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Flow-stripes and Foliations of the Antarctic Ice Sheet

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Abstract

Longitudinal surface structures are flow parallel curvilineations visible on satellite imagery which are commonly observed on ice shelves, ice streams and glaciers. Their distribution and genesis has the ability to inform us about ice sheet history and glacial processes. Multiple hypotheses have been proposed for their formation. Here we present continental-scale mapping of these features across the entire Antarctic ice sheet. The accompanying map details 42,311 polylines representing longitudinal surface structures identified on satellite imagery (Landsat, RADARSAT and MODIS). The subtlety of these features provides many challenges for their identification and mapping. This work will provide the basis for future research on the morphology and formative conditions of these features in order to shed light on their genesis.

1. Introduction

Subtle flow-parallel features are visible on satellite images of the surface of the Antarctic ice sheet. They are generally observed on its outlet glaciers, ice streams and ice shelves (Figure 1). Collectively they are referred to as longitudinal surface structures (LSS's; Glasser and Gudmundsson, 2012) and are commonly subdivided into two categories. The term flow-stripe (alternatively "flow-band", "streakline" or "flow-line") is usually retained for features which occur on top of fast flowing ice streams of Antarctica (Figure 1A) and that continue onto ice shelves (Figure 1B), sustaining themselves for 100's of km (Crabtree and Doake, 1980; Swithinbank et al., 1988; Merry and Whillans, 1993). Alternatively, the term foliation is usually applied to features which are found on the surface of glaciers (Figure 1C), with numerous examples occurring worldwide (Hambrey, 1975; Hooke and Hudleston, 1978; Jennings et al., 2014). A key distinguishing feature between the two terms is that foliations are the surface expression of a three dimensional structure, caused by deformation and recrystallization of the ice (Hambrey and Glasser, 2003), whereas flow-stripes may represent variations in surface reflectance of the ice which are non-topographic (Hulbe and Whillans, 1997). However, where the three dimensional nature of LSS's visible on satellite images has been demonstrated in Antarctica (i.e. in bare ice areas), they too have been classified as foliation (e.g. Reynolds and Hambrey, 1988; Hambrey and Dowdeswell, 1994).

As LSS's align themselves parallel with flow direction, and have a long residence time on the ice surface (Casassa and Whillans, 1994), relict features have been used in Antarctica to infer ice sheet history. On ice shelves, where their orientation or position deviates from current flow conditions, they have been used to reconstruct palaeo-flow configurations (e.g. Fahnestock et al., 2000; Wuite and Jezek, 2009). LSS's found in the ice sheet interior have also been used to demonstrate switching ice stream flow direction and tributary configuration (Joughin et al., 1999; Conway et al., 2002). Additionally, flow-stripes found on the Bugenstock Ice Rise have been used to support evidence for flow direction change in the Weddell Sea sector of West Antarctica (Siegert et al., 2013). Elsewhere, the configuration of LSS's across Antarctica suggests that the configuration of the ice sheet has remained unchanged for several thousands of years (Glasser et al., 2014). However, whilst LSS's can be used as useful records of flow direction, their formation is not fully understood.

Multiple hypotheses have been proposed for the formation of LSS's (see Glasser and Gudmundsson, 2012, for a review). A leading hypothesis for the formation of flow-stripes sees them as the transmission of basal bumps in the bed to the ice surface for cases where the rate of basal sliding is high compared to internal deformation (Gudmundsson et al., 1998). Additionally, it has been suggested that the basal bump which produces flow-stripes, under the right conditions, could be a subglacial bedform (Schoof, 2002). A further relationship between LSS's and subglacial bedforms is proposed within the groove-ploughing hypothesis for the formation of mega-scale glaciation lineations (Clark et al., 2003), whereby topographic undulations on the ice surface (foliations) might prolong the attenuation of basal keels ploughing into the underlying till. Under these hypotheses, LSS's may be able to inform us about the nature of the ice-bed interface. Conversely, foliations are hypothesised to form when pre-existing inhomogeneites in the ice (i.e. crevassing, stratification) are deformed and stretched down ice flow (Hambrey, 1977), occurring where ice flow is laterally compressive and longitudinally extensional (Hooke and Huddleston, 1978; Glasser and Scambos, 2008). LSS's also form as the consequence of shear between converging tributaries (Glasser and Gudmundsson, 2012). These models view LSS's as a product of cumulative ice strain (Hambrey and Lawson, 2000, P.70), as opposed a response to properties of the bed.

The numerous examples of LSS's, and the diverse array of glaciological settings, means Antarctica is the ideal place to examine their characteristics and test the above models. Previous mapping has focused upon individual ice stream systems or ice shelves (e.g. Reynolds and Hambrey, 1988; Glasser et al., 2009; 2011; Braun et al., 2009; Holt et al., 2013 a, b). Here our aim is to document LSS's across the entire Antarctic continent. Similar work has focussed on the utility of LSS's for reconstructing ice sheet history, focussing on individual ice streams (Glasser et al., 2014). However, the aim of our mapping is to shed light on how these enigmatic features might form. It is hoped that future morphometric analysis, combined with the GIS databases detailing the glaciological characteristics of Antarctica (e.g. Rignot et al., 2011; Fretwell et al., 2013), will provide us with insight into the genesis of these features, in a similar manner to that which has been conducted upon subglacial bedforms (e.g. Spagnolo et al., 2014). Here we document and present our mapping of LSS's visible on satellite imagery across the entire Antarctic continent.

2. Methods

2.1. Data and Software

Mapping was conducted through manual on-screen digitisation at multiple scales in ESRI ArcMap 10. Cloud-free Landsat ETM+ pan sharpened images of the Antarctic ice sheet are freely available for the region of Antarctica north of 82.5˚S, and possess a horizontal pixel resolution of 15 m (http://lima.usgs.gov/). Multiple band combinations were used in this study. RADARSAT Antarctic Mapping Mission-2 SAR images have a slightly lower resolution, 25 m, but are freely available for the entire continent (http://bprc.osu.edu/rsl/radarsat/data/). In some localities the SAR waves likely penetrate the upper firn layers of the surface to depths of approximately 10-20 m (Ng and King, 2013). Additional reference was made to the MODIS Mosaic of Antarctica (http://nsidc.org/data/nsidc-0280.html). The multiple illumination angles composited into the mosaic allow for greater identification of subtle features such as LSS's. However, MODIS data has lower spatial resolution (250 m), meaning smaller features, typically found on valley glaciers, are unidentifiable on the images. Additionally, the oblique look angle of the MODIS satellite precludes mapping in valleys, as imagery is often obscured by valley walls. Although the resolution and sensor properties of the three sources of data all vary, in many places across

Antarctica the number of identifiable features, their distribution and alignment is indistinguishable between different sources of imagery (e.g. Figure 2).

The subtlety of flow-stripes and foliations makes their identification problematic. Topographic LSS's on the Amery Ice Shelf have been shown to be only 1-2 m high, with a spacing of around 1 km (Hambrey and Dowdeswell, 1994; Raup et al., 2005). Adaptive contrast stretching (i.e. using local image statistics) was utilised in order to enhance the satellite images. LSS's were mapped along their perceived crest i.e. the point of highest reflection or backscatter values. Often, features were interrupted by crevassing or by other surface features, only to reappear down-stream (Figure 3). On ice shelves, this included disruption by features which have been interpreted to be the surface manifestation of subglacial channels (LeBrocq et al., 2013; Figure 3c). Occasionally a feature would fade out as it was traced downstream. . Frequently, a second feature may reappear aligned with the original downstream, giving the impression of LSS's fading in and out of focus. As it would introduce ambiguity into our mapping, features were not joined across such interruptions. Whilst the higher resolution datasets (Landsat and RADARSAT) were preferred for mapping, all three sources were used to increase the likelihood of identifying features. Our map is genesis blind, labelling features as only LSS's, rather than classifying into separate groups.

The final map was produced in ArcGIS 10.1 and then imported into Inkscape v0.48. It is comprised of 42,311 polylines representing either entire or portions of LSS's. The background for the map is a semi-transparent hillshade of the Radarsat Antarctic Mapping Project (RAMP) DEM v.2, underlain by the elevation model itself (http://nsidc.org/data/nsidc-0082.html). The grounding line position, where ice flowing into the ocean begins to float (Schoof, 2007), is also included on in order to the map to differentiate between grounded ice and ice shelves. This was also obtained by the RAMP (http://nsidc.org/data/nsidc-0082.html). The map is projected in WGS 1984 Antarctic Polar Stereographic. In order to highlight our mapping in key regions of the ice sheet, a series of three larger scale maps is also provided.

2.2. Accuracy and Completeness of Mapping

As our map covers the whole continent of Antarctica, ground-truthing of our mapping would be inconceivable. Even so, the subtlety of LSS's may preclude their identification in the field. An alternative is to compare the satellite data in which we perceive a mappable relief to high-resolution elevation models of relief. Figure 4 shows a comparison between Landsat data and a 2 m LiDAR-derived DEM of Taylor glacier (downloaded from http://nsidc.org/data/antarctic_dem.html). As Figure 4 demonstrates, there is good agreement between the two sources of data. This provides us with some confidence that the satellite images are representative of the glacier surface at an appropriate scale for identifying LSS's. However, to our knowledge, this is the only freely available high resolution DEM covering Antarctica which contains LSS's. Although our mapping is the result of multiple passes of interpretation and from three sources of data, the large scale of the task may mean that some individual features may be missing from the final map. Additionally, subtle features that were undetected here may require more sensitive satellite instruments to detect.

3. Results

3.1. The Length of Longitudinal Surface Structures

The length and persistence of LSS's is one facet that any formational model must address (Merry and Whillans, 1993; Gudmundsson et al., 1998). Figure 5 is a histogram of the length of all mapped polylines. The sum of our length measurements totals over 650,000 km, roughly 16 times around the equator. The longest single traceable feature occurs on the Ronne Ice Shelf, and is 450 km in length. However, the distribution is heavily positively skewed (Figure 5), with the majority of measurements (80%) falling below 100km. The histogram is unimodal, and therefore does not suggest separate morphometric populations. The distribution roughly approximates a log-normal or exponential function. The histogram is strongly peaked, with a modal bin of 10km. Longitudinal surface structures are generally longer over ice shelves as opposed to on the surface of ice streams or glaciers. This is at least partially a consequence of other surface features interrupting our ability to trace longitudinal surface structures (e.g. Merry and Whillans, 1993; Figure 3B). Overall, whilst exceptionally long LSS's occur, many much smaller features can also be noted. This is perhaps partially a consequence of our mapping technique, as we chose not to interpolate between possible disruptions in LSS's (e.g. Figure 3). However, the median length of a polyline is still above 8.6 km (Figure 5), highlighting that they persist for long distances on the surface of the ice sheet.

3.2. Spatial Distribution

The accompanying map shows that longitudinal surface structures are concentrated into the ice streams and outlet glaciers of the Antarctic Ice Sheet, and producing an arborescent pattern. The majority of longitudinal surface structures therefore correspond to fast flowing areas of the ice sheet (Figure 6). Most occur where ice is flowing above 50 ma^{-1}, and nearly all features were recorded in regions where ice flows above 20 ma^{-1}. However, notable exceptions to this do occur; these are labelled on figure 6. Longitudinal surface structures are not limited to just the main channels of ice streams and outlet glaciers, and occur kilometres upflow, into their onset zones (Figure 7). Mapped features also appear to be regularly spaced

(Figure 8), especially once they have converged into a channel. However, this assertion awaits further morphometric analysis.

4. Conclusions

Our mapping reveals the distribution and occurrence of longitudinal surface structures across the Antarctic ice sheet. Landsat and RADARSAT images agree with high resolution DEMs where available, suggesting that the satellite images are of an appropriate resolution for mapping these features. However, additional high resolution datasets would provide more information on this issue and allow for a further level of morphometric analysis. Many longitudinal surface features are exceptionally long, but many shorter features also exist. The distribution of longitudinal surface structures across Antarctica conforms with the arborescent pattern of ice flow, with features generally starting at onset zones to fast flow and converging into channels where their spacing appears to be regular. The map presented here will provide the basis for further research into longitudinal surface structures on the Antarctic Ice Sheet.

5. Software

Mapping and data manipulation were conducted in ESRI ArcGIS 10.1. Further figure production was conducted in Inkscape v.0.46.

6. Acknowledgements

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7. Map Design

The accompanying map is designed to be printed on an A0 page, on account of continent wide mapping of features. The multitude of distinct features requires that a large printing size in order that they be distinguished from each other. The background of a hill-shaded digital elevation model was chosen to provide a neutral backdrop for the features, and to highlight the different between the smooth ice shelves and the interior of the ice sheet, also highlighted by the grounding-line position. The three larger scale maps of key areas of the ice sheet are presented in a similar cartographic style. Cartography was greatly improved by www.dvdmaps.co.uk.

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9. Figure Captions

Figure 1. Examples of longitudinal surface structures in different glaciological settings. A) Landsat ETM+ image of flow-stripes on the surface of MacAyeal Ice Stream. B) MODIS image of flow-stripes on the Ross Ice Shelf. C) RADARSAT image of foliations on Erskine Glacier, Antarctic Peninsula.

Figure 2. Comparison of the three sources of data used for mapping. Images of Ice Stream D, ice flow is from the top left of the image to bottom right. A) Landsat ETM+ image (15m resolution). B) RADARSAT SAR image (25m resolution). C) MODIS mosaic image (125m resolution). Features in this area are possibly clearest upon the MODIS imagery. However, there is a high level of agreement between all the images.

Figure 3. Examples of disrupted longitudinal surface structures. Disruptions labelled with arrows. A) Landsat image of crevassing disrupting longitudinal surface structures as ice flows from Lepekhin Glacier towards the top right of the image onto the Amery Ice Shelf. B) Landsat image of larger surface topography (transverse waves) interrupting longitudinal surface structures on Recovery Glacier C) MODIS image an ice shelf surface channel emanating from Slessor

Glacier, disrupting longitudinal surface structures on the Filchner Ice Shelf (formation discussed in Le Brocq et al. (2013)).

Figure 4. Visual comparison between a Landsat image (A), a hillshaded high resolution (2m) LiDAR DEM (B) and mapping (C) of longitudinal surface structures on Taylor Glacier. Whilst identification is easier upon high resolution elevation models, no new features were identified upon the higher resolution model.

Figure 5. Histogram and descriptive statistics of longitudinal surface structure length. Bin width is 500 m. Note the strong positive skew of the distribution.

Figure 6. The correspondence between longitudinal surface structures and ice velocity. Velocity data from Rignot et al. (2011) (http://nsidc.org/data/nsidc-0484.html). Areas labelled are those where structures occur on ice flowing less than 20ma-1 are labelled: S) Siple Ice Stream (Conway et al., 2002) K) Kamb Ice Stream (Catania et al., 2005) B) The Bugenstock Ice Rise (Siegert et al., 2013).

Figure 7. Longitudinal surface structures occurring in onset zones.. Images from MODIS, velocity data from Rignot et al. (2011). A) Subtle features at the onset to Lambert Glacier. B) Onset zones of Whillans and Kamb Ice Streams.

Figure 8. Examples of regular spacing of longitudinal surface structures. Background is semi-transparent MODIS image. A) Mapped longitudinal surface structures of Byrd Glacier. Note how features become evenly spaced as they converge into the main trunk of the glacier. B) Regularly spaced flow-stripes of the Institute Ice Stream (I), Bugenstock Ice Rise (B) and Foundation Ice Stream (F).