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The Cryosphere Discussions

Antecedent control on active ice sheet retreat revealed by seafloor geomorphology, offshore Windmill Islands, Antarctica

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Abstract. Understanding past retreat of Antarctic ice margins provides valuable insight for predicting how ice sheets may respond to future environmental change. This study, based on high resolution multibeam bathymetry from the nearshore region of the Windmill Islands, East Antarctica, reveals a style of retreat that has been rarely observed on the Antarctic margin. A suite of seafloor features record the final retreat stages of a relatively thin, and increasingly fractured tidewater glacier confined within narrow troughs and embayments, forming a suite of features more typical of warm-based ice, but occurring here in a region of cold-based ice with limited surface meltwater production. The pattern of moraines and crevasse squeeze ridges, reveals strong topographic and substrate control on the nature of ice sheet retreat. Topographic control is indicated by fine-scale variability in the orientation and distribution of glacial landforms, which show that the seabed topography influenced the shape of the ice margin, caused deflection of ice flow and led to the separation of flow downstream from topographic highs. The availability of water saturated marine sediments within the troughs and depressions also had a profound effect on the landform record, facilitating the construction of moraines and crevasse squeeze ridges within topographic lows, corresponding to areas of modern sediment accumulation. Surrounding areas of crystalline bedrock, by contrast, acted as "sticky spots" and lack a well-developed landform record. This seafloor glacial record emphasises the importance of understanding the bed topography and substrate when predicting the nature of ice margin retreat and provides new perspectives for understanding the stability of the East Antarctic margin.

1 Introduction

Features revealed by high resolution multibeam mapping on glaciated margins are increasingly providing new insights into the processes, behaviour and patterns of ice margin advance and retreat over glacial and interglacial cycles on the Antarctic margin (e.g. Anderson et al., 2001; Fernandez et al., 2018; Halberstadt et al., 2016; Heroy and Anderson, 2005; Jakobsson et al., 2012; Livingstone et al., 2013; Wellner et al., 2001; Wellner et al., 2006), and ice sheet response to Holocene climate variability in Antarctic (e.g. García et al., 2016; Munoz and Wellner, 2018) and other glacial settings (e.g. Dowdeswell et al., 2016; Dowdeswell and Vásquez, 2013; Ottesen and Dowdeswell, 2009). Understanding the past behaviour of ice sheets is crucial for anticipating the effects of future warming on ice sheet retreat. Much recent work has focussed on those parts of the

Antarctic ice sheet that are grounded below sea level on reverse-sloping beds. Ice sheets in these settings are particularly vulnerable to rapid retreat due to sub-glacial marine incursion, causing marine ice sheet instability (Bindschadler, 2006; Schoof, 2007). For the East Antarctic Ice Sheet (EAIS), these areas have the potential to contribute ~20 m to global sea level rise (Fretwell et al., 2013). However, over 60% of the EAIS is contained in basins grounded above sea level on beds that are not on reverse slopes. The potential response of these seemingly more stable parts of the EAIS to changes in climate is not well understood.

Patterns and rates of ice sheet flow have been shown to be strongly governed by the topography and substrates of the sub-glacial bed (e.g. Alley, 1993; Jamieson et al., 2016; Livingstone et al., 2016; Stokes et al., 2007). At large scales, airborne geophysical surveys over the East Antarctic Ice Sheet (EAIS) have confirmed the correlation between thick marine sedimentary basins and areas of high ice flow rates (e.g. Aitken et al., 2014; Bamber et al., 2006; Ferraccioli et al., 2009). At local-scales, the distribution of sediment versus bedrock on Antarctic inner shelf margins is reflected in the spatial variability of seafloor glacial features (e.g. Klages et al., 2013; Larter et al., 2009; Livingstone et al., 2013; Nitsche et al., 2013). Extensive areas of crystalline bedrock can create pinning points (e.g. Hogan et al., 2020) and “sticky spots” beneath the ice sheet resulting in very slow moving or static ice (e.g. Alley, 1993; Stokes et al., 2007). The resulting contrasts in ice velocity between areas of slower and faster-moving ice create stress within the ice sheet (Stokes et al., 2007), which can result in lateral shear zones (Stokes and Clark, 2002).

Topographic variation also influences ice sheet flow patterns. At the scale of the continental shelf, ice sheets flow around features such as large shelf banks (e.g. Halberstadt et al., 2016; Shipp et al., 1999), while at much smaller scales ice flow can become confined within coastal embayments and nearshore fjords (Dowdeswell and Vásquez, 2013; García et al., 2016; Munoz and Wellner, 2018; Ottesen and Dowdeswell, 2006). As the ice margin thins the influence of the underlying bed topography and substrate variability become more pronounced and the ice margin more dynamic. Thin retreating tidewater glaciers record features, such as overlapping moraine ridges and crevasses squeeze ridges (CSRs), indicative of rapid reorganization of the ice front and the formation of surging fingers of ice (Todd and Shaw, 2012) intersected by longitudinal radial crevasses (Boulton, 1986; Evans et al., 2016, 2017).

This paper utilises the high-resolution survey data obtained by Carson et al. (2017) to present a detailed interpretation focussed largely on the glacial retreat features preserved on the seafloor in the northern Windmill Islands region. Carson et al. (2017) provided evidence of expansion of the Law Dome ice margin onto the East Antarctic continental shelf leaving behind a complex record of glacial geomorphological features preserved on the seafloor. Some of the features, such as meltwater channels, likely represent ice sheet expansion over several glacial cycles, while others may correspond to a more recent advance of the western Law Dome ice margin. Terrestrial research suggests a mid- to late Holocene readvance of the Law Dome ice margin after ~ 4.5 to 4.0 ka BP (Goodwin, 1998). This paper focusses on the most recent part of the landform record, which may correspond to this mid- to late Holocene readvance of the Law Dome margin. A new interpretation of the geometry and style of ice margin retreat is presented, consistent with modern observations of glacial retreat on Iceland (e.g. Boulton, 1986; Evans et al., 2016, 2017) and seafloor features observed in other coastal embayments and channels including Svalbard

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(Ottesen and Dowdeswell, 2006), Chile (Dowdeswell and Vásquez, 2013) and the Antarctic Peninsula (García et al., 2016; Munoz and Wellner, 2018). The features presented here reveal the dynamics of an actively retreating tidewater glacier during the final stages of retreat, and demonstrate that the pattern of retreat was controlled by antecedent conditions, largely the bedrock topography and the distribution of sediments within small sedimentary depressions, troughs and channels.

2 Setting

The survey area is located on the western flank of Law Dome; an ice dome isolated from the main EAIS on the Wilkes Land coast of East Antarctica between 110°E and 115°E. A significant proportion of the western part of the Law Dome and EAIS are drained via the Aurora subglacial basin into Vincennes Bay by the Vanderford and Adams glaciers (Young et al., 2011). The Windmill Islands region comprises a number of typically ice- and snow-free peninsulas and offshore islands (Figure 1). Its southern limit, located 25 km to the south of Casey station, is marked by the Vanderford Glacier which occupies a northwest-trending trough up to c. 2100 m deep at the seaward-end (Harris et al., 1997). The topography of the northern part of the Windmill Islands region is typically low-lying, whereas to the south the landscape is more rugged with high, steep coastal cliffs. The bedrock geology is dominated by Mesoproterozoic granulite-facies metamorphic and igneous crystalline rocks (Paul et al., 1995; Post et al., 1997; Zhang et al., 2012). Brittle faulting, most likely related to the break-up of eastern Gondwana and rifting of Australia from Antarctica during the Cretaceous, has had a strong control on the glacial landform record across this area (Carson et al., 2017).

Early- to mid-Holocene raised beach sequences have been mapped at elevations of ~30 m on Clarke and Bailey Peninsulas (Goodwin, 1993). Observations across the Windmill Islands have been used to derive a Holocene sea-level curve, indicating that sea level across the northern Windmill Islands was +40 m following deglaciation (at ~12 ka), and decreased gradually to the modern day in response to isostatic rebound (Whitehouse et al., 2012).

3 Methods

High-resolution multibeam sonar data were acquired as part of a collaborative programme between the Australian Antarctic Division (AAD), Royal Australian Navy (RAN) and Geoscience Australia (GA) in the Windmill Islands region, offshore Casey research station (for details see Carson et al., 2016; Carson et al., 2017). In summary, an area of 7 km^2 was surveyed by the RAN in 2013/14 with a dual frequency Reson 7125 (200–400 kHz) single-head multibeam sonar system, with an additional 27 km^2 surveyed in 2014/15 by GA/RAN using a Kongsberg EM3002D (300 kHz) dual-head multibeam sonar system. All multibeam data was processed using CARIS (HIPS and SIPS) v7 and v8 software. Tidal corrections were made using tide data recorded from the Casey wharf tide gauge and sound velocity profiles taken regularly across the survey area (Carson et al., 2016). The final bathymetric grids were produced at 1 m resolution. A backscatter mosaic at 2 m resolution was produced for the Kongsberg data using QPS FMGT. The quality of the Reson backscatter data was insufficient to produce a mosaic.

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Glacial features preserved on the seafloor of the Windmill Islands were mapped in ArcGIS through manual digitisation of glacial landforms as vectors. Profiles were drawn across key features using the ArcGIS 3D Analyst toolbar. Glacial features are referred to here as 'glacial landforms' to distinguish them from bedforms produced as a result of contemporary marine processes. Landform definitions were revised from those presented in Carson et al. (2017) to include CSRs and to map many additional smaller moraines that define the shape of the ice margin during retreat (e.g. Fig. 2). Major moraines were also mapped separately from other moraines to highlight pinning points and pauses in ice sheet retreat. The definition and interpretation of these features is further explained in Sect. 3.

4 Results and interpretation

4.1 Lineations

4.1.1 Observations

Lineations are relatively rare and subtle features in this dataset. They are most common in troughs, channels and depressions, where they record an ice advance direction of SE–NW to E–W (Fig. 2–5); Carson et al. (2017) also observed streamlining over areas of bedrock. The lineations range in length from 15–500 m, are often only <1 m high and 5 – 30 m wide.

4.1.2 Interpretation

The orientation of the lineations indicates that ice flow was aligned to the primary SE–NW direction within the major fault-controlled troughs and channels, becoming more E–W directed further offshore and away from the fault controlled troughs and channels. The subtle, smooth nature of the features indicates that they have been overridden since their formation.

4.2 Moraines

4.2.1 Observations

Extensive areas of moraines are preserved in four main settings within the Windmill Islands area, namely: bedrock depressions (Fig. 2); low relief sediment-lined depressions (Fig. 3); narrow troughs and channels (Fig. 4, 5); and within broad embayments (Fig. 4; Table 1). Low backscatter intensity across these areas (where available) indicates that they also correspond to areas of modern sediment accumulation, consistent with the smooth appearance of the seafloor between landforms. Areas of rough bedrock forming shallow banks (e.g. around Dahl and Beall Reefs), by contrast, have high backscatter indicating coarser grained material or rock at the surface. Moraines are either poorly developed or absent over these bedrock areas (Carson et al., 2017).

Moraines vary in shape from linear to rectilinear, arcuate, hairpinned and irregular forms, according to changes in the local bed topography and structure of the ice sheet margin. Hairpinned and arcuate forms occur within the narrowest and most constricted parts of troughs and channels and are confined within these topographic lows (Fig. 4 and 5), while rectilinear to linear forms are associated with broadening channels and embayments (Fig. 4). The moraines and associated CSRs often truncate older moraines (see Fig. 4). In all settings the moraines form closely spaced sets (Table 1).

Most moraines are sharp crested and vary between symmetric to asymmetric in cross-section. Asymmetric moraines have a steeper distal (down-flow) facing slope (e.g. profiles on Fig. 4). The moraines are generally low amplitude, reaching only a few meters in height. However, a few do reach up to 25 m high and are laterally more continuous and have a much greater width (Table 1) than the low amplitude moraines. These larger moraines are distinguished as “major moraines” and are most pronounced within troughs where they are associated with bedrock highs (Fig. 4b).

The orientation of the moraines records the changing shape and orientation of the ice margin during its retreat across the Windmill Islands. Areas furthest offshore record a retreat from W–E (Fig. 3). However, within the two main fault controlled troughs and channels (i.e. the trough connected to Newcomb and the channel extending from O’Brien Bay) the orientation of the moraines indicates a shift in retreat towards NW–SE, parallel to the trough/channel orientation (Fig. 4). Channel ‘A’, to the south of Beall Reef is orientated ENE–WSW. The orientation of moraines within this channel indicates a W–E directed retreat, while smaller channels immediately to the south record a return to NW to SE retreat, consistent with the orientation of these small channels (e.g. Robertson Channel; Fig. 5). The steep escarpment north of Channel ‘A’ provides evidence for a single breach in the ice margin onto the bedrock platform; a small channel incised into the bedrock west of Beall Reef contains a number of small recessional moraines (Fig. 5).

4.2.2 Interpretation

As described by Carson et al. (2017), the geometry of the moraines observed across the offshore Windmill Islands is consistent with their formation as push moraines. This indicates an active retreat punctuated by minor readvances, occurring possibly on a seasonal to decadal time-scale in response to local climate driven changes in advance (winter) and retreat (summer) (Boulton, 1986; Ottesen and Dowdeswell, 2006; Evans et al., 2016). The close spacing of moraine ridges within the troughs and channels indicates that the velocity of winter ice flow is just exceeded by the summer retreat rate (Boulton, 1986). The moraines are typically arcuate or at least rectilinear, asymmetric to symmetric, with a steeper distal facing slope, reflecting the remoulding of material at the front of the ice margin during minor readvances (e.g. Boulton, 1986; Evans et al., 2016; Ottesen and Dowdeswell, 2006). The arcuate form of the moraines is typical of push moraines that form from a lobate ice margin, intersected by longitudinal crevasses (Boulton, 1986). Arcuate push moraines have been reported from many fjords and embayments, including Svalbard (Ottesen and Dowdeswell, 2006), Nova Scotia (Todd and Shaw, 2012), Chile (Dowdeswell and Vásquez, 2013), and the Antarctic Peninsula (García et al., 2016) and are associated with retreating tidewater glaciers. In these settings, as in the Windmill Islands region, push moraines have been observed to become increasingly arcuate, or finger-like, in areas where they are constrained by the fjord or channel walls, turning to follow the bathymetric contours. Overlapping ridges form complex networks, with older moraines overprinted by younger moraines, reflecting continual reorganization of a dynamic ice front, characterized by surging fingers of thin ice during overall retreat (Todd and Shaw, 2012). Sharp crests indicate that these features have not been overridden during slight readvances of the ice margin.

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A number of much larger (15–25 m high) laterally continuous moraines (“major moraines”) extend over areas of bedrock in the trough leading into Newcomb Bay (Fig. 4b, Table 1). These features clearly truncate and therefore postdate the relatively smaller recessional moraines present immediately to the northwest (ice distal) of these more prominent features. These relatively large moraines are typically located on the crests of bedrock highs, which acted as pinning points leading to the construction of larger moraine ridges. The construction of ridges of this magnitude likely requires a still stand in ice retreat lasting decades to centuries (DaSilva et al., 1997).

4.3 Crevasse squeeze ridges

4.3.1 Observations

Crevasse squeeze ridges (CSRs) observed in the Windmill Islands area are relatively straight and are characterised by sharp crests and a symmetric cross-sectional shape, typical of their formation in other nearshore settings (Ottesen and Dowdeswell, 2006). Lineations, by contrast, have a much more subdued imprint. The CSRs are 0.5–2 m high and typically occur at the ends of moraines, or between limbs of the moraines (Fig. 3, 4 and 5), and are orientated oblique to the push moraines and sub-parallel to ice flow. They are well-developed on the margins of the sediment-lined troughs and channels where they reach lengths up to 300 m (Fig. 4). CSRs in this area were previously mapped as part of moraines and as lineations (Carson et al., 2017, Fig. 3). Their separation as distinct features in this study reflects a new interpretation of the geometry and style of ice margin retreat, consistent with modern observations of tidewater glacial retreat (e.g. Boulton, 1986; Evans et al., 2016, 2017).

4.3.2. Interpretation

The sharp crested nature of the CSRs and their clear spatial and morphological link to the recessional moraines clearly distinguishes them from the low-lying more gently undulating streamlined lineations. The subdued character of the lineations results from them having been partially overridden during minor readvances of the ice sheet during its overall retreat, associated with the formation of push moraines. The sharp crests of the CSRs indicates that these features have not been overridden, and are therefore associated with the final stages of ice streaming and deglaciation, facilitating their preservation.

Crevasse squeeze ridges are typically well-developed adjacent to margins of the troughs and channels, possibly reflecting a greater crevassing within the ice caused by lateral shear against the bedrock slopes of these features. This pattern of shearing is particularly pronounced along the margin of the trough northwest of Newcomb Bay where ridges up to 250 m long are preserved (Fig. 4b). The occurrence of longitudinal ridges adjacent to channel walls has also been mapped within Marguerite Bay (García et al., 2016), Hope Bay and Potter Cove (Munoz and Wellner, 2018) on the Antarctic Peninsula. In Hope Bay and Potter Cove, these ridges are identified as CSRs and occur as cross-cutting or isolated ridges within confined, shallow settings, similar to their occurrence in the Windmill Islands region. This contrasts to observations of CSRs from open shelf settings on the Antarctic margin, where they have been recorded as symmetric ridges formed transverse to ice flow (e.g. Greenwood et al., 2018; Klages et al., 2013). Longitudinal CSRs formed sub-parallel to ice flow direction are more typical of features

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observed in both marine and terrestrial terminating glaciers on Iceland (Boulton, 1986; Evans et al., 2016, 2017) where an irregular and highly fractured ice margin is intersected by longitudinal radial crevasses separating finger-like pecten of ice (e.g. Fig. 6). Radial crevasses at the glacial margins form networks of ridges orientated obliquely to push moraine crests as subglacial sediment is squeezed up into the crevasses. We propose that this mechanism best explains the features recorded within troughs and channels in the Windmill Islands.

4.4 Boulder chains

4.4.1 Observations

Boulders (erratics, up to 2 m high) are scattered across an area of low lying bedrock to the northwest of Clark Peninsula. Many of these form NW-SE-trending chains occurring parallel to CSRs and streamlined bedforms, and NE-SW-trending boulder chains which occur parallel to the recessional moraines (see inset on Fig. 2). Large erratic boulders are also observed perched on the crests and slopes of the moraines.

4.4.2. Interpretation

The ice flow parallel boulder chains are analogous (but on a smaller scale) to ‘rubble flutings’ described from the bed of the Laurentide Ice Sheet in Alberta Canada where they represent detached blocks of bedrock incorporated into the base of the ice (Atkinson et al., 2018; Fenton et al., 1993). In contrast the perched boulders and erratic chains which occur parallel to the recessional moraines are more likely to represent debris falling from the ice sheet margin during retreat, which suggests that there was no ice shelf formed during this stage of the retreat. The absence of an ice shelf would indicate that the water depth was shallow relative to the thickness of the ice, forming a tidewater glacier. Relative sea level measurements (Whitehouse et al., 2012) and raised beach deposits (Goodwin, 1993) in the area indicate that Holocene sea level was slightly higher than the present water depth of 40–50 m across this depression. The available multibeam data suggests that the boulder chains are largely restricted to the area northwest of Clark Peninsula suggesting that there is a bedrock and topographic control on the occurrence of the relatively higher concentration of erratics in this area.

5. Discussion

The glacial landforms from the Windmill Islands record the steady retreat of an increasingly fractured ice sheet margin across the seafloor. Interpretation of the glacial landforms provides important context for understanding the dynamics and drivers of ice margin retreat across a shoaling bed, demonstrating the sensitivity of this region to a changing climate. Two main factors drive the pattern of ice retreat across the Windmill Islands: the distribution of sediments versus bedrock at the glacial bed and the shape of the underlying topography.

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5.1 Sedimentary control on ice sheet behaviour

Local-scale variations in ice sheet basal processes can reflect the distribution of sediment versus bedrock, as has been recorded by spatial variability in landform records on Antarctic inner shelf margins (e.g. Klages et al., 2013; Larter et al., 2009; Livingstone et al., 2013; Nitsche et al., 2013). Within the Windmill Islands, constructional glacial landforms, such as moraines and CSRs, are most well-developed within troughs, channels and minor depressions, while they are poorly preserved over adverse slopes and bedrock highs (Fig. 2–5; Carson et al., 2017). The channels/troughs and depressions are areas of modern sediment accumulation, as revealed by low backscatter intensity (where available), the smooth appearance of the seafloor between landform features and the partial burial of finer scale features. The availability of water saturated marine sediments within the channels/troughs and depressions likely enhanced lubrication at the bed, and provided a source of sediments with which to construct and preserve a landform history. The lack of sediment over topographic highs, by contrast, would have prevented landform construction. The bedrock depression west of Clark Peninsula (Fig. 3) reveals a clear association between areas of recent sediment accumulation (as indicated by low backscatter intensity) and the previous formation of minor moraine ridges, while areas of surrounding bedrock, which have no evidence for sediment accumulation, contain no moraines.

The extensive areas of crystalline bedrock (e.g. surrounding Dhal, Gibney and Beall Reefs) may have also created "sticky spots" beneath the ice sheet, resulting in either very slow moving or even static ice (e.g. Alley, 1993; Stokes et al., 2007). The potential occurrence of "sticky spots" beneath the western margin of the Law Dome during its advance over the Windmill Islands region is supported by the absence or, at best, weakly developed nature of streamlined landforms in the topographically higher bedrock areas (see Carson et al., 2017). In contrast to these bedrock highs, water-rich marine sediments within the depressions (including troughs and channels) would have reduced friction at the base of the ice sheet, promoting forward motion by either basal slip and/or soft-bed deformation, and preserving streamlined lineations within the sediment-lined depressions and channels/troughs (Fig. 3, 4, and 5) (c.f. García et al., 2016; Larter et al., 2009; Livingstone et al., 2013). The association between areas of sediment accumulation in topographic lows and the formation of constructional glacial features indicates the importance of both a local sediment source and topographic control in producing the landform record.

5.2 Topographic control on ice sheet behaviour

Topographic control on ice margin behaviour during retreat is a distinctive feature of the Windmill Islands data, creating fine-scale variability in the orientation and distribution of glacial landforms. The influence of the underlying topography is revealed by the changing shape of the ice margin, the deflection of ice flow by the topography, and the separation of flow by topographic features.

5.2.1 Ice margin shape

The shape and orientation of the moraines records the changing shape of the ice margin during retreat. Highly arcuate landforms occur within the main troughs and channels (Fig. 4), similar to those observed within fjord settings around the

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Antarctic Peninsula and Svalbard (e.g. García et al., 2016; Munoz and Wellner, 2018; Ottesen and Dowdeswell, 2006). The moraines curve at the margins to follow the bathymetric contours along the channel/trough walls, indicating they are influenced by this underlying topography. The channel/trough walls also preserve long, sharp crested ridges, parallel to ice flow, that commonly attach to the end of the moraines. These likely formed due to crevassing within the ice along the edge of the steep escarpment due to strong topographic control as the ice sheet thinned (Fig. 7a). Contrasts in ice velocity, such as between areas of slower and faster-moving ice, create stress or "side drag" within the ice sheet (Stokes et al., 2007), as also observed at the boundaries of inter-ice streams in the Amundsen Sea Embayment (Klages et al., 2013). Crevasse squeeze ridges formed between the edges of the channels/troughs and adjacent bedrock highs in the Windmill Islands is evidence of strain within the ice sheet creating a fractured ice front at the intersection of slower or static ice over bedrock highs and adjacent faster-moving ice within the sediment-lined troughs.

While the moraines are best developed within the main SE-NW channels/troughs leading out of Newcomb and O'Brien Bays, the formation of smaller moraines within adjacent smaller channels between bedrock highs provides broader insight into the shape of the ice margin during retreat. The main trough leading out of Newcomb Bay is intersected by a number of smaller channels gouged into the bedrock, and these contain sets of small rectilinear and arcuate recessional moraines and CSRs (Fig. 7a). These record a radiating pattern of ice flow, with the shape of the margin controlled by the distribution of longitudinal crevasses, which separate pecten or narrow blades of ice (c.f. Evans et al., 2016). As the ice margin retreated beyond the axis of the main channels/troughs and into local embayments, the moraines become more linear in shape and laterally extensive and CSRs are less pronounced (Fig. 4). This reflects a reduction in shear stress within the ice margin as it broadens into these embayments from the relatively narrow channels/troughs.

5.2.2 Deflection of ice flow

The major troughs and channels across the Windmill Islands are orientated SE–NW, consistent with northwest trending bedrock faults (Carson et al., 2017). The channel south of Beall Reef (Channel 'A'), however, trends ENE–WSW, almost at right angles to these main troughs and to smaller channels to the south (e.g. Robertson Channel). Variably preserved lineations within these southern channels record a pattern of north-westerly ice flow offshore via O'Brien Bay and other smaller coastal inlets/embayments (Fig. 4c, 5). As the ice flowed across the ENE–WSW-trending Channel 'A', it abutted the steep 80 m high northern wall of the trough (Fig. 5), which impeded the NW-directed flow. This caused the ice to turn westwards (flow oblique to the axis of the trough) and divide into a series of individual, fracture-bound flow sets. The margins of these proposed flow sets are defined by a dense network of roughly parallel, approximately E–W-trending CSRs extending from the ends of the recessional moraines (Fig. 5). A single breach in the steep northern escarpment (Fig. 5) reflects the advance of only a small lobe of ice onto the bedrock surface near Beall Reef. The redirection of flow within the 80 m deep channel indicates that the ice at this time was thin enough to be strongly influenced by the orientation of the underlying topography.

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5.2.3 Downstream separation of flow sets

The final example of topographic control on this ice sheet during its retreat is seen in the separation of flow within the sediment-lined depression (Fig. 3) east of Gibney Reef. The eastern part of this depression contains recessional moraines separated into two discrete sets, occurring downstream from two small troughs incised into the 50 m high bedrock platform directly to the east. There are no recessional landforms between the two sets of moraines down-ice of the bedrock high that separates these troughs. The ice flowing westwards out of the bedrock incised troughs may have formed two discrete "fingers" or pecten with the margins of these relatively narrow corridors of more active retreat controlled by zones of E-W-trending, longitudinal crevasses (Fig. 7b, c). The absence of landforms down-ice of the bedrock high separating the troughs is thought to represent a "shadow" formed in the lee of this topographic high. These relationships are interpreted as reflecting the increasing influence of bedrock topography on the pattern of retreat and the focusing of ice flow into the troughs, suggesting that the ice sheet was thin enough, at least at its margin, for the seabed topography to influence the pattern of ice flow, active retreat and crevassing within the ice (Fig. 7b, c).

Bedrock topography has been shown to influence ice sheet retreat patterns at large scales on the Antarctic and other glaciated margins, including the focussing of flow around large shelf banks (e.g. Halberstadt et al., 2016; Shipp et al., 1999), and at much smaller scales through the confinement of ice flow within coastal embayments and nearshore fjords (Dowdeswell and Vásquez, 2013; García et al., 2016; Munoz and Wellner, 2018; Ottesen and Dowdeswell, 2006). The Windmill Islands dataset illustrates further controls of even quite subtle topographic variations on ice flow and retreat and emphasises the importance of geophysical data in providing an understanding of conditions at the bed, which will enable better prediction of future behaviour of modern ice streams.

5.3 Landform associations and ice margin sensitivity in shallow embayments

The landform associations of highly arcuate moraines and associated longitudinal CSRs preserved in the offshore Windmill Islands are not typical of those observed elsewhere on the Antarctic margin, with the exception of features mapped within shallow Hope Bay on the Antarctic Peninsula (Munoz and Wellner, 2018). The longitudinal CSRs and arcuate moraines preserved in Hope Bay are similar to, but not nearly as extensive as those observed in the Windmill Islands, however, the mechanism for their formation is likely similar. The features also bear striking similarity to those observed in coastal fjords and embayments on Iceland (Boulton, 1986; Evans et al., 2016, 2017), Svalbard (Ottesen and Dowdeswell, 2006) and Chile (Dowdeswell and Vásquez, 2013). Evidence from these tidewater glaciers suggests that the formation of these features is associated with extensive fracturing of a relatively thin ice sheet during its final phase of retreat (e.g. Boulton, 1986; Dowdeswell and Vásquez, 2013; Evans et al., 2016, 2017; Ottesen and Dowdeswell, 2006). The fractures, separating finger-like pecten of ice, form longitudinal crevasses into which the sediment is squeezed. Most CSRs observed on the Antarctic margin, however, have formed transverse to ice flow on the open Antarctic shelf, and moraines in these settings form broad, continuous ridges (e.g. Greenwood et al., 2018; Klages et al., 2013; Shipp et al., 2002). The transverse CSRs have been

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interpreted to form within basal crevasses directly behind the grounding line, with their preservation indicating full-thickness calving. The absence of longitudinal crevasses and arcuate moraines in most Antarctic records likely reflects the lack of high resolution datasets from within shallow confined coastal embayments associated with tidewater glaciers. The high resolution of the Windmill Islands dataset allows new insight into fine-scale sub-glacial processes, and reveals the sensitivity of this ice margin to topographic and substrate control.

Previous observations of longitudinal CSRs have been in settings associated with relatively temperate, warm-based ice, favouring the formation of water-saturated till. The Law Dome ice sheet, however, is typically cold-based, has limited surface meltwater production and low sediment delivery due to basal freezing (Morgan et al., 1997). The CSRs in the Windmill Islands are therefore unlikely to have formed from saturated till, suggesting an alternative sediment source. We propose that there must have been a sufficient volume of pre-existing saturated marine sediments within shallow embayments and troughs to form these features. The features preserved in the Windmill Islands are sharp, almost pristinely preserved, with only limited evidence for subsequent burial by marine sedimentation. This points to recent formation of these features. Sediment cores from the southern Windmill Islands indicate high sedimentation rates over the Holocene, averaging 90–97 cm/1000 years (Cremer et al., 2003). While sedimentation rates likely vary across the region, these cores indicate high biological production in nearby surface waters, which may have provided the volume of sediment required to produce the extensive constructional retreat features observed in the high resolution bathymetry dataset. The timing for formation of these features cannot be constrained at this stage, however, their preservation and the mechanism proposed to form these landforms suggests that it must have been relatively recently, at a time when sufficient marine sediments had accumulated within bathymetric depressions. The last glacial retreat in the northern Windmill Islands was at ~5930 yr BP (Goodwin and Zweck, 2000) and a readvance of the Law Dome margin is suggested from evidence onshore after 4500–4000 yr BP (Goodwin, 1996). Following last glacial retreat and prior to a readvance of the margin, we suggest that there must have been enough time for a sufficient volume of marine sediments to accumulate within the troughs, channels and embayments of the Windmill Islands to subsequently form the landform record.

The features in this offshore dataset further strengthens the case for a readvance of the Law Dome ice margin during the mid-late Holocene, as also suggested for similar features on the Antarctic Peninsula (García et al., 2016; Munoz and Wellner, 2018). While the nature and pace of ice sheet retreat in this region is not catastrophic, as observed in settings where basal melt can lead to rapid retreat (e.g. Jenkins et al., 2010; Pritchard et al., 2012), this study demonstrates the sensitivity of ice sheets on shoaling beds to climate variability during the Holocene and to local topographic conditions.

6 Conclusions

High resolution ice sheet-ocean models continue to be constrained by the lack of topographic information beneath grounded ice and across the continental shelf (Colleoni et al., 2018). This study reveals the interplay between the local scale topography, substrate (bedrock vs sedimentary) and a relatively thin retreating ice margin in preserving a landform record that has been rarely observed on the Antarctic margin. The record demonstrates that even subtle changes in topography and bed roughness, can have profound effects on the shape of the ice margin and its style of retreat, causing the ice to flow around features, creating strain in the ice margin downstream of topographic highs and constraining flow within topographic lows. The occurrence of water saturated marine sediments within channels, troughs and embayments enhanced the relationship between flow patterns and topography. These sediments increased bed lubrication during ice margin advance, while providing a source of sediments to form and preserve a landform history during its retreat. In contrast, areas of crystalline bedrock formed "sticky spots" of slow-moving or static areas of ice. Landforms, including arcuate to rectilinear moraines and extensive longitudinal CSRs, reflect the antecedent variability in both the underlying topography and the substrates, which in the final stages of retreat formed an irregular and highly fractured ice margin with large open longitudinal crevasses separating finger-like pecten of ice. The style of retreat revealed is similar to that observed in other nearshore and fjord glacier systems, but has been rarely observed on the Antarctic margin, so provides new insights into Antarctic nearshore glacial dynamics.

Data availability. All multibeam bathymetry data collected by RAN in 2013/14 and GA/RAN in 2014/15 can be accessed from: https://ecat.ga.gov.au/geonetwork/srv/eng/catalog.search#/metadata/100885.

Author contribution. AP, EP and CC undertook the geomorphic mapping. AP and EP interpreted the landform history and prepared the manuscript. JS contributed to survey planning and CC led the survey. All authors contributed to interpretations and final preparation of the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

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Tables

Table 1: Characteristics of moraines in different settings across the Windmill Islands. Numbers in brackets refer to the dimensions of "major moraines".

Setting	Height	Spacing	Cross-sectional shape	Description	Figure
Sediment-lined depression	1–3 m (5 m)	20–40 m	Symmetric to asymmetric	Rectilinear in shape, sharp crested	2
Bedrock depression	1–3 m	10–30 m	Symmetric to asymmetric	Linear, to irregular, to arcuate in form. Sharp crested	3
Troughs and channels	0.5–6 m (15–25 m)	15–50 m	Symmetric to asymmetric	Hairpinned, arcuate, linear, rectilinear. Sharp crested. Major moraines are associated with bedrock pinning points.	4, 5
Embayments	0.5–8 m	20–100 m	Mostly asymmetric	Arcuate to linear in form. Sharp crested.	4

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Figures

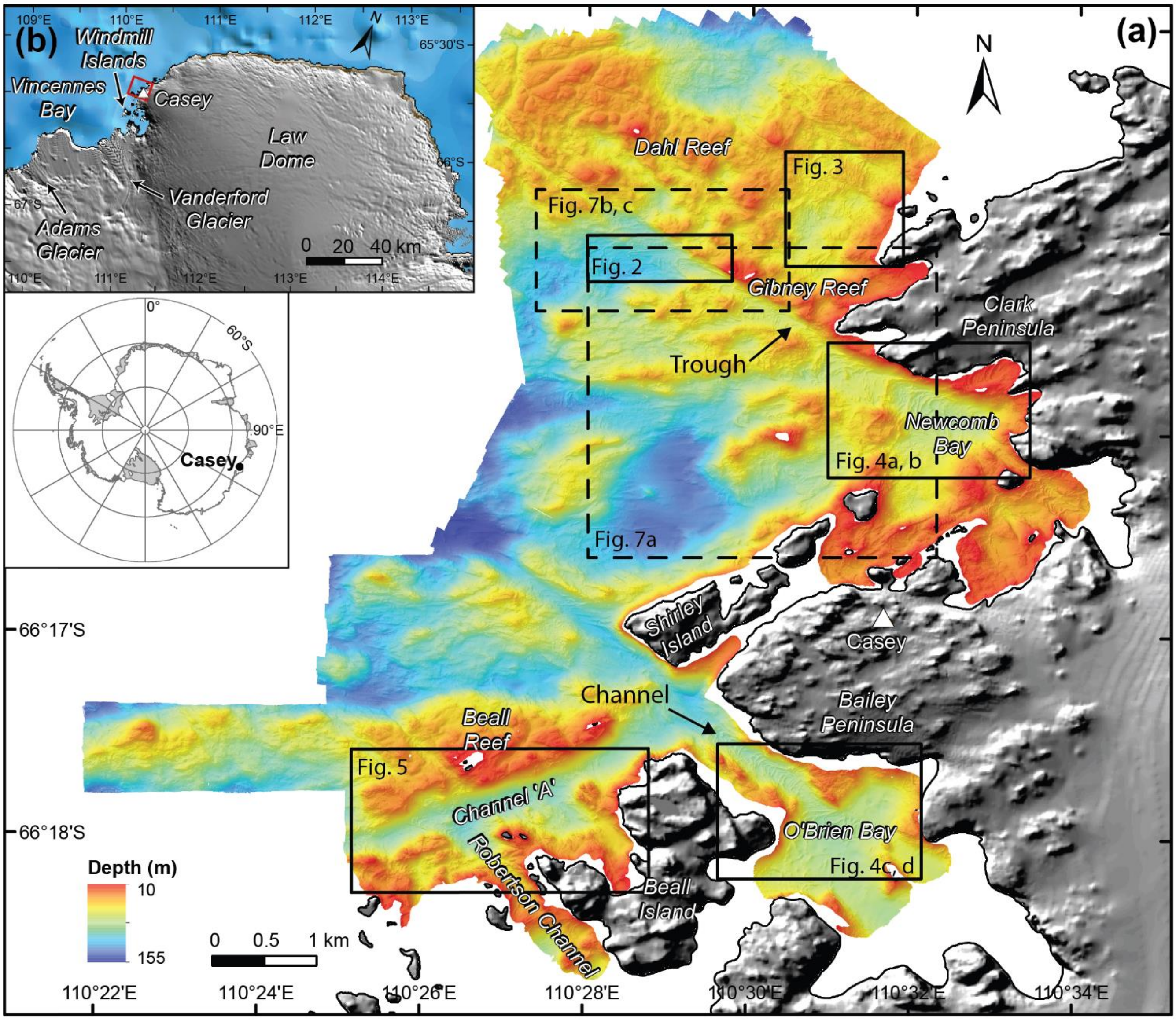

Figure 1: (a) Multibeam data from the northern Windmill Islands gridded at 1 m resolution. Areas shown in Figures 2–5 and 7 are highlighted. Onshore digital elevation model courtesy of the Australian Antarctic Division. (b) Regional context of the survey area on the western margin of Law Dome showing surface elevation from REMA (Howat et al., 2019). The red rectangle indicates the extent of Figure 1a.

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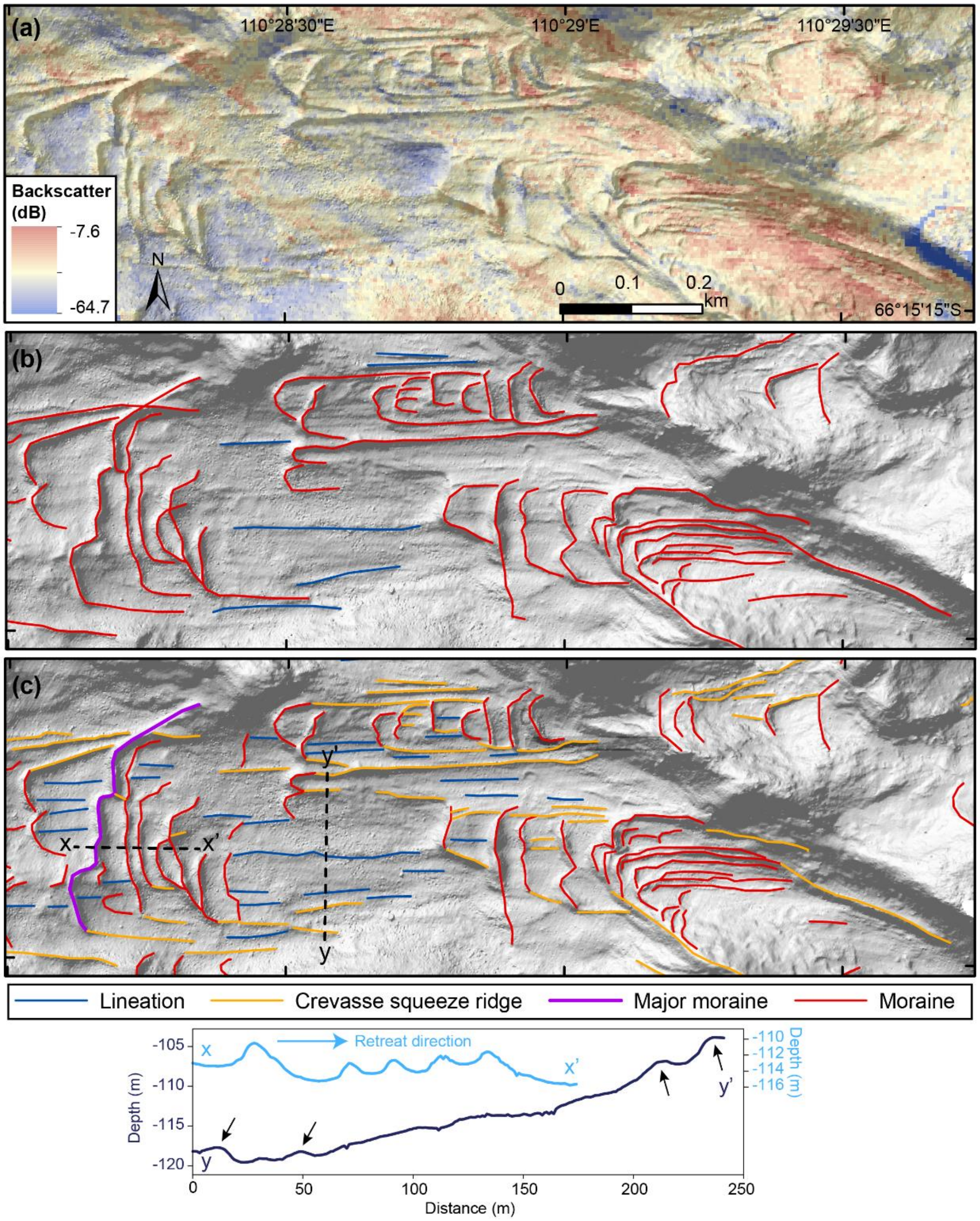

515 **Figure 2:** (a) Backscatter intensity draped over hillshade within a sediment-lined depression east of Gibney Reef. (b) Hillshaded image showing original geomorphic mapping by Carson et al. (2017) of moraines and lineations. c) Hillshaded image of revised geomorphic mapping, including crevasse squeeze ridges (CSRs) and major moraines. CSRs are distinguished from lineations based on their much sharper profiles and extension from the ends of moraine ridges, as discussed in the text. Arrows on profile y-y' point to symmetrical CSRs. Lineations cannot be clearly discerned on the profile. Profile x-x' reveals symmetrical to asymmetrical moraines formed in response to minor ice-push during overall retreat. For location refer to Figure 1.

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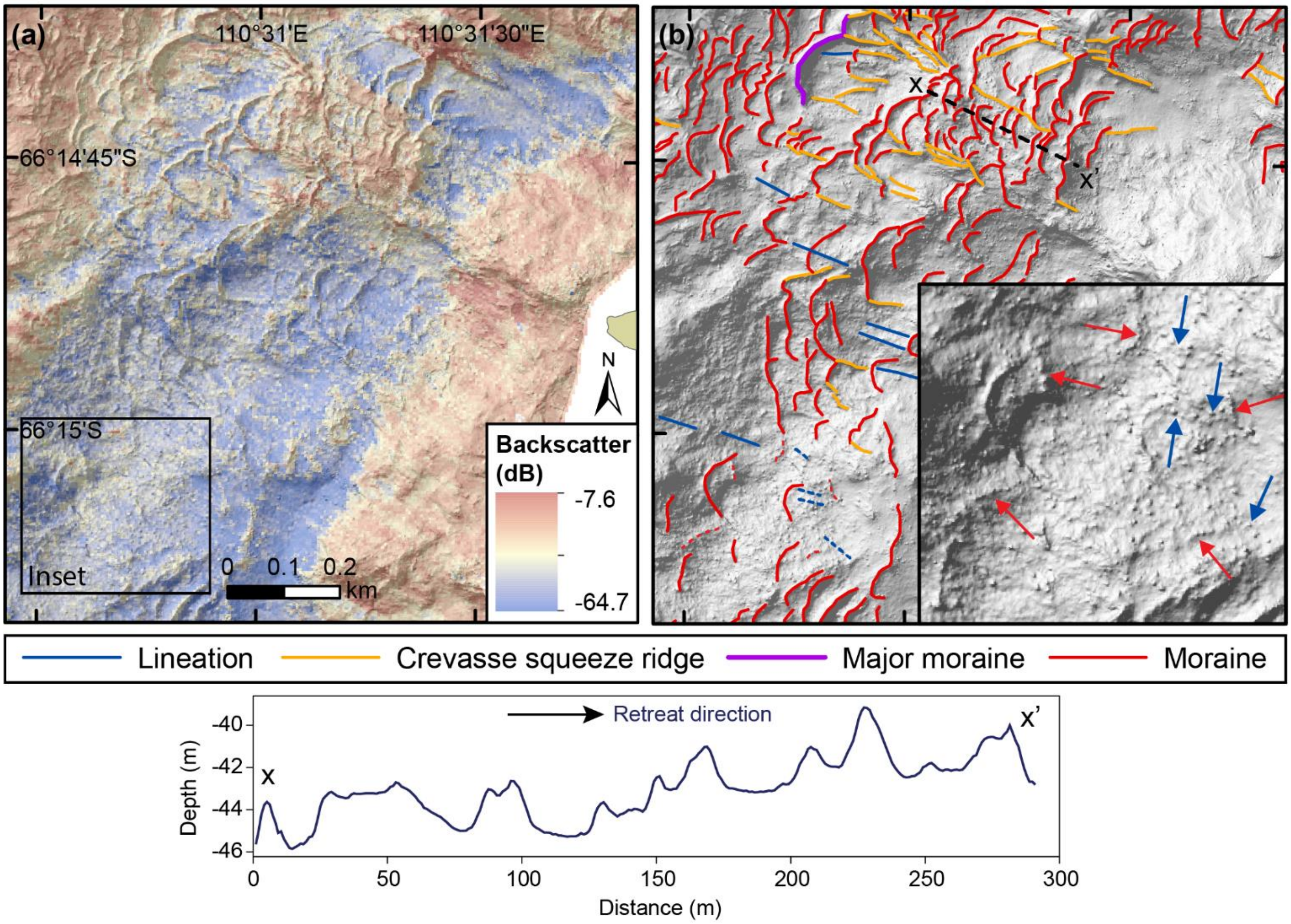

Figure 3: (a) Backscatter intensity draped over hillshade within a low-lying bedrock depression west of Clark Peninsula. (b) Geomorphic features within the low-lying bedrock depression. Arrows on inset indicate chains of boulders forming moraines (red) and rubble flutings (blue). Examples of these features are also mapped by dashed red and blue lines respectively on
525 Figure 3b within the area of the inset. Other boulders in the area are more randomly distributed. Profile x-x' indicates retreat towards the southeast recorded by a series of small push moraines. For location refer to Figure 1.

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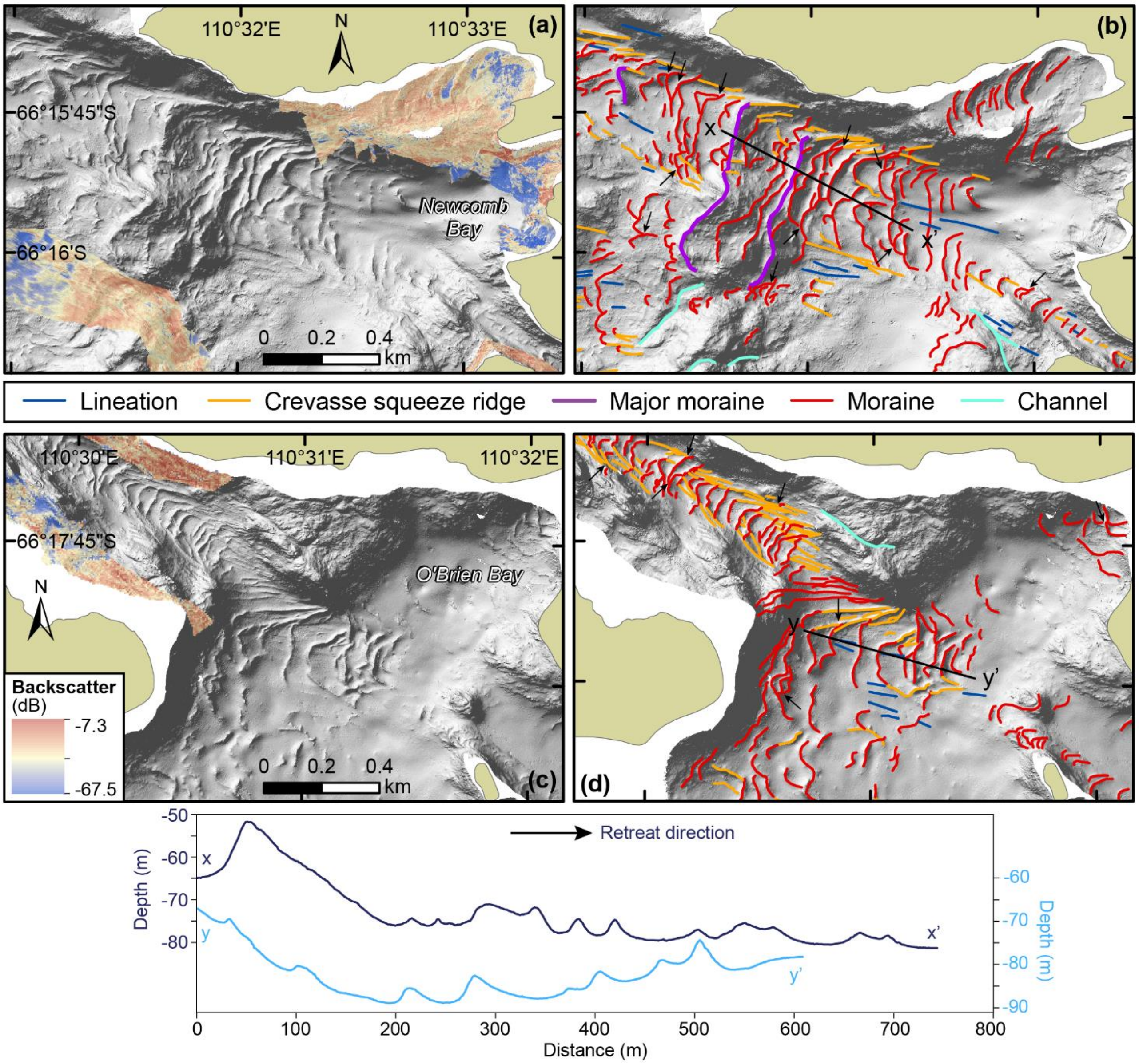

530 **Figure 4:** (a) Backscatter intensity (where available) draped over hillshade within Newcomb Bay and the NW-SE trending trough. (b) Geomorphic features mapped within Newcomb Bay area. (c) Backscatter intensity (where available) draped over hillshade within O'Brien Bay and the narrow NW-SE trending trough. (d) Geomorphic features mapped in the O'Brien Bay area. Arrows on (b) and (d) point to areas where older moraines and crevasse squeeze ridges are truncated by more recent features. Profile x-x' reveals a well-developed sequence of recessional moraines in the northern part of Newcomb Bay, including across a large asymmetrical moraine mapped as a "major moraine". Profile y-y' includes a series of smaller asymmetric to symmetric moraines within O'Brien Bay. For locations refer to Figure 1.

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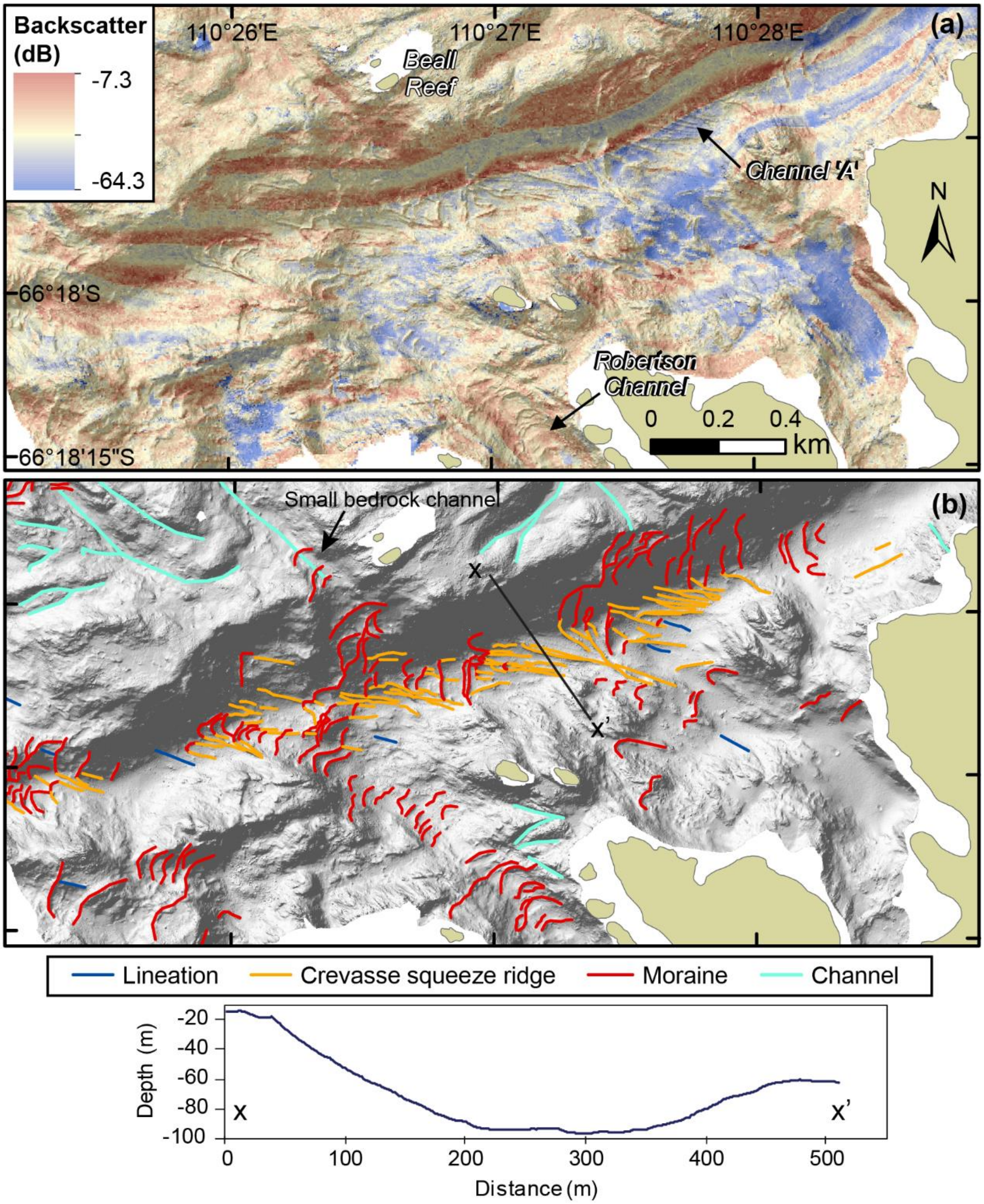

535 **Figure 5:** (a) Backscatter intensity draped over hillshade within Channel 'A', south of Beall Reef. Stripes in the backscatter are due to artefacts in the data. (b) Geomorphic features within Channel 'A' and the surrounding area. Profile x-x' illustrates that Channel 'A' forms a deep trough bounded by a bedrock escarpment to the north and more gently dipping bedrock towards the coast. For locations refer to Figure 1.

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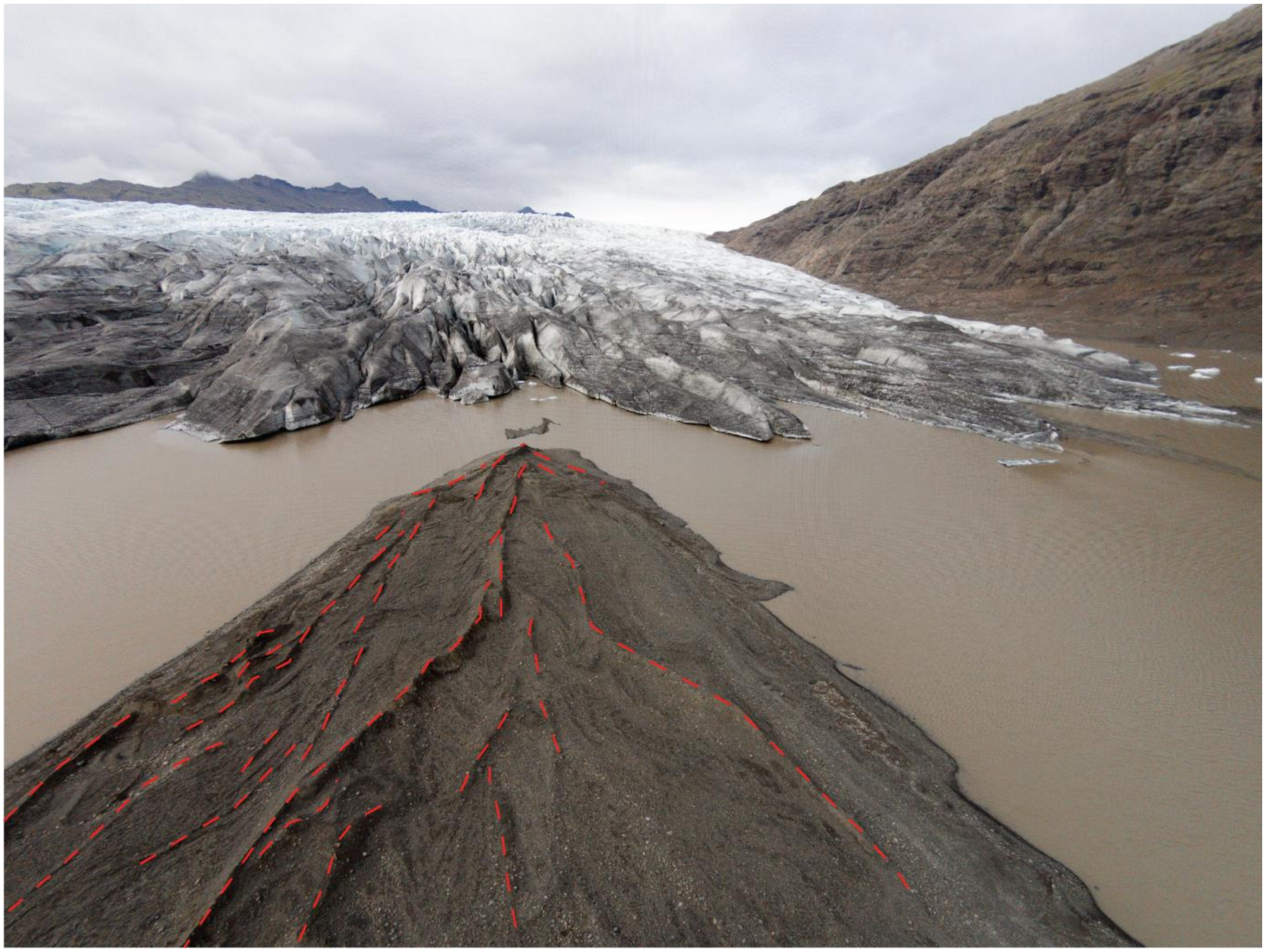

540 **Figure 6:** Crevasse squeeze ridges (CSRs, red dotted lines) and arcuate moraines at the snout of Fláajökull, Iceland. The ice margin is highly irregular, with longitudinal crevasses separating pecten of ice. CSRs are aligned with crevasses in the retreating ice margin and merge into the limbs of saw tooth moraines. Image reproduced with permission from D. Evans and M. Ewertowski.

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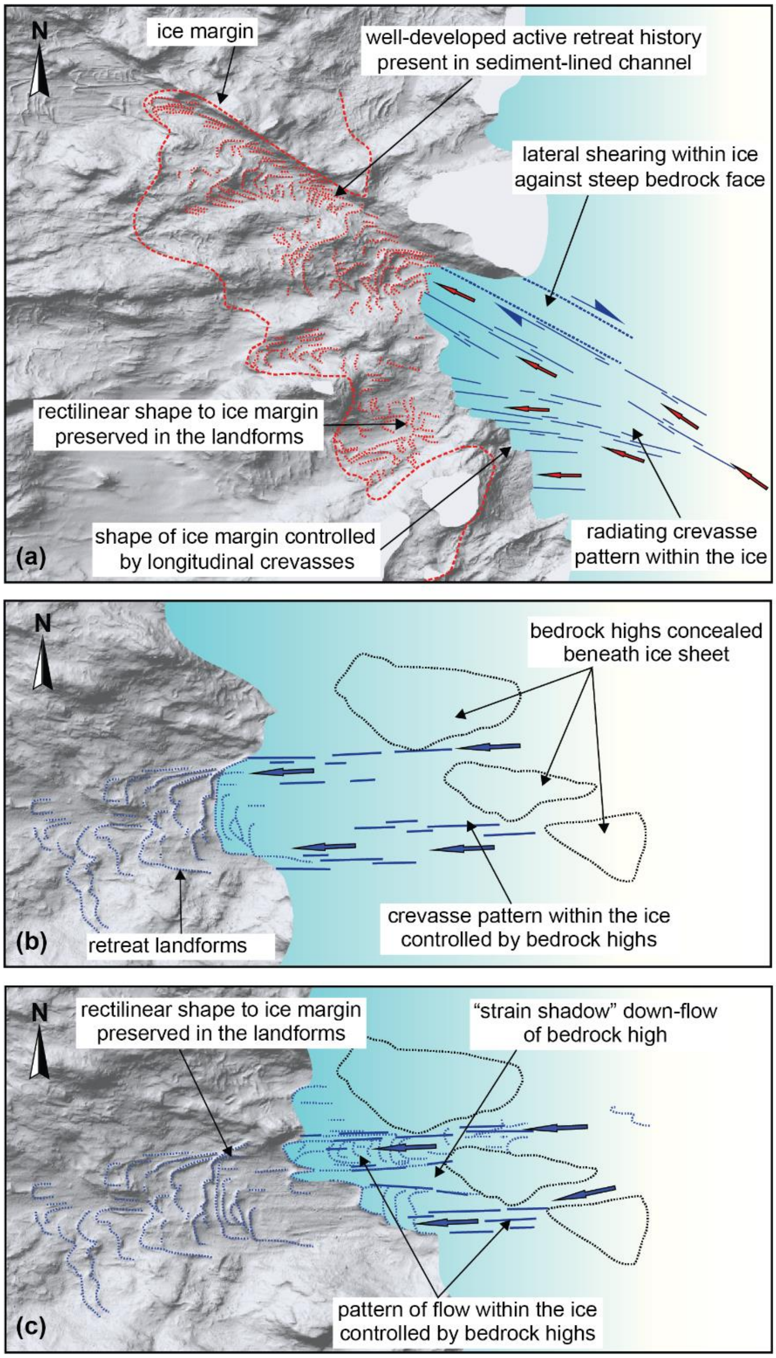

Figure 7: (a) Model of retreat within the trough leading out of Newcomb Bay. The landforms indicate that the shape of the ice margin was controlled by longitudinal crevasses, which radiated within small bedrock troughs. The escarpment created lateral shearing within the ice due to stronger topographic control as the ice sheet thinned. (b) Model of retreat within the sediment-lined depression east of Gibney Reef. Increased crevassing of the margin was controlled by bedrock highs beneath the ice; c) Modelled further retreat within the sediment-lined depression. As the ice retreated towards the escarpment two flow sets formed associated with a "strain shadow" down-flow of a bedrock high. For locations refer to Figure 1.