nature geoscience

ARTICLES

PUBLISHED ONLINE: 20 JULY 2009 | DOI: 10.1038/NGEO581

# Formation of mega-scale glacial lineations observed beneath a West Antarctic ice stream

E. C. King[1]*, R. C. A. Hindmarsh[1] and C. R. Stokes[2]

**Most discharge from large ice sheets takes place through fast-flowing ice streams and their speed is strongly modulated by interactions between the ice and the underlying sediments. Seismic surveys and investigations through boreholes have revealed a spatial association between fast ice flow and saturated deformable sediments. Nevertheless, our knowledge of the morphology of the interface between ice and sediments is still limited, resulting in only rudimentary understanding of the basal boundary conditions beneath ice streams and the generation of subglacial bedforms. Here we present radar data from the bed of a West Antarctic ice stream that reveal the presence of mega-scale glacial lineations. We combine these data with previously published seismic data and show that these lineations develop in areas of dilatant deforming till and are part of a dynamic sedimentary system that undergoes significant change by erosion and deposition on decadal timescales. We find that the mega-scale glacial lineations are indistinguishable from those found on beds of palaeo-ice streams, providing conclusive evidence for the hypothesis that highly elongate bedforms are a characteristic of fast-flow regions in ice sheets.**

Rapidly flowing ice streams dominate the mass balance and stability of continental ice sheets and much effort has focused on elucidating the conditions at the ice–bed interface that promote their rapid flow. Initial radio-echo sounding[1] suggested that Antarctic ice streams were characterized by high basal melt rates compared with the adjacent slow-flowing ridges. Subsequent seismic experiments beneath one ice stream indicated 5–6 m of deforming subglacial till with high porewater pressure[2,3], which was later confirmed by borehole investigation[4]. This led to the idea that ice streaming may be dependent on a soft, water-saturated, deformable bed that offers minimal frictional resistance[5]. However, both the strength of the bed and subglacial water pressure have been shown to vary under individual ice streams, suggesting that their motion results from a combination of both till deformation and basal sliding, modulated by changes in the subglacial water system and the resistance from localized 'sticky spots'[6,7].

Understanding basal processes under ice streams requires improved knowledge of both the composition of subglacial sediments and their spatial organization. Previous data[8,9] comprise sparsely distributed seismic lines that provide limited information about the three-dimensional appearance of the ice–sediment interface across large areas. Two seismic lines on Whillans Ice Stream[8] suggested the presence of flutes in the base of the till aligned parallel to flow, whereas geophysical observations from Rutford Ice Stream revealed elongate bedforms associated with active erosion, deposition and hydrological processes[10,11]. Meanwhile, much work has focused on the exposed beds of palaeo-ice streams[12], resulting in the untested hypothesis that fast ice flow produces highly elongate bedforms, known as mega-scale glacial lineations[13–15] (MSGLs). Their genesis is the subject of conflicting hypotheses[13,16,17] and, until now, their presence under active ice streams has been purely conjectural owing to the lack of observations at sufficient resolution.

## Ice stream bed morphology from radar data

We conducted a radio-echo sounding survey of Rutford Ice Stream in an area where the surface flow speed is about 375 $\mathrm{M\,yr^{-1}}$ (Fig. 1). The equipment was a 3 MHz mono-pulse ground radar, with a pulse repetition rate of 1 kHz and a digitization period of 10 ns. The ice thickness was determined at 7.5 m intervals along track and the values interpolated onto a 50 m grid. The data are shown in Fig. 2, converted to bed elevations with a vertical resolution of $\pm 3$ m (based on timing resolution of 10 ns and estimated system timing and picking accuracies). The mean ice-surface elevation in the survey area is 300 m above geoid. The profile of the bed perpendicular to ice flow is shaped like a 'W', with a central ridge at 1,800 m below geoid and flanking troughs at 2,100 m below. Downstream of our survey area, there is a prominent knoll on the central ridge that rises about 300 m above the mean. A smoothing filter was applied to remove the low spatial-frequency trend from the bed elevation to isolate the fine detail (Fig. 3a). The data shown in Figs 2 and 3 are at a comparable resolution to typical marine swath bathymetry data that reveal subglacial bedforms on palaeo-ice stream beds around Antarctica[14,18].

The detrended basal topography (Fig. 3a) shows an alternating pattern of ridges and troughs with wavelengths transverse to flow of 300–1,000 m. Peak-to-trough amplitudes range from 5 to 90 m with a mean of 10 m. The longest features extend for $>18$ km and have elongation (length/width) ratios from 15:1 to $>35$:1, placing them in the class of MSGLs (ref. 13). Some of the MSGLs have well-defined upstream initiation points, including the most prominent ridge, which corresponds to the feature labelled as 'The Bump' in previous seismic surveys[9,10]. Repetition of these surveys over decadal timescales[10] detected high sediment transport rates and bedform evolution/growth at the downstream end of what we now know is a MSGL. The most clearly defined initiation points have a streamlined stoss face and over-deepenings in the adjacent troughs.

## Ice stream bed properties from seismic data

Repeated seismic surveys have been conducted within our radar grid area[10,11] and reveal two important characteristics: the subglacial sediment has bimodal geotechnical properties and is highly mobile. The acoustic impedance and polarity of the seismic waves reflected from the bed show that water-saturated, dilatant till of varying thickness (Fig. 3d) overlies, unconformably, a stiff,

[1]British Antarctic Survey, Madingley Road, Cambridge CB3 0ET, UK, [2]Department of Geography, Durham University, Durham DH1 3LE, UK.
*e-mail: ecki@bas.ac.uk.

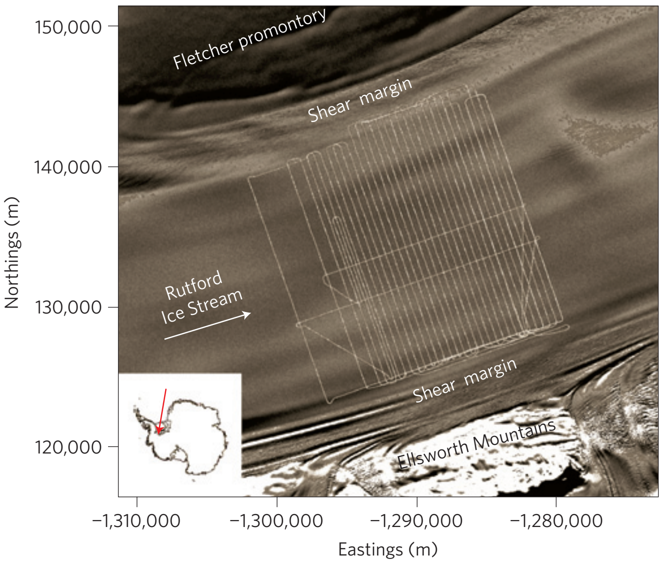


**Figure 1 | Location map for radar survey.** Landsat image of the radar survey on Rutford Ice Stream, West Antarctica. The white arrow indicates ice flow direction. The lines were oriented orthogonal to the flow with 500 m spacing. The image is a polar stereographic projection, north is to the left and the grid interval is 10 km. Inset: Location of Rutford Ice Stream within Antarctica.

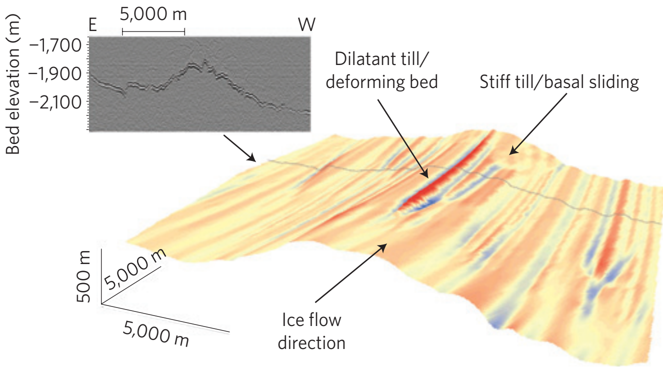


**Figure 2 | Radar results.** Top: Three-dimensional image of the bed of Rutford Ice Stream viewed from the northeast, looking in the downstream direction. The colour shading is based on the difference between the short-wavelength topography and a long-wavelength trend surface. Highly elongate bedforms known as MSGLs dominate the topography. Bottom: Example radar profile. Data processing comprised band-pass filtering, spherical-divergence correction and two-dimensional migration.

overconsolidated, lodgement till that locally outcrops at the ice–sediment interface. One of the seismic lines was repeated twice, which showed that one 500-m-wide section of the bed was eroded by 6 m in six years. Subsequently, a 100-m-wide, 10-m-high bedform was deposited within a period of seven years. Data recorded by passive seismometers[19] showed that more microseismic events originated in the area underlain by stiff till, whereas the area underlain by dilatant till was seismically quiet. This indicates that the sliding of ice across the surface of the stiff till generates seismic events, whereas few seismic events arise where movement is accommodated by continuous, pervasive deformation of the dilatant till[19]. Thus, although low effective pressures and dilatant till can lead to basal sliding across the till surface[6], this scenario seems very unlikely under Rutford Ice Stream. Significantly, our new data reveal that the basal sliding zones coincide with areas of the bed that have a more subdued topography with fewer and poorly streamlined bedforms (labelled stiff till/basal sliding in Fig. 2), contrasting with the zones of highly elongate, streamlined bedforms elsewhere.

Both horizontal and vertical gradients in porosity might be expected to result from similarly directed gradients in effective pressure and subglacial water pressure[20], but the seismic data (Fig. 3) clearly indicate a binary distribution of subglacial sediment types based on acoustic impedance[9–11]. It is possible that such gradients are below the seismic resolution, but the simplest interpretation is that where the acoustic impedance of the basal till is low, it must have high porosity, low density and low shear strength[3] and the zone of maximum shear induced by the ice stream motion is located within the sediment. Very simple mechanical arguments[20] show that the thickness of dilatant till is related to the effective pressure, and we infer that it is this, rather than till porosity, that reflects trends in the effective pressure.

## Ice stream bed properties from radar data

The power of the radar bed reflection is plotted in Fig. 3c. The 'brightest' reflections coincide with the crests of the MSGLs in the central part of the survey, whereas the reflections are relatively 'dim' where the MSGLs are absent and over MSGLs in the flanking troughs. In the discussion that follows, we assume that high-amplitude radar reflections from the bed indicate free water in some form (for example, ref. 21); that is, 'bright' indicates water of sufficient thickness (>0.04 m) to be detectable at the ice–bed interface.

The radar bed reflection power is high where previous seismic data[11] show that the dilatant till is present but thin; and is low where the dilatant till is either absent or thick (Fig. 3c,d). This suggests that there is more water at the ice–till interface in the thin areas of dilatant till. Conversely, the thick areas of soft sediment and the basal outcrop of stiff till have little or no free water at the ice–bed interface, resulting in low bed reflection power. Lateral bed slopes are an order of magnitude greater than ice surface slopes, making it difficult to quantify hydraulic pathways, and determine whether water is flowing parallel or transverse to the MSGLs, and thus relate brightness return to water flow patterns. We observe that the thick layer of dilatant/soft till in the northeast and southwest troughs either side of the central ridge (Fig. 3d) is continuous downstream (based on seismic data for the northeast trough[22]), whereas on the central ridge the dilatant till pinches out against the basal outcrop of stiff till. In particular, the free water does not seem to be localized within cavities at the lee ends of the MSGLs. The presence of free water where the dilatant till is pinching out might be explained by changes in the hydraulic pathways, or might equally arise perhaps from collapse of the dilatant deforming till into stiff till and the expulsion of the water. The presence of stiff till at the highest point on the central ridge most likely reflects an increase in effective pressure due to freeze-on induced by cooling ice above a topographic rise and the hydrostatic increase of effective pressure with elevation, possibly facilitated by weak hydraulic gradients at a meltwater drainage divide along the ridge[20,23].

One important implication of the bed reflection data, therefore, is that the development of individual MSGLs and the distribution of a free-water layer at the bed are independent of each other. However, seismically observed changes in till properties clearly show that sediment porosity, water content and water pressure can change over significant areas on short (<10 year) timescales[10]. Thus, both the shape and the physical properties of the bed (including MSGL formation) are actively evolving and the boundary between the MSGL and the 'stiff till' area is unlikely to be fixed.

## Comparison with palaeo-ice stream beds

The morphology of the MSGL beneath Rutford Ice Stream is indistinguishable from relict features reported from palaeo-ice stream beds in both marine[14,24] and terrestrial settings[12,15] (Fig. 4).

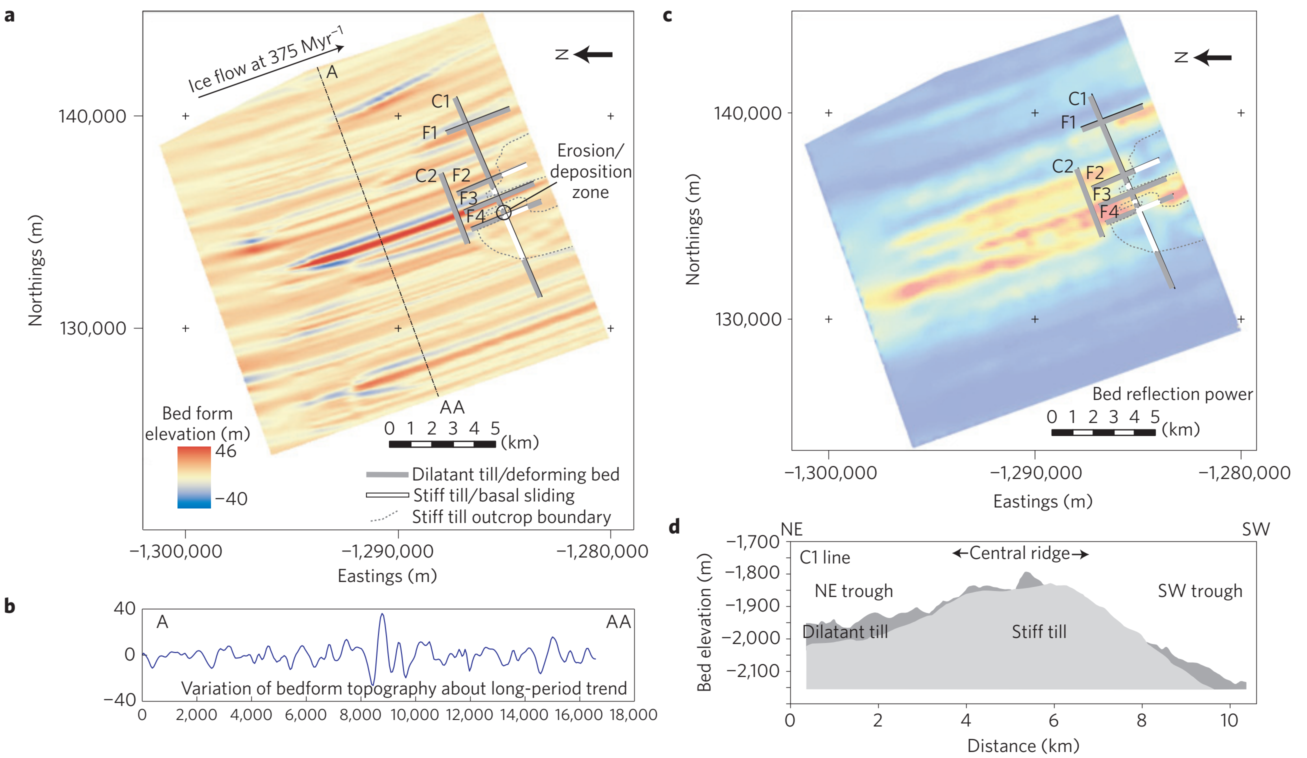


**Figure 3 | Comparison between radar and seismic data. a**, Map view of MSGLs beneath Rutford Ice Stream. C1, C2 and F1–4 denote published seismic lines[9–11]. Basal outcrops of stiff, consolidated till, coincide with areas of subdued topography. Repeated seismic surveys showed erosion followed by deposition occurring near the intersection of C1 and F4. **b**, De-trended topographic profile. **c**, Radar bed reflection power. Warm colours are stronger reflections thought to indicate free water at the ice–sediment interface; cool colours suggest that basal water is distributed within the sediment or exists in a thin layer (<0.04 m). **d**, Seismic cross-section[11]. Dilatant till is relatively thin on the crest of the central ridge and thickens in the flanking troughs.

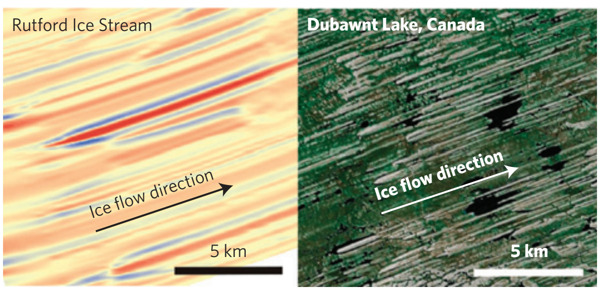


**Figure 4 | Comparison of modern and relict bedforms. a**, Rutford bedforms. **b**, Landsat satellite image of relict bedforms from the Dubawnt Lake palaeo-ice stream bed[16], northern Canada. The images are reproduced at the same scale and rotated for comparison. The plan forms and scales are very similar but the active MSGLs beneath Rutford ice stream have larger amplitudes. On the Dubawnt Lake ice stream, water-filled moats occur around some initiation points (black in the image).

Like the relict examples, the length and width of the Rutford MSGLs is variable; longer and shorter lineations occur next to each other; and MSGLs can form directly downstream of (that is, within) the grooves. The intervening troughs also have variable widths and some narrow grooves are superimposed on larger lineations. This has been reported from relict MSGLs (ref. 16) and may be suggestive of a composite snapshot landscape of evolving bedforms.

Observations of marine sediments and landform assemblages[14,24,25] associate MSGLs with a soft 'deformation' till, underlain by a consolidated 'lodgement' till. We suggest that these are the direct equivalents of our dilatant and stiff tills, and note the consistency of the marine geomorphological evidence with our subglacial observations.

## Bedform genesis and elongation

We now use these first observations of MSGLs under an active ice stream to qualitatively examine current hypotheses of their formation. The meltwater flood hypothesis[17] suggests that high-discharge, turbulent subglacial water flows erode soft beds into mega-lineations. The seismic data[10] show that one of the Rutford MSGLs either migrated or extended during the period 1997–2004. During this period, no ice-surface elevation events due to large-scale subglacial water movement[26] were recorded in the area. In addition, we note that most MSGLs are developed in areas of low radar return, which implies minimal (<0.04 m) thickness of meltwater at the ice–bed interface.

A groove-ploughing theory of MSGL formation[16] invokes keels of ice (created by passage over hard bedrock upstream) ploughing furrows in subglacial sediment to create largely erosional lineations. The available seismic data show that the bed of the ice stream is underlain by till and unlithified sediment at least tens of metres thick[11,27]. There is little evidence, therefore, that these MSGLs are emanating from or controlled by bedrock outcrops upstream and nor is there any detectable difference between the till within the MSGLs compared to the intervening furrows, which might indicate their initiation from more resistant till cores[13,20]. We also note MSGLs initiating within some grooves/troughs, which is difficult to explain through a single episode of groove-ploughing. As the till is weaker than the ice, the MSGLs must either be migrating downstream at the same speed as the irregularities in the basal ice or be forming in place by a process that allows the ice to flow laterally and vertically to create the bedform (or a combination of both processes).

One instability theory[28] proposes a mechanism for MSGL formation by suggesting that transverse flows in basal ice, under extra non-standard assumptions about ice rheology, can happen when normal stresses in shearing flow are non-uniform owing to pre-existing basal topography. This results in the generation of spiral flow in the basal ice, which excavates troughs and builds ridges in the underlying sediment. However, the theory at present predicts growth times around 1,800 years compared with the decadal timescales observed for bedform growth in this area at the downstream end of one of the MSGLs (ref. 10).

The observations presented here provide a valuable data set for further development of such theories because model parameters (such as ice thickness, velocity, basal shear stress) are very well constrained. Indeed, the high-resolution topographic detail, coincident with existing seismic data, place important new constraints on a theory of MSGL genesis, which must be able to explain their formation in dilatant, deforming till of varying thickness (greater than a few metres) and without the need for resistant cores or substantial meltwater at the ice–sediment interface. It should also account for their non-synchronous evolving pattern of formation and their migration/extension downstream on decadal timescales and over areas of stiffer till. In this respect, our observations favour a dilatant till instability model, perhaps with similar till properties to one that can explain some aspects of ribbed moraine formation[29,30] but that allows bedform evolution on a decadal timescale.

The presence of MSGLs under Rutford Ice Stream provides indisputable evidence for their association with fast-flowing ice and provides further evidence to support previous suggestions that bedform elongation is related to ice velocity[13,15,31]. Moreover, the radar and seismic data sets presented and reviewed here provide a unique insight into the dynamic environment of subglacial sedimentary beds. It is clear that subglacial bedforms evolve rapidly, as do the properties of the sediments forming them. The challenge now is to understand the critical controlling factors in sediment distribution, sediment properties, water distribution, effective pressure and temperature. Repetition of this work (5–10 years) will provide further important observations of the temporal evolution of bed processes beneath Rutford Ice Stream and powerful constraints on the modelling of ice stream dynamics with implications for our ability to predict their future modes of operation.

Received 27 November 2008; accepted 19 June 2009; published online 20 July 2009

## References


1. Rose, K. E. Characteristics of ice flow in Marie Byrd Land, Antarctica. *J. Glaciol.* **24**, 63–75 (1979).
2. Alley, R. B., Blankenship, D. D., Bentley, C. R. & Rooney, S. T. Deformation of till beneath ice stream-B, West Antarctica. *Nature* **322**, 57–59 (1986).
3. Blankenship, D. D., Bentley, C. R., Rooney, S. T. & Alley, R. B. Seismic measurements reveal a saturated porous layer beneath an active Antarctic ice stream. *Nature* **322**, 54–57 (1986).
4. Engelhardt, H., Humphrey, N., Kamb, B. & Fahnestock, M. Physical conditions at the base of a fast moving Antarctic ice stream. *Science* **248**, 57–59 (1990).
5. Anandakrishnan, S., Blankenship, D. D., Alley, R. B. & Stoffa, P. L. Influence of subglacial geology on the position of a West Antarctic ice stream from seismic observations. *Nature* **394**, 62–65 (1998).
6. Engelhardt, H. & Kamb, B. Basal sliding of ice stream B, West Antarctica. *J. Glaciol.* **44**, 223–230 (1998).
7. Alley, R. B. In search of ice-stream sticky spots. *J. Glaciol.* **39**, 447–454 (1993).
8. Rooney, S. T., Blankenship, D. D., Alley, R. B. & Bentley, C. R. Till beneath ice stream-B .2. Structure and continuity. *J. Geophys. Res.* **92**, 8913–8920 (1987).
9. Smith, A. M. Basal conditions on Rutford ice stream, West Antarctica, from seismic observations. *J. Geophys. Res.* **102**, 543–552 (1997).
10. Smith, A. M. *et al.* Rapid erosion, drumlin formation, and changing hydrology beneath an Antarctic ice stream. *Geology* **35**, 127–130 (2007).
11. Smith, A. M. & Murray, T. Bedform topography and basal conditions beneath a fast-flowing West Antarctic ice stream. *Quat. Sci. Rev.* **28**, 584–596 (2008).
12. Stokes, C. R. & Clark, C. D. Palaeo-ice streams. *Quat. Sci. Rev.* **20**, 1437–1457 (2001).
13. Clark, C. D. Mega-scale glacial lineations and cross-cutting ice-flow landforms. *Earth Surf. Process. Landf.* **18**, 1–29 (1993).
14. Ó Cofaigh, C., Pudsey, C. J., Dowdeswell, J. A. & Morris, P. Evolution of subglacial bedforms along a paleo-ice stream, Antarctic Peninsula continental shelf. *Geophys. Res. Lett.* **29**, 1199 (2002).
15. Stokes, C. R. & Clark, C. D. Are long subglacial bedforms indicative of fast ice flow? *Boreas* **31**, 239–249 (2002).
16. Clark, C. D., Tulaczyk, S. M., Stokes, C. R. & Canals, M. A groove-ploughing theory for the production of mega-scale glacial lineations, and implications for ice-stream mechanics. *J. Glaciol.* **49**, 240–256 (2003).
17. Shaw, J., Pugin, A. & Young, R. R. A meltwater origin for Antarctic shelf bedforms with special attention to megalineations. *Geomorphology* **102**, 364–375 (2008).
18. Wellner, J. S., Heroy, D. C. & Anderson, J. B. The death mask of the Antarctic ice sheet: Comparison of glacial geomorphic features across the continental shelf. *Geomorphology* **75**, 157–171 (2006).
19. Smith, A. M. Microearthquakes and subglacial conditions. *Geophys. Res. Lett.* **33**, L24501 (2006).
20. Boulton, G. S. & Hindmarsh, R. C. A. Sediment deformation beneath glaciers: Rheology and geological consequences. *J. Geophys. Res.* **92**, 9059–9082 (1987).
21. Murray, T., Corr, H., Forieri, A. & Smith, A. M. Contrasts in hydrology between regions of basal deformation and sliding beneath Rutford Ice Stream, West Antarctica, mapped using radar and seismic data. *Geophys. Res. Lett.* **35**, L12504 (2008).
22. Vaughan, D. G., Smith, A. M., Nath, P. C. & Le Meur, E. Acoustic impedance and basal shear stress beneath four Antarctic ice streams. *Ann. Glaciol.* **36**, 225–232 (2003).
23. Christoffersen, P. & Tulaczyk, S. Response of subglacial sediments to basal freeze-on - 1. Theory and comparison to observations from beneath the West Antarctic Ice Sheet. *J. Geophys. Res.* **108**, 2222 (2003).
24. Dowdeswell, J. A., Ottesen, D., Evans, J., Ó Cofaigh, C. & Anderson, J. B. Submarine glacial landforms and rates of ice-stream collapse. *Geology* **36**, 819–822 (2008).
25. Larter, R. D. *et al.* Subglacial bedforms reveal complex basal regime in a zone of paleo-ice stream convergence, Amundsen Sea embayment, West Antarctica. *Geology* **37**, 411–414 (2009).
26. Wingham, D. J., Siegert, M. J., Shepherd, A. & Muir, A. S. Rapid discharge connects Antarctic subglacial lakes. *Nature* **440**, 1033–1036 (2006).
27. King, E. C., Woodward, J. & Smith, A. M. Seismic and radar observations of subglacial bed forms beneath the onset zone of Rutford Ice Stream Antarctica. *J. Glaciol.* **53**, 665–672 (2007).
28. Schoof, C. G. & Clarke, G. K. C. A model for spiral flows in basal ice and the formation of subglacial flutes based on a Reiner-Rivlin rheology for glacial ice. *J. Geophys. Res.* **113**, B05204 (2008).
29. Dunlop, P., Clark, C. D. & Hindmarsh, R. C. A. Bed ribbing instability explanation: Testing a numerical model of ribbed moraine formation arising from coupled flow of ice and subglacial sediment. *J. Geophys. Res.* **113**, F03005 (2008).
30. Hindmarsh, R. C. A. Drumlinization and drumlin-forming instabilities: Viscous till mechanisms. *J. Glaciol.* **44**, 293–314 (1998).
31. Hart, J. K. Identifying fast ice flow from landform assemblages in the geological record: A discussion. *Ann. Glaciol.* **28**, 59–66 (1999).


## Acknowledgements

We thank A. M. Smith for permission to use the seismic interpretations shown in Fig. 3. R. Stilwell and the Operations staff of Rothera Research Station are thanked for support in the field.

## Author contributions

E.C.K. collected and processed the radar data, prepared the figures and wrote the draft paper. C.R.S. and R.C.A.H. contributed to the interpretation of the data and the writing of the paper.

## Additional information

Reprints and permissions information is available online at http://npg.nature.com/reprintsandpermissions. Correspondence and requests for materials should be addressed to E.C.K.