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## Geology

### A temperate former West Antarctic ice sheet suggested by an extensive zone of subglacial meltwater channels

Kathryn C. Rose, Neil Ross, Robert G. Bingham, Hugh F.J. Corr, Fausto Ferraccioli, Tom A. Jordan, Anne M. Le Brocq, David M. Rippin and Martin J. Siegert

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#### Notes

# A temperate former West Antarctic ice sheet suggested by an extensive zone of subglacial meltwater channels

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## ABSTRACT

Several recent studies predict that the West Antarctic Ice Sheet will become increasingly unstable under warmer conditions. Insights on such change can be assisted through investigations of the subglacial landscape, which contains imprints of former ice-sheet behavior. Here, we present radio-echo sounding data and satellite imagery revealing a series of ancient large sub-parallel subglacial bed channels preserved in the region between the Möller and Foundation Ice Streams, West Antarctica. We suggest that these newly recognized channels were formed by significant meltwater routed along the ice-sheet bed. The volume of water required is likely substantial and can most easily be explained by water generated at the ice surface. The Greenland Ice Sheet today exemplifies how significant seasonal surface melt can be transferred to the bed via englacial routing. For West Antarctica, the Pliocene (2.6–5.3 Ma) represents the most recent sustained period when temperatures could have been high enough to generate surface melt comparable to that of present-day Greenland. We propose, therefore, that a temperate ice sheet covered this location during Pliocene warm periods.

## INTRODUCTION

The marine-based West Antarctic Ice Sheet (WAIS) is considered highly susceptible to ocean and climate warming (Pritchard et al., 2012; Joughin et al., 2014), experiencing numerous oscillations since its formation (Naish et al., 2009). In order to assess the extent to which past changes to the WAIS are representative of its future behavior, it is important to understand the glaciological processes involved in those changes. Central to this is an appreciation of climate and ice-flow regimes, in particular the manner in which former ice sheets responded to a warmer climate. Greenland today provides useful examples of surface melting (Mote, 2007) influencing ice flow (Shepherd et al., 2009; Bartholomew et al., 2010, 2011).

Geomorphological analyses of subglacial topography have played a key role in reconstructing the nature of former ice masses in Antarctica (Young et al., 2011), as landscape evolution can be linked to glacial processes (Sugden and John, 1976, p.192–209). While radio-echo sounding (RES) is the primary tool used to map topography beneath modern ice sheets (Fretwell et al., 2013), satellite imagery of the ice surface has been shown to provide insights where RES is unavailable (Ross et al., 2014). Using this combination of data sets, we have identified a series of large (kilometer-scale), linear subglacial features, which we interpret as preserved, ancient subglacial meltwater channels. We assess the geometry of these channels in the context of their geographic location and the present-day hydrological setting of the ice sheet. We then infer the mechanism for their formation and suggest the most recent time at which this may have occurred, based on the climatic conditions required to support substantial, sustained subglacial meltwater routing at the ice-sheet bed. Our findings

have implications for the processes driving former ice-sheet oscillations and the response of the WAIS to warmer climatic conditions.

## METHODS

Mapping of the bed topography across the study area is derived from a detailed RES survey of the Institute and Möller Ice Streams and Bedmap2 (Fretwell et al., 2013; Ross et al., 2014). The former data set was acquired using a coherent system with a 12 MHz bandwidth and 150 MHz carrier frequency (Ross et al., 2012), providing an ~10 m along-track sampling interval. Differential GPS, with a horizontal accuracy of ~5 cm, was used for positioning and to determine the elevation of the ice-sheet surface. Bed elevations were calculated by subtracting ice thickness measurements from ice surface elevations. In combination with Bedmap2, data were then rendered onto a 1-km-grid mesh, using the Topo to Raster function in ArcGIS (<http://www.esri.com/software/arcgis>; see the GSA Data Repository<sup>1</sup>).

The Moderate-Resolution Imaging Spectroradiometer (MODIS) Mosaic of Antarctica was used to examine the ice-sheet surface (Haran et al., 2005 [updated 2013]). Brightness variations in the image radiometry produce a detailed picture of the morphology of the ice-sheet surface (see the Data Repository), which was used to map surface features and provide information on subglacial topography.

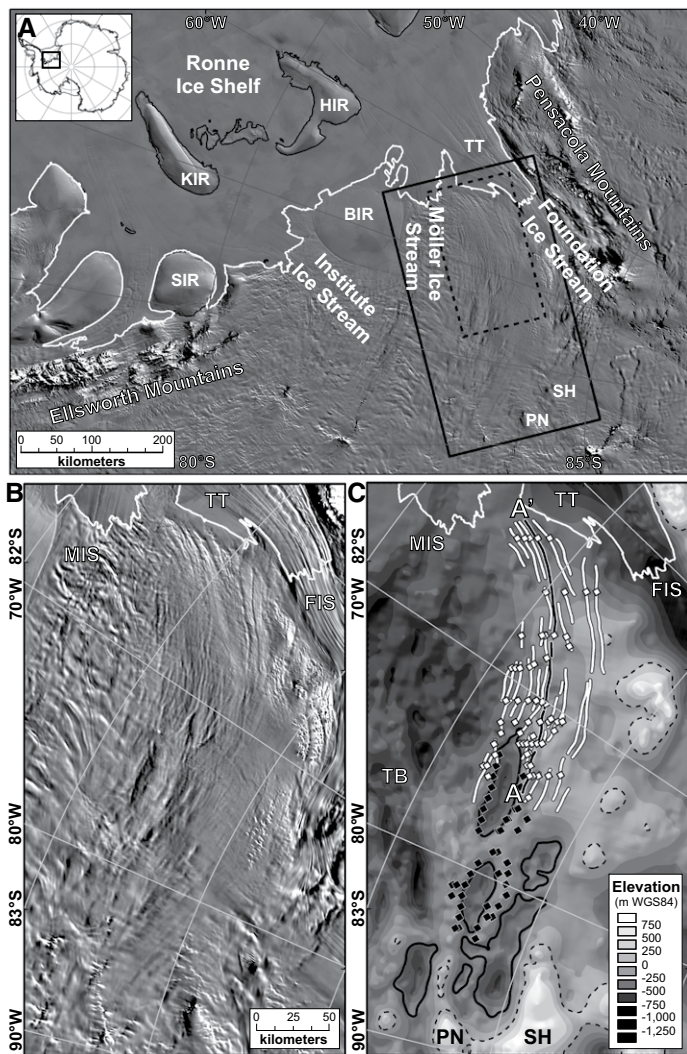
## RESULTS

RES data and satellite imagery reveal preserved, major subglacial channels incised into subglacial topography in the region between the Möller and Foundation Ice Streams (MIS and FIS, respectively) in West Antarctica (Fig. 1; Figs. DR1 and DR2 in the Data Repository). Topography in this region is characterized by hills and valleys, predominantly lies below sea level (mean of –585 m, range of –700 to 300 m), and marks the geological boundary between West and East Antarctica (Jordan et al., 2013). In the upper MIS catchment, there are six elongate subglacial basins, known as the Marginal Basins (Fig. 1C). The boundaries of these basins are associated with magnetic lineaments and Jurassic intrusions, some of which form nunataks (Jordan et al., 2013). The channels are located adjacent to these basins, beneath presently slow-flowing (<10 m yr<sup>-1</sup>; Rignot et al., 2011), thin (≤1 km) and therefore cold-based (non-erosive) ice, providing appropriate conditions under which basal topographic features may be preserved (Sugden and John, 1976, p.192–209) and visible in surface imagery (Ross et al., 2014).

RES data show that channel cross-profiles are broad (average width of 2.6 km) and relatively shallow (average depth of 158.9 m), with an average elevation of –623 m (Figs. 2A–2D; Table DR1 in the Data Repository).

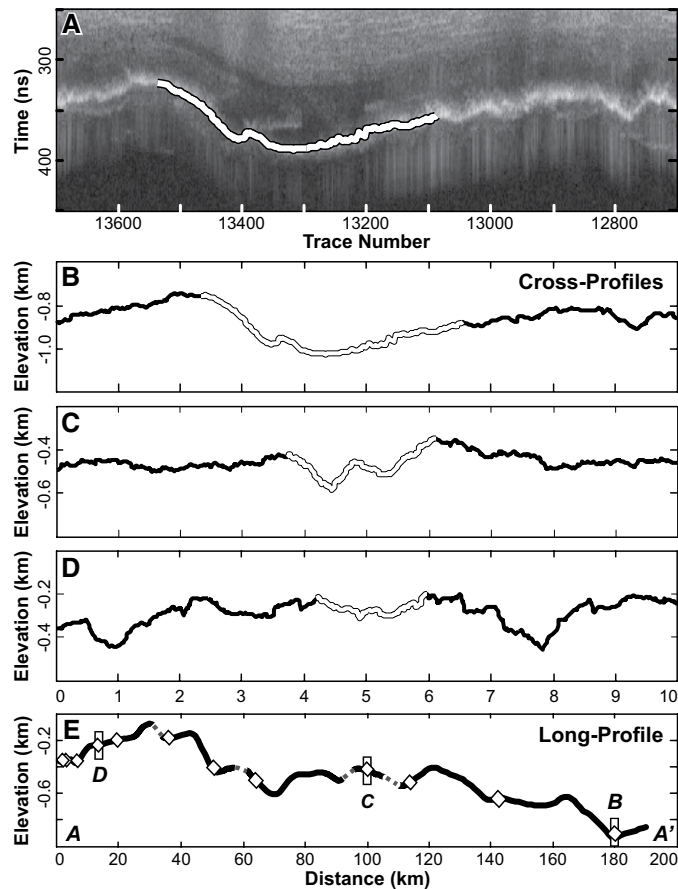
<sup>1</sup>GSA Data Repository item 2014343, methods, Table DR1 (example channel cross-profile dimensions) and Figures DR1–DR6, is available online at [www.geosociety.org/pubs/ft2014.htm](http://www.geosociety.org/pubs/ft2014.htm), or on request from [editing@geosociety.org](mailto:editing@geosociety.org) or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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**Figure 1.** A: Moderate Resolution Imaging Spectroradiometer (MODIS) Mosaic of Antarctica satellite imagery showing location of study area within the inner Weddell Sea embayment, West Antarctica. Black box marks extent of B and C. Dashed black box is examined in Figs. DR2 and DR4 (see footnote 1). B: Linear surface features identified in MODIS imagery. C: Subglacial topography overlain with channel locations (white lines) observed in MODIS imagery (in B) on bed topography. Among these channels, the black line (A-A') marks the channel long-profile plotted in Figure 2E. White diamonds identify subglacial channels that are visible in both MODIS imagery and radio-echo sounding (RES) data. Black diamonds mark channels only visible in RES data. Black dashed line is the 0 m elevation contour. Solid black lines are the Marginal Basins (–650 m contour). BIR—Bungenstock Ice Rise; FIS—Foundation Ice Stream; HIR—Henry Ice Rise; KIR—Korff Ice Rise; MIS—Möller Ice Stream; PN—Pagano Nunatak; SIR—Skytrain Ice Rise; SH—Stewart Hills; TB—Transitional Basins; TT—Thiel Trough.

In MODIS imagery (Haran et al., 2005 [updated 2013]), the underlying channels are expressed as linear features in the ice-sheet surface (Fig. 1B), in regions where ice velocities fall below  $10 \text{ m yr}^{-1}$  (Rignot et al., 2011; Fig. DR3). We mapped 32 linear to sinuous channels, oriented independently of ice surface slope (Fig. 1C). The channels are evident as far as ~200 km inland from the grounding line, but are discontinuous in the satellite imagery, with average segment lengths of 42 km (Fig. DR4A). Over short (~5 km) distances, however, it is reasonable to extrapolate across the data gap with confidence so that, in some instances, combinations of segments can be classified as single channels (see the Data Repository



**Figure 2.** Long- and cross-profiles from an example channel network. A: Example radar echogram showing the cross-profile plotted in B. B–D: Channel cross-profiles derived from flight-line data (vertical exaggeration of ~1.5 $\times$ ). White segments mark interpreted channel width along the black line, which records bed elevation. Cross-profile locations correspond with white horizontal lines shown in Fig. DR4A (see footnote 1). Cross-profiles are displayed looking downstream toward the grounding line (i.e., Möller Ice Stream on left, Foundation Ice Stream on right). E: Long-profile of channel floor elevations (vertical exaggeration of 1:25 $\times$ ) (Fig. 1C, black line A-A'). Vertical boxes mark locations of cross-profiles in B–D. White diamonds show intersections with flight-line data.

text, and Fig. DR4B). Channel-floor long-profiles reveal an irregular form, with several “reverse” (i.e., upstream/inland dipping) sections (Fig. 2E; Fig. DR5). Overall, the persistence and coincidence of both surface and bed features between flight lines, and their consistent orientation, indicate that they are associated and continuous.

## DISCUSSION

### Channel Formation

Several lines of evidence suggest that the channels observed were formed subglacially. Crucially, the channels are located well below sea level, even if the topography is rebounded to account for the removal of the modern ice-sheet load (Fig. 2; Figs. DR2 and DR5), thus precluding a pre-glacial fluvial origin. The formation of individual, straight channel segments in bedrock, often in a sub-parallel arrangement, is typically associated with subglacial meltwater erosion, where the primary control on channel formation is ice movement (“ice-directed channels”; Sugden and John, 1976, p. 304). Furthermore, the channels track over present-day reverse slopes, across the subglacial upland, and toward the modern grounding line, forming an “up-and-down” profile (Fig. 2E). This is par-



ticularly indicative of a subglacial fluvial origin, whereby pressurized flow under ice can drive water over subglacial obstacles (Sugden and John, 1976, p. 308). Indeed, we find evidence from RES data for water driven over topographic highlands in Antarctica today (Wright et al., 2014). Second, the broad, shallow channel cross-profiles observed (Fig. 2) are indicative of meltwater cross-profiles, which are commonly many times wider than they are deep, rather than the parabolic or U-shaped forms typically associated with glacial erosion by ice (Sugden and John, 1976, p. 178). At the margins of Antarctica, similar-scale, linear channels incised in bedrock have been found and are associated with erosion by abundant volumes of meltwater (Nitsche et al., 2013, and references therein).

### Subglacial Meltwater Source

Geothermal heating and/or subglacial frictional melting are insufficient to generate the magnitude of meltwater required to erode the scale of channels observed (Nitsche et al., 2013). Wingham et al. (2006) identified, from satellite observations of discrete ice-sheet surface elevation changes, a 1.8 km<sup>3</sup> water pulse issued from an East Antarctic lake and routed >200 km at the bed. Lewis et al. (2006) suggested that similar discharges in the past may have formed the channelized landscape of the Labyrinth, in the Wright Dry Valley, Antarctica. We note that no substantial subglacial lake is presently observed upstream of the channels, despite technological advances that have allowed most (if not all) of the largest Antarctic subglacial lakes to be identified (Wright and Siegert, 2012). Nonetheless, we cannot discount the possibility that the enclosed Marginal Basins (Fig. 1C), which are ~22 km across and just over 800 m deep, may have formed subglacial lakes in the past. Indeed, the coupled orientation and proximity of the channels to the lakes suggests that the two are likely related. However, the channels are evidence of an abundance of basal water, more than is likely from subglacial lake discharges alone. This is because, irrespective of the volume of stored basal water, the physical mechanism of lake drainage self-regulates water outputs, so that lakes may only drain a small proportion of their total volume before the drop in water level reduces pressure at the lake outlet and causes the ice above to draw down and reseal (Fowler, 2009). Thus, while subglacial lake filling and episodic drainage may have occurred as an interrelated component of the subglacial hydrological system, a continuous and significant meltwater input is required to drive channel formation. We suggest, therefore, that the channels result from significant meltwater inputs to the bed from the ice surface, as the simplest explanation.

In a setting analogous to present-day Greenland (Bartholomew et al., 2011), for example, seasonal surface meltwater generation (Mote, 2007) can provide the intermittent, large pulses of meltwater required for this scale of channel formation over time (Schoof, 2010; Cowton et al., 2012). Formation of subglacial channels is likely to occur in association with enhanced ice-flow units, such as ice streams and outlet glaciers (Bartholomew et al., 2010). We note that in such regions of the Greenland Ice Sheet, surface melt rates, surface slopes, and ice-flow velocities are too high (Bamber et al., 2013) to retain a surface expression of subglacial channels, thus explaining their apparent absence in Greenland Ice Sheet surface imagery. However, as ice velocities are low across the studied region of the WAIS today, a surface expression of these channels has developed (Rignot et al., 2011).

### Timing and Process of Channel Formation

We consider that channel development under present-day Antarctic ice-sheet conditions is not possible for six reasons.

(1) The channel orientations are not consistent with today's ice-surface contours (Fretwell et al., 2013) and, thus, the hydrological potential pathways for the region (Le Brocq et al., 2013) (see the Data Repository text, and Fig. DR6). Instead, channel orientation indicates that they formed under a different ice-sheet configuration and have since been preserved. During their formation, meltwater, and presumably ice flow,

drained toward the Thiel Trough (Fig. 1C; Fig. DR6). We have confidence that the locations of modeled pathways under present ice-sheet conditions are robust, given that they correspond with active meltwater outlets at the grounding line (Le Brocq et al., 2013).

(2) As we see no RES evidence for water in the channels (Fig. DR1) and the overlying ice is thin (<1 km), we believe that the ice sheet is frozen to the bed today.

(3) The inference of cold-based conditions is supported by the low ice velocities (2–10 m yr<sup>-1</sup>) in this region (Rignot et al., 2011). If large quantities of meltwater were present, we might expect higher velocities and/or more dynamic ice flow. However, the majority of present-day ice flow (and the direction of hydraulic potential pathways) is focused along the MIS and FIS, which flank the channelized region (Figs. DR3 and DR6).

(4) There is no obvious source for subglacial water in the region today (Wright and Siegert, 2012). Antarctica is characterized by a polar desert climate where (with the exception of the Antarctic Peninsula and other coastal regions with ice shelves) surface melt rates are predominantly very low (<25 mm w.e. [water equivalent] yr<sup>-1</sup>) (Trusel et al., 2013). Therefore, under present conditions, any surface melt that is produced refreezes. Although subglacial meltwater may be produced at pressure under thick (>2 km) ice, such thicknesses are not recorded here, and in the absence of a large subglacial lake, irrespective of the likely drainage mechanism, the quantity of stored water at the bed today is insufficient to erode channels of the scale observed.

(5) There is no indication of a significant, active, meltwater outlet corresponding to the location of the channels at the grounding line (Le Brocq et al., 2013).

(6) ICESat (Ice, Cloud, and Land Elevation Satellite) shows no evidence for ice surface elevation change associated with these channels (Smith et al., 2009), as might be expected if subglacial lake drainage were occurring (Wingham et al., 2006).

Consequently, we believe that supraglacial meltwater is the most likely driver of basal channel formation (Cowton et al., 2012).

The process of large-scale surface melting, leading to englacial transfer of water and basal flow (Shepherd et al., 2009; Bartholomew et al., 2011), requires temperate climate conditions. In such a setting, ice-sheet fluctuations are more equally controlled by a combination of atmospheric and oceanic changes, rather than the ocean-driven variations that dominate Antarctica today (Pritchard et al., 2012). Over the past 50 m.y., the world has experienced substantial global cooling, interspersed with marked periods of high warmth (Zachos et al., 2008). Of these warm periods, the Miocene (23–5.3 Ma) and, most recently, the Pliocene (5.3–2.6 Ma) are the most likely times in which surface ice-sheet melting was possible. While interglacials (e.g., marine isotope stage 11) are also warmer than today, they are likely cooler than these periods and relatively short in duration (on the order of thousands of years). In the Miocene, although the climate was adequately warm, the WAIS may not have been sufficiently well developed for large-scale grounded ice to form at this location for long periods (DeConto and Pollard, 2003). This, therefore, leaves the Pliocene as the most recent opportunity for the WAIS to have experienced Greenland-style behavior over a sustained time period.

During this period, global temperatures were generally 2–3 °C warmer (Dowsett, 2007) and sea level was, at times, up to 22 ± 10 m higher than present, implying a reduction in the size of both West and East Antarctic Ice Sheets (Miller et al., 2012). Indicative of such behavior, offshore sediments record fluctuations in WAIS extent. In particular, an early Pliocene 60-m-thick bed of diatomite in the ANDRILL (Antarctic Geological Drilling; <http://www.andrill.org>) core shows that the Ross Ice Shelf (and likely the West Antarctic Ice Sheet) disappeared for a period of over 200,000 yr and several glacial cycles (Naish et al., 2009, p. 323). Similarly, dynamic change is recorded at the margins of the East Antarctic Ice Sheet (EAIS) (Cook et al., 2013). Recent models of ice volume change for the late Pliocene–early Pleistocene have attributed this EAIS

behavior to summer melting at the ice-sheet margin (Raymo et al., 2006). Using glaciological and sea-level studies, the mass balance of the EAIS was shown to be comparable to that of today's Greenland Ice Sheet, where mean annual surface temperatures of  $-2^{\circ}\text{C}$  to  $-8^{\circ}\text{C}$  can accommodate ablation via both calving and summer surface melt (Raymo et al., 2006, their figure 3). Consequently, it follows that the WAIS would be subject to the same principles of summer insolation-driven surface melt and mass-balance processes. This suggests that the raised global temperatures of the Pliocene were capable of allowing meltwater to form and pond seasonally at the WAIS surface. This, in turn, indicates that the WAIS was characterized by temperate ice-sheet conditions during this time. In a setting similar to today's Greenland Ice Sheet, surface meltwater could have thereby reached the subglacial environment via englacial routing (Bartholomew et al., 2011) to erode the subglacial meltwater channels observed (Cowton et al., 2012). Importantly, we note that the channels are located  $>500$  m below sea level today and would remain below sea level even with the removal of the modern ice-sheet load (Fig. DR2). Consequently, the temperate ice sheet responsible for their formation must have been marine based, at least in the study region (noting that we cannot extrapolate to the whole of the WAIS).

## CONCLUSIONS

Using a combination of RES data and satellite imagery we have identified a series of subglacial meltwater channels incised into the bed between the Möller and Foundation Ice Streams, West Antarctica. We envisage that these channels formed under temperate ice-sheet conditions, when large volumes of supraglacial water was routed to the bed, whereupon it was driven by ice overburden to the margin, forming and further incising the channels by fluvial erosion. The most recent time when sustained surface melting could have taken place in Antarctica is the Pliocene. If this interpretation is correct, it means that ice was still present (at least periodically) in this location during the Pliocene and, potentially, the Miocene.

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