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SCIENCE

Glacial geomorphology of Marguerite Bay Palaeo-Ice stream, western Antarctic Peninsula

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This paper presents a glacial geomorphological map of over 17,000 landforms on the bed of a major palaeo-ice stream in Marguerite Bay, western Antarctic Peninsula. The map was compiled using various geophysical datasets from multiple marine research cruises. Eight glacial landform types are identified: mega-scale glacial lineations, crag-and-tails, whalebacks, gouged, grooved and streamlined bedrock, grounding-zone wedges, subglacial meltwater channels, gullies and channels, and iceberg scours. The map represents one of the most complete marine ice-stream signatures available for scrutiny, and these data hold much potential for reconstructing former ice sheet dynamics, testing numerical ice sheet models, and understanding the formation of subglacial bedforms beneath ice streams. In particular, they record a complex bedform signature of palaeo-ice stream flow and retreat since the last glacial maximum, characterised by considerable spatial variability and strongly influenced by the underlying geology. The map is presented at a scale of 1: 750,000, designed to be printed at A2 size, and encompasses an area of 128,420 km^2.

Keywords: marine; palaeo-ice stream; glacial geomorphology; Antarctica; bedform variability; geology

1. Introduction

Rapidly flowing ice streams and outlet glaciers account for dynamic mass loss from the Greenland and Antarctic ice sheets, and recent observations of their thinning and acceleration suggest that their contribution to sea-level rise is increasing (Pritchard, Arthern, Vaughan, & Edwards, 2009; Shepherd et al., 2012). Their pattern of retreat is, however, characterised by a variable, often asynchronous behaviour at short (decadal) time-scales (e.g. Moon, Joughin, Smith, & Howat, 2012; Pritchard et al., 2009). This short-term variability introduces considerable uncertainty in understanding recent ice-sheet changes and predicting near future sea-level rise, as highlighted by the Intergovernmental Panel on Climate Change (IPCC, 2007). To provide a long-term context for recent changes, therefore, numerous workers have recognised the potential of

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reconstructing palaeo-ice streams. There are now well-established criteria for recognising former ice streams in the geological record (Dyke & Morris, 1988; Stokes & Clark, 1999), which represent important archives for reconstructing ice-stream dynamics and investigating basal processes (e.g. Graham et al. 2009; Ó Cofaigh et al., 2005).

In Antarctica, the advent of multi-beam swath bathymetry systems in the mid 1990s was fundamental in facilitating the identification of marine-terminating palaeo-ice streams from the glacial geomorphic imprint preserved on the sea-floor. Over 30 palaeo-ice streams have now been documented in deep cross-shelf bathymetric troughs surrounding Antarctica, detailing the expansion of ice out towards the continental shelf edge prior to deglaciation during the last glacial maximum (cf. Livingstone et al., 2012 for a review) and several of these have been mapped in detail (e.g. Camerlenghi et al., 2001; Evans, Pudsey, Ó Cofaigh, Morris, & Domack, 2005; Graham et al., 2009; Jakobsson et al., 2012; Nitsche et al. 2013; Reinardy et al., 2011).

One of the best-studied palaeo-ice streams, with a wealth of geophysical data, was located in the area now known as Marguerite Bay on the west side of the Antarctic Peninsula (Figure 1). It constitutes a 50–80 km wide bathymetric trough, which extends for about 370 km from the inner bay at the mouth of George VI Sound to the continental shelf edge. The trough is characterised by a reverse-sloping bed that deepens from 500 m at the continental shelf edge to 1600 m on the inner shelf (Figure 1) (Jamieson et al., 2012). The inner shelf of Marguerite Bay comprises rugged bedrock characterised by large, isolated basins (up to 900 m deep), leading westwards into a network of smaller connected basins 800–1000 m deep (Anderson & Oakes-Fretwell, 2008).

2. Previous work in marguerite bay

Previous marine geophysical and geological studies of the glacial geomorphology of Marguerite Bay document a number of glacial landforms orientated along the axis of the trough and interpreted to indicate streaming flow to the shelf edge during the last glaciation (Ó Cofaigh, Pudsey, Dowdeswell, & Morris, 2002). This includes a transition from ice-moulded bedrock, drumlins and subglacial meltwater channels formed predominantly in crystalline bedrock in the inner bay, to classical drumlins, highly attenuated drumlins and mega-scale glacial lineations (MSGLs) on the mid-shelf. MSGLs up to 20 km in length are formed in sediment across the outer shelf (e.g. Anderson & Oakes-Fretwell, 2008; Dowdeswell, Ó Cofaigh, & Pudsey, 2004a, 2004b; Kennedy & Anderson, 1989; Ó Cofaigh et al., 2002, 2005, Ó Cofaigh, Evans, Dowdeswell, & Larter, 2007). Marine sediment cores recovered from the main trough in Marguerite Bay suggest a non-linear pattern of ice-stream retreat characterised by rapid deglaciation of the outer shelf at ~14 cal. ka BP, followed by a slower phase of retreat through the mid shelf, thought to be associated with the break-up of an ice-shelf (Kilfeather et al., 2011). Thereafter, retreat proceeded rapidly to the inner-shelf at ~9 cal. ka BP (Heroy & Anderson, 2007), with George VI Sound becoming ice free between 6.6 and 9.6 cal. ka BP (Hjort, Bentley, & Ingólfsson, 2001; Smith et al., 2007; Sugden & Clapperton, 1981). This final phase of deglaciation was accompanied by rapid ice-sheet thinning in the hinterland (Bentley et al., 2011). However, despite the wealth of geomorphological, and sedimentological and chronological data available for the Marguerite Bay Palaeo-Ice Stream (MBIS), a detailed map of the ice stream bed has not yet been produced. This paper draws together the available geophysical datasets and compiles a comprehensive map of the glacial landforms and sediments along MBIS (see main map) in order to develop a baseline dataset for investigating the basal properties of ice streams and for testing ice-stream models (e.g. Jamieson et al., 2012).

3. Methods

Marine geophysical data were collected on cruises JR59, JR71 and JR157 of the RRS *James Clark Ross* (*JCR*) and NBP0201 of the RV/IB *Nathaniel B. Palmer* (*NBP*) (Figure 1). Swath

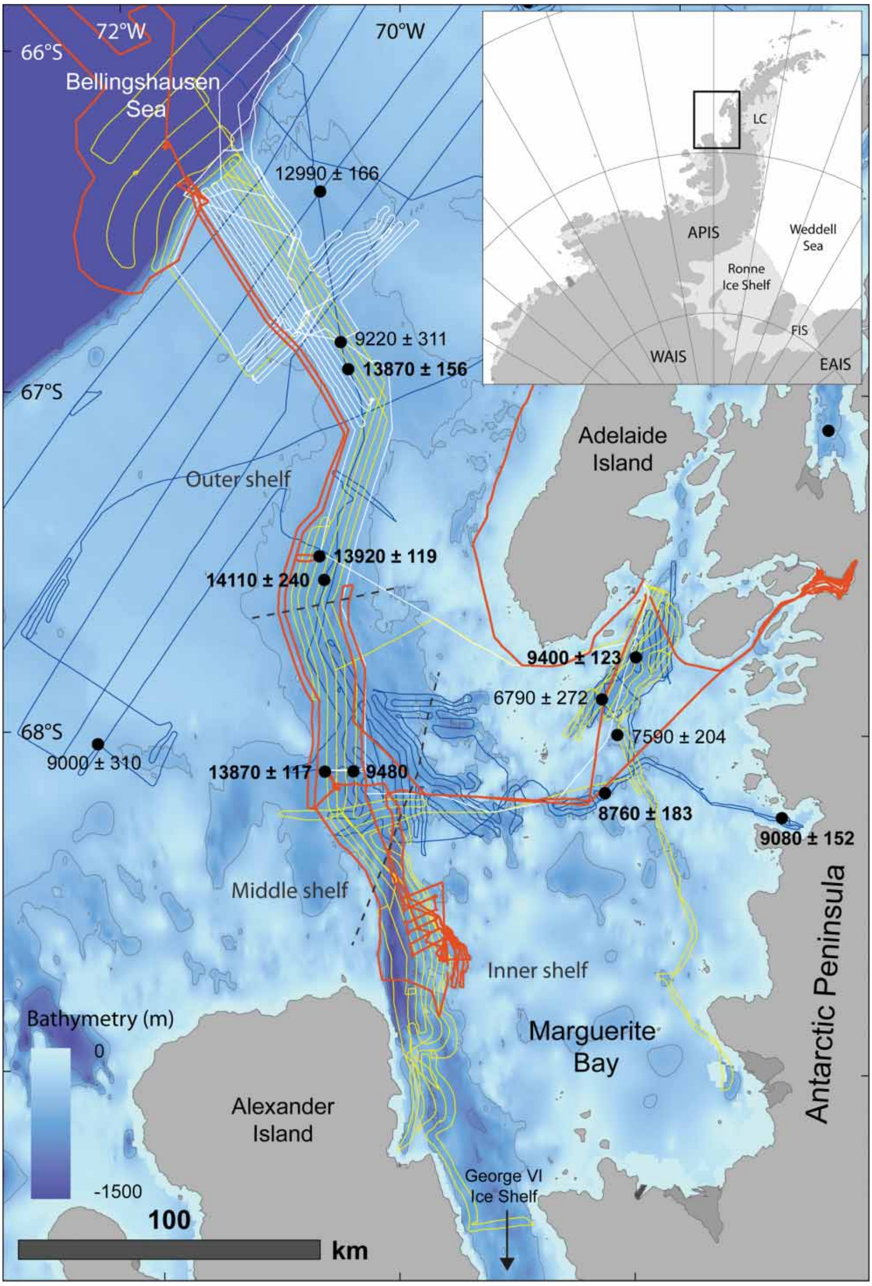

Figure 1. Overview map of Marguerite Bay Ice Stream. Swath bathymetry tracks are as follows: dark blue line: NBP0201 RV/IB *Nathaniel B. Palmer* cruise tracks; yellow line: JR59; white line: JR71; and orange line: JR157 RRS *James Clark Ross* cruise tracks. Ages (in calibrated years before present, BP) derived from marine sediment cores (as per Livingstone et al., 2012) are displayed with 1 sigma error and the dates in bold refer to the most reliable core dates (i.e. those derived from calcareous micro-(fossils) and not affected by iceberg turbation). Note that the dates suggest rapid retreat of the outer-mid shelf at ~14 cal. ka BP, followed by a period of slower retreat through the mid shelf and then another phase of rapid retreat off the inner shelf ~9 cal. ka BP (see Heroy & Anderson, 2007; Kilfeather et al., 2011). APIS: Antarctic Peninsula Ice Sheet; EAIS: East Antarctic Ice Sheet; WAIS: West Antarctic Ice Sheet; LC = Larsen C Ice Shelf; FIS = Filchner Ice Shelf.

bathymetry data were obtained using Kongsberg EM120 (*JCR*) and hull-mounted SeaBeam 2100 (*NBP*) systems. The EM120 system has a 1° × 1° beam configuration and emits 191 beams each with a frequency of 12 kHz and the hull-mounted SeaBeam 2100 system emits 120 beams at 12 kHz. Swath data were processed in MB-System (Caress & Chayes, 2003) to remove anomalous data points, corrected to include sound-velocity profiles, and gridded at 15 × 45 m cell sizes.

Table 1. Criteria for identifying and mapping glacial landforms (modified from Graham et al., 2009).

Glacial landform type	Count	Identification characteristics	Mapping style
Mega-scale glacial lineations (MSGLs)	5037	Highly elongate, parallel ridge-groove sets formed in the upper, transparent acoustic unit (soft till).	Crest-line of individual landforms
Crag-and-tail	452	A ‘tear-drop’ shaped landform with exposed bedrock at the stoss end and with a tail of tapering sediment.	Crest-line of individual landforms
(Asymmetric) whaleback/ drumlin	2761	Streamlined ‘tear-drop’ or ‘oval’ shaped hill formed in bedrock, often attenuated in the down-flow direction and with a stoss face that is sometimes steeper than the lee face. Often associated with crescentic scours around the stoss head.	Break-of slope outline of individual landforms
Iceberg scour	4246	Curvilinear furrows formed in sediment and displaying multiple orientations, which often cross-cut one another.	Crest-line of individual landforms
Gouged, grooved and streamlined bedrock	4000	Elongate, parallel or roughly parallel ridge/groove sets incised into bedrock.	Baseline of individual landforms
Grounding zone wedge (GZW)	12	Wedge-shaped landform formed in glacigenic sediment, with a steep distal sea-floor ramp and shallow back-slope. The back-slope is often lineated. Typically tens of km’s wide-long and tens of m’s high.	Crest-line of scarp slope
Subglacial meltwater channels	844	Straight to sinuous channels predominantly cut into the crystalline bedrock (although also rarely observed in sediment); typically form anastomosing networks that connect with basins or as smaller isolated channels that cut across bedrock knolls. Abrupt initiation and termination points and undulating thalwegs.	Break-of slope outline of individual channels or baseline of individual landforms; too narrow to accurately delineate the break of slope.
Gullies	181	Straight to sinuous channels formed in sediment on the continental slope, often with dendritic patterns that converge down-slope. Typically initiating at the shelf edge, gullies are sometimes eroded back into the shelf, thereby forming ‘amphitheatre’ or ‘cauliflower’ shaped heads.	Baseline of individual landforms

Vertical and horizontal uncertainties are about 1 and 5 m, respectively. Solar relief-shaded visualisations of the compiled grid were used to conduct the mapping. Two orthogonally shaded images were used to avoid azimuth bias (e.g. Smith & Clark, 2005) and the images were vertically exaggerated 20–50 times to aid identification. Glacial bedforms along Marguerite Trough were manually identified and systematically mapped in ArcGIS 9.3. The bedforms were identified according to conventional criteria (e.g. Graham et al., 2009) listed in Table 1 and discussed below.

4. Glacial landforms

4.1 *Mega-scale glacial lineations (MSGLs)*

MSGLs are highly attenuated parallel sets of grooves and ridges formed in till and commonly observed on the beds of Antarctic marine palaeo-ice streams (e.g. Canals, Urgeles, & Calafat, 2000; Evans et al., 2005; Graham et al., 2009; Shipp, Anderson, & Domack, 1999). Over 5000 MSGLs have been mapped along the length of MBIS, extending all the way to the shelf break, where they are increasingly disrupted by iceberg ploughmarks (Figure 2). MSGLs are confined to regions of weak till (e.g. Ó Cofaigh et al., 2007) and are 100–18,000 m long and 100–600 m wide, with amplitudes and wavelengths typically between 2 and 8 m and 100–700 m, respectively. The longest MSGLs are observed along the central axis of the outer-shelf trough, with the bedrock-dominated inner- and mid-shelf restricted to shorter bedforms. Although

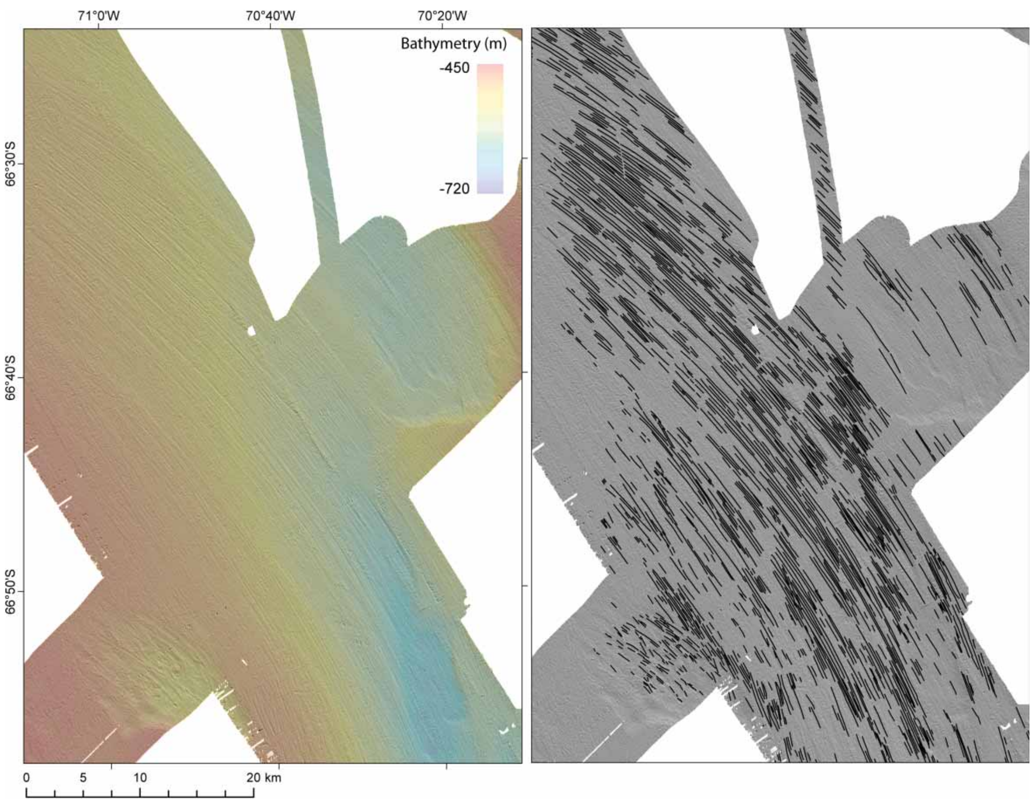

Figure 2. Example of mega-scale glacial lineations (MSGLs) on the outer-shelf of the palaeo-ice stream. The left-hand panel is the relief-shaded image and the right-hand panel shows the mapped landforms (colours are the same as in the main map). The relief-shaded image is x20 exaggeration and is shaded from the NE.

subtle shifts in MSGL orientation are observed along the length of MBIS, often associated with grounding-zone wedge (GZW) positions, they generally conform to the orientation of the trough.

4.2 *Crag-and-tails*

Crag-and-tails are tear-drop shaped bedforms with exposed bedrock at the stoss end and a tail of tapering sediment (Graham et al., 2009). The tail of sediment relates to the protection or inflow of sediment in the lee of the bedrock crag. These features are restricted to areas of bedrock with an upstream supply of sediment, either as isolated features or broad swathes in the lee of escarpments. Over 450 crag-and-tail bedforms have been mapped along MBIS, predominantly on the mid-shelf where there is a mix of bedrock and unconsolidated sediment (Figure 3). They display similar characteristics to neighbouring MSGLs, including orientation and size.

4.3 *Grooved, gouged and streamlined bedrock*

The crystalline bedrock of the inner and mid-shelf has been preferentially eroded parallel to palaeo-ice flow, creating a grooved and streamlined appearance (Figure 4), similar to other regions around Antarctica (cf. Livingstone et al. 2012; Wellner, Heroy, & Anderson, 2006). Grooves, gouges and streamlined ridges tend to be concentrated along the axis of the trough, and across highs separating

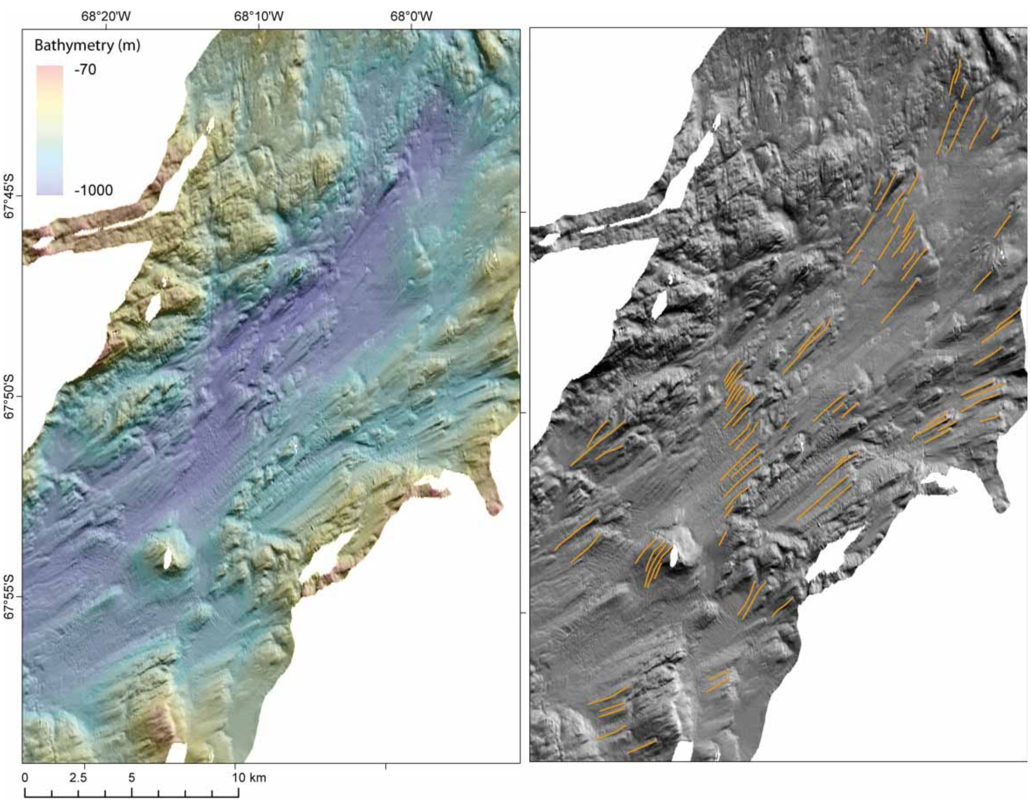

Figure 3. Example of crag-and-tails in a large isolated basin on the inner shelf. The left-hand panel is the relief-shaded image and the right-hand panel shows the mapped landforms (colours are the same as in the main map). The relief-shaded image is x20 exaggeration and is shaded from the NE.

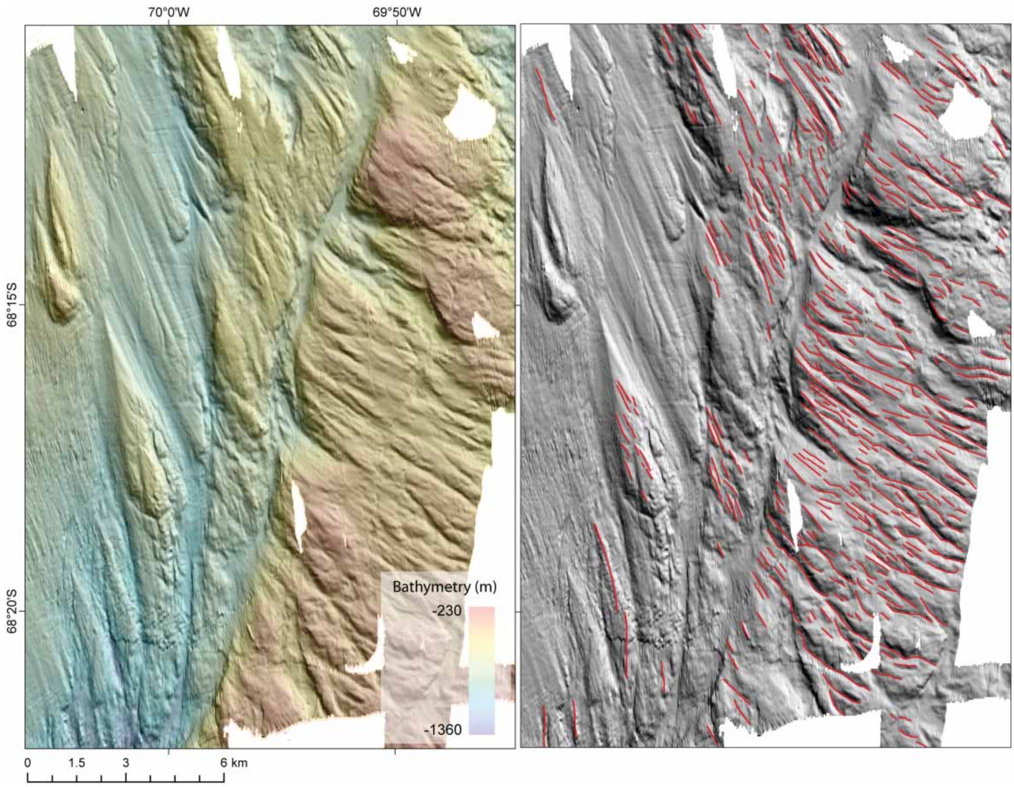

Figure 4. Example of grooved, gouged and streamlined bedrock on the mid-shelf at the transition between crystalline bedrock and sediment. Note the deep roughly parallel gouges on the east side of the image, which give way into streamlined hills, whalebacks and MSGLs further west and north. The left-hand panel is the relief-shaded image and the right-hand panel shows the mapped landforms (colours are the same as in the main map). The relief-shaded image is x20 exaggeration and is shaded from the NE.

and surrounding basins (Figure 4), while the trough flanks and the rough interior of Marguerite Bay are crudely streamlined. The features are typically 10 s of metres deep/high, although streamlined hills up to 200 m high are also observed, albeit rarely. In contrast to MSGLs, the grooves and gouges are often curvilinear, probably related to the structure of the underlying bedrock.

4.4 *Whalebacks*

Whalebacks are 'tear-drop' or 'oval' shaped hills formed in bedrock and can be described as symmetric or classically asymmetric (Table 1, e.g. Roberts & Long, 2005). They are commonly found on the inner- and mid-shelf of MBIS in crystalline bedrock, and range from crudely sculpted symmetrical features <3 km long, with elongation ratios of 2:1–4:1, to large asymmetric whalebacks up to 10 km long and with elongation ratios up to 18:1 (Figure 5). In places, whalebacks are associated with crescentic scours around their stoss ends. A clear evolution is apparent between the stubbier, crudely streamlined forms on the inner shelf, especially outside of the main trough, and the more elongate, increasingly asymmetric whalebacks observed towards the mid-shelf and on the floors of the large isolated and connected basins on the rugged inner shelf. Nearly 3000 whalebacks have been mapped along MBIS, whereas drumlins formed in unconsolidated sediment are entirely absent.

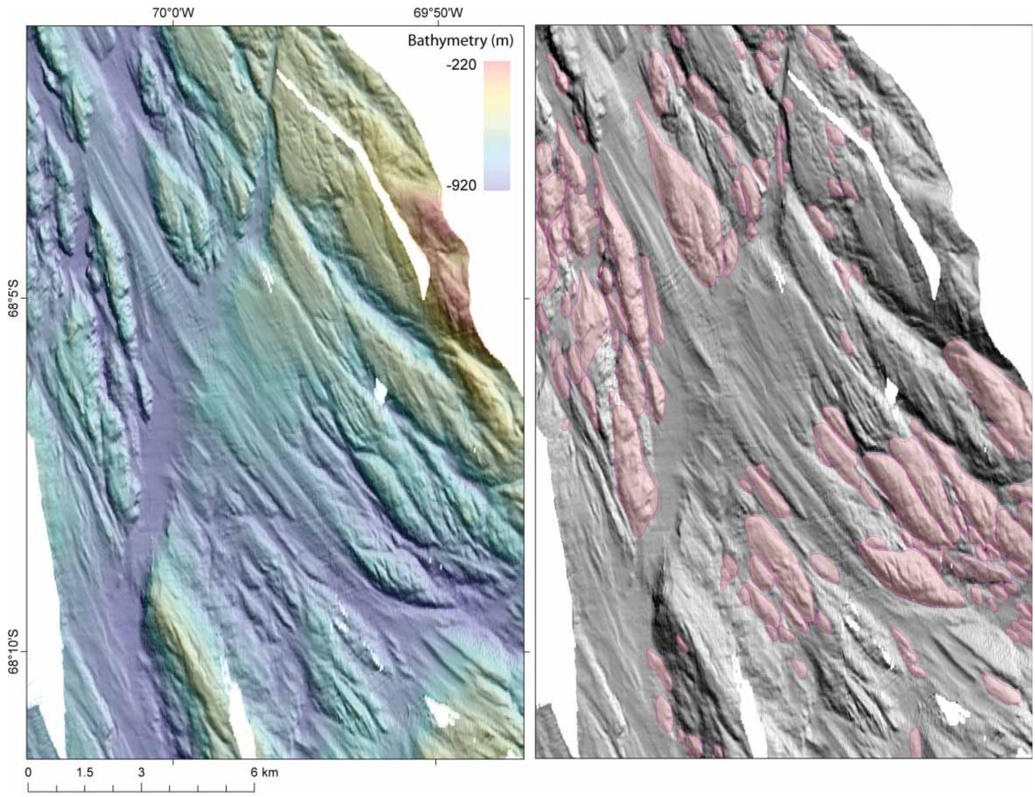

Figure 5. Examples of asymmetric whalebacks on the mid-shelf (the polygons have been filled with a red colour to further pick out the features). Note, how these features have been crudely streamlined. The left-hand panel is the relief-shaded image and the right-hand panel shows the mapped landforms (colours are the same as in the main map). The relief-shaded image is x20 exaggeration and is shaded from the NE.

4.5 *Meltwater channels*

An extensive network of subglacial meltwater channels incised into crystalline bedrock has been identified on the inner- and mid-shelf sections of MBIS (Figure 6, e.g. Anderson & Oakes-Fretwell, 2008). The channels range from straight to sinuous; have U- to V-shaped cross-profiles; abrupt initiation and termination points; undulating thalwegs; and orientations that vary from parallel to oblique to the palaeo-ice flow direction. Meltwater channels in the rugged eastern interior of Marguerite Bay are small isolated features that typically extend into large basins from bedrock highs and dissect bedrock knolls. These channels evolve westward into a coherent, anastomosing network of large meltwater channels, 300–550 m wide and 30–200 m deep, which connect deep basins and converge towards the main trough. The trough is also characterised by an anastomosing network of well-connected channels that are up to 1.5 km wide and 100 m deep (Figure 6). The meltwater channels become more disparate seawards of the transition from bedrock to sedimentary substrate, and are not observed on the sediment-floored outer-shelf.

4.6 *Grounding zone wedges (GZWs)*

GZWs are common features of Antarctic palaeo-ice streams (e.g. Graham et al., 2009; Larter & Vanneste, 1995; Ó Cofaigh et al., 2005; Shipp et al., 1999), and are characterised by a steep distal

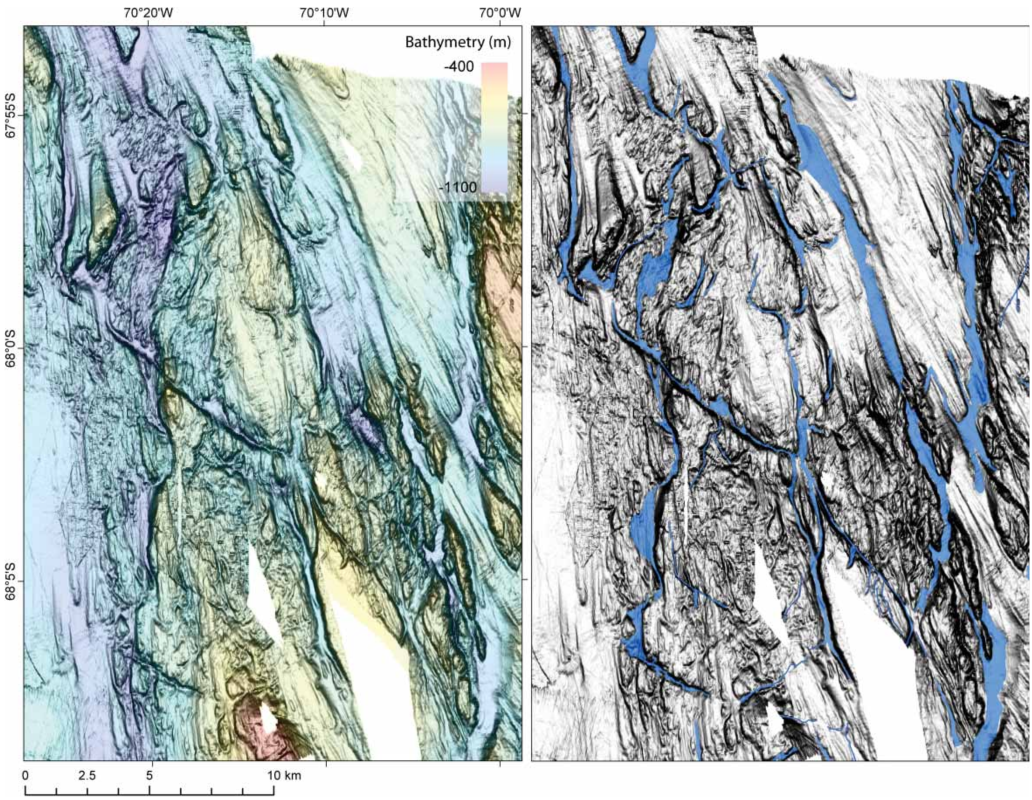

Figure 6. Example of anastomosing meltwater channel network on the mid shelf incised into crystalline bedrock. The left-hand panel is the relief-shaded image and the right-hand panel shows the mapped landforms (colours are the same as in the main map). The relief-shaded image is x20 exaggeration and is shaded from above (birds-eye view).

sea-floor ramp and shallow, commonly lineated back-slope (Figure 7). They are composed of diamicton tens of metres thick and extend for tens of kilometres (Livingstone et al., 2012). They are thought to form by the advection and deposition of sediment at the grounding-line during temporary still-stands or minor readvances (e.g. Alley, Blankenship, Rooney, & Bentley, 1989), although the exact process for sediment advection is debated (see Livingstone et al., 2012). Nine GZWs have been identified on the mid and outer shelf of MBIS, occurring both along the central axis (e.g. Figure 7) and flanks of the trough (see also Jamieson et al., 2012). Three additional GZWs have been mapped outside the confines of the main trough close to the shelf edge. These GZWs are associated with the partial preservation of MSGLs in front of their scarps. The GZWs are typically 10–40 m thick (maximum 80 m), 5–14 km wide and 3–14 km long.

4.7 *Gullies and channels*

Gullies are preserved on the uppermost continental slope in front of and to either side of the trough mouth (Figure 8, also see Dowdeswell et al., 2004a; Noormets, Dowdeswell, Larter, Ó Cofaigh, & Evans, 2009; Ó Cofaigh, Taylor, Dowdeswell, & Pudsey, 2003). They are characteristically straight to sinuous channels formed in sediment, often with a dendritic pattern converging down-slope. The gullies rarely extend more than 10 km down-slope and display a V-shaped

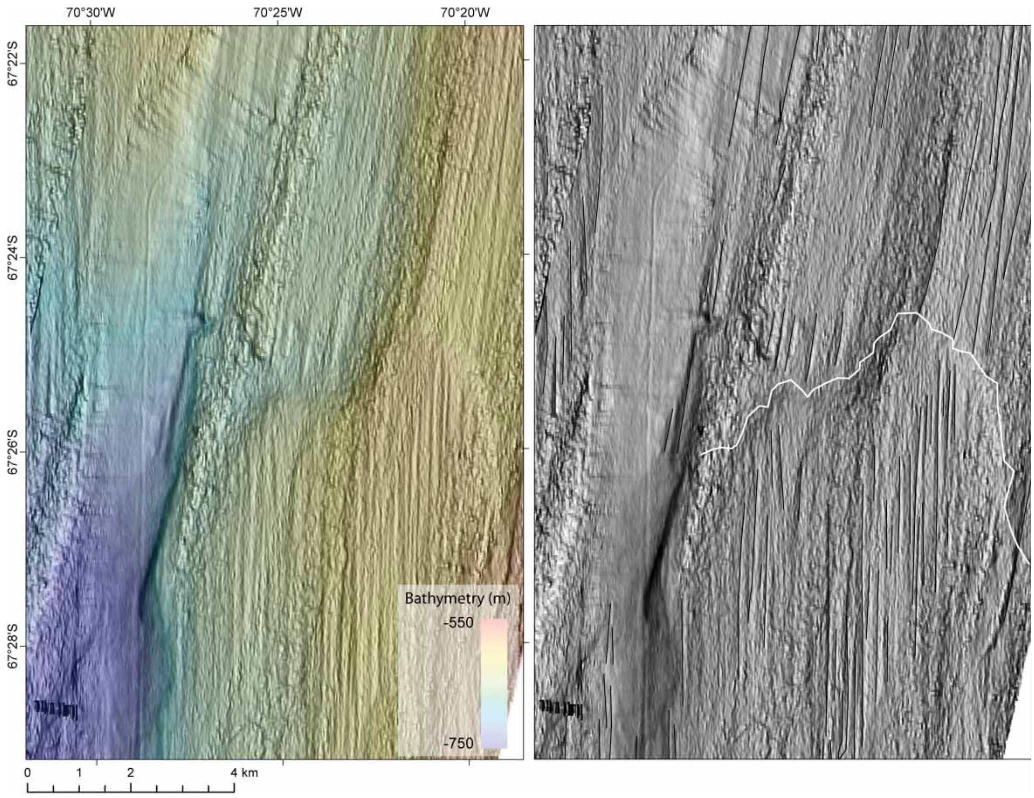

Figure 7. Example of grounding zone wedge on the outer shelf. Note the subtle difference in orientation of the MSGLs either side of the wedge crest (white line). The left-hand panel is the relief-shaded image and the right-hand panel shows the mapped landforms (colours are the same as in the main map). The relief-shaded image is x20 exaggeration and is shaded from the NE.

profile. In front of the trough, the gullies display wavelengths between 300 and 1500 m and are typically <120 m deep. Gullies on either side of the trough mouth are typically initiated at the shelf edge, but those offshore of the trough mouth are frequently seeded further down-slope. The gullied upper slope gives way to a smooth lower slope and then into large channels and sediment drifts on the upper continental rise (Figure 8).

4.8 *Iceberg scours*

Iceberg scours are present on the sediment-floored mid- and outer-shelf forming cross-cutting curvilinear furrows that are superimposed onto all the other mapped glacial features (Figure 9). They occur in water depths of 300–750 m, with a mean of 480 m, and become more prevalent towards the outer shelf, where the bed shallows. Although the iceberg scours display multiple orientations, a general SW-NE trend is apparent.

5. Discussion

The map depicts over 17,000 glacial landforms in Marguerite Bay, which record the extent of a significant (>370 km long) palaeo-ice stream along the trough that was fed by ice from George

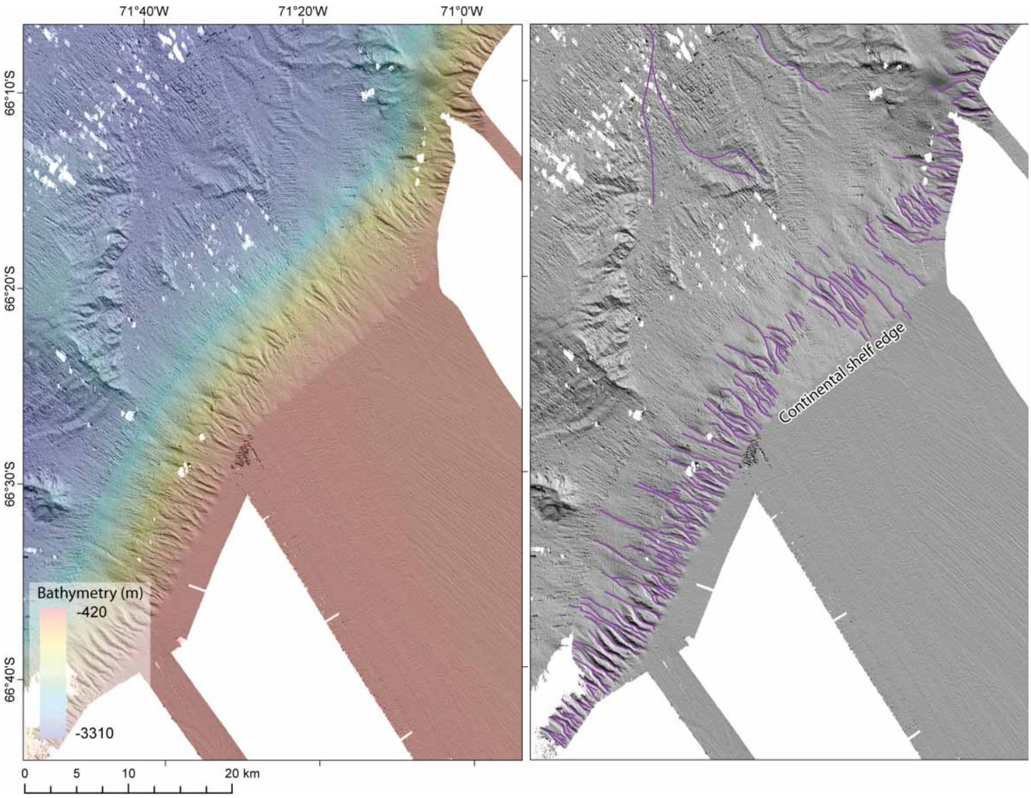

Figure 8. Example of gullies and channels on the continental slope and rise, respectively. The left-hand panel is the relief-shaded image and the right-hand panel shows the mapped landforms (colours are the same as in the main map). The relief-shaded image is x20 exaggeration and is shaded from the NE.

VI Sound and surrounding tributary regions on the inner shelf (cf. Ó Cofaigh et al., 2002, 2005). The distribution of MSGLs indicates that ice flow along the central axis of the over-deepened trough was rapid and that ice reached the shelf edge at some point during the last glacial. The identification of twelve GZWs on the landward-sloped outer- and mid-shelf documents the advection and build-up of glacigenic sediment during temporary pauses in the ice stream's recession. These GZWs are within a region thought to have undergone rapid (millennial-scale) retreat from the outer-shelf (Kilfeather et al., 2011) and must, therefore, have formed rapidly.

The spatial distribution and evolution of glacial bedforms along the MBIS is typical of Antarctic palaeo-ice streams (e.g. Camerlenghi et al., 2001; Canals et al., 2000; Evans et al., 2005; Graham et al., 2009; Jakobsson et al., 2012; Wellner et al., 2006). The rough bedrock-dominated inner-shelf region is characterised by a wide variety and spatial arrangement of bedforms, including patches of lineated sediment and a deeply incised anastomosing network of meltwater channels, which converge on the main trough. The highly variable size, elongation and depth of bedrock incisions imply a complex ice-flow history conditioned by the bedrock properties. The bedforms associated with bedrock (channels, whalebacks, and gouged, grooved and streamlined bedrock) were probably eroded over several glacial cycles (and different stages of ice-stream activity) and therefore reflect a long history of seascape evolution heavily influenced by the bedrock structure and geology (e.g. Anderson & Oakes-Fretwell, 2008; Canals et al., 2000;

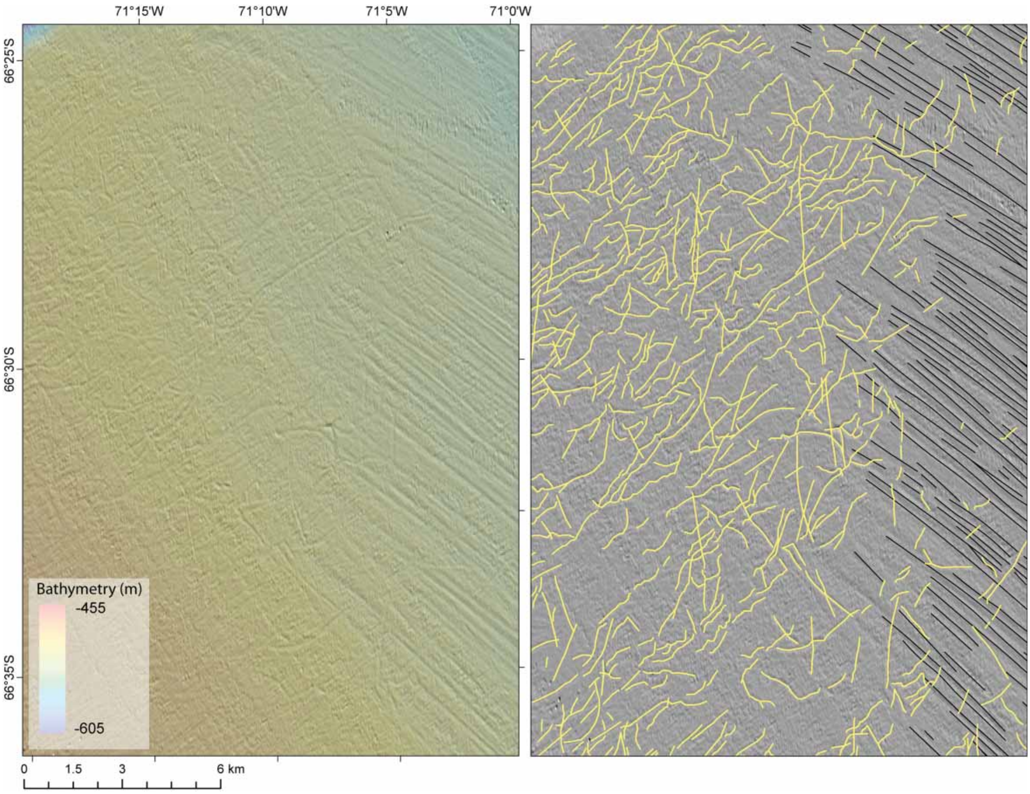

Figure 9. Example of iceberg scours on the outer-shelf. Note that the lineations are increasingly disrupted by iceberg scours and eventually disappear in a westward direction. The left-hand panel is the relief-shaded image and the right-hand panel shows the mapped landforms (colours are the same as in the main map). The relief-shaded image is x20 exaggeration and is shaded from the NE.

Graham et al., 2009; Nitsche et al., 2013; Wellner et al., 2006). Conversely, the bedforms in glacial sediments (crag-and-tail, GZWs and MSGLs) are likely to have formed during the most recent phase of ice streaming (e.g. Graham et al., 2009; Ó Cofaigh et al., 2005).

The outer shelf is dominated by highly elongate MSGLs formed in till (e.g. Ó Cofaigh et al., 2007), which probably relate to the final imprint of palaeo-ice stream activity. Although there is considerable variation in MSGL elongation, it generally increases downstream and towards the centre of the trough. Unlike the bedrock-floored inner- and mid-shelf there is no evidence of melt-water channels or related fluvial sediments on the sedimentary substrate of the outer-shelf (e.g. Kilfeather et al., 2011; Ó Cofaigh et al., 2007). Bedrock channels on the inner shelf are interpreted to have formed over many glacial cycles (e.g. Anderson & Oakes-Fretwell, 2008) and thus reflect an entirely separate temporal signature of subglacial water production and flow. It is therefore not surprising that similar features are not documented on the sediment-floored outer shelf. However, it is unknown how subglacial meltwater drained through this sector of the palaeo ice-stream. Possible mechanisms include: (i) water flow through meltwater channels or canals below the resolution of the instruments; (ii), flow as part of a dynamic network, where channels were constantly evolving due to the 'competition' between water flux and sediment creep; or (iii), via Darcian flow through the sediment (see Noormets et al., 2009).

6. Conclusions and implications

This paper presents a detailed geomorphological map of the glacial landforms along the MBIS. It shows a complex landform arrangement characterised by a progression from bedrock moulded whalebacks, gouged and grooved terrain and deeply incised meltwater channels on the inner shelf to MSGLs formed in unconsolidated sediment on the outer shelf. The mapping carried out in this study is a useful dataset for further detailed quantitative analysis of the bed characteristics of the MBIS and the formation of subglacial bedforms. Furthermore, it offers robust boundary conditions for ice-stream modelling experiments (e.g. Jamieson et al., 2012), which require data about the spatial extent and direction of flow in combination with data about the strength of the ice stream bed. With this in mind, the geomorphological record is supplemented by information from marine sediment cores and shallow acoustic seismic profiles collected along the length of the palaeo-ice stream (e.g. Ó Cofaigh et al., 2002, 2005, 2007; Kilfeather et al., 2011), which provide further data on the sedimentology and deglacial chronology of the region. The latter is well constrained by marine radiocarbon dates predominantly obtained from calcareous (micro-) fossils (Heroy & Anderson, 2007; Kilfeather et al., 2011; Livingstone et al., 2012).

Software

MB-System was used to process and grid the geophysical data collected on the research cruises. Relief-shaded visualisations of the bathymetry data and on-screen digitisation of the landforms were produced using Esri ArcMap 9.3. The map was initially produced in ArcMap 9.3 and then exported to Adobe Illustrator for editing.

Acknowledgments

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