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Are longitudinal ice-surface structures on the Antarctic Ice Sheet indicators of long-term ice-flow configuration?

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Abstract

Continent-wide mapping of longitudinal ice-surface structures on the Antarctic Ice Sheet reveals that they originate in the interior of the ice sheet and are arranged in arborescent networks fed by multiple tributaries. Longitudinal ice-surface structures can be traced continuously down-ice for distances of up to 1200 km. They are co-located with fast-flowing glaciers and ice streams that are dominated by basal sliding rates above tens of $\mathrm{m\,yr^{-1}}$ and are strongly guided by subglacial topography. Longitudinal ice-surface structures dominate regions of converging flow, where ice flow is subject to non-coaxial strain and simple shear. Associating these structures with the AIS' surface velocity field reveals (i) ice residence times of ~ 2500 to 18 500 years, and (ii) undeformed flow-line sets for all major flow units analysed except the Kamb Ice Stream and the Institute and Möller Ice Stream areas. Although it is unclear how long it takes for these features to form and decay, we infer that the major ice-flow and ice-velocity configuration of the ice sheet may have remained largely unchanged for several thousand years, and possibly even since the end of the last glacial cycle. This conclusion has implications for our understanding of the long-term landscape evolution of Antarctica, including large-scale patterns of glacial erosion and deposition.

1 Introduction

There are no centennial to millennial records of ice-velocity and associated dynamic changes in the Greenland and Antarctic ice sheets because direct measurement of the ice-sheets are restricted to satellite-derived observations of the last 50 years (Bindschadler and Vornberger, 1998; Rignot and Kanagaratnam, 2006; Rignot et al., 2008). Field velocity data on the ice sheets are temporally and spatially restricted, and it is only recently that their contemporary velocity field has been quantified using balance velocity calculations and InSAR velocity data (Bamber et al., 2000; Rignot and Kanagaratnam, 2006; Rignot et al., 2011). In Antarctica, these data reveal an ice sheet organised into a complex set of size- and speed-varying tributaries dominated by basal sliding (Rignot et al., 2011). Today, these fast-flowing tributaries extend hundreds to thousands of kilometres inland into the Antarctic continent but it is unclear when this velocity structure emerged and how it evolved through time.

Entirely independently of surface-derived or modelled ice-sheet velocities we have for the first time documented the continent-wide distribution of nearly 3500 individual longitudinal ice-surface structures that mark the flow of the Antarctic Ice Sheet (Figs. 1 and 2; Table 1). These flow-parallel features are commonly referred to in the literature as “flow stripes”, “flow bands”, “flow lines” or “streaklines” (Crabtree and Doake, 1980; Reynolds and Hambrey, 1988; Swithinbank et al., 1988; Casassa and Brecher, 1993; Casassa et al., 1991; Gudmundsson et al., 1998; Jacobel et al., 1993, 1999; Fahnestock et al., 2000; Hulbe and Fahnestock, 2004, 2007). They originate in the interior of the ice sheet and continue onto its fringing ice shelves (Fahnstock et al., 2000; Hambrey and Dowdeswell, 1994). In this paper we describe only the patterns of surface features mapped in satellite images, although we later discuss how our study relates to internal ice-sheet features such as buckled layers and folds inferred from radar studies (Conway et al., 2002; Campbell et al., 2008; Ross et al., 2011; Siegert et al., 2013; Martín et al., 2014).

Longitudinal ice-surface structures are commonly developed parallel to the margins of individual ice-flow units and are therefore inferred to represent relict or contemporary flow lines within an ice sheet (Fahnestock et al., 2000). They are present both in snow-covered zones of the ice sheet, where they are picked out by variations in surface topography, and in bare ice areas, where they represent the surface manifestation of the three-dimensional structure, longitudinal foliation (Fig. 3) (Hambrey and Dowdeswell, 1994). Longitudinal ice-surface structures are formed: (i) in zones of extensional flow in areas of ice acceleration and at glacier confluences (Glasser and Gudmundsson, 2012), where they are the surface expression of rapid glacier flow and may represent stretching lineations; and (ii) in ice-flow convergence zones, where stratified ice from the polar plateau enters troughs, leading to folding with flow-parallel

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀I ▶I
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

axial planes and associated foliation in the manner of valley glaciers fed from multiple accumulation basins (Hambrey and Glasser, 2003).

Glasser and Gudmundsson (2012) reviewed the formation of longitudinal ice-surface structures and noted that the physical explanation for the origin of these structures is unclear. Based on previous descriptions they identified four possible explanations for the formation of these features (1–4 in the list below) and, based on their observations, added a fifth (5 in the list below):

1. *They form as a result of lateral compression in topographic situations where glaciers flow from wide accumulation basins into a narrow tongue*. In this case the longitudinal surface structures would be the surface expression of three-dimensional folding within the ice under strong lateral compression (i.e. a longitudinal foliation; Hambrey and Glasser, 2003). In this situation, longitudinal ice-surface structures should be concentrated in areas where multiple accumulation basins feed single glacier tongues.

2. *They form where two glacier tributaries, possibly flowing at different velocities, converge and are therefore associated with shear margins between individual flow units*. In this situation, longitudinal ice-surface structures should be concentrated at the boundaries between individual glacier flow units.

3. *They are the surface expression of subglacial bed perturbations created during rapid basal sliding*. In this case the longitudinal ice-surface structures represent features transmitted to the ice surface by flow across an irregular subglacial topography. In this situation, there would be little or no relationship between the configuration of individual flow units and the development of longitudinal surface structures. Instead these structures simply reflect rapid ice-flow across rough glacier beds.

4. *They are the surface expression of* vertical sheets of changed ice fabric (Whillans and Van der Veen, 1997; Hulbe and Whillans, 1997).

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

5. *They form at the confluence of glacier tributaries and in the lee of nunataks as a result of strong transverse convergence and a concomitant longitudinal extension in the horizontal plane* (Glasser and Gudmundsson, 2012). In this case longitudinal ice-surface structures are formed in zones of ice acceleration and extensional flow at glacier confluences. They represent stretching lineations formed in areas of rapid ice-sheet velocity.

2 Methods

Longitudinal ice-surface structures were mapped from three sources:

1. The Moderate Resolution Imaging Spectroradiometer (MODIS) Mosaic of Antarctica (MOA) product (available from nsidc.org/data/moa and described by Scambos et al., 2007). The MODIS MOA is a composite of 260 swaths comprised of both Terra and Aqua MODIS images acquired between 20 November 2003 and 29 February 2004. It provides a cloud-free view of the Antarctic Ice Sheet at a grid scale of 125 m and an estimated resolution of 150 m.
2. The Landsat Image Mosaic of Antarctica (LIMA; available from lima.usgs.gov). LIMA is a virtually cloudless, seamless, and high resolution satellite view of Antarctica, created from more than 1000 Landsat ETM+ scenes. Images have a spatial resolution of 30 m in Bands 1–6 and 15 m spatial resolution in the panchromatic band.
3. RADARSAT images (available from https://nsidc.org/data/radarsat/index.html). Radar images are particularly useful for identifying areas of rapid ice flow because of the contrasts in radar backscatter intensity or "brightness" at the lateral margins of ice streams (Ng and King, 2013).

We mapped the entire surface of the Antarctic Ice Sheet, digitizing the location of all longitudinal surface structures in a GIS (ARCMap10) (Fig. 1). These longitudinal ice-structures indicate the direction and magnitude of ice-surface flow (Glasser and Gudmundsson, 2012). The distribution of ice-surface flow structures was compared to the recently compiled velocity map of Antarctica (Rignot et al., 2011), a high-resolution, digital mosaic of ice motion assembled from multiple satellite interferometric synthetic-aperture radar (InSAR) data, available from http://nsidc.org/data/nsidc-0484.html. We also compared our data set to the subglacial topography of Antarctica as compiled in BEDMAP-2 (Fretwell et al., 2013). The map of Antarctic Ice Sheet flow structure presented here was produced entirely independently of the BEDMAP-2 and InSAR velocity maps.

3 Results

Almost without exception, all large Antarctic ice streams, glaciers and their tributaries are marked by longitudinal ice-surface structures emanating from onset zones in the interior of the ice sheet (Figs. 1, 2a–c, and 4). They are arranged in arborescent networks that reflect transfer from individual flow units into trunk glaciers. Areas dominated by longitudinal ice-surface structures have sharp lateral boundaries with surrounding ice, inferred to be shear margins. They can be traced without interruption as continuous features over distances of >1000 km to glacier termini and onto ice shelves. The longitudinal ice-surface structures indicate that dynamic glacier flow reaches deep into the interior of the ice sheet. They are consistently located within areas of high glacier velocity or high strain (Fig. 4c), and are preferentially aligned over deep bedrock troughs (Fig. 4d). The distribution of longitudinal ice-surface structures indicates that ice flow and simple shear is organised into major glacier trunks, where cumulative strain is most intense, and steered strongly by the subglacial topography. Away from these zones of rapid ice flow are zones of slow-flowing ice where longitudinal ice-surface structures are entirely absent.

In Recovery Glacier, longitudinal ice-surface structures mark a single glacier flow unit fed by a small number of distinct tributaries (Fig. 2a). In the Lambert Glacier–Amery

Ice Shelf System the main glacier trunk is fed by numerous hierarchical tributaries arranged into a broad arborescent network (Fig. 2b). The middle reach of this glacier system is an area of net ablation, and bare ice exists over a length of several hundred km and reveals pervasive longitudinal foliation, which locally is distorted transverse to flow (Fig. 3) (Hambrey and Dowdeswell, 1994; Hambrey, 1991). On Pine Island Glacier (Fig. 2c) a broad catchment feeds a narrow tongue and glacier flow is marked by strongly convergent longitudinal ice-surface structures.

We identified only two major areas across the entire Antarctic continent where the longitudinal ice-surface structures are not smoothly aligned parallel to the along-flow velocity vector. The first of these two areas is the area occupied by the now-stagnant Kamb Ice Stream (formerly known as Ice Stream C) on the Siple Coast, a tributary to the Ross Ice Shelf. Here, distorted (folded) longitudinal structures are visible on the surface of the former ice stream (indicated by numbers 1–3 on Fig. 2d) in an area where the ice-sheet velocity is now negligible (Rignot et al., 2011). Kamb Ice Stream began to stagnate ~ 150 years ago (Retzlaff and Bentley, 1993; Jacobel et al., 1996) and we argue that the ice-surface folds are deformed longitudinal ice-surface structures inherited from the time when the ice stream was active, and that they have subsequently been deformed by a notable change in the velocity structure following ice-stream shutdown (Fahnestock et al., 2000; Hulbe and Fahnestock, 2007; Catania et al., 2012). The inference is that the ice-surface folds on the Ross Ice Shelf indicate that centennial-scale changes in ice flow have taken place in response to temporal variations in input from the Siple Coast ice streams (Bindschadler and Vornberger, 1998; Fahnestock et al., 2000; Hulbe and Fahnestock, 2007; Catania et al., 2012).

The second area is the Ronne Ice Shelf–Thiel Trough area (Fig. 5a). Here ice flow inferred from longitudinal ice-surface structures clearly follows the subglacial topography everywhere other than in the Thiel Trough (Fig. 5b). Longitudinal surface structures are clear on the Möller and Institute Ice Streams, but are rare or absent through the Thiel Trough, even though this is a deep subglacial feature where we would logically expect rapid ice flow. Mapped longitudinal ice-surface structures superimposed on InSAR velocities also show a good match across the area in all locations other than the Thiel Trough and its immediate upstream continuation where flowlines currently exist in areas of slow or non-existent ice flow (Fig. 5c). This interpretation of the ice-flow configuration is supported by radar studies of internal layering in the Bungenstock Ice Rise (Siegert et al., 2013). Here, longitudinal ice-surface structures are aligned across the ice rise irrespective of contemporary ice flow, and internal layers are buckled, indicating significant recent change to ice flow there and upstream. We infer that ice flow initially crossed Bungenstok Ice Rice and drained through the Thiel Trough, before switching at some point in the past towards the Ronne Ice Shelf (Fig. 5d).

4 Discussion and conclusion

Clearly, an understanding of how longitudinal ice-surface structures form is central to our discussion of the wider significance of these mapped features at the continental scale. Merry and Whillans (1993) considered that these features form in relation to localised high shear strain rates in ice streams near their onset areas. Another possibility is that they represent “shear zones” within individual flow units. However, Casassa and Brecher (1993) found no velocity discontinuities across the boundaries between “flow stripes” on the Byrd Glacier, which suggests that their formation and down-ice persistence cannot be explained by lateral shear between individual stripes. Another possible explanation is that these structures are created by the visco-plastic deformation or folding of pre-existing inhomogeneities, i.e. primary stratification, under laterally compressive and longitudinally tensile stresses (Hambrey, 1977; Hooke and Hudleston, 1978). Mathematical modelling also demonstrates that longitudinal ice-surface structures can form as ice flows over a localized bedrock undulation when the flow is characterized by high rates of basal motion compared to rates of internal ice deformation (Gudmundsson et al., 1998). Their model experiments suggest that longitudinal ice-surface structures form under conditions of rapid basal sliding and persist as surface features for several hundred years after rapid sliding has stopped (Gudmundsson et al., 1998). They concluded that basal perturbations of wavelengths comparable to ice thickness cause a surface expression at the top of an ice stream.

One of the most striking attributes of these features is their down-ice persistence. In the absence of any downstream overprinting, Glasser and Scambos (2008) noted that longitudinal ice-surface structures on tributary glaciers and their ice-shelf continuations can be traced for distances of >100 km, and we have extended this to >1000 km with the new mapping presented here. Glasser and Scambos (2008) inferred that tributary glaciers to ice shelves are fast-flowing or active where these longitudinal ice-surface features are present, and that glaciers are slow-flowing or less active where longitudinal ice-surface features are absent. Glasser and Gudmundsson (2012) studied longitudinal ice-surface structures in a variety of settings in Antarctica and concluded that they form at the confluence of glacier tributaries and in the lee of nunataks as a result of strong transverse convergence and a concomitant longitudinal extension in the horizontal plane. In this case longitudinal ice-surface structures are formed in zones of ice acceleration and extensional flow at glacier confluences. They represent stretching lineations in area of rapid ice-sheet velocity.

Ice-sheet movement in the Antarctic Ice Sheet is dominated by basal sliding in the zones of rapid velocity and by deformation-dominated ice-sheet flow elsewhere (Rignot et al., 2011). Measured surface velocity starts to exceed that attributed to deformation alone within a few hundred km of ice divides, typically at velocities greater than about 15 $\mathrm{m\,yr^{-1}}$, indicating that basal motion generally initiates above this value (Fig. 4c). Longitudinal ice-surface structures also only appear above this threshold velocity (Fig. 4b), indicating that these features form in zones of ice acceleration where non-coaxial strain and simple shear is a feature of the ice dynamics (Glasser and Gudmundsson, 2012). Ice flow is also steered largely by subglacial topography (Fig. 4d). By implication, the ice-velocity configuration of the Antarctic Ice Sheet can be inferred from ice-surface structural features, and this confirms that the overall organisation is one of rapid-flowing, warm-based ice streams, separated from slow-flowing frozen-bed zones by abrupt shear margins.

The Kamb Ice Stream and Ronne Ice Shelf–Thiel Trough areas are crucial for our overall interpretation of the ice-velocity configuration of the ice sheet because they are the only locations across the entire continent where mapped longitudinal ice-surface structures do not match the contemporary glacier velocities. In the first case (Kamb Ice Stream) this can be explained by ice-stream shutdown and in the second case (Ronne Ice Shelf–Thiel Trough area) by Late Holocene ice-sheet and grounding-line changes. The fact that we can identify these two areas increases our confidence that everywhere else on the continent we have correctly identified contemporary ice-flow configuration from the distribution of longitudinal ice-surface structures.

It is important to know the length of time for which flowlines hold palaeo-ice flow information. To investigate the longevity of these surface features we integrated the contemporary glacier velocities along the longitudinal ice-surface structures on four of the main glacier systems from their onset zones to their coastal termini; two sets of flowlines each for the large Lambert Glacier and the large Recovery Glacier, and one flowline each for the smaller Byrd Glacier and Pine Island Glacier (Fig. 6). These calculations indicate ice-sheet residence times of ~ 2500 to $\sim 18\,500$ years (Fig. 6). These are minimum estimates of ice-residence time because our calculations start some way downstream of the low-velocity onset areas. Actual ice residence times may be longer. Since longitudinal ice-surface structures can be followed without interruption, folding or buckling over their entire length, we infer that these structures develop near the start of flowlines. If this is correct, then it is possible that ice velocities have been stable both within flow units and between adjacent (tributary-trunk) flow units, over centennial to millennial timescales.

Although there is compelling evidence for recent and very rapid changes in the velocity (Pritchard et al., 2009) and surface elevation (Johnson et al., 2014) of individual outlet glaciers in Antarctica, we speculate that the basic ice-flow configuration in Antarctica has remained unchanged over these ice-residence times. We cannot comment on the slower-flowing areas of the ice sheet because longitudinal ice-surface structures only form in areas of relatively high velocity and are therefore generally absent in these locations. On the basis of our ice-residence time calculations we therefore infer that the basic, large-scale, ice-sheet dynamical configuration may have remained unchanged for ~2500 to ~18 500 years. If this is the case, the basic elements of the flow configuration have been stable since the end of the last glacial cycle and through the entire Holocene. In support of this conclusion we note that: (1) continental-shelf landforms deposited by an expanded Antarctic Ice Sheet indicate prolonged periods of sediment delivery focused at trough mouths, implying that these areas have been occupied by fast-flowing glaciers and ice streams for a considerable period of time (Dowdeswell et al., 2003, 2008); (2) numerical ice-sheet modelling studies (Pollard and DeConto, 2009) and evidence from blue-ice areas indicate that the central dome and overall patterns of ice flow in the West Antarctic Ice Sheet have remained intact for > 200 000 years (Fogwill et al., 2012); (3) radar stratigraphic studies indicate near-stationary flow conditions over millennia near major ice divides (Ross et al., 2011) and locally at ice rises (Martín et al., 2014).

If the basic ice-dynamical organisation of the ice sheet has not changed much in the recent past, then this has implications for Earth surface processes. Ice discharge is focused along deep subglacial troughs, many of which contain considerable thicknesses of subglacial sediment (Bamber et al., 2006). Enhanced glacial erosion in these troughs ensures a positive feedback between glacial erosion and ice discharge (Siegert, 2008), helping to reinforce this basic ice-dynamical organisation. This explains the location and formation of landforms representing rapid ice-flow under the contemporary ice sheet (Smith et al., 2007; King et al., 2009) and elements of the long-term landscape evolution of Antarctica by selective glacial erosion (Bo, 2009; Ferraccioli, 2011). Elongate landforms on the beds of palaeo-ice sheets including drumlins, megaflutes and mega-scale glacial lineations inferred to represent palaeo-ice streams (Stokes and Clark, 2001; Kleman and Glasser, 2007; Clark et al., 2009) also indicate that this basic ice-flow configuration holds for palaeo-ice sheets.

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Table 1. Details of the dataset created from mapping the longitudinal ice-surface structures of the Antarctic Ice Sheet.

Mapped Area	Number of Polylines (flowlines)	Number of Vertices (data points)
Lambert Glacier	642	12 559
Pine Island Glacier	43	740
Recovery Glacier	383	5757
Remainder of Antarctic continent	2399	14 005
Overall total	3467	33 061

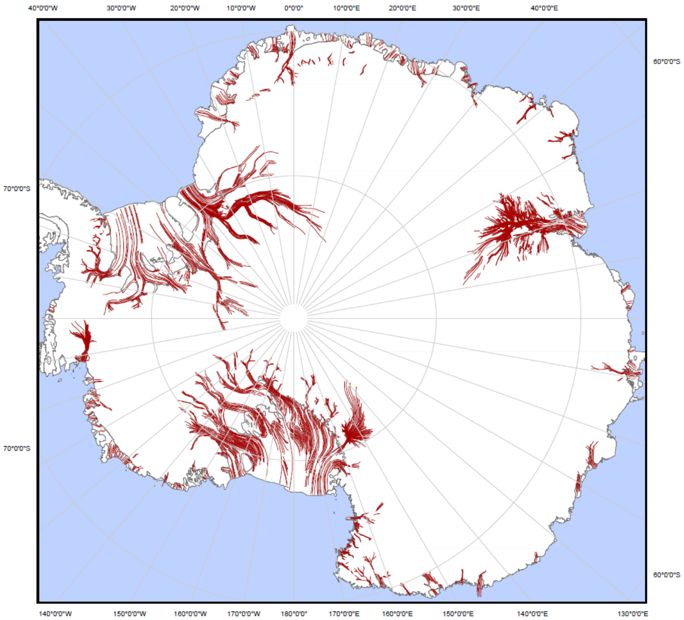

Figure 1. Continent-wide distribution of longitudinal ice-surface structures on the Antarctic Ice Sheet. The map is compiled from ca. 3500 individual longitudinal ice-surface structures.

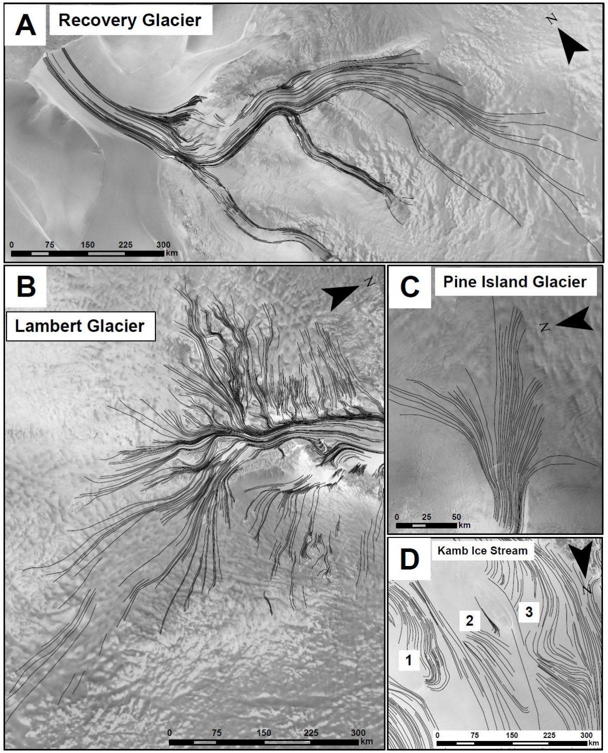

Figure 2. Detail of the surface structures of the Antarctic Ice Sheet in four key localities: **(a)** Recovery Glacier **(b)** the Lambert Glacier–Amery Ice Shelf System **(c)** Pine Island Glacier **(d)** Part of the Kamb Ice Stream (Ice Stream C) on the Ross Ice Shelf. Numbers 1–3 indicate disturbances in the longitudinal surface structures created when ice flow re-organised after ice-stream shutdown. Locations are marked on Fig. 4.

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
I◄
►I
◄
►
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

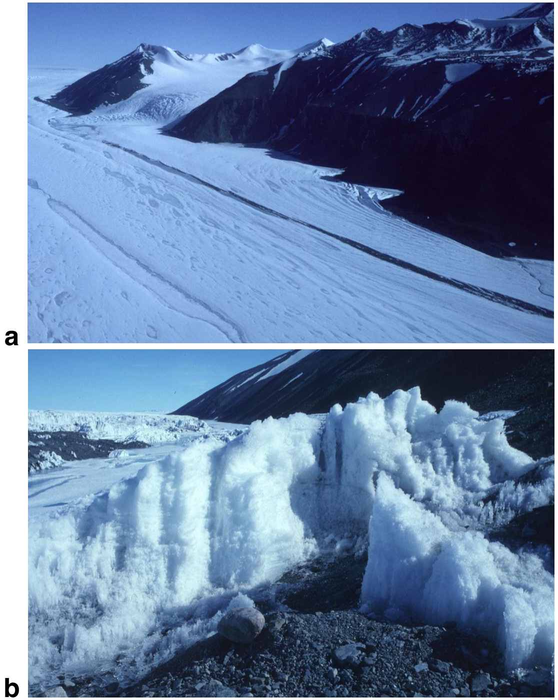

Figure 3. Longitudinal ice-surface structures, demonstrably foliation, at the western margin of the Lambert Glacier–Amery Ice Shelf System, East Antarctica, adjacent to Fisher Massif. **(a)** Oblique aerial photograph illustrating longitudinal foliation parallel to a medial moraine, defining a flow-unit boundary between the main glacier and a local tributary, and showing the close relationship between supraglacial meltwater channels and ponds. **(b)** Ground view of near-vertical longitudinal foliation, defined by differential weathering, at the edge of the glacier system.

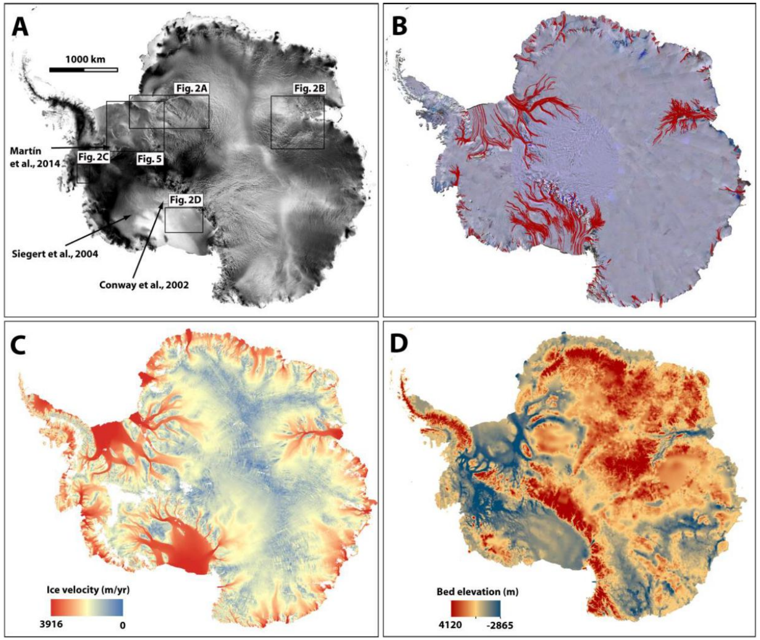

Figure 4. Comparison between longitudinal ice-surface structures and other Antarctic data sets. **(a)** Synthetic Aperture Radar (SAR) mosaic of Antarctica showing the surface of the ice sheet. The locations of enlarged areas shown in Figs. 2a–d and 5 are indicated. Locations of radar stratigraphic studies of Conway et al. (2002), Siegert et al. (2004) and Martín et al. (2014) are also shown. **(b)** Continent-wide distribution of longitudinal ice-surface structures on the Antarctic Ice Sheet draped over LIMA mosaic. **(c)** Velocity map of the Antarctic continent from the MEASURES project (Rignot et al., 2011). **(d)** Subglacial topography of Antarctica as compiled in BEDMAP-2 (Fretwell et al., 2013). Note the co-location of longitudinal ice-surface structures with areas of rapid velocity in areas underlain by deep subglacial troughs.

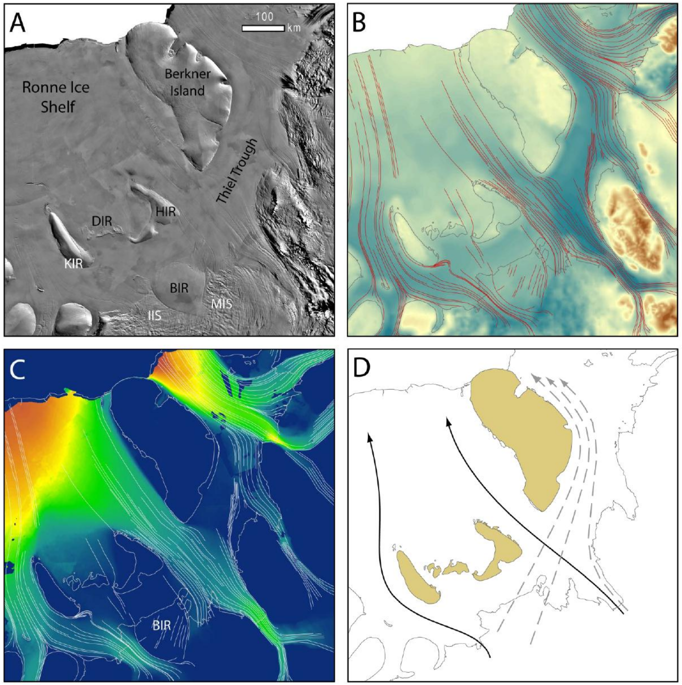

Figure 5. Map of the Ronne Ice Shelf/Thiel Trough area showing **(a)** ice sheet/ice shelf surface from MOA. HIR = Henry Ice Rise, DIR = Doake Ice Rumples, KIR = Korff Ice Rise. BIR = Bungenstock Ice Rise, IIS = Institute Ice Stream, MIS = Möller Ice Stream. **(b)** Flowlines inferred from longitudinal ice-surface structures superimposed on BEDMAP-2 (Fretwell et al., 2013). Note how the flowlines follow the topography everywhere other than the Thiel Trough; **(c)** surface flowlines superimposed on velocities from the MEASURES project (Rignot et al., 2011) showing good match between the two in all locations other than the Thiel Trough and its upstream continuation at the Bungenstock Ice Rise; **(d)** inferred sequence of events, with initial flow through the Thiel Trough (dashed lines and arrows) followed by a switch of flow towards the Ronne Ice Shelf under contemporary conditions (solid lines and arrows).

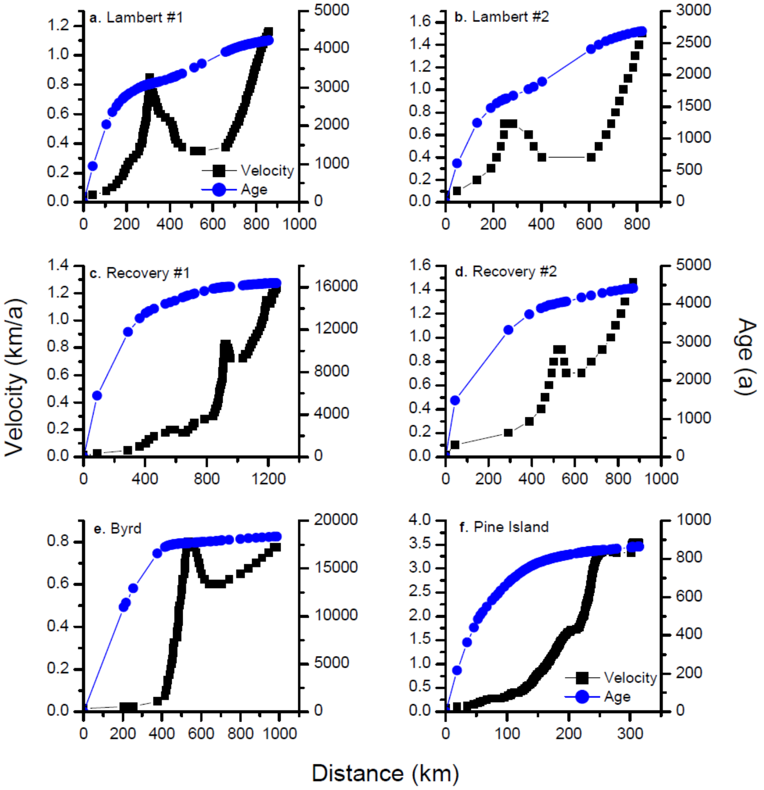

Figure 6. Plots of velocity and cumulative age with distance along un-interrupted longitudinal ice-surface structures for selected Antarctic glaciers: **(a)** and **(b)** Lambert Glacier; **(c)** and **(d)** Recovery Glacier; **(e)** Byrd Glacier; **(f)** Pine Island Glacier.