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Glasser, Neil; Jennings, Stephen James Arthur; Hambrey, Michael; Hubbard, Bryn

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Origin and dynamic significance of longitudinal structures (“flow stripes”) in the Antarctic Ice Sheet

N. F. Glasser, S. J. A. Jennings, M. J. Hambrey, and B. Hubbard

Department of Geography and Earth Sciences, Aberystwyth University, SY23 3DB, Wales, UK

Correspondence to: N. F. Glasser (nfg@aber.ac.uk)

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Abstract. Longitudinal ice-surface structures in the Antarctic Ice Sheet can be traced continuously down-ice for distances of up to 1200 km. A map of the distribution of ~ 3600 of these features, compiled from satellite images, shows that they mirror the location of fast-flowing glaciers and ice streams that are dominated by basal sliding rates above tens of metres per annum 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. They can be traced continuously through crevasse fields and through blue-ice areas, indicating that they represent the surface manifestation of a three-dimensional structure, interpreted as foliation. Flow lines are linear and undeformed for all major flow units described here in the Antarctic Ice Sheet except for the Kamb Ice Stream and the Institute and Möller Ice Stream areas, where areas of flow perturbation are evident. Parcels of ice along individual flow paths on the Lambert Glacier, Recovery Glacier, Byrd Glacier and Pine Island Glacier may reside in the glacier system for ~ 2500 to 18 500 years. Although it is unclear how long it takes for these features to form and decay, we infer that the major ice-flow configuration of the ice sheet may have remained largely unchanged for the last few hundred years, and possibly even longer. 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

Flow-parallel features on glaciers and ice sheets are commonly referred to in the literature as “flow stripes”, “flow bands”, “flowlines” or “streaklines” (Crabtree and Doake, 1980; Reynolds and Hambrey, 1988; Swithinbank et al., 1988; Casassa et al., 1991; Casassa and Brecher, 1993; Gudmundsson et al., 1998; Jacobel et al., 1993, 1999; Fahnestock et al., 2000; Hulbe and Fahnestock, 2004, 2007). In Antarctica, they originate in the interior of the ice sheet and continue into its fringing ice shelves (Hambrey and Dowdeswell, 1994; Fahnestock et al., 2000). “Flow stripes”, “flow bands”, “flowlines” or “streaklines” are commonly used to infer past and present Antarctic Ice Sheet ice-flow configuration. It is important to establish their origin – and in particular their genetic relation to longitudinal foliation on glaciers – in order to fully understand their glaciological significance. The contribution of this paper is to establish hypotheses for the for-

mation of longitudinal ice-surface structures (“flow stripes”) on glaciers and ice sheets, to present a map of the distribution of these features across the entire Antarctic continent, and to evaluate their glaciological significance (Figs. 1 and 2).

Longitudinal ice-surface structures are commonly developed parallel to ice-flow direction along the margins of individual ice-flow units and are inferred to represent relict or contemporary flowlines within an ice sheet (Fahnestock et al., 2000). They are present both in accumulation areas of the ice sheet, where they are snow-covered and they are picked out by variations in surface topography, and in areas of surface ablation (blue-ice areas), where they represent the surface manifestation of the three-dimensional structure, longitudinal foliation (Fig. 3) (Hambrey and Dowdeswell, 1994). Longitudinal features on the surface of ice shelves can also correspond to meltwater channels beneath the shelves, which may or may not be aligned with present-day flow direction (Le Brocq et al., 2013; Millgate et al., 2013). An understand-

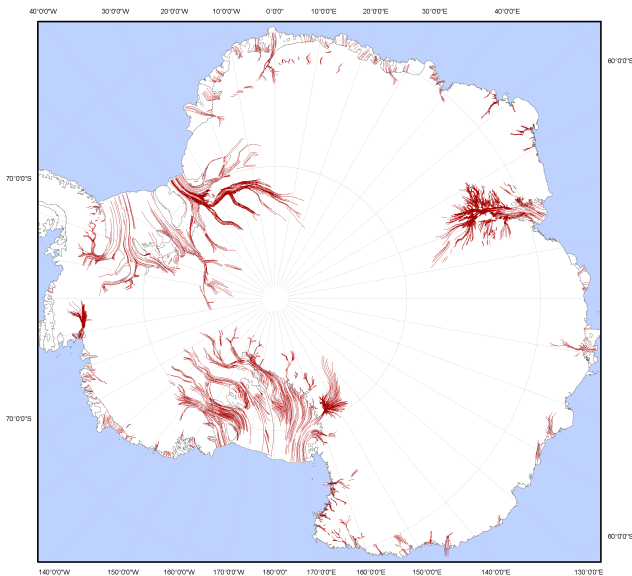


Figure 1. Continent-wide distribution of longitudinal ice-surface structures on the Antarctic Ice Sheet. The map is compiled from ca. 3600 individual longitudinal ice-surface structures. Antarctic Peninsula glaciers and ice shelves already mapped by Glasser and Scambos (2008) and Glasser et al. (2009) are not included.

ing of how these longitudinal ice-surface structures form in three dimensions is clearly central to a discussion of their wider glaciological significance.

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 individual and adjacent “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. There is evidence for this from field observations in valley glaciers and ice caps (Hambrey, 1977; Hooke and Hudleston, 1978).

Mathematical modelling also demonstrates that longitudinal ice-surface structures can form as ice flows over a localised bedrock undulation when the flow is characterised by high rates of basal motion compared to rates of internal ice deformation (Gudmundsson et al., 1998). Numerical 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). Gudmundsson et al. (1998) concluded that basal perturbations of wavelengths comparable to ice thickness cause a surface expression at the

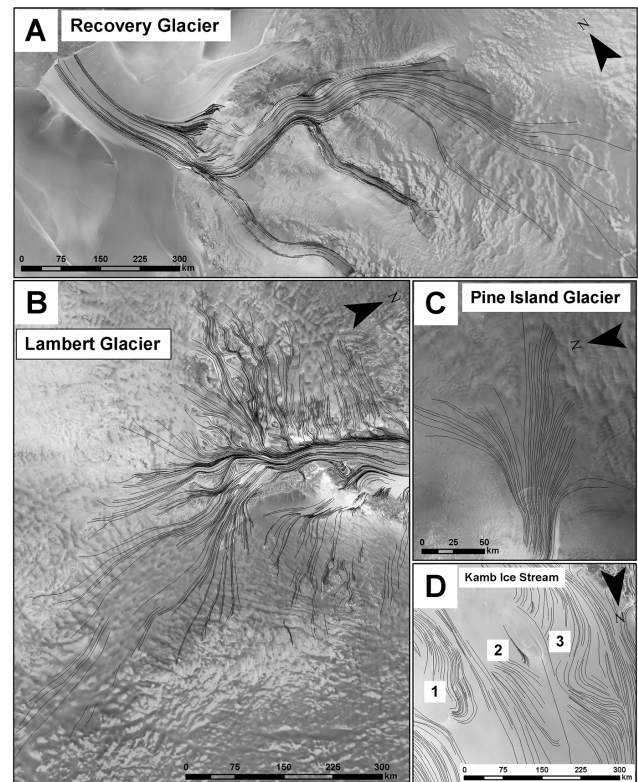


Figure 2. Detail of the surface structures of the Antarctic Ice Sheet in four key localities: (a) Recovery Glacier, (b) the Lambert Glacier–Amery Ice Shelf system, (c) Pine Island Glacier and (d) part of the Kamb Ice Stream (Ice Stream C) on the Ross Ice Shelf. Numbers 1 to 3 indicate disturbances in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

top of an ice stream. 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) concluded that longitudinal ice-surface structures 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 areas of rapid ice-sheet velocity.

From these observations emerge three hypotheses for how these features form:

- Hypothesis 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 are the surface expression of three-dimensional folding within the ice

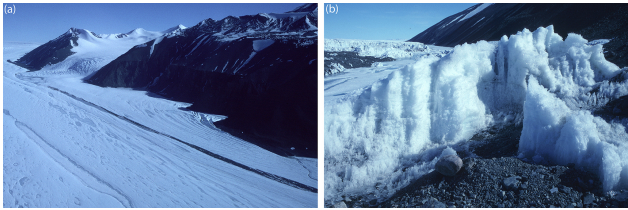


Figure 3. Longitudinal ice-surface structures, demonstrably foliation, at the western margin of the Lambert Glacier–Amery Ice Shelf system, East Antarctica, adjacent to Fisher Massif. **(a)** Oblique aerial photograph illustrating longitudinal foliation parallel to a medial moraine, defining a flow-unit 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. Photographs: M. J. Hambrey.

under strong lateral compression (i.e. a longitudinal foliation with flow-parallel axial planes; Hambrey and Glasser, 2003). They can also 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 both cases they represent three-dimensional structures.

- Hypothesis 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 particularly concentrated at the boundaries between individual glaciers or glacier flow units. They can also be represented as the surface expression of shear by vertical sheets of changed ice fabric. In this case the longitudinal structures represent aligned-crystal bands related to shear within the ice formed within “weak bands” in the ice sheet (Hulbe and Whillans, 1997; Whillans and Van der Veen, 1997).
- Hypothesis 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 (Gudmundsson et al., 1998).

The aim of this paper is to map the distribution of longitudinal ice-surface structures (“flow stripes”) in the Antarctic Ice Sheet from satellite images (Figs. 1 and 2, Table 1) and to compare their distribution with independently derived ice-sheet velocities and subglacial topography (Fig. 4). After mapping and describing the pattern of surface features on the Antarctic Ice Sheet, we discuss their possible origin in relation to these three hypotheses and consider their relationship with internal ice-sheet features, such as buckled layers

Table 1. Details of the data set 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

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).

2 Methods

The surface of the Antarctic Ice Sheet was mapped manually from optical (MODIS and LIMA) and radar (RADARSAT) satellite images. Surface features were digitised on-screen and stored in a geographical information system (ARCMAP10) (Fig. 1).

Details of the three data sources are as follows:

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. MODIS images were used to map ice shelves and their tributary glaciers.
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. LIMA images were used to map ice shelves and their tributary glaciers.
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). RADARSAT images have a resolution of 25 m and were used to map the interior of the ice sheet and its ice streams.

Longitudinal surface features are present in (and consistent between) each of the different types of satellite images de-

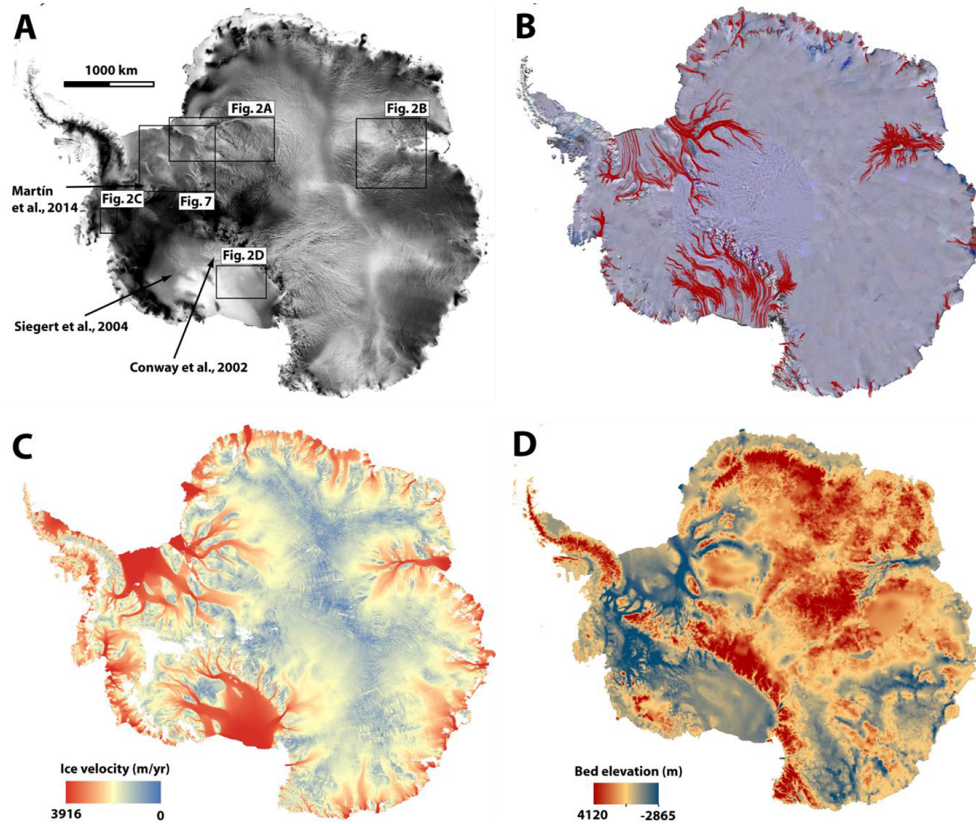


Figure 4. Comparison between longitudinal ice-surface structures and other Antarctic data sets. **(a)** Synthetic aperture radar (SAR) mosaic of Antarctica showing the surface of the ice sheet (available from <https://nsidc.org/data/radarsat/index.html>). The locations of enlarged areas shown in Figs. 2a to d and Fig. 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 the 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 that the location of longitudinal ice-surface structures mirrors areas of rapid velocity in areas underlain by deep subglacial troughs.

spite the imagery originating from different sensors (i.e. optical and radar), giving us confidence that they are real and not an artefact of the imagery. For the scale of mapping used in this study (longitudinal surface features often covering many hundreds of kilometre), variations in image resolution had no effect on the accuracy of mapping.

The distribution of ice-surface flow structures was compared to the recently compiled velocity map of Antarctica (Rignot et al., 2011), which is 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> (Fig. 4c). The distribution of ice-surface flow structures was also compared to the subglacial topography of Antarctica as compiled in BEDMAP-2 (Fretwell et al., 2013) (Fig. 4d). The map of Antarctic Ice Sheet flow structure presented here was produced entirely independently of the BEDMAP-2 and InSAR velocity maps. Ice-residence time for parcels of ice in the glaciers was estimated by integrating the contemporary

glacier velocities along longitudinal ice-surface structures on four of the main glacier systems (Lambert Glacier, Recovery Glacier, Byrd Glacier and Pine Island Glacier) from their onset zones to their coastal termini. The calculations are based on the assumption that the contemporary glacier velocities are generally representative of Holocene glacier velocities and that these have not varied greatly over this time. If contemporary velocities are lower today than in the past (for instance, if the glaciers experience stick-slip motion), the ice-residence times will be overestimates. However, the calculations start some way downstream of the low-velocity onset areas. As a result, actual ice-residence times for individual parcels of ice may be longer than the values calculated in this paper, and in that case they will be underestimates.

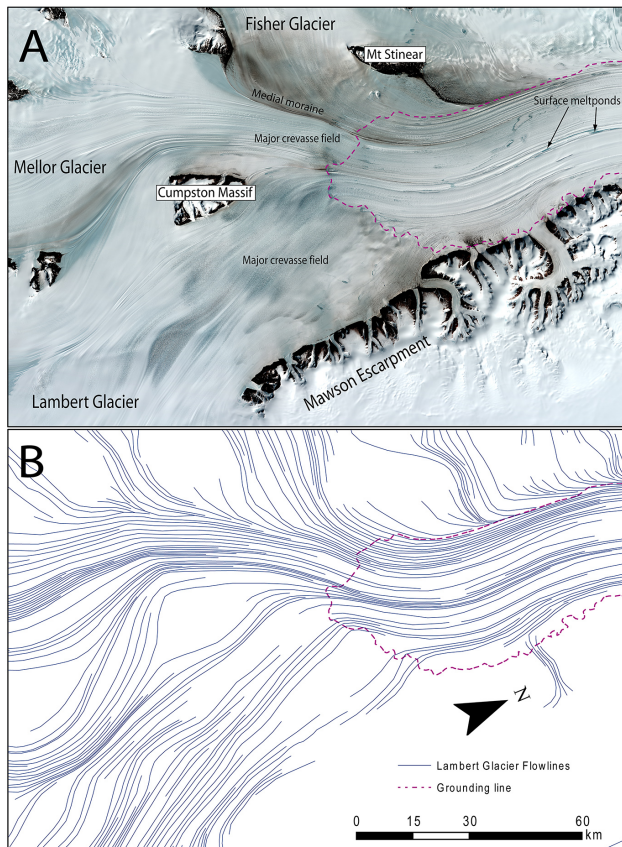


Figure 5. The confluence of the Lambert, Mellor and Fisher glaciers in East Antarctica: (a) Landsat image and (b) structural interpretation. Note that the longitudinal ice-surface structures pass uninterrupted through major crevasse fields and into an area dominated by surface ablation with visible surface melt ponds. The longitudinal ice-surface structures could not persist through crevasse fields and could not survive in areas of glacier surface melt unless they are three-dimensional structures.

3 Flow structure of the Antarctic Ice Sheet and representative ice streams

3.1 Surface areas demonstrating steady-state flow

Almost without exception, all major 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 numerous contributing lower-order tributaries into a few major outlet ice streams. Areas dominated by longitudinal ice-surface structures have sharp lateral boundaries with surrounding ice, inferred to be dominated by simple shear. They can be traced without interruption as continuous features over distances of > 1000 km through the ice streams and commonly into ice shelves. They can also be traced through crevasse fields and

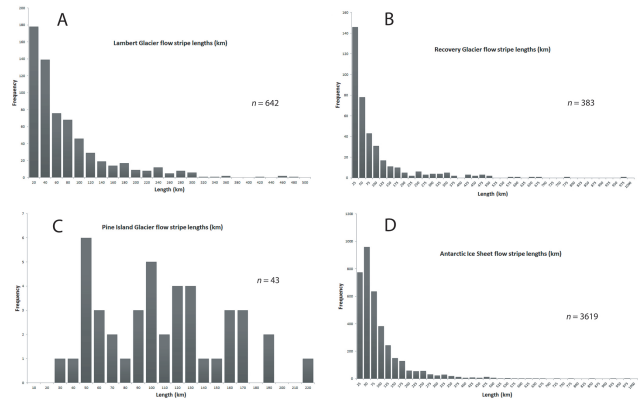


Figure 6. Histograms showing mapped flow stripe lengths for (a) the Lambert Glacier system, (b) Recovery Glacier, (c) Pine Island Glacier and (d) the entire Antarctic Ice Sheet. Note the variation in the frequency scale. The distribution is strongly positively skewed for the Lambert Glacier system, Recovery Glacier and the Antarctic Ice Sheet as a whole but not for Pine Island Glacier. Reasons for this are discussed in the text.

areas of surface ablation (blue-ice areas), implying that they are three-dimensional structures (Fig. 5).

The longitudinal ice-surface structures indicate that glacier flow reaches deep into the interior of the ice sheet. They are consistently located within areas of high glacier velocity, typically at velocities greater than about 15 m a^{-1} , or high shear 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 ice streams, where cumulative strain is greatest, 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.

Further information is provided by three high-resolution case studies. In Recovery Glacier, longitudinal ice-surface structures mark a single glacier flow unit fed by distinct tributaries (Fig. 2a). In the Lambert Glacier–Amery Ice Shelf system, three major ice streams – the Lambert, Fisher and Mellor – flow into a deep trough, a glacier-excavated tectonic rift, occupied by the Amery Ice Shelf. In addition, the ice shelf component is fed by numerous hierarchical tributaries arranged into a broad arborescent network. They are derived from the Mawson Escarpment in the east, and between various nunataks in the west (Fig. 2b). The middle reach of this glacier system is an area of net ablation, embracing both the grounded constituent ice streams and part of the ice shelf (Fig. 5). Bare ice exists over a length of several hundred kilometres and reveals pervasive longitudinal foliation, which locally is distorted transverse to flow in distributaries (Fig. 3) (Hambrey, 1991; Hambrey and Dowdeswell, 1994). The persistence of the foliation over hundreds of kilometres and its survival through crevasse fields and through areas of

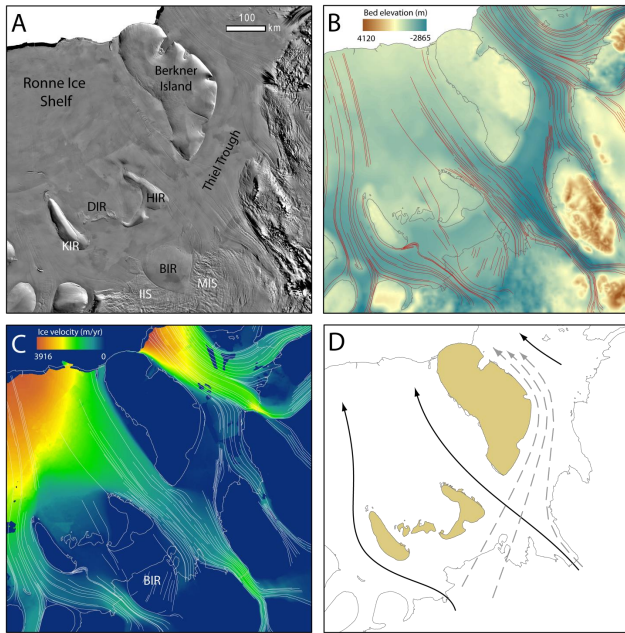


Figure 7. Maps of the Ronne Ice Shelf–Thiel Trough area. **(a)** Ice sheet/ice shelf surface from MOA. HIR: Henry Ice Rise; DIR: Doake Ice Rumples; KIR: Korff Ice Rise; BIR: Bungenstock Ice Rise; IIS: Institute Ice Stream; MIS: Möller Ice Stream. **(b)** Longitudinal ice-surface structures superimposed 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).

surface ablation indicates that this is a deep-seated, three-dimensional structure. This interpretation is supported by ground observations adjacent to one of the nunataks (Fisher Massif) on the western flank of the glacier system. The continuity of demonstrable longitudinal foliation with flowlines in snow-covered areas upstream and downstream indicates that the same three-dimensional structure is involved. 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.

The distribution of mapped flow stripe lengths (Fig. 6) is strongly positively skewed for two of the high-resolution case studies (the Lambert Glacier system and the Recovery Glacier) and for the Antarctic Ice Sheet as a whole. The distribution for Pine Island Glacier is very different, and does not display the same positive skew. This is largely a result of the satellite imagery, which does not allow us to view the full extent of flowlines for the glacier (in particular in its upper regions where there is poor contrast in the LIMA images).

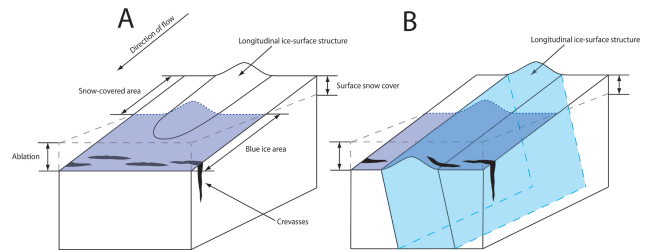


Figure 8. Schematic diagram to illustrate the expected down-ice changes in **(a)** a two-dimensional longitudinal ice-surface structure and **(b)** a three-dimensional longitudinal ice-surface structure. The major difference is that, because it is a surface-only feature, a two-dimensional longitudinal ice-surface structure cannot survive surface ablation and thus disappears down-ice as it is advected into an area of glacier surface ablation such as a blue-ice area. A three-dimensional longitudinal ice-surface structure, however, can survive surface ablation and therefore persists down-ice.

3.1.1 Surface areas demonstrating perturbed ice flow

There are two major areas of Antarctica where the longitudinal ice-surface structures appear to be perturbed relative to contemporary velocities.

1. Variations in ice discharge on the Siple Coast tributaries to the Ross Ice Shelf have been described previously (Fahnestock et al., 2000; Hulbe and Fahnestock, 2007; Catania et al., 2012). Distorted (folded) longitudinal structures are visible on the surface of the now-stagnant Kamb Ice Stream (formerly known as Ice Stream C), indicated by numbers 1 to 3 in Fig. 2d. Here 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; Engelhardt and Kamb, 2013). The ice-surface folds are interpreted as deformed longitudinal ice-surface structures inherited from a time when the ice stream was active, and subsequently 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 folding on the ice surface on the Ross Ice Shelf is a response to centennial-scale variations in input from the Siple Coast ice streams (Bindshadler and Vornberger, 1998; Fahnestock et al., 2000; Hulbe and Fahnestock, 2007; Catania et al., 2012). Similar structures occur in surge-type valley glaciers, creating distorted foliation and surface moraines in response to the switch between active and quiescent phases of flow (Lawson et al., 1994; Lawson, 1996). Thus the distorted flow structures in Kamb Ice Stream are likely to represent foliation that has become folded during a switch in flow behaviour, analogous to surge-type flow, but on longer timescales.

2. The Ronne Ice Shelf–Thiel Trough area (Fig. 7a). Large-scale ice-flow configuration in this area has been described by Siegert et al. (2013). Here, the longitudinal ice-surface structures mirror the subglacial topography everywhere other than in the Thiel Trough (Fig. 7b). 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 dominated by 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 (Fig. 7c). Here flowlines currently exist in areas of slow or non-existent ice flow. This interpretation of the large-scale ice-flow configuration is supported by radar studies of internal layering in the Bungenstock Ice Rise (Siegert et al., 2013). 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. The inference is that ice flow initially crossed Bungenstock Ice Rise and drained through the Thiel Trough, before switching at some point in the past towards the Ronne Ice Shelf (Fig. 7d).

4 Discussion

4.1 Origin of longitudinal ice-surface structures

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.

These observations above can be used to comment on the three hypotheses outlined at the outset of the paper:

- Hypothesis 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 are the surface expression of three-dimensional folding and foliation development within the ice that is under strong lateral compression. By analogy with valley glaciers with converging flow units, this process is represented by longitudinal foliation, which forms either (i) in axial planar relationship with similar-style folds or (ii) from transposition of stratification by attenuation of isoclinally folded limbs. In both cases fold axes and foliation are parallel to flow, as demonstrated by Hambrey and Glasser (2003). The continuation of longitudinal foliation through crevassed areas and through areas of

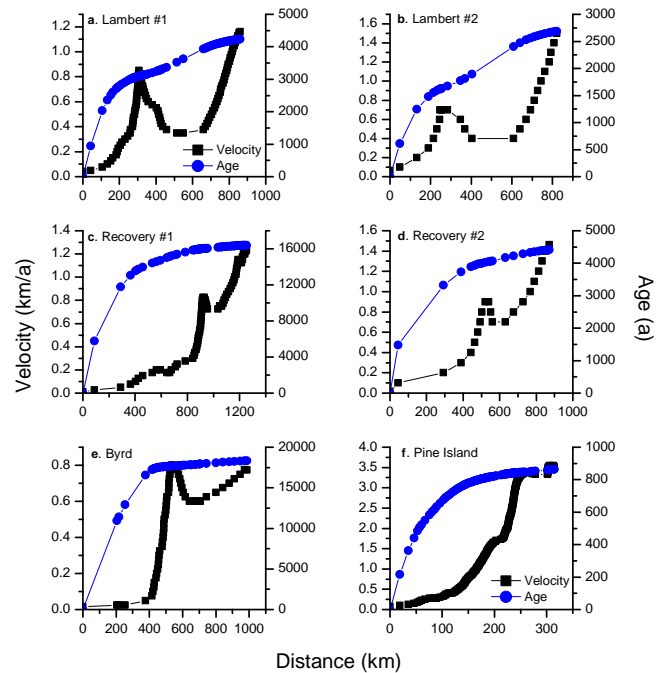


Figure 9. Plots of velocity and cumulative age with distance along uninterrupted longitudinal ice-surface structures for selected Antarctic glaciers: (a, b) Lambert Glacier, (c, d) Recovery Glacier, (e) Byrd Glacier, and (f) Pine Island Glacier.

surface ablation (e.g. in the Lambert Glacier–Amery Ice Shelf system; Fig. 5) clearly demonstrates that this is a three-dimensional structure because a surface-only structure could not persist in this manner (Fig. 8). There is therefore strong evidence in support of this hypothesis.

- Hypothesis 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. There is evidence that, where two glacier tributaries join, differential flow exists initially, promoting simple shear. This occurs throughout the depth of the flow units, so again is a three-dimensional effect. Differential flow might cease almost immediately or be maintained for short distances downstream. In the first case the structure forms initially and then is transported passively; in the second case simple shear across the flow-unit boundaries allows the longitudinal structure to continue to evolve. The three-dimensional nature of the features (see above) and their appearance at flow-unit boundaries are both lines of evidence that support this hypothesis. Related to this, and at a much smaller scale, it is possible that longitudinal ice-surface structures are the sur-

face expression of vertical sheets of changed ice fabric, but detailed field investigations are required to establish this.

- Hypothesis 3: they are the surface expression of subglacial bed perturbations created during rapid basal sliding. In this case the longitudinal ice-surface structures represent surface-only 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. Our observation that the longitudinal structures reflect the configuration of individual flow units (formation in areas of lateral compression, concentration of features at flow-unit boundaries, and formation in areas of flow convergence around nunataks) tends to suggest that these features are not the surface expression of subglacial bed perturbations.

4.2 The dynamic significance of longitudinal ice-surface structures and their relationship to ice-sheet velocities

Movement in the Antarctic Ice Sheet is dominated by basal sliding in zones of rapid velocity (ice streams) 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 kilometres of ice divides, typically at velocities greater than about 15 m a^{-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 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 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.

This is an important observation because there are no centennial to millennial records of ice velocity and associated dynamic changes in the Antarctic Ice Sheet. Direct measurement of the ice sheet is restricted to satellite-derived observations of the last 50 years (Bindschadler and Vornberger, 1998; Rignot and Kanagaratnam, 2006; Rignot et al., 2008). Velocity data from the field are temporally and spatially restricted, and it is only recently that the 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 velocity-varying components (ice streams) dominated by basal sliding (Rignot et al., 2011).

4.3 Steady-state vs. perturbed ice flow

The Kamb Ice Stream and Ronne Ice Shelf–Thiel Trough areas are important for interpreting the ice-velocity configuration of the ice sheet because they are the only locations across the entire continent where large-scale mapped longitudinal ice-surface structures do not match the contemporary glacier velocities. In the first case (Kamb Ice Stream) this can be explained by changes caused by ice-stream shutdown, and in the second case (Ronne Ice Shelf–Thiel Trough area) they can be explained by late Holocene ice-sheet and grounding-line changes. These two exceptions confirm that, for elsewhere on the continent, contemporary ice-flow configuration can be identified from the distribution of longitudinal ice-surface structures.

It is important to establish 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 Lambert Glacier and the Recovery Glacier, and one flowline each for the Byrd Glacier and Pine Island Glacier (Fig. 9). These calculations indicate that a parcel of ice may take between ~ 2500 and $\sim 18\,500$ years to travel through these glacier systems (Fig. 9). These are minimum estimates because our calculations start some way downstream of the low-velocity onset areas and actual ice-residence times may be longer. Since longitudinal ice-surface structures can commonly be followed without interruption, folding or buckling over their entire length, we infer that these structures develop near the start of flowlines and may represent the attenuated limbs of folds (transposition foliation) or axial planar foliation.

4.4 Implications for Antarctic glacial history

If there has been little change to the basic ice-dynamical organisation of the ice sheet in the recent past, then this has implications for Antarctic glacial history. 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; Taylor et al., 2004), 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, megafutes and mega-scale glacial lin-

eations 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.

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, it is possible that the basic ice-flow configuration (in terms of geometry and particle-path orientation and therefore the location of comparatively large-scale ice streams) in Antarctica has remained unchanged over these ice-residence times. It is difficult to 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. 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 the mouths of glacial troughs, creating trough-mouth fans with several hundred metres of sediment, implying that these areas have been occupied by fast-flowing glaciers and ice streams for tens of millennia (Dowdeswell et al., 2003, 2008), or even tens of millions of years, as in the case of the Lambert Glacier–Amery Ice Shelf system (Barron et al., 1991; Hambrey et al., 1991; Taylor et al., 2004); (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); and (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).

4.5 Uncertainties and further work

As noted in the Introduction, there is still uncertainty over exactly how these longitudinal ice-surface structures form and whether they are scale-dependent or scale-independent. Field studies of longitudinal ice-surface structures have by necessity concentrated on relatively small-scale valley glaciers (e.g. Hambrey and Glasser, 2003) and remote-sensing studies have concentrated on continental-scale patterns. A fruitful area for further work might therefore include investigations of the origin of flow stripes at intermediate-scale glaciers systems with bare ice in Antarctica (the Ferrar–Taylor and Hatherton glaciers are good examples). Remote-sensing studies supported by three-dimensional ground measurements and radar cross sections could be particularly insightful in this respect, as could numerical modelling of cumulative strain to demonstrate the role of simple shear at flow-unit boundaries and in zones of converging flow.

5 Conclusions

Longitudinal ice-surface structures (flow stripes) dominate the surface of the Antarctic Ice Sheet. They can be traced continuously through crevasse fields and through blue-ice areas, indicating that they represent the surface manifestation of a three-dimensional structure, interpreted here as foliation. Although longitudinal foliation can develop on glaciers in a number of situations, the most likely origin is from lateral compression and simple shear created by converging ice flow. Although it is unclear how long it takes for these features to form and decay, we infer that the major ice-flow configuration of the ice sheet may have remained largely unchanged for the last few hundred years, and possibly even longer. Ice-residence time calculations indicate that the basic, large-scale ice-sheet dynamical configuration may have remained unchanged for some parts of the continent for ~ 2500 to ~ 18 500 years. This conclusion has implications for our understanding of the long-term landscape evolution of Antarctica, including large-scale patterns of glacial erosion and deposition.

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