworth Mountains and inland of the Amundsen and Bellingshausen Seas. Areal scour is widespread in the interior, particularly in East Antarctica, and is found in the regions that lie between alpine landscapes or in areas where topography is comparatively low in relief compared to elsewhere. There are only small zones of areal scour in West Antarctica. However, we note that there are regions within BM2 where there are hundreds of km between bed measurements and thus where topography may appear smoother than reality (Fig. 1). We therefore highlight areas (grey shading in Fig. 7) where data quality may have a significant impact upon the classification of the landscape.

The boxed morphometric classification provides a low-resolution template for a second, finer-scale, qualitative classification (Fig. 8). The key result of this is the significantly expanded coverage of ‘mainly alpine’ landscape and we suggest preserved alpine landscapes may be much more commonplace than previously realised under the Antarctic Ice Sheets, particularly beneath the EAIS. For example, the region inland of the coastal mountains of DML is extended and reaches towards the mainly alpine GSM, which are themselves extended beyond previous knowledge. Though smaller in extent, we suggest isolated alpine ranges may also be found throughout the region between Dome C and the coast, and in Enderby Land. The VSH are also picked out as being potentially alpine, as are inter-ice stream regions in the Recovery Basin. The TAM and core of the AP and MBL highlands are also mainly alpine, as is most of the Ellsworth-Whitmore region. We also note that as selective erosion occurs under continental-scale ice, flow-parallel alpine chains may have been preserved in Coates Land and the Recovery ‘basin’.

Zones of areal scour are delineated in coastal areas of CL, DML, PEL, Wilhelm II Land, Queen Mary Land (QML) and TA where topography is relatively smooth and is not topographically-confined at a small scale. Scour is also suggested to be found under the South Pole, in a region between Dome C and the VSH, and between the alpine topographies of DML and the GSM. In these three cases, the areas of scour are surrounded by alpine topography and are therefore defined by zones where ice flow direction under smaller-scale ice may have been significantly different from flow direction under continental-scale ice.

Selective linear erosion is used to describe the remainder of the landscape. It effectively radiates from the alpine centres and occupies zones through which continental-scale ice has, or still, drains to the coast. It is also picked out on the range fronts of DML, the TAM and in the AP where overdeepened trough features reach to sea level. The bed of much of

West Antarctica is also indicated to be selectively eroded although our analysis does not directly distinguish parts of the WAIS bed that have been strongly affected by tectonic processes or marine sedimentation.

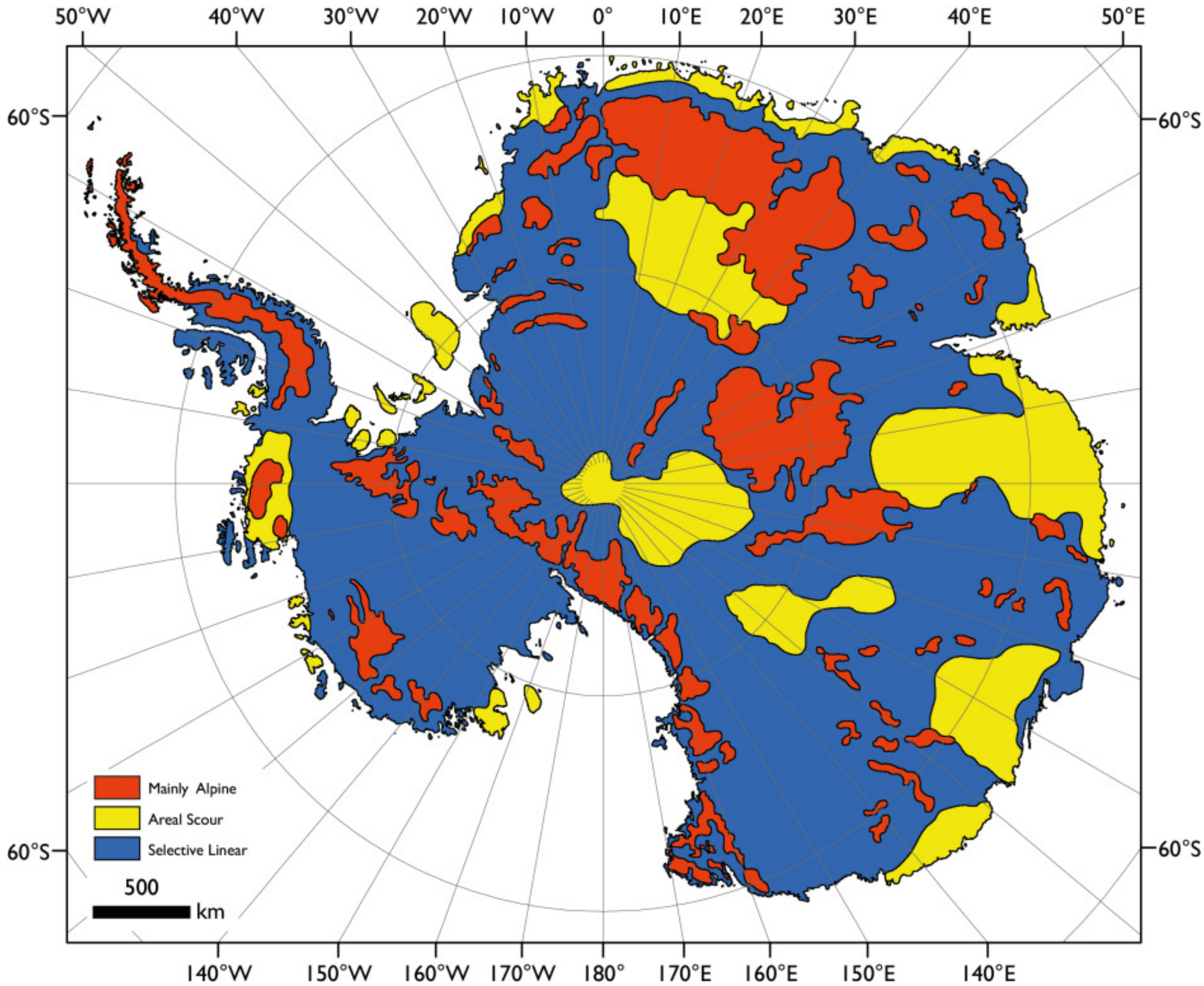

Figure 8: Hypothesised glacial erosion domain classification developed upon the earlier framework of glacial landscape evolution developed by Sugden and John (1976).

Discussion

Geomorphic interpretation of past Antarctic ice dynamics

Many of the alpine landscapes correspond to regions which, under the modern ice sheet, are thought to have high basal-friction coefficients and thus low rates of basal sliding (Morlighem *et al.* 2013). Consistent with modelling studies for Antarctica (Jamieson & Sugden 2008, Jamieson *et al.* 2010, Golledge *et al.* 2013), and with geomorphological studies from Northern Hemisphere ice sheet beds (Kleman 1994, Kleman & Stroeven 1997), the implication is that these regions are subject to little or no erosion and therefore favour large-scale preservation of alpine landscapes. Remarkably, the logical extension of this model for preservation is that in these areas the cold-base of the overlying ice sheet must have remained unchanged despite evolving through around 58 glacial cycles during the last 13 Myrs (McKay *et al.* 2009). This is consistent with investigations of likely sites for the discovery of ice older than 1 million years (Van Liefferinge & Pattyn 2013). However, as a result of our analysis, we hypothesise that these cold-based regions may be more extensive in DML as indicated by the distribution of peaks, and thus rougher topography, in this area (Fig. 4).

The alpine landscapes reflect restricted ice extents that existed in the past and which had topographically-confined radial flow and a largely warm basal thermal regime. However, because the scale of valley and peak spacing is inconsistent with continental patterns of ice flow, many of the currently buried and preserved landscapes are likely to be ancient (Jamieson & Sugden 2008, Siegert 2008, Rose *et al.* 2013). However, it is likely that all the alpine landscapes are time-transgressive. For example, an equilibrium-line altitude (ELA) that intersects the topography at 2000 m elevation would have enabled ice growth in the TAM, AP, MBL, GSM, VSH and DML but it would have to have been depressed by another 500-800 m to enable valley glaciers to grow in the more isolated alpine areas between the coast and the GSM. During such a drop in ELA, ice in the initially-glaciated regions would likely have advanced and coalesced into mountain ice caps or regional ice sheets (Jamieson *et al.* 2010). Therefore, although there is evidence for warm-based valley glaciation in a number of areas near the coast since the expansion of the continental ice sheet (Holmlund & Näslund 1994, Armienti & Baroni 1999, Di Nicola *et al.* 2012), it is possible that the larger alpine domains (e.g. GSM and VSH) were last incised by valley glaciers before 14 Ma and that the ice masses that fluctuated between 33.7 and 14 Ma may never have retreated as far as these interior alpine systems. Thus, although it cannot be confirmed, it is also a possibility that they could represent sites eroded during the initiation of the EAIS at 33.7 Ma. This gives rise to the scenario that the distribution of potential sites for initial ice growth, at least in East Antarctica, may be broader than previously realised (DeConto & Pollard 2003, Jamieson & Sugden 2008).

To find landscapes of selective linear erosion in the interior of a glaciated terrain is unusual because the process relies upon ice being thin enough to preserve parts of the landscape whilst being thicker in existing depressions such that ice can be warm-based and erosive. However, the unique nature of Antarctic glaciation allows the ice sheet margins to fluctuate significantly over an extended period of time (Naish *et al.* 2001, DeConto & Pollard 2003). Although the positions of ice margins are not constrained, it is likely that under smaller, regional-scale ice sheets, ice in the interior of the continent would be thinner and thus more sensitive to topographically-driven contrasts in basal thermal regime and enhanced selectivity than would be the case under a continental ice sheet. Therefore, the presence of selectively eroded landscapes suggests that, in the past, ice was thin enough to erode selectively, and that margins were likely to have retreated inland of the coast. At present, these areas are often buried under thick, slow-flowing ice that is less likely to significantly erode. We also note that the presence of a sedimentary drape, such as noted in West

Antarctica during recent surveys (Bingham & Siegert 2009, Ross *et al.* 2012), may alter patterns of hard bed erosion and may also mask the past signal of erosion by smoothing the bed landscape.

We identify a number of areas in the interior where alpine landscapes are inset within selective linear erosion landscapes whose orientations are inconsistent with continental ice flow. These include areas inboard of Enderby Land (EL) and the interior of WL and QML. In these cases we suggest the landscape may effectively be preserving at least 2 scales of ice behaviour prior to the onset of full-polar glaciation. For example, Young *et al* (2011) identify a fjord landscape in QML indicative of a dynamic early ice sheet where we further suggest that a contemporaneous or earlier alpine landscape may have been eroded and then selectively preserved in the uplands between the fjords.

Furthermore, the preservation of pre-glacial landscape remnants is most likely where the direction of ice flow under a selective erosion regime remains constant under both a regional- and a continental-scale ice sheet. Examples of pre-glacial landscape preservation include Scandinavia (Kleman & Stroeven 1997, Hättestrand & Stroeven 2002), DML (Näslund 1997) and Scotland (Sugden 1989) all of which have pre-glacial landscape remnants that often lie at similar elevations over large areas and are separated by sharp boundaries such as trough walls (Goodfellow 2007). We suggest that the selectively eroded landscape between the GSM and the Lambert trough may contain such landscape fragments. This is identified by the relatively consistent elevation of peak heights in this area. Here, convergent, topographically-steered ice flow patterns are likely to have been very consistent since the onset of East Antarctic glaciation. Drainage from the GSM to the Lambert was established early and is unlikely to have changed significantly during periods of either expanded or reduced ice-sheet extent (Jamieson *et al.* 2005). This pattern of flow has led to significant incision and erosion-driven uplift on the flanks of the Lambert Graben (Lisker *et al.* 2003), particularly between 34 and 24 Ma (Tochilin *et al.* 2012, Thomson *et al.* 2013). We suggest that the uplift between the GSM and the Lambert Graben caused an increasingly selective basal thermal regime to evolve whereby thicker, warmer ice in trough floors got warmer, and colder, thinner ice on peaks became colder. This would enhance the likelihood of maintaining cold-based ice over the pre-glacial topography fragments and is consistent with generating the crustal upwarping noted by Ferraccioli et al (2011).

The age of subglacial landscapes

Our knowledge of the scale and timing of ice-sheet fluctuations remains limited, as does the impact and scale of tectonically-driven changes to landscape and ice flow. The evolution of different scales of glacial erosion is time-transgressive, and we therefore build on work by Siegert (2008) and Jamieson and Sugden (2008) to suggest broad scenarios for the ages of the eroded and protected glacial landscapes. For example, before 33.7 Ma, it is likely that local, warm-based, ephemeral alpine glaciers eroded the highest elevation coastal and interior highlands of East Antarctica, and possibly along the Antarctic Peninsula and the highlands of West Antarctica depending on their elevation (e.g. Wilson *et al.* 2013).

The period between 33.7 and 14 Ma would have supported a significant range of erosion configurations depending on the scale of cyclical margin advance and retreat. Under restricted ice conditions, alpine glaciers would erode and deposit at high elevation in the coastal and interior mountains of East Antarctica such as Dronning Maud Land, Vostok Subglacial Highlands, Gamburtsev Subglacial Highlands, and the Transantarctic Mountains as well as in the highlands of West Antarctica. Under regional ice conditions, alpine erosion would occur in lower elevation mountain blocks (including in Enderby Land, Recovery Basin, Queen Maud Land and Terre Adéle) whilst over the coastal and interior highlands, larger, regional ice caps or ice sheets would selectively erode in pre-existing valleys in a radial pattern. The highest parts of the mountains could have been protected under thin, cold-based ice. Depending upon the elevation and pre-existing valley orientations of West Antarctica, significant ice domes could have been present, radially and selectively eroding the landscape. During the periods when regional ice masses coalesced to become continental-scale ice, alpine glacial erosion would have been more limited. Instead, a mix of continentally or regionally radial selective linear erosion and areal scour would have been likely in East and West Antarctica at, and since, the E-O transition (Ehrmann & Mackensen 1992, Naish *et al.* 2001, Ivany *et al.* 2006). Such warm-based ice sheets have also deposited sediment multiple times and at many sites in East Antarctica (Webb *et al.* 1996, Hambrey & McKelvey 2000, Baroni *et al.* 2008). Selective erosion would be most prevalent near the coast of East Antarctica where local relief could exert the greatest control of ice drainage and basal thermal regime. If the ice margin were near the coast, extensive regions of cold-based, protective ice would be likely over high-elevation mountain peaks and plateaus.

Since 14 Ma, alpine glacial erosion would be likely to have been largely restricted to the Antarctic Peninsula, and to coastal mountain ranges depending on the scale of ice margin fluctuations (McKay *et al.* 2009). However, in East Antarctica, it is possible that the large alpine domains in the interior have been preserved under a relatively stable and cold basal thermal regime for 12-14 Myrs or longer (Bo *et al.* 2009, Rose *et al.* 2013). This is unlikely towards the coast where valley glaciers were last eroding at between 8.2 and 7.5 Ma in the Northern Victoria Land sector of the TAM (Armienti & Baroni 1999, Di Nicola *et al.* 2012) and until 2.5 Ma in DML (Holmlund & Näslund 1994). Notwithstanding the potential for alpine-scale ice to erode intermittently, and given the cold-polar climate and generally large-scale ice sheets, continental-scale selective linear erosion and areal scour are likely to have dominated in both East and West Antarctica. In the TAM and Mac Robertson Land (MRL) this selectivity has driven significant uplift in a response to erosional unloading (Stern *et al.* 2005, Tochilin *et al.* 2012, Thomson *et al.* 2013), although in the TAM, little of this uplift occurred after 3 Ma (Brook *et al.* 1995). The area covered by protective, cold-based ice would have been largest during this period, selectively covering mountain plateau tops on a large-scale in the East Antarctic interior, and to a lesser extent over lower elevation mountain ridges and plateaus. The transition into this thermal state may have been rapid in the interior of the continent, as suggested by the lack of ice-sheet scale modification to areas like the GSM (Rose *et al.* 2013), but slower towards the coast (Armienti & Baroni 1999). The stable hyper-arid polar climate means that preserved, or only slightly modified landscapes are also found beyond the ice margin (e.g. Baroni *et al.* 2005, Di Nicola *et al.* 2012) or above the ice surface (e.g. Näslund 2001). If, as is hypothesised, the Pliocene West Antarctic Ice Sheet collapsed between 5 and 3 Ma (McKay *et al.* 2009), then radially selective ice flow from the remaining isolated ice domes would have prevailed, and these would likely retain small cores of thin, cold-based ice.

Throughout these time periods, if erosion has been selective or topographically confined, there is potential for an evolving feedback between topography, tectonics, ice flow and erosion. Although we have not explicitly accounted for tectonic processes in our analysis of the subglacial landscape, it is important to note that erosion patterns could either be enhanced or muted over time depending on the direction and scale of any active tectonic uplift or lithospheric subsidence.

Erosion and its influence upon ice behaviour

The dendritic nature of the drainage network, particularly in East Antarctica (Fig. 3), is an indicator that although glacial erosion has modified the landscape, it is likely that on a large scale the fluvial network has been retained and selectively exploited by glacial erosion. The pre-glacial drainage network itself is controlled by the influence of tectonics because selective erosion around the coast, for example in the TAM, corresponds closely with the valley spacing generated during passive margin uplift following continental separation (Näslund 2001, Stern *et al.* 2005, Jamieson & Sugden 2008). Furthermore, although the central TAM uplifted in response to episodic tectonic events during the Cretaceous and Cenozoic (Fitzgerald & Stump 1997), models predict that 32-50% of the peak elevation may have been a response to lithospheric unloading by selective linear erosion (Stern *et al.* 2005). This may have acted to ensure erosion was increasingly focussed along consistent flow lines, and shows that the interaction between TAM uplift and trough incision is important for ice sheet behaviour (Kerr & Huybrechts 1999). Large-scale tectonic features have also controlled and re-enforced the ice flow, and therefore erosion, patterns across Antarctica (Jamieson *et al.* 2005, Jamieson & Sugden 2008). For example, in the Lambert basin of MRL, 1.6-2.5 km of selective erosion during the Early Oligocene was focussed along the pre-existing graben and resulted in significant uplift of the Prince Charles Mountains in response to the removal of material (Tochilin *et al.* 2012, Thomson *et al.* 2013). The importance of tectonic features is also indicated by the scale of the longitudinal drainage routing behind the TAM, which is similar to the Indus and Brahmaputra river systems which follow the structural grain of the Himalaya for thousands of kilometres before turning to the coast. We also note that, in many cases, the internal basins correspond to present-day, and probably former, subglacial lake locations (Fig. 3), and are often situated in rift basins (Ferraccioli *et al.* 2005, Jordan *et al.* 2010, Ferraccioli *et al.* 2011, Bingham *et al.* 2012, Jordan *et al.* 2013) or may correspond to overdeepenings eroded by ice (Rose *et al.* 2013, Ross *et al.* 2014). Thus, via selective erosion, the pre-glacial tectonically-controlled river drainage may have become increasingly important for steering regional ice flow. We further note that in places, these depo-centres may contain sedimentary drapes emplaced by marine sedimentation at times when the ice sheet was less extensive (Ross *et al.* 2012).

The importance of topographic feedbacks in controlling ice behaviour extends further. When comparing our classification (Fig. 8) to reconstructions of basal friction (Morlighem *et al.* 2013), we find that, on a broad scale, the mainly alpine regions correspond with high friction, areal scour with intermediate friction, and selective linear erosion with lower friction. This is consistent with previous analyses indicating that smoother regions of the bed tend to correspond with areas of faster flow (Rippin *et al.* 2004, Siegert *et al.* 2005, Bingham & Siegert 2009). Thus, in a system eroding into bedrock, a topographically-controlled feedback can be envisaged whereby smooth beds may be eroded over time to become more streamlined and thus more efficient in terms of ice drainage. In other words, smooth topography promotes fast flow, which promotes further smoothing (Rippin *et al.* 2011). Conversely, the rugged nature of alpine topographies preserved beneath the ice sheet means that ice flow cannot be fast, that ice is more likely to remain cold-based and that subglacial topographic gradients are often in different directions to continental-scale ice surface gradients. Thus, rough topography may enhance its own preservation potential.

The erosion of glacier and ice-sheet beds to elevations below sea-level may have important implications for ice-sheet stability. This is because the landscape controls the susceptibility of the overlying ice mass to reaching flotation, becoming influenced by ocean currents, and to a feedback where ice discharge becomes enhanced as it retreats into regions that have become progressively glacially overdeepened (Thomas 1979). Thus, where our map of selective linear erosion (Fig. 8) corresponds to beds that would lie near or below sea-level under a modern ice load (Fig. 1), we expect the magnitude of that potential destabilising influence to be increased slowly but surely. Supporting this notion, reconstructions of past Antarctic topography suggest that more of the landscape lay above sea level prior to the onset of glaciation and glacial erosion, particularly in West Antarctica (Wilson *et al.* 2012). This is confirmed by the volume of the offshore sediment and indicates that over the past 14-34 million years the West Antarctic landscape was significantly and progressively lowered below sea level. The implication is that over successive glacial cycles, the WAIS has become potentially more susceptible to catastrophic retreat.

In East Antarctica, the transition towards a progressively less stable topographic context is not so clearly identified. This may be addressed by improving estimates of the volume of sediment lying offshore, but these are subject to potentially significant errors because survey data are relatively sparse, sediment on the continental shelf is reworked on a large-scale (Gohl *et al.* 2013), and because the degree to which the continental shelf captures sediment eroded from Antarctica is not well constrained (Jamieson *et al.* 2005, Wilson *et al.* 2012). Current estimates of eroded sediment, however, are not significant enough to confirm any widespread lowering of the East Antarctic landscape over time (Wilson *et al.* 2012), with a few selected sites of glacial erosion accounting for much of the sediment (Taylor *et al.* 2004). However, given the scale of potential depo-centres within the East Antarctic landmass (Fig. 4), we suggest that upland parts of the region may have been higher in the past and that significant volumes of the eroded sediment were never transported to the coast. Instead this sediment may lie in the depo-centres, where it may be acting to reduce basal friction conditions, and may contain intriguing records of past ice-sheet behaviour.

Conclusions

Using Sugden and John's (1976) subglacial-landscape classification scheme as a starting point, we have undertaken a new morphometric analysis of the ice-sheet bed of Antarctica from BEDMAP2 (Fretwell *et al.* 2013) to identify signals of alpine glacial erosion, selective linear erosion and areal scour. As well as applying the scheme to the updated bed-map, we have also extended it using quantitative and qualitative criteria. We find that:

- A low resolution morphometric analysis indicates the presence of alpine landscapes both along the coast, and isolated in the interior of East Antarctica. They are surrounded mostly by zones of selective linear erosion, but in areas where topography lies at high elevation between alpine regions, areal scour is more likely.
- The morphometric approach is limited by its reliance on a significant areal unit within which criteria can be applied. Therefore, a more speculative classification based upon the morphometric analysis but with additional qualitative criteria was produced. This relies on the assumption that both plateaus and entire alpine ranges can be selectively preserved within regions of selective linear erosion. The resulting map is a hypothesis for processes of glacial erosion under the Antarctic Ice Sheets.
- Our analysis suggests that extensive areas have 'mainly alpine' morphologies. These include well-documented coastal ranges that are partially exposed as well as significant expanses that are not fully resolved by high-density measurements in BEDMAP2. The coverage of the alpine morphology of the Gamburtsev Subglacial Mountains and the Dronning Maud Highlands is hypothesised to be significantly larger than previously identified.
- The different erosion processes are likely to reflect different phases of ice growth in Antarctica, with the preserved alpine landscapes likely older than 14 Ma. Future surveys of these regions may resolve smaller-scale features such as cirques, which may enable quantitative reconstruction of past environmental conditions such as the equilibrium line altitude of former valley glaciers.

- The dominance of selective linear erosion is proposed to represent partly the impact of continental-scale ice sheet flow that is consistent in pattern, and partly to represent the presence, between 33.7 and 14 Ma, of potentially thinner, less extensive ice in East Antarctica. Small-scale selectivity along and through coastal ranges may also be the result of regional ice masses. The importance of pre-glacial topography in steering ice flow during all phases of ice growth is suggested by the distribution of selective erosion. Flow and erosion pathways follow routes of pre-glacial drainage and tectonic structures.
- We suggest that the long-term impact of erosion, and in particular selective linear erosion, is to gradually introduce potential instability to regions of the subglacial landscape that would lie near or below sea level. Given our hypothesis for the degree to which the previous ice flow has been steered and how it has been selectively eroded, we infer that the pattern of future erosion is predictable and is defined by the existing topography.
- We anticipate that the hypotheses of landscape evolution and preservation presented here, and especially the map in Figure 8, can be tested during future radio-echo sounding surveys of the Antarctic Ice Sheet bed.

Acknowledgements

This work was supported by Natural Environmental Research Council (NERC) UK Fellowship grant NE/J018333/1 awarded to Jamieson and a Philip Leverhulme Prize awarded to Stokes. The data produced during this research are available via the Supplementary Material or upon request from the corresponding author. We thank Martin Siegert and an anonymous reviewer whose thoughtful suggestions encouraged us to ‘boost’ the manuscript in a few key areas.

References

ANDREWS, J.T. & LEMASURIER, W.E. 1973. Rates of Quaternary Glacial Erosion and Corrie Formation, Marie Byrd Land, Antarctica. *Geology,* **1**, 75-80, 10.1130/0091-7613(1973)1<75:roqgea>2.0.co;2.

ARMIENTI, P. & BARONI, C. 1999. Cenozoic climatic change in Antarctica recorded by volcanic activity and landscape evolution. *Geology,* **27**, 617-620, 10.1130/0091-7613(1999)027<0617:ccciar>2.3.co;2.

BARONI, C., NOTI, V., CICCACCI, S., RIGHINI, G. & SALVATORE, M.C. 2005. Fluvial origin of the valley system in northern Victoria Land (Antarctica) from quantitative geomorphic analysis. *Bulletin of the Geological Society of America,* **117**, 212.

Baroni, C., Fasano, F., Giorgetti, G., Salvatore, M.C. & Ribecai, C. 2008. The Ricker Hills Tillite provides evidence of Oligocene warm-based glaciation in Victoria Land, Antarctica. *Global and Planetary Change,* **60**, 457-470.

Bingham, R.G. & Siegert, M.J. 2009. Quantifying subglacial bed roughness in Antarctica: implications for ice-sheet dynamics and history. *Quaternary Science Reviews,* **28**, 223-236, 10.1016/j.quascirev.2008.10.014.

Bingham, R.G., Ferraccioli, F., King, E.C., Larter, R.D., Pritchard, H.D., Smith, A.M. & Vaughan, D.G. 2012. Inland thinning of West Antarctic Ice Sheet steered along subglacial rifts. *Nature,* **487**, 468-471, 10.1038/nature11292.

Bo, S., Siegert, M.J., Mudd, S., Sugden, D., Fujita, S., Xiangbin, C., Yunyun, J., Xueyuan, T. & Yuansheng, L. 2009. The Gamburtsev mountains and the origin and early evolution of the Antarctic Ice Sheet. *Nature,* **459**, 690-693.

Brook, E.J., Brown, E.T., Kurz, M.D., Ackert, R.P., Raisbeck, G.M. & Yiou, F. 1995. Constraints on age, erosion, and uplift of Neogene glacial deposits in the Transantarctic Mountains determined from in situ cosmogenic ^{10}Be and ^{26}Al. *Geology,* **23**, 1063-1066, 10.1130/0091-7613(1995)023<1063:coaeau>2.3.co;2.

Cook, C.P., van de Flierdt, T., Williams, T., Hemming, S.R., Iwai, M., Kobayashi, M., Jimenez-Espejo, F.J., Escutia, C., Gonzalez, J.J., Khim, B.-K., McKay, R.M., Passchier, S., Bohaty, S.M., Riesselman, C.R., Tauxe, L., Sugisaki, S., Galindo, A.L., Patterson, M.O., Sangiorgi, F., Pierce, E.L., Brinkhuis, H., Klaus, A., Fehr, A., Bendle, J.A.P., Bijl, P.K., Carr, S.A., Dunbar, R.B., Flores, J.A., Hayden, T.G., Katsuki, K., Kong, G.S., Nakai, M., Olney, M.P., Pekar, S.F., Pross, J., Rohl, U., Sakai, T., Shrivastava, P.K., Stickley, C.E., Tuo, S., Welsh, K. & Yamane, M. 2013. Dynamic behaviour of the East Antarctic ice sheet during Pliocene warmth. *Nature Geosci,* **6**, 765-769, 10.1038/ngeo1889.

Cramer, B.S., Miller, K.G., Barrett, P.J. & Wright, J.D. 2011. Late Cretaceous–Neogene trends in deep ocean temperature and continental ice volume: Reconciling records of benthic foraminiferal geochemistry (δ18O and Mg/Ca) with sea level history. *Journal of Geophysical Research: Oceans,* **116**, C12023, 10.1029/2011JC007255.

DeConto, R.M. & Pollard, D. 2003. Rapid Cenozoic glaciation of Antarctica induced by declining atmospheric CO_2. *Nature,* **421**, 245-249.

Di Nicola, L., Baroni, C., Strasky, S., Salvatore, M.C., Schlüchter, C., Akçar, N., Kubik, P.W. & Wieler, R. 2012. Multiple cosmogenic nuclides document the stability of the East Antarctic Ice Sheet in northern Victoria Land since the Late Miocene (5–7 Ma). *Quaternary Science Reviews,* **57**, 85-94, 10.1016/j.quascirev.2012.09.026.

Ehrmann, W.U. & Mackensen, A. 1992. Sedimentological evidence for the formation of an East Antarctic ice sheet in Eocene/Oligocene time. *Palaeogeography, Palaeoclimatology, Palaeoecology,* **93**, 85-112, 10.1016/0031-0182(92)90185-8.

ESRI 2012. ArcGIS 10.1. Redlands, California: Environmental Systems Research Institute.

Ferraccioli, F., Jones, P.C., Curtis, M.L. & Leat, P.T. 2005. Subglacial imprints of early Gondwana break-up as identified from high resolution aerogeophysical data over western Dronning Maud Land, East Antarctica. *Terra Nova,* **17**, 573-579, 10.1111/j.1365-3121.2005.00651.x.

Ferraccioli, F., Finn, C.A., Jordan, T.A., Bell, R.E., Anderson, L.M. & Damaske, D. 2011. East Antarctic rifting triggers uplift of the Gamburtsev Mountains. *Nature,* **479**, 388-392, 10.1038/nature10566.

Fitzgerald, P.G. & Stump, E. 1997. Cretaceous and Cenozoic episodic denudation of the Transantarctic Mountains, Antarctica: New constraints from apatite fission track thermochronology in the Scott Glacier region. *Journal of Geophysical Research-Solid Earth,* **102**, 7747-7765.

Fretwell, P., Pritchard, H.D., Vaughan, D.G., Bamber, J.L., Barrand, N.E., Bell, R., Bianchi, C., Bingham, R.G., Blankenship, D.D., Casassa, G., Catania, G., Callens, D., Conway, H., Cook, A.J., Corr, H.F.J., Damaske, D., Damm, V., Ferraccioli, F., Forsberg, R., Fujita, S., Gim, Y., Gogineni, P., Griggs, J.A., Hindmarsh, R.C.A., Holmlund, P., Holt, J.W., Jacobel, R.W., Jenkins, A., Jokat, W., Jordan, T., King, E.C., Kohler, J., Krabill, W., Riger-Kusk, M., Langley, K.A., Leitchenkov, G., Leuschen, C., Luyendyk, B.P., Matsuoka, K., Mouginot, J., Nitsche, F.O., Nogi, Y., Nost, O.A., Popov, S.V., Rignot, E., Rippin, D.M., Rivera, A., Roberts, J., Ross, N., Siegert, M.J., Smith, A.M., Steinhage, D., Studinger, M., Sun, B., Tinto, B.K., Welch, B.C., Wilson, D., Young, D.A., Xiangbin, C. & Zirizzotti, A. 2013. Bedmap2: improved ice bed, surface and thickness datasets for Antarctica. *The Cryosphere,* **7**, 375-393, 10.5194/tc-7-375-2013.

Gohl, K., Uenzelmann-Neben, G., Larter, R.D., Hillenbrand, C.-D., Hochmuth, K., Kalberg, T., Weigelt, E., Davy, B., Kuhn, G. & Nitsche, F.O. 2013. Seismic stratigraphic record of the Amundsen Sea Embayment shelf from pre-glacial to recent times: Evidence for a dynamic West Antarctic ice sheet. *Marine Geology,* **344**, 115-131, 10.1016/j.margeo.2013.06.011.

Golledge, N.R., Levy, R.H., McKay, R.M., Fogwill, C.J., White, D.A., Graham, A.G.C., Smith, J.A., Hillenbrand, C.-D., Licht, K.J., Denton, G.H., Ackert Jr, R.P., Maas, S.M. & Hall, B.L. 2013. Glaciology and geological signature of the Last Glacial Maximum Antarctic ice sheet. *Quaternary Science Reviews,* **78**, 225-247, 10.1016/j.quascirev.2013.08.011.

Goodfellow, B.W. 2007. Relict non-glacial surfaces in formerly glaciated landscapes. *Earth-Science Reviews,* **80**, 47-73, 10.1016/j.earscirev.2006.08.002.

Hambrey, M.J. & McKelvey, B. 2000. Major Neogene fluctuations of the East Antarctic ice sheet: Stratigraphic evidence from the Lambert Glacier region. *Geology,* **28**, 887-890.

Hättestrand, C. & Stroeven, A.P. 2002. A relict landscape in the centre of Fennoscandian glaciation: Geomorphological evidence of minimal Quaternary glacial erosion. *Geomorphology,* **44**, 127-143.

Holmlund, P. & Näslund, J.O. 1994. The glacially sculptured landscape in Dronning-Maud Land, Antarctica, formed by wet-based mountain-glaciation and not by the present ice-sheet. *Boreas,* **23**, 139-148.

Ivany, L.C., Van Simaeys, S., Domack, E.W. & Samson, S.D. 2006. Evidence for an earliest Oligocene ice sheet on the Antarctic Peninsula. *Geology,* **34**, 377-380.

Jamieson, S.S.R., Hulton, N.R.J., Sugden, D.E., Payne, A.J. & Taylor, J. 2005. Cenozoic landscape evolution of the Lambert basin, East Antarctica: the relative role of rivers and ice sheets. *Global and Planetary Change,* **45**, 35-49.

Jamieson, S.S.R., Hulton, N.R.J. & Hagdorn, M. 2008. Modelling landscape evolution under ice sheets. *Geomorphology,* **97**, 91-108.

Jamieson, S.S.R. & Sugden, D.E. 2008. Landscape evolution of Antarctica. *In* Cooper, A.K., Barrett, P.J., Stagg, H., Storey, B., Stump, E., Wise, W. & 10th ISAES editorial team, *eds. Antarctica: A Keystone in a Changing World - Proceedings of the 10th International Symposium on Antarctic Earth Sciences.* Washington D.C.: The National Academies Press, 39-54.

Jamieson, S.S.R., Sugden, D.E. & Hulton, N.R.J. 2010. The evolution of the subglacial landscape of Antarctica. *Earth and Planetary Science Letters,* **293**, 1-27, doi:10.1016/j.epsl.2010.02.012.

Jordan, T.A., Ferraccioli, F., Vaughan, D.G., Holt, J.W., Corr, H., Blankenship, D.D. & Diehl, T.M. 2010. Aerogravity evidence for major crustal thinning under the Pine Island Glacier region (West Antarctica). *Geological Society of America Bulletin,* **122**, 714-726, 10.1130/b26417.1.

Jordan, T.A., Ferraccioli, F., Armadillo, E. & Bozzo, E. 2013. Crustal architecture of the Wilkes Subglacial Basin in East Antarctica, as revealed from airborne gravity data. *Tectonophysics,* **585**, 196-206, 10.1016/j.tecto.2012.06.041.

Katz, M.E., Miller, K.G., Wright, J.D., Wade, B.S., Browning, J.V., Cramer, B.S. & Rosenthal, Y. 2008. Stepwise transition from the Eocene greenhouse to the Oligocene icehouse. *Nature Geosci,* **1**, 329-334, 10.1038/ngeo179.

Kerr, A. & Huybrechts, P. 1999. The response of the East Antarctic ice-sheet to the evolving tectonic configuration of the Transantarctic Mountains. *Global and Planetary Change,* **23**, 213-229.

Kessler, M.A., Anderson, R.S. & Briner, J.P. 2008. Fjord insertion into continental margins driven by topographic steering of ice. *Nature Geoscience,* **1**, 365-369.

Kleman, J. 1994. Preservation of landforms under ice sheets and ice caps. *Geomorphology,* **9**, 19-32, 10.1016/0169-555X(94)90028-0.

Kleman, J. & Stroeven, A.P. 1997. Preglacial surface remnants and Quaternary glacial regimes in northwestern Sweden. *Geomorphology,* **19**, 35-54.

Lisker, F., Brown, R. & Fabel, D. 2003. Denudational and thermal history along a transect across the Lambert Graben, northern Prince Charles Mountains, Antarctica, derived from apatite fission track thermochronology. *Tectonics,* **22**, 1055, 10.1029/2002TC001477.

Liu, Z., Pagani, M., Zinniker, D., DeConto, R., Huber, M., Brinkhuis, H., Shah, S.R., Leckie, R.M. & Pearson, A. 2009. Global cooling during the Eocene-Oligocene climate transition. *Science,* **323**.

McKay, R., Browne, G., Carter, L., Cowan, E., Dunbar, G., Krissek, L., Naish, T., Powell, R., Reed, J., Talarico, F. & Wilch, T. 2009. The stratigraphic signature of the late Cenozoic Antarctic Ice Sheets in the Ross Embayment. *Geological Society of America Bulletin,* **121**, 1537-1561, 10.1130/b26540.1.

Miller, K.G., Wright, J.D., Katz, M.E., Browning, J.V., Cramer, B.S., Wade, B.S. & Mizintseva, S.F. 2008. A view of Antarctic ice-sheet evolution from sea-level and deep-sea isotope changes during the Late Cretaceous-Cenozoic. *In* Cooper, A.K., Barrett, P., Stagg, H., Storey, B., Stump, E., Wise, W. & team, t.I.e., *eds. Antarctica: A Keystone in a Changing World - Proceedings of the 10th International Symposium on Antarctic Earth Sciences.* Washington D.C.: The National Academies Press, 55-70.

Morlighem, M., Seroussi, H., Larour, E. & Rignot, E. 2013. Inversion of basal friction in Antarctica using exact and incomplete adjoints of a higher-order model. *Journal of Geophysical Research: Earth Surface,* 1746-1753, 10.1002/jgrf.20125.

Naish, T.R., Woolfe, K.J., Barrett, P.J., Wilson, G.S., Atkins, C., Bohaty, S.M., Bucker, C.J., Claps, M., Davey, F.J., Dunbar, G.B., Dunn, A.G., Fielding, C.R., Florindo, F., Hannah, M.J., Harwood, D.M., Henrys, S.A., Krissek, L.A., Lavelle, M., van der Meer, J., McIntosh, W.C., Niessen, F., Passchier, S., Powell, R.D., Roberts, A.P., Sagnotti, L., Scherer, R.P., Strong, C.P., Talarico, F., Verosub, K.L., Villa, G., Watkins, D.K., Webb, P.N. & Wonik, T. 2001. Orbitally induced oscillations in the East Antarctic ice sheet at the Oligocene/Miocene boundary. *Nature,* **413**, 719-723.

Näslund, J.O. 1997. Subglacial preservation of valley morphology at Amundsenisen, western Dronning Maud Land, Antarctica. *Earth Surface Processes and Landforms,* **22**, 441-455.

Näslund, J.O. 2001. Landscape development in western and central Dronning Maud Land, East Antarctica. *Antarctic Science,* **13**, 302-311.

Perkins, S.F. 1984. *Subglacial landscape in Antarctica*. Unpublished thesis, University of Aberdeen.

Pusz, A.E., Thunell, R.C. & Miller, K.G. 2011. Deep water temperature, carbonate ion, and ice volume changes across the Eocene-Oligocene climate transition. *Paleoceanography,* **26**, PA2205, 10.1029/2010PA001950.

Rippin, D.M., Bamber, J.L., Siegert, M.J., Vaughan, D.G. & Corr, H.F.J. 2004. The role of ice thickness and bed properties on the dynamics of the enhanced-flow tributaries of Bailey Ice Stream and Slessor Glacier, East Antarctica. *Annals of Glaciology, Vol 39, 2005.* Annals of Glaciology, **39**, 366-372.

Rippin, D.M., Vaughan, D.G. & Corr, H.F.J. 2011. The basal roughness of Pine Island Glacier, West Antarctica. *Journal of Glaciology,* **57**, 67-76.

Rose, K.C., Ferraccioli, F., Jamieson, S.S.R., Bell, R.E., Corr, H., Creyts, T.T., Braaten, D., Jordan, T.A., Fretwell, P.T. & Damaske, D. 2013. Early East Antarctic Ice Sheet growth recorded in the landscape of the Gamburtsev Subglacial Mountains. *Earth and Planetary Science Letters,* **375**, 1-12, 10.1016/j.epsl.2013.03.053.

Ross, N., Bingham, R.G., Corr, H.F.J., Ferraccioli, F., Jordan, T.A., Le Brocq, A., Rippin, D.M., Young, D., Blankenship, D.D. & Siegert, M.J. 2012. Steep reverse bed slope at the grounding line of the Weddell Sea sector in West Antarctica. *Nature Geosci,* **5**, 393-396.

Ross, N., Jordan, T.A., Bingham, R.G., Corr, H.F.J., Ferraccioli, F., Le Brocq, A., Rippin, D.M., Wright, A.P. & Siegert, M.J. 2014. The Ellsworth Subglacial Highlands: Inception and retreat of the West Antarctic Ice Sheet. *Geological Society of America Bulletin,* **126**, 3-15, 10.1130/B30794.1.

Scambos, T.A., Haran, T.M., Fahnestock, M.A., Painter, T.H. & Bohlander, J. 2007. MODIS-based Mosaic of Antarctica (MOA) data sets: Continent-wide surface morphology and snow grain size. *Remote Sensing of Environment,* **111**, 242-257, 10.1016/j.rse.2006.12.020.

Siegert, M.J., Taylor, J. & Payne, A.J. 2005. Spectral roughness of subglacial topography and implications for former ice-sheet dynamics in East Antarctica. *Global and Planetary Change,* **45**, 249-263, 10.1016/j.gloplacha.2004.09.008.

Siegert, M.J. 2008. Antarctic subglacial topography and ice-sheet evolution. *Earth Surface Processes and Landforms,* **33**, 646-660, 10.1002/esp.1670.

Smith, A.M., Murray, T., Nicholls, K.W., Makinson, K., Aoalgeirsdottir, G., Behar, A.E. & Vaughan, D.G. 2007. Rapid erosion, drumlin formation, and changing hydrology beneath an Antarctic ice stream. *Geology,* **35**, 127-130.

Stern, T.A., Baxter, A.K. & Barrett, P.J. 2005. Isostatic rebound due to glacial erosion within the Transantarctic Mountains. *Geology,* **33**, 221.

Stokes, C.R. & Clark, C. 1999. Geomorphological criteria for identifying Pleistocene ice streams. *Annals of Glaciology,* **28**, 67-74.

Stroeven, A.P., Fabel, D., Harbor, J., Hättestrand, C. & Kleman, J. 2002. Quantifying the erosional impact of the Fennoscandian ice sheet in the Torneträsk-Narvik corridor, northern Sweden, based on cosmogenic radionuclide data. *Geografiska Annaler, Series A: Physical Geography,* **84**, 275-287.

Sugden, D. & Denton, G. 2004. Cenozoic landscape evolution of the Convoy Range to Mackay Glacier area, Transantartic Mountains: Onshore to offshore synthesis. *Bulletin of the Geological Society of America,* **116**, 840-857.

Sugden, D.E. 1974. Landscapes of glacial erosion in Greenland and their relationship to ice, topographic and bedrock conditions. *In* Waters, R.S. & Brown, E.H., *eds. Progress in Geomorphology.* Institute of British Geographers Special Publication, **7**, London: Institute of British Geographers, 177-195.

Sugden, D.E. 1976. A case against deep erosion of shields by ice sheets. *Geology,* **4**, 580-582, 10.1130/0091-7613(1976)4<580:acadeo>2.0.co;2.

Sugden, D.E. & John, B.S. 1976. *Glaciers and Landscape*. Edward Arnold, 376 pp.

Sugden, D.E. 1978. Glacial erosion by the Laurentide ice sheet. *Journal of Glaciology,* **20**, 367-391.

Sugden, D.E. 1989. Modification of old land surfaces by ice sheets. *Zeitschrift fur Geomorphologie, Supplementband,* **72**, 163-172.

Sugden, D.E. 1996. The East Antarctic ice sheet: unstable ice or unstable ideas? *Transactions - Institute of British Geographers,* **21**, 443-454.

Sugden, D.E., Balco, G., Cowdery, S.G., Stone, J.O. & Sass Iii, L.C. 2005. Selective glacial erosion and weathering zones in the coastal mountains of Marie Byrd Land, Antarctica. *Geomorphology,* **67**, 317-334.

Sugden, D.E., Bentley, M.J. & Ó Cofaigh, C. 2006. Geological and geomorphological insights into Antarctic ice sheet evolution. *Philosophical Transactions of the Royal Society A,* **364**, 1607-1625.

Taylor, J., Siegert, M.J., Payne, A.J., Hambrey, M.J., O'Brien, P.E., Cooper, A.K. & Leitchenkov, G. 2004. Topographic controls on post-Oligocene changes in ice-sheet dynamics, Prydz Bay region, East Antarctica. *Geology,* **32**, 197-200.

Thomas, R.H. 1979. The dynamics of marine ice sheets. *Journal of Glaciology,* **24**, 167-177.

Thomson, S.N., Reiners, P.W., Hemming, S.R. & Gehrels, G.E. 2013. The contribution of glacial erosion to shaping the hidden landscape of East Antarctica. *Nature Geosci,* **6**, 203-207, 10.1038/ngeo1722.

Tochilin, C.J., Reiners, P.W., Thomson, S.N., Gehrels, G.E., Hemming, S.R. & Pierce, E.L. 2012. Erosional history of the Prydz Bay sector of East Antarctica from detrital apatite and zircon geo- and thermochronology multidating. *Geochemistry, Geophysics, Geosystems,* **13**, Q11015, 10.1029/2012gc004364.

USGS 2010. Global Multi-resolution Terrain Elevation Data (GMTED2010). **2013**, 27th September 2013: United States Geological Survey.

van de Flierdt, T., Hemming, S.R., Goldstein, S.L., Gehrels, G.E. & Cox, S.E. 2008. Evidence against a young volcanic origin of the Gamburtsev Subglacial Mountains, Antarctica. *Geophysical Research Letters,* **35**, L21303, 10.1029/2008GL035564.

Van Liefferinge, B. & Pattyn, F. 2013. Using ice-flow models to evaluate potential sites of million year-old ice in Antarctica. *Clim. Past Discuss.,* **9**, 2859-2887, 10.5194/cpd-9-2859-2013.

Webb, P.N., Harwood, D.M., Mabin, M.G.C. & McKelvey, B.C. 1996. A marine and terrestrial Sirius group succession, middle Beardmore glacier Queen Alexandra range, Transantarctic mountains, Antarctica. *Marine Micropaleontology,* **27**, 273-297.

Wilson, D.S., Jamieson, S.S.R., Barrett, P.J., Leitchenkov, G., Gohl, K. & Larter, R.D. 2012. Antarctic Topography at the Eocene-Oligocene Boundary. *Palaeogeography, Palaeoclimatology, Palaeoecology,* **335-336**, 24-34.

Wilson, D.S., Pollard, D., DeConto, R.M., Jamieson, S.S.R. & Luyendyk, B.P. 2013. Initiation of the West Antarctic Ice Sheet and estimates of total Antarctic ice volume in the earliest Oligocene. *Geophysical Research Letters,* 4305-4309, 10.1002/grl.50797.

Wood, J. 2005. Landserf - http://www.soi.city.ac.uk/~jwo/landserf/.

Young, D.A., Wright, A.P., Roberts, J.L., Warner, R.C., Young, N.W., Greenbaum, J.S., Schroeder, D.M., Holt, J.W., Sugden, D.E., Blankenship, D.D., van Ommen, T.D. & Siegert, M.J. 2011. A dynamic early East Antarctic Ice Sheet suggested by ice-covered fjord landscapes. *Nature,* **474**, 72-75, 10.1038/nature10114.

Description of Supplemental Material

There are 2 files containing supplementary material. The first, 'JamiesonEtAlBEDMAP2r.zip', contains Supplementary Dataset 1. The second, 'JamiesonEtAlSupplementaryMaterial.pdf' contains supplementary Figure S1 and supplementary table S1. These are all described below and are also available via the corresponding author.

Supplementary Dataset 1: The rebounded bed topography of Antarctica (BEDMAP2r). The dataset is compressed into a .zip file and when 'unzipped' is in an ASCII format compatible with ArcGIS. The projection of the dataset is identical to that of BEDMAP2 (Fretwell *et al.* 2013): polar stereographic with scale correct at 71 °S and a WGS84 spheroid. There are 6381 columns and 5201 rows in the dataset which has a lower left corner coordinate, in meters, of -3190000.5, -2650000.5. The resolution is 1,000 m and areas of no data are recorded using the value -9999. Therefore, the first data row has a y coordinate of 2550000.5 m and lists elevation values in meters from x = -3190000.5 to x= 3190000.5 m. The last record similarly lists elevation values for y = -2650000.5 m.

Supplementary Figure S1: The index for subdivisions used during the morphometric analysis of Antarctica. The map shows the analysis boxes and their ID numbers which correspond to the 'Box ID' in Supplementary Table S1.

Supplementary Table S1: Morphometric data for each box subdivision of BEDMAP2r. The Box ID is illustrated in Figure S1. The column containing '# of peaks > 1km' is a count of the number of peaks that sit 250 m proud of any surrounding landscape within the 250 x 250 km study box.

Supplementary Material

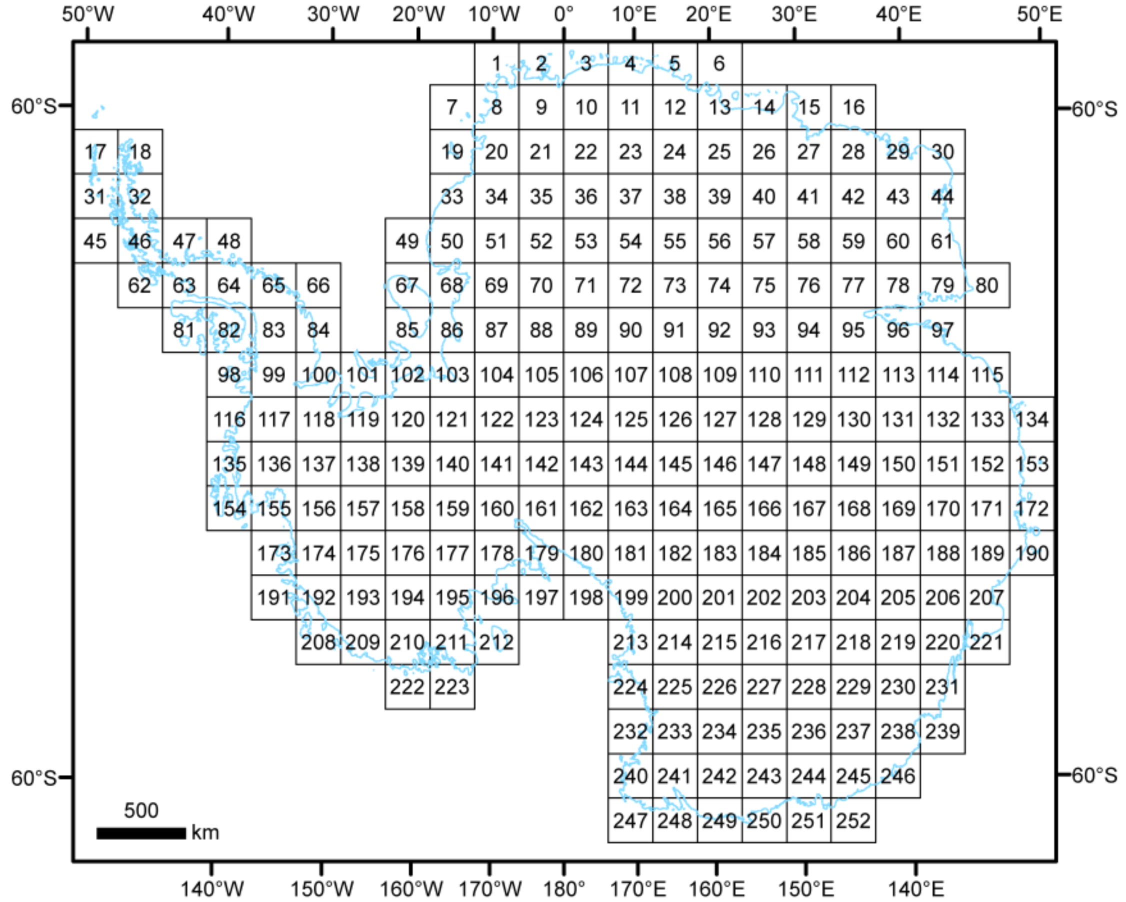

Figure S1: The index for subdivisions used during the morphometric analysis of Antarctica. The map shows the analysis boxes and their ID numbers which correspond to the 'Box ID' in Supplementary Table S1. The MOA grounding line is shown in light blue for orientation (Scambos *et al.* 2007).

Box ID	Mean elevation	Max elevation	Relief	Mean elevation	HI	Min slope	Max slope	Mean slope	Slope range	Kurtosis	Skewness	# of peaks > 1km
1	-416.0	144.0	560.0	-127.3	0.5	0.0	3.9	1.0	3.9	-0.1	1.1	0
2	-942.0	1162.0	2104.0	-93.6	0.4	0.0	18.6	2.2	18.6	1.1	1.5	1
3	-458.0	1629.0	2087.0	-0.8	0.2	0.0	11.2	1.3	11.2	2.1	1.8	1
4	-1140.0	1462.0	2602.0	-27.2	0.4	0.0	21.0	2.0	21.0	1.0	1.4	5
5	-888.0	478.0	1366.0	-293.0	0.4	0.0	6.5	1.2	6.5	-0.2	1.1	0
6	-323.0	-33.0	290.0	-112.5	0.7	0.0	1.8	0.8	1.8	0.8	1.2	0
7	-385.0	-84.0	301.0	-178.7	0.7	0.0	2.4	0.9	2.4	0.4	1.2	0
8	-925.0	1495.0	2420.0	120.2	0.4	0.0	22.5	1.6	22.5	1.4	1.3	1
9	-1364.0	2836.0	4200.0	935.8	0.5	0.0	27.9	4.1	27.9	-1.2	0.5	44
10	-94.0	2973.0	3067.0	1497.6	0.5	0.0	31.3	3.1	31.3	0.6	1.2	37
11	-167.0	3200.0	3367.0	1648.8	0.5	0.0	29.9	3.6	29.9	-0.7	0.9	41
12	-572.0	2824.0	3396.0	931.9	0.4	0.0	20.4	2.2	20.4	-0.3	0.7	24
13	-978.0	2916.0	3894.0	278.9	0.3	0.0	27.9	2.5	27.9	6.8	2.5	17

14	-513.0	752.0	1265.0	55.4	0.4	0.0	5.3	1.0	5.3	-1.3	-0.5	0
15	-546.0	680.0	1226.0	-4.4	0.4	0.0	6.1	1.2	6.1	-0.5	0.1	0
16	-91.0	666.0	757.0	279.5	0.5	0.0	6.3	1.6	6.3	0.6	1.4	0
17	-111.0	933.0	1044.0	197.5	0.3	0.0	8.0	2.4	8.0	-1.2	0.8	0
18	-302.0	1304.0	1606.0	245.9	0.3	0.0	13.4	3.1	13.4	-0.2	1.0	2
19	-713.0	178.0	891.0	-173.3	0.6	0.1	5.0	1.5	4.9	-1.1	0.6	0
20	-719.0	2878.0	3597.0	498.4	0.3	0.0	26.7	2.5	26.7	0.0	0.9	15
21	149.0	3062.0	2913.0	1172.7	0.4	0.0	19.4	2.4	19.4	-1.0	0.7	21
22	149.0	1871.0	1722.0	1164.6	0.6	0.0	8.8	1.6	8.8	-1.5	0.5	14
23	642.0	1996.0	1354.0	1296.6	0.5	0.0	6.5	1.6	6.5	-1.4	0.2	15
24	884.0	2488.0	1604.0	1592.7	0.4	0.0	6.6	0.9	6.6	0.8	1.3	5
25	-637.0	2915.0	3552.0	1524.3	0.6	0.0	20.2	1.8	20.2	0.2	0.9	11
26	-93.0	2648.0	2741.0	1093.3	0.4	0.0	25.0	1.5	25.0	-0.5	0.5	10
27	-919.0	1672.0	2591.0	609.7	0.6	0.0	14.8	1.6	14.8	-0.8	0.8	9
28	-285.0	1951.0	2236.0	712.8	0.4	0.0	7.9	1.8	7.9	-0.9	0.5	13
29	-988.0	1804.0	2792.0	424.1	0.5	0.0	22.7	2.8	22.7	-0.8	0.6	8
30	-522.0	2160.0	2682.0	564.4	0.4	0.0	24.1	2.9	24.1	-1.2	0.1	8
31	-252.0	1592.0	1844.0	387.6	0.3	0.0	15.6	3.5	15.6	0.3	1.2	3
32	-448.0	2059.0	2507.0	698.3	0.5	0.0	23.5	4.9	23.5	-0.4	0.3	3
33	-532.0	1187.0	1719.0	350.2	0.5	0.0	5.6	1.2	5.6	0.0	0.9	3
34	-980.0	1555.0	2535.0	490.4	0.6	0.0	7.9	1.6	7.9	0.2	0.9	13
35	-475.0	1586.0	2061.0	373.5	0.4	0.0	8.7	1.1	8.7	-0.1	0.9	6
36	119.0	1556.0	1437.0	903.8	0.5	0.0	5.7	0.7	5.7	-0.1	1.0	5
37	614.0	1855.0	1241.0	1152.6	0.4	0.0	6.2	0.6	6.2	1.5	1.6	2
38	899.0	2441.0	1542.0	1548.2	0.4	0.0	5.8	0.9	5.8	-1.6	0.2	4
39	949.0	2352.0	1403.0	1642.9	0.5	0.0	5.9	1.0	5.9	-1.1	0.5	11
40	875.0	2295.0	1420.0	1621.6	0.5	0.0	6.2	1.1	6.2	-1.0	0.5	11
41	319.0	2074.0	1755.0	1143.2	0.5	0.0	5.7	1.1	5.7	-1.1	0.4	9
42	82.0	1949.0	1867.0	1039.9	0.5	0.0	7.9	1.4	7.9	0.6	1.2	12
43	-22.0	2567.0	2589.0	1219.0	0.5	0.0	26.6	1.9	26.6	0.6	1.3	30
44	-725.0	2228.0	2953.0	543.6	0.4	0.0	23.9	2.6	23.9	0.2	1.0	13
45	-128.0	1373.0	1501.0	355.4	0.3	0.1	13.7	2.5	13.6	0.8	1.1	0
46	-804.0	1972.0	2776.0	814.4	0.6	0.0	30.2	4.9	30.2	-1.0	-0.4	18
47	-701.0	1579.0	2280.0	391.0	0.5	0.0	27.5	4.6	27.5	-0.3	0.6	1
48	-318.0	1427.0	1745.0	254.6	0.3	0.0	13.9	2.7	13.9	5.1	2.2	1
49	-398.0	480.0	878.0	39.7	0.5	0.0	6.0	1.7	6.0	-0.2	0.8	0
50	-1367.0	1509.0	2876.0	97.5	0.5	0.0	27.5	1.5	27.5	4.4	1.8	5
51	-1854.0	1298.0	3152.0	117.9	0.6	0.0	8.4	1.4	8.4	0.7	1.3	2
52	-412.0	1717.0	2129.0	455.9	0.4	0.0	9.0	1.3	9.0	0.8	1.2	3
53	135.0	1177.0	1042.0	774.7	0.6	0.0	3.4	0.4	3.4	0.6	1.1	0
54	592.0	1607.0	1015.0	1091.1	0.5	0.0	3.1	0.3	3.1	1.5	1.5	1
55	836.0	2632.0	1796.0	1394.9	0.3	0.0	6.2	0.8	6.2	0.6	1.4	5
56	983.0	2495.0	1512.0	1701.4	0.5	0.0	6.8	1.2	6.8	0.6	1.2	13
57	797.0	2362.0	1565.0	1332.8	0.3	0.0	5.7	1.0	5.7	-0.6	0.9	8
58	465.0	2204.0	1739.0	1298.2	0.5	0.0	7.3	1.1	7.3	-1.1	0.5	8
59	398.0	1909.0	1511.0	1046.2	0.4	0.0	6.0	1.1	6.0	-0.5	0.6	10

60	193.0	2350.0	2157.0	1194.4	0.5	0.0	8.6	1.5	8.6	0.5	1.2	12
61	-583.0	2130.0	2713.0	565.3	0.4	0.0	16.7	2.1	16.7	-0.8	0.7	20
62	-335.0	1566.0	1901.0	351.3	0.4	0.0	18.7	4.2	18.7	-0.3	0.7	6
63	-941.0	2767.0	3708.0	804.6	0.5	0.0	33.8	5.9	33.8	-1.8	0.1	49
64	-985.0	2593.0	3578.0	856.0	0.5	0.0	30.3	5.0	30.3	-1.4	0.2	87
65	-788.0	2096.0	2884.0	917.3	0.6	0.0	28.1	4.2	28.0	-0.1	0.8	35
66	-828.0	996.0	1824.0	63.5	0.5	0.1	11.9	2.9	11.8	0.7	1.5	0
67	-706.0	195.0	901.0	-129.5	0.6	0.0	5.9	0.7	5.9	-0.4	0.7	0
68	-1788.0	1391.0	3179.0	-486.8	0.4	0.0	28.8	2.3	28.8	-0.9	0.9	0
69	-1945.0	2052.0	3997.0	166.1	0.5	0.0	34.5	2.7	34.5	5.7	2.1	35
70	-971.0	1798.0	2769.0	308.3	0.5	0.0	6.0	1.0	6.0	0.2	0.9	2
71	-136.0	1180.0	1316.0	513.2	0.5	0.0	6.5	0.6	6.5	-0.6	0.4	0
72	-51.0	2206.0	2257.0	1140.8	0.5	0.0	5.8	0.6	5.8	2.6	1.9	4
73	600.0	2227.0	1627.0	1360.2	0.5	0.0	5.6	0.8	5.6	-1.1	0.3	6
74	430.0	2509.0	2079.0	1316.4	0.4	0.0	7.6	1.0	7.6	-1.2	0.4	7
75	367.0	1926.0	1559.0	1176.0	0.5	0.0	6.9	0.8	6.9	-0.8	0.8	5
76	-220.0	2329.0	2549.0	1183.6	0.6	0.0	9.6	1.5	9.6	-0.7	0.9	12
77	-1200.0	2562.0	3762.0	847.0	0.5	0.0	34.2	2.8	34.2	-0.5	0.8	31
78	-785.0	2439.0	3224.0	822.3	0.5	0.0	26.2	3.3	26.2	-0.8	0.3	41
79	-684.0	2309.0	2993.0	258.0	0.3	0.0	24.8	1.9	24.8	6.5	2.7	13
80	-294.0	72.0	366.0	-91.6	0.6	0.1	2.7	0.8	2.6	-0.2	0.9	0
81	-728.0	2430.0	3158.0	207.0	0.3	0.0	30.9	3.3	30.9	9.4	3.0	3
82	-464.0	1765.0	2229.0	105.5	0.3	0.0	22.1	2.9	22.1	2.8	2.0	6
83	-787.0	2505.0	3292.0	682.0	0.4	0.0	26.5	3.2	26.5	-0.8	0.6	54
84	-680.0	1714.0	2394.0	597.0	0.5	0.0	22.2	4.3	22.2	-0.8	-0.7	17
85	-799.0	121.0	920.0	-306.1	0.5	0.0	3.9	0.6	3.9	1.8	1.5	0
86	-1444.0	1309.0	2753.0	-25.8	0.5	0.0	14.9	1.7	14.9	3.3	1.8	3
87	-184.0	1452.0	1636.0	751.0	0.6	0.0	5.7	0.4	5.7	5.5	2.4	1
88	459.0	1062.0	603.0	774.6	0.5	0.0	1.4	0.3	1.4	0.3	1.0	0
89	-303.0	1450.0	1753.0	602.0	0.5	0.0	6.8	0.5	6.8	-0.4	0.9	2
90	-44.0	2099.0	2143.0	1210.3	0.6	0.0	7.8	0.8	7.8	2.5	1.8	8
91	749.0	2172.0	1423.0	1492.7	0.5	0.0	6.0	0.8	6.0	0.0	1.0	8
92	395.0	2544.0	2149.0	1272.1	0.4	0.0	7.4	0.8	7.4	1.7	1.7	5
93	-42.0	2374.0	2416.0	1305.6	0.6	0.0	7.6	1.3	7.6	-0.1	0.8	14
94	-566.0	2441.0	3007.0	942.2	0.5	0.0	11.2	3.1	11.2	-0.6	0.3	33
95	-1894.0	2070.0	3964.0	300.1	0.6	0.0	35.2	3.3	35.2	0.0	1.0	12
96	-985.0	2141.0	3126.0	321.9	0.4	0.0	24.6	2.0	24.6	4.5	2.2	4
97	-553.0	931.0	1484.0	319.7	0.6	0.0	15.9	1.3	15.9	5.5	2.4	0
98	-587.0	950.0	1537.0	67.9	0.4	0.0	8.0	1.3	8.0	10.2	3.0	0
99	-1969.0	1728.0	3697.0	-166.9	0.5	0.0	27.4	3.2	27.3	2.9	1.7	26
100	-1616.0	1422.0	3038.0	-292.7	0.4	0.0	20.3	2.1	20.3	1.0	1.3	2
101	-900.0	35.0	935.0	-379.0	0.6	0.0	5.3	1.1	5.3	-0.3	0.0	0
102	-1466.0	-275.0	1191.0	-809.8	0.6	0.0	4.1	0.6	4.1	6.8	2.5	0
103	-1870.0	2245.0	4115.0	-30.6	0.4	0.0	23.8	3.3	23.8	-1.0	0.3	28
104	-760.0	1956.0	2716.0	343.7	0.4	0.0	9.3	0.9	9.3	0.3	1.0	3
105	-106.0	1296.0	1402.0	688.7	0.6	0.0	5.7	0.4	5.7	3.2	1.8	0

106	-86.0	2031.0	2117.0	864.0	0.4	0.0	6.3	0.6	6.3	-0.9	0.9	2
107	166.0	2135.0	1969.0	1199.6	0.5	0.0	7.0	1.1	7.0	-1.3	0.3	4
108	765.0	3179.0	2414.0	1626.9	0.4	0.0	7.4	1.1	7.4	3.6	1.9	9
109	560.0	3293.0	2733.0	1779.2	0.4	0.0	8.4	1.9	8.4	0.5	1.3	19
110	393.0	3223.0	2830.0	1993.4	0.6	0.0	10.1	2.5	10.1	-1.2	0.5	24
111	-684.0	2937.0	3621.0	873.6	0.4	0.0	12.2	3.1	12.1	-1.6	0.1	22
112	-370.0	2050.0	2420.0	1156.1	0.6	0.0	8.0	0.9	8.0	5.8	2.4	4
113	370.0	2637.0	2267.0	1100.7	0.3	0.0	27.3	0.8	27.3	4.2	2.4	5
114	-137.0	1667.0	1804.0	764.7	0.5	0.0	6.5	1.3	6.5	-0.8	0.5	8
115	-763.0	1198.0	1961.0	228.4	0.5	0.0	6.3	1.2	6.3	1.4	1.5	2
116	-714.0	578.0	1292.0	-8.5	0.5	0.0	6.7	1.3	6.7	-1.2	0.5	0
117	-1919.0	614.0	2533.0	-250.8	0.7	0.0	8.8	1.7	8.8	-0.3	1.0	0
118	-2045.0	3961.0	6006.0	-121.0	0.3	0.0	32.3	3.7	32.3	-0.3	0.9	9
119	-1358.0	4193.0	5551.0	488.1	0.3	0.0	29.9	3.8	29.9	-0.9	0.7	24
120	-1511.0	2672.0	4183.0	-290.6	0.3	0.0	18.1	2.3	18.1	-1.3	0.6	5
121	-1277.0	2475.0	3752.0	65.3	0.4	0.0	24.5	2.3	24.5	1.9	1.6	10
122	-418.0	2301.0	2719.0	797.1	0.4	0.0	15.8	1.8	15.8	-0.6	0.6	11
123	-156.0	1536.0	1692.0	713.5	0.5	0.0	5.3	0.8	5.3	4.2	1.8	4
124	-367.0	2046.0	2413.0	771.7	0.5	0.0	6.9	1.3	6.9	-0.6	0.7	6
125	240.0	1663.0	1423.0	991.3	0.5	0.0	4.7	0.8	4.7	-0.1	0.9	1
126	839.0	3095.0	2256.0	1512.6	0.3	0.0	7.7	1.8	7.7	-0.3	1.0	10
127	822.0	3339.0	2517.0	1977.8	0.5	0.0	8.6	2.8	8.6	-1.1	0.5	22
128	731.0	3199.0	2468.0	1915.3	0.5	0.0	7.6	2.2	7.6	-1.2	-0.1	13
129	-300.0	2296.0	2596.0	1312.5	0.6	0.0	10.4	1.1	10.4	11.6	3.1	11
130	1111.0	1479.0	368.0	1308.0	0.5	0.0	0.9	0.1	0.9	2.1	1.7	0
131	384.0	1904.0	1520.0	1076.2	0.5	0.0	6.7	0.6	6.7	1.1	1.6	5
132	275.0	1279.0	1004.0	820.7	0.5	0.0	4.0	0.3	4.0	0.3	1.1	0
133	-961.0	1234.0	2195.0	256.5	0.6	0.0	7.1	0.8	7.1	-1.4	0.3	1
134	-736.0	328.0	1064.0	-161.7	0.5	0.0	6.5	1.1	6.5	-0.9	0.3	0
135	-676.0	1818.0	2494.0	83.6	0.3	0.0	16.8	1.8	16.8	0.5	1.3	3
136	-1219.0	1106.0	2325.0	-266.8	0.4	0.0	15.3	1.6	15.3	-0.7	0.7	1
137	-1544.0	1106.0	2650.0	-459.0	0.4	0.0	9.9	1.8	9.9	-1.0	0.7	0
138	-1382.0	2671.0	4053.0	138.6	0.4	0.0	11.9	2.6	11.9	-0.9	0.3	17
139	-694.0	2975.0	3669.0	592.4	0.4	0.0	19.3	2.3	19.3	-0.5	1.0	12
140	-727.0	3055.0	3782.0	815.4	0.4	0.0	22.2	3.1	22.2	-1.1	0.6	27
141	-79.0	2556.0	2635.0	1253.4	0.5	0.0	18.3	1.6	18.3	-1.0	0.7	12
142	239.0	3132.0	2893.0	1306.9	0.4	0.0	18.9	1.5	18.9	-1.5	0.5	10
143	490.0	2025.0	1535.0	1077.8	0.4	0.0	6.6	0.9	6.6	1.2	1.5	6
144	510.0	1287.0	777.0	826.3	0.4	0.0	4.3	0.4	4.3	-0.1	1.1	2
145	368.0	2257.0	1889.0	1107.6	0.4	0.0	8.8	0.7	8.8	2.5	1.7	5
146	384.0	2234.0	1850.0	1346.3	0.5	0.0	5.5	1.1	5.5	0.3	1.1	6
147	464.0	2647.0	2183.0	1592.2	0.5	0.0	6.0	1.2	6.0	-1.3	0.5	9
148	477.0	2532.0	2055.0	1523.9	0.5	0.0	7.9	1.5	7.9	-0.5	1.0	12
149	686.0	2307.0	1621.0	1273.7	0.4	0.0	6.3	0.5	6.3	15.2	3.9	5
150	495.0	2172.0	1677.0	1157.8	0.4	0.0	6.5	0.9	6.5	3.0	1.9	7
151	50.0	2247.0	2197.0	976.7	0.4	0.0	7.2	0.9	7.2	6.6	2.6	8

152	-159.0	1681.0	1840.0	686.8	0.5	0.0	5.4	0.6	5.4	-1.2	-0.1	1
153	-417.0	665.0	1082.0	-14.2	0.4	0.0	4.7	0.9	4.7	-1.1	0.7	0
154	-647.0	793.0	1440.0	-11.6	0.4	0.0	11.4	1.8	11.4	-0.5	1.0	0
155	-1000.0	851.0	1851.0	-200.5	0.4	0.0	16.2	1.9	16.2	-1.2	0.5	0
156	-1348.0	412.0	1760.0	-631.8	0.4	0.0	8.6	1.5	8.6	-0.4	0.9	0
157	-1483.0	1062.0	2545.0	-401.1	0.4	0.0	9.2	2.2	9.2	-0.7	0.8	1
158	-1715.0	1331.0	3046.0	-119.3	0.5	0.0	8.5	1.8	8.5	1.6	1.5	1
159	-1452.0	2397.0	3849.0	-244.2	0.3	0.0	16.6	2.2	16.5	0.6	1.3	0
160	-1448.0	3406.0	4854.0	218.7	0.3	0.0	22.2	2.9	22.2	6.1	2.3	49
161	-773.0	3800.0	4573.0	1507.0	0.5	0.0	22.8	3.5	22.8	2.1	1.7	91
162	788.0	3221.0	2433.0	1566.2	0.3	0.0	19.0	1.3	19.0	-1.4	0.3	20
163	-87.0	1573.0	1660.0	820.0	0.5	0.0	4.7	0.5	4.7	7.0	2.7	1
164	182.0	1774.0	1592.0	901.4	0.5	0.0	4.9	0.6	4.9	-0.1	1.1	1
165	554.0	2189.0	1635.0	1247.9	0.4	0.0	6.6	0.9	6.6	0.5	1.2	5
166	-313.0	2393.0	2706.0	1150.7	0.5	0.0	7.2	1.0	7.2	2.0	1.8	4
167	-403.0	2241.0	2644.0	1015.6	0.5	0.0	8.5	1.5	8.5	1.1	1.5	7
168	338.0	1647.0	1309.0	1040.8	0.5	0.0	5.0	0.7	5.0	1.1	1.4	3
169	101.0	1701.0	1600.0	939.9	0.5	0.0	4.6	0.5	4.6	0.0	1.0	2
170	-84.0	1683.0	1767.0	654.2	0.4	0.0	6.6	0.6	6.6	-0.3	0.7	2
171	-1193.0	1890.0	3083.0	454.8	0.5	0.0	19.1	1.6	19.1	-1.4	0.3	13
172	-1382.0	517.0	1899.0	-83.1	0.7	0.0	11.6	1.3	11.6	-0.6	1.0	0
173	-903.0	1633.0	2536.0	-52.7	0.3	0.0	18.2	2.6	18.1	-0.5	1.0	0
174	-1716.0	3682.0	5398.0	-109.2	0.3	0.0	27.8	3.9	27.8	-0.3	1.1	7
175	-910.0	1375.0	2285.0	-59.5	0.4	0.0	10.7	2.3	10.7	0.3	1.1	3
176	-931.0	890.0	1821.0	-187.1	0.4	0.0	6.9	1.5	6.9	-0.9	0.8	0
177	-860.0	195.0	1055.0	-375.2	0.5	0.0	4.9	0.9	4.9	0.9	1.1	0
178	-962.0	-108.0	854.0	-407.7	0.6	0.0	3.2	0.4	3.2	-1.2	0.5	0
179	-777.0	3759.0	4536.0	161.6	0.2	0.0	24.1	3.4	24.1	21.5	4.6	57
180	-983.0	3942.0	4925.0	1449.6	0.5	0.0	28.0	6.1	28.0	3.5	1.7	193
181	310.0	3411.0	3101.0	1136.9	0.3	0.0	23.7	1.5	23.7	1.1	1.6	29
182	70.0	1559.0	1489.0	783.8	0.5	0.0	7.6	0.9	7.6	-1.2	0.2	4
183	428.0	1359.0	931.0	858.6	0.5	0.0	3.4	0.4	3.4	0.3	1.1	1
184	327.0	2105.0	1778.0	838.2	0.3	0.0	3.7	0.5	3.7	2.7	1.7	1
185	-226.0	1384.0	1610.0	745.2	0.6	0.0	6.3	0.6	6.3	-0.6	0.7	0
186	-140.0	1400.0	1540.0	427.1	0.4	0.0	5.3	0.7	5.3	0.3	1.1	2
187	-680.0	1633.0	2313.0	209.2	0.4	0.0	8.4	1.1	8.4	0.2	1.1	2
188	-748.0	1628.0	2376.0	410.2	0.5	0.0	8.0	1.4	8.0	0.6	1.0	4
189	-672.0	1880.0	2552.0	547.9	0.5	0.0	7.4	1.1	7.4	-1.6	0.2	4
190	-294.0	448.0	742.0	226.1	0.7	0.0	3.4	0.7	3.4	2.5	1.3	0
191	-454.0	262.0	716.0	-175.5	0.4	0.0	5.2	1.6	5.2	-0.9	0.4	0
192	-838.0	2538.0	3376.0	188.2	0.3	0.0	9.1	1.7	9.1	-0.6	1.0	3
193	-435.0	3878.0	4313.0	840.8	0.3	0.0	18.3	2.0	18.3	6.5	2.5	15
194	-980.0	994.0	1974.0	1.1	0.5	0.0	7.5	1.0	7.5	-0.8	0.0	0
195	-863.0	105.0	968.0	-362.2	0.5	0.0	5.5	0.8	5.5	-0.1	0.6	0
196	-585.0	-28.0	557.0	-287.3	0.5	0.0	2.9	0.4	2.9	-0.4	0.9	0
197	-392.0	-179.0	213.0	-327.0	0.3	0.0	1.6	0.6	1.6	0.0	1.0	0

198	-789.0	2309.0	3098.0	347.4	0.4	0.1	19.1	6.9	19.1	-1.4	0.4	5
199	-2563.0	3001.0	5564.0	759.2	0.6	0.0	31.7	4.7	31.7	0.1	1.2	133
200	26.0	1182.0	1156.0	530.8	0.4	0.0	7.1	1.0	7.1	-0.8	0.7	1
201	151.0	1163.0	1012.0	623.0	0.5	0.0	5.6	0.6	5.6	0.4	0.6	0
202	-85.0	1967.0	2052.0	938.9	0.5	0.0	7.4	1.1	7.4	-1.1	0.3	5
203	-3.0	1705.0	1708.0	765.5	0.4	0.0	8.4	1.2	8.4	-0.4	0.7	7
204	-20.0	1567.0	1587.0	658.2	0.4	0.0	6.4	0.9	6.4	-1.3	-0.2	4
205	-386.0	1495.0	1881.0	425.5	0.4	0.0	5.9	1.1	5.9	2.5	1.8	2
206	-550.0	1201.0	1751.0	272.0	0.5	0.0	6.6	1.2	6.6	-0.2	1.0	2
207	-1772.0	1006.0	2778.0	31.8	0.6	0.0	9.9	2.0	9.9	3.3	1.8	1
208	-479.0	2193.0	2672.0	62.5	0.2	0.0	8.5	2.3	8.5	2.8	2.0	1
209	-1319.0	3107.0	4426.0	419.4	0.4	0.0	29.8	2.4	29.8	-0.4	1.0	16
210	-838.0	1524.0	2362.0	419.6	0.5	0.0	20.3	3.3	20.3	-1.5	-0.3	34
211	-905.0	1133.0	2038.0	-43.3	0.4	0.0	12.5	2.4	12.5	-0.4	0.8	1
212	-568.0	120.0	688.0	-198.4	0.5	0.0	2.7	0.6	2.7	5.3	2.4	0
213	-511.0	3173.0	3684.0	1059.1	0.4	0.0	28.5	5.0	28.5	-1.6	0.1	50
214	204.0	1904.0	1700.0	700.1	0.3	0.0	7.9	1.3	7.9	-0.8	0.8	9
215	-98.0	1356.0	1454.0	453.9	0.4	0.0	5.1	0.8	5.1	0.2	1.1	0
216	-425.0	1858.0	2283.0	745.1	0.5	0.0	6.4	1.2	6.3	0.3	1.2	7
217	-177.0	1962.0	2139.0	750.6	0.4	0.0	8.6	1.2	8.6	0.8	1.0	4
218	166.0	1606.0	1440.0	737.5	0.4	0.0	5.7	0.8	5.7	0.1	0.9	5
219	-125.0	1036.0	1161.0	413.7	0.5	0.0	5.1	0.7	5.1	-1.0	0.8	0
220	-1973.0	802.0	2775.0	-11.3	0.7	0.0	7.8	1.3	7.8	2.0	1.7	0
221	-1852.0	809.0	2661.0	52.5	0.7	0.0	11.8	1.5	11.8	1.2	1.5	0
222	-438.0	555.0	993.0	-130.4	0.3	0.0	9.2	1.6	9.2	-0.4	1.0	0
223	-406.0	288.0	694.0	-78.8	0.5	0.0	4.7	1.4	4.7	-1.2	0.4	0
224	-407.0	2685.0	3092.0	934.8	0.4	0.0	28.0	5.1	28.0	-1.2	-0.5	31
225	-71.0	2380.0	2451.0	884.6	0.4	0.0	33.5	2.3	33.5	-1.1	0.5	37
226	-81.0	983.0	1064.0	330.7	0.4	0.0	4.7	0.7	4.7	-1.1	0.7	0
227	-175.0	1589.0	1764.0	546.6	0.4	0.0	6.3	0.8	6.3	-1.1	0.5	2
228	-201.0	1986.0	2187.0	938.5	0.5	0.0	8.5	1.1	8.5	1.5	1.6	8
229	-379.0	1624.0	2003.0	811.1	0.6	0.0	7.4	1.4	7.4	-1.3	0.4	11
230	-611.0	1309.0	1920.0	475.3	0.6	0.0	7.2	1.0	7.2	1.8	1.7	4
231	-934.0	809.0	1743.0	208.8	0.7	0.0	6.8	1.1	6.8	2.1	1.6	0
232	-1098.0	2913.0	4011.0	760.7	0.5	0.0	34.6	7.1	34.6	-1.1	0.4	12
233	-516.0	3649.0	4165.0	823.5	0.3	0.0	40.3	3.4	40.3	1.4	1.6	41
234	-494.0	1037.0	1531.0	302.8	0.5	0.0	7.2	1.2	7.2	-0.7	0.8	1
235	-821.0	1250.0	2071.0	124.2	0.5	0.0	6.5	1.2	6.5	1.1	1.4	1
236	-1142.0	1432.0	2574.0	470.8	0.6	0.0	8.1	1.4	8.1	-0.5	0.8	5
237	-1278.0	1860.0	3138.0	517.1	0.6	0.0	8.2	1.5	8.2	-0.3	0.7	8
238	-803.0	1260.0	2063.0	256.4	0.5	0.0	7.2	1.1	7.2	-1.3	0.4	0
239	-525.0	552.0	1077.0	-15.3	0.5	0.0	8.3	1.6	8.3	0.4	0.7	0
240	-878.0	3366.0	4244.0	1263.2	0.5	0.0	42.0	8.6	41.9	-1.6	0.0	146
241	-1007.0	2952.0	3959.0	942.2	0.5	0.0	30.6	6.0	30.6	-1.2	0.4	146
242	-1143.0	1640.0	2783.0	196.3	0.5	0.0	8.0	1.3	8.0	0.7	1.5	1
243	-1538.0	744.0	2282.0	-207.2	0.6	0.0	6.9	1.5	6.9	-1.4	0.3	0

244	-1168.0	1378.0	2546.0	245.5	0.6	0.0	8.0	1.3	8.0	0.2	0.9	1
245	-678.0	1124.0	1802.0	373.5	0.6	0.0	8.5	1.1	8.5	-0.1	1.1	3
246	-821.0	589.0	1410.0	108.3	0.7	0.0	7.4	1.4	7.4	-0.5	0.7	0
247	-746.0	1879.0	2625.0	378.1	0.4	0.0	23.9	7.3	23.9	-0.6	0.8	17
248	-1187.0	2282.0	3469.0	407.1	0.5	0.0	26.4	5.5	26.4	0.2	1.0	24
249	-699.0	1855.0	2554.0	321.5	0.4	0.0	20.6	3.1	20.6	-1.4	0.2	36
250	-1475.0	605.0	2080.0	-289.6	0.6	0.0	11.1	1.6	11.1	0.1	0.7	0
251	-586.0	590.0	1176.0	19.7	0.5	0.0	13.7	1.7	13.7	-1.3	0.4	0
252	-493.0	289.0	782.0	80.1	0.7	0.0	6.3	1.1	6.3	0.7	1.4	0

Supplementary Table S1: Morphometric data for each box subdivision of BEDMAP2r. The Box ID is illustrated in Figure S1. The column containing ‘# of peaks > 1km’ is a count of the number of peaks that sit 250 m proud of any surrounding landscape within the 250 x 250 km study box.

References

SCAMBOS, T.A., HARAN, T.M., FAHNESTOCK, M.A., PAINTER, T.H. & BOHLANDER, J. 2007. MODIS-based Mosaic of Antarctica (MOA) data sets: Continent-wide surface morphology and snow grain size. *Remote Sensing of Environment,* **111**, 242-257, http://dx.doi.org/10.1016/j.rse.2006.12.020.