Submarine glacial-landform distribution along an Antarctic Peninsula palaeo-ice stream: a shelf-slope transect through the Marguerite Trough system (66° to 70°S)

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The Antarctic Peninsula comprises a thin spine of mountains and islands presently covered by an ice sheet up to 500 m thick that drains eastwards and westwards via outlet glaciers (Davies *et al*. 2012). Recently, the Peninsula has undergone rapid warming, resulting in the collapse of fringing ice shelves and the retreat, thinning and acceleration of marine-terminating outlet glaciers (e.g. Pritchard & Vaughan 2007). At the Last Glacial Maximum (LGM), the ice sheet expanded to the continental-shelf break around the Peninsula, and was organised into a series of ice streams that drained along cross-shelf bathymetric troughs (Ó Cofaigh *et al*. 2014). Marguerite Bay is located on the west side of the Antarctic Peninsula, at about 66° to 70° S (Fig. 1). A 12–80 km wide and 370 km long trough extends across the bay from the northern terminus of George VI Ice Shelf to the continental shelf edge. Extensive marine-geophysical surveys of the trough reveal a suite of glacial landforms which record past flow of an ice stream, which extended to the shelf edge at, or shortly after, the LGM. Subsequent retreat of the ice stream was underway by ~14 kyr ago and proceeded rapidly to the mid-shelf, where it slowed before accelerating once again to the inner shelf at ~9 kyr (Kilfeather *et al*. 2011).

Description of shelf-slope landforms

Inner shelf

The seafloor morphology is very rugged on the inner shelf of Marguerite Bay (Fig. 2) and TOPAS sub-bottom profiler data demonstrate that sediment cover is thin or absent (Fig. 2b) (Ó Cofaigh *et al*. 2005; Anderson & Fretwell 2008). This is consistent with seismic profiles, interpreted as evidence that the seafloor is underlain by crystalline bedrock (Fig. 1b) (Kennedy & Anderson 1989). The eastern region of the inner shelf comprises large isolated basins (up to 900 m deep) leading westwards into a network of smaller, connected basins, 800–1000 m deep (Anderson & Fretwell 2008). The area surrounding the basins is crudely streamlined with small, stubby, oval-shaped bedrock hills (<3 km long with elongation ratios of 2:1 to 4:1), gouged and grooved bedrock, and channels extending into the basins from bedrock highs and cutting across streamlined bedrock knolls (Anderson & Fretwell 2008; Livingstone *et al*. 2013). The isolated basins are heavily sculpted with asymmetric bedrock hills formed on the basin floors (0.5–3.2 km long, 0.1–2 km wide with elongation ratios of 2:1 to 6:1) and the higher relief is gouged, grooved and scoured (Ó Cofaigh *et al*. 2002, 2005; Anderson & Fretwell 2008; Livingstone *et al*. 2013). The largest basin is floored by lineated sediment; some lineations are seeded in the lee of bedrock outcrops (Fig. 2d). The shelf region further to the south shows similar bedrock features, but streamlined landforms are less frequent.

The connected basins further to the west are related to a well-developed, anastomosing network of large channels that converge westwards into the main trough (Anderson & Fretwell 2008). Channels typically have widths of 300–550 m and are incised 30–200 m into bedrock. The basins and surrounding terrain are heavily streamlined, with bedrock gouged, grooved and streamlined. Asymmetric bedrock hills are larger and more elongate than those further to the east, with lengths between 0.5–6 km, widths of 0.1–2 km and elongation ratios of 2:1 to 10:1 (Livingstone *et al*. 2013).

The main trough is 6–12 km wide and up to 1600 m deep (Fig. 1). It emanates from George VI Ice Shelf and is dominated by erosional landforms incised into the rugged crystalline bedrock. These landforms include gouged and grooved bedrock, asymmetric bedrock hills and large channels up to 1.5 km wide and 100 m deep (Livingstone *et al*. 2013). At the terminus of George VI Ice Shelf, asymmetric bedrock hills are small and stubby (lengths of 1.1–3.5 km and widths of 0.3–1.9 km), with elongation ratios of 2:1 to 4:1 (Ó Cofaigh *et al*. 2002). Bedrock within the trough is covered by patches of lineated sediment in some places (Ó Cofaigh *et al*. 2005).

Mid-shelf trough

The mid-shelf trough corresponds with a transition from crystalline bedrock to sedimentary substrate, which is expressed at the seafloor by a shift from bedrock outcrops to relatively smooth, unconsolidated glacigenic sediments and a wide variety of streamlined landforms (Figs. 1b, 2a,c) (Kennedy & Anderson 1989; Ó Cofaigh *et al*. 2002; Livingstone *et al*. 2013). Bedrock outcrops are common in the eastern part of the trough, whereas sediment cover prevails further west.

The bedrock is heavily gouged, grooved and streamlined, with tails of tapering sediment commonly originating at the down-stream side of bedrock outcrops (Fig. 2c). Streamlined features are 0.5–10 km long and 200–2000 m wide, with elongation ratios of 2:1 to 18:1 (Ó Cofaigh *et al*. 2002; Livingstone *et al*. 2013, 2016). Bedrock outcrops are incised by a well-developed network of anastomosing channels (e.g. Fig. 2c) that are up to 800 m wide and 100 m deep and run parallel and sometimes oblique to the former ice-flow direction (Livingstone *et al*. 2013).

On the western flank of the trough, the seafloor becomes smoother and tails of sediment seeded at bedrock outcrops, tear-drop shaped hills attenuated in the downstream direction and highly elongate, linear to curvilinear ridges and grooves are common (Fig. 2a). Most of the streamlined landforms are orientated along the long-axis of the trough, apart from those at the very western edge where streamlined features are orientated NW-SE towards a subsidiary elongate depression (Livingstone *et al*. 2013). Some of the tear-drop shaped hills have crescentic depressions around their heads (Fig. 2b). Several prominent scarps, up to 80 m high, characterised by steep seaward slopes and shallow, lineated backslopes are observed at ~68°S (Livingstone *et al*. 2013).

Outer-shelf trough

The outer-shelf trough is composed of a thick sequence of glacigenic sedimentary strata, laid down over multiple glacial advances (Fig. 1b) (Bart & Anderson 1995; Larter *et al*. 1997; Eyles *et al*. 2001). The cross-shelf trough, which deepens inland from ~500 m at the shelf edge, is dominated by highly elongate (2:1 to 90:1) ridges and grooves orientated along the trough axis and extending to the shelf edge (Fig. 3a,c). These ridges and grooves are 100–18,000 m long and 100–600 m wide, and display consistent heights and wavelengths of 2–8 m and

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100–700 m, respectively (Ó Cofaigh *et al*. 2002; Livingstone *et al*. 2013, 2016). Shorter lineations are widespread and may be nestled amongst the longer forms, which are more prevalent in the centre of the trough and towards the shelf edge (Livingstone *et al*. 2013, 2016) The streamlined features are almost wholly confined to the broad (25–45 km wide) trough. However, they are increasingly disrupted by curvilinear furrows with multiple orientations (Fig. 3c) that are observed in water depths of 400–600 m towards the shelf edge. There is also some evidence of divergence, or fanning out of ridges and grooves on the mid-outer shelf, where the direction of the lineations changes from N-S to NW-SE (Livingstone *et al*. 2013). Channels have not been documented on the outer shelf, and cores taken through the soft till did not recover any meltwater related sediments (e.g. Ó Cofaigh *et al*. 2002, 2005, 2007; Dowdeswell *et al.* 2004a; Kilfeather *et al*. 2011). There are no signs of channels in the outer-shelf seafloor sediments.

TOPAS sub-bottom profiler data and sediment cores reveal that the streamlined ridges and grooves are formed in the top of a 1–19 m thick acoustically-transparent unit comprising low shear-strength (0–40 kPa), matrix-supported diamict (Fig. 3b) (Dowdeswell *et al*. 2004a; Ó Cofaigh *et al*. 2005, 2007; Livingstone *et al*. 2013, 2016). The acoustically transparent unit sits over a strong basal reflector that is generally smooth to undulating, although it becomes grooved towards the eastern flank of the trough. A series of large buried ridges orientated across the trough also appear on adjacent TOPAS lines at about 67°S (Ó Cofaigh *et al*. 2005). The soft till directly overlies a much stiffer (>90 kPa), matrix-supported diamicton and is capped by a thin (<1 m) drape of acoustically transparent muds that thins towards the shelf break (Dowdeswell *et al*. 2004a; Ó Cofaigh *et al*. 2007).

Localised asymmetric wedges with steeper seaward faces and shallow, lineated back-slopes were imaged at irregular intervals along the length of the trough (Fig. 3a, d, e) (Ó Cofaigh *et al*. 2005; Livingstone *et al*. 2013, 2016). They are typically 10–40 m thick, 5–14 km wide and 3–14 km long, with lineated back-slopes that record a subtle change in direction in places.

Continental slope and rise

The upper continental slope is relatively steep (6–12°), with a sigmoidal slope profile beyond the trough-mouth and concave profiles either side of it (Fig. 3a). Gullies are present both in front, and to either side, of the trough-mouth (Dowdeswell *et al*. 2004b). They are typically straight to sinuous, have a V-shaped profile and often display a dendritic organisation that converges downslope (Livingstone *et al*. 2013). Those imaged in front of the trough have a typical spacing of ~1500 m, are generally <120 m deep and frequently initiate down-slope from the shelf edge. Either side of the main trough, gullies are seeded at the shelf edge, are more closely spaced (800–900 m spacing) and reach depths of >200 m (Dowdeswell *et al*. 2004b; Noormets *et al*. 2009).

A sediment core collected from the upper slope directly in front of the trough-mouth recovered a ~3.7 m thick massive diamicton, whilst cores collected from the upper slope on either side of the trough-mouth retrieved only short (< 0.4 m long) sequences of massive gravel and diamicton (Dowdeswell *et al*. 2004b). The gullied upper continental slope gives way to a smooth lower slope, and large channels and sediment mounds characterise the upper continental rise (Fig. 3a) (Dowdeswell *et al*. 2004b). Channels are typically 80–150 m deep and 3–8 km wide, while the sediment mounds reach 150 km long, 80 km wide and stand up to 400 m above the surrounding seafloor.

Interpretation of shelf-slope landforms

Inner shelf

The rugged inner shelf of Marguerite Bay (Fig. 2) is dominated by streamlined bedrock features probably eroded over multiple glacial cycles (e.g. Anderson & Fretwell 2008; Livingstone *et al.* 2013). The small oval to tear-drop shaped bedrock hills are interpreted as whalebacks and the tails of tapering sediment seeded at bedrock obstacles are interpreted as crag-and-tails. The orientation of landforms indicates convergent ice flow into the deep trough emanating from George VI Sound. This would have resulted in ice-flow acceleration, consistent with a general increase in bedform elongation into the trough (Anderson & Fretwell 2008).

The isolated and connected basins (e.g. Fig. 2d) are thought to be tectonically controlled, although glacial landforms on their floors and connected bedrock channels further west also imply additional erosion by glacial ice and meltwater (Anderson & Fretwell 2008). The undulating thalwegs of the channels and their incision into bedrock point to a subglacial meltwater origin. Similar channels and connected basins have been observed on the inner-shelf troughs of palaeo-ice streams around Antarctica (Lowe & Anderson 2003; Domack *et al*. 2006; Graham *et al*. 2009; Nitsche *et al*. 2013). The presence of an organised network of channels demonstrates abundant subglacial meltwater drainage at the ice-bed interface during episodes of glacial activity (e.g. Lowe & Anderson 2003). However, the timing and source of water is unclear.

Although ice flow is likely to have been predominantly by basal sliding, the rough terrain and channel network (e.g. Fig. 2a) would have produced a spatially variable pattern of basal shear stresses, whereas patches of lineated sediment also attest to localised zones of sediment deformation (Graham *et al*. 2009). The lack of sedimentary depocentres such as moraines or grounding-zone wedges implies rapid ice retreat across the inner shelf (Dowdeswell *et al*. 2008a), and this is supported by ages showing deglaciation of inner Marguerite Bay and thinning of ice on the surrounding hinterlands at ~9 cal. ka BP (Bentley *et al*. 2011; Kilfeather *et al.* 2011).

Mid-shelf trough

The transition from bedrock to sediment in the mid-shelf trough of Marguerite Bay has resulted in a complex array of glacial bedforms (Fig. 2a, c). At the eastern end of the trough, where bedrock dominates, the distribution of landforms is similar to the inner shelf. However, the increasing influence of sediment has also produced highly elongate ridges and grooves orientated parallel to the trough long-axis. These features are interpreted as MSGLs, which are indicative of depositional and deformation processes at the bed of a fast-flowing ice stream. MSGLs orientated away from the main trough towards a subsidiary elongate depression extending to the shelf break near 75° W (Bentley and Anderson 1998; Livingstone *et al*. 2013) may mark another fast-flowing outlet draining through Marguerite Bay. A seaward increase in bedform elongation and the transition from a bedrock-floored to sediment-floored trough from the inner to the outer shelf is typical of palaeo-ice stream troughs around Antarctica and Greenland (Wellner *et al*. 2001; Graham *et al*. 2009; Livingstone *et al*. 2012; Ó Cofaigh *et al*. 2013; Dowdeswell *et al*. 2014).

In contrast to bedrock-floored portions of the mid-shelf trough, there is very little evidence of meltwater flow over the unconsolidated sedimentary substrate. The exception is crescentic overdeepenings around the stoss ends of drumlins (Fig. 2b), which may have been produced by localised subglacial meltwater erosion (Ó Cofaigh *et al.* 2002).

The streamlined sediment, which is relatively thin based on the sub-bottom profiler data (Dowdeswell *et al*. 2004a), is composed of hybrid till formed by a combination of subglacial sediment deformation and lodgement (Dowdeswell *et al*. 2004a; Ó Cofaigh *et al.* 2005, 2007). Two scarps with shallow lineated backslopes at ~68° S are interpreted as grounding-zone wedges (GZWs). Although there is no acoustic data through these features, they have similar dimensions and morphologies to other seismically imaged GZWs that are commonly observed in palaeo-ice stream troughs around Antarctica and Greenland (e.g. Dowdeswell & Fugelli 2012; Batchelor & Dowdeswell 2015). GZWs are sedimentary wedges formed by the transport and deposition of deforming subglacial sediment at a grounding-zone during decade to centuries long still-stands in deglacial retreat (e.g. Dowdeswell & Fugelli 2012; Batchelor & Dowdeswell 2015). The presence of GZWs in the mid-shelf trough of Marguerite Bay implies episodic ice stream retreat across this region (Ó Cofaigh *et al.* 2008). This is supported by sediment cores and dating control, which indicate a slow retreat across the mid-shelf associated with the break-up of an ice shelf (Kilfeather *et al*. 2011).

Outer-shelf trough

The outer-shelf trough of Marguerite Bay is dominated by well-developed, highly elongate (up to 90:1) ridges and grooves that are interpreted as MSGLs formed in a subglacial hybrid till (Fig. 3) (Dowdeswell *et al*. 2004a; Ó Cofaigh *et al*. 2005, 2007). The MSGLs record the development of a fast-flowing palaeo-ice stream, which advanced to the shelf edge at the LGM. The size, shape and distribution of MSGLs in Marguerite Bay are characteristic of MSGLs observed in other palaeo-ice stream troughs and also from beneath modern West Antarctic ice streams (e.g. Graham *et al*. 2009; King *et al*. 2009; Spagnolo *et al*. 2014; Livingstone *et al*. 2016). Variability in MSGL length, with shorter bedforms nestled amongst longer forms, suggests that the MSGLs are at different stages of maturity (Livingstone *et al*. 2013, 2016). MSGLs are most elongate towards the shelf edge along the central axis of the trough and where the soft till is thicker. This is consistent with model predictions of where the greatest ice velocities and highest amount of soft sediment deformation would be expected (Jamieson *et al*. 2016).

The well-preserved nature of the MSGLs, their position on top of GZWs (see below), and a lack of cross-cutting, suggests that they record the final imprint of palaeo-ice stream activity in the trough (Livingstone *et al*. 2016).

Localised asymmetric sediment wedges found both within and outside Marguerite Trough (Fig. 3a, d, e) are interpreted as GZWs (Ó Cofaigh *et al*. 2005; Livingstone *et al*. 2013). Dipping sub-bottom reflectors in a few of the GZWs suggest that their development involved mass-wasting at their distal end (Ó Cofaigh *et al*. 2005). Buried GZWs imaged on the outer shelf at about 67° S record former still-stand positions during advance or a previous retreat (Ó Cofaigh *et al*. 2005).

The deposition of GZWs on a reverse bed-slope is significant as it demonstrates that the grounding-zone retreat rate slowed down or temporarily paused despite the reverse gradient. This finding adds complexity to an often-cited theory, which predicts unstable retreat as a consequence of marine ice stream beds deepening inland (Schoof 2007). It therefore suggests that local factors other than vertical bed topography can modulate grounding-zone stability and retreat. For example, the width of the ice stream trough has been demonstrated to have controlled grounding-zone retreat rates in Marguerite Bay (Jamieson *et al*. 2012, 2014), and the existence of a buttressing ice-shelf has been shown to enable modelled grounding-zone stability on reverse slopes (e.g. Gudmundsson *et al.* 2013).

Radiocarbon ages on sediment cores suggest that the grounded ice stream retreated rapidly back to the mid-shelf at ~14 cal. ka BP, within the error-margin of the dates (Kilfeather *et al*. 2011). This implies high sediment fluxes to form the GZWs in their entirety during this rapid retreat (<1000 years). This is within the time-scale calculated for similar-sized GZWs observed in palaeo-ice stream troughs around Antarctica and Greenland (e.g. Dowdeswell & Fugelli, 2012; Batchelor & Dowdeswell 2015).

Continental slope and rise

The diamictons on the continental slope offshore of Marguerite Trough are interpreted as glacigenic debris-flow deposits delivered by a fast-flowing ice stream that extended to the shelf edge (Dowdeswell *et al*. 2004b). However, in contrast to many other palaeo-ice stream margins (e.g. Vorren *et al*. 1998; Dowdeswell *et al*. 2008b), there is no trough-mouth fan. This may be because the steep continental slope promoted rapid down-slope transfer of sediment by turbidity currents that evolved rapidly out of debris flows and slides (Ó Cofaigh *et al*. 2003). The turbidity currents are thought to have cut the submarine channels present on the slope and produced the large fine-grained mounds or drifts on the upper continental rise (e.g. Pudsey 2000).

There is a close association between submarine gully morphology, slope gradient and the location of the cross-shelf bathymetric trough (e.g. Noormets *et al*. 2009). This implies that gullies were formed by the drainage of sediment-laden meltwater emanating from a grounded ice margin, turbidity currents or the sinking of dense shelf water masses (Dowdeswell *et al*. 2004b; Noormets *et al*. 2009; Livingstone *et al*. 2013).

Discussion: landform distribution and schematic model

The landform distribution in the Marguerite Trough shelf-slope system (Fig. 4a) is characteristic of a fast-flowing palaeo-ice stream that drained to the shelf edge along a >370 km long trough fed by ice from George VI Ice Shelf and surrounding full-glacial tributary regions. The transition of glacial landforms along the palaeo-ice stream, from (i) streamlined bedrock incised by meltwater channels on the inner shelf through (ii) a mixed bedrock-sediment zone comprising a complex arrangement of crag-and-tails, streamlined bedrock, drumlins, lineations and GZWs to (iii) MSGLs and GZWs on the sediment-floored outer shelf (Fig. 4b) is characteristic of palaeo-ice streams around Antarctica (e.g. Wellner *et al*. 2001; Graham *et al*. 2009; Livingstone *et al*. 2012; Ó Cofaigh *et al.* 2014). Radiocarbon ages indicate that deglaciation had begun ~14 kyr ago and proceeded rapidly to the mid-shelf, where it slowed before accelerating once again to the inner shelf at ~9 kyr (Kilfeather *et al*. 2011). Retreat was interrupted by a series of slow-downs or pauses resulting in the deposition of GZWs on the outer and mid shelf (e.g. Livingstone *et al.* 2013).

The wide variety and spatial arrangement of landforms on the rough bedrock-floored inner shelf imply a complex multi-temporal signature of ice-flow, probably eroded over several glaciations and different stages of ice-stream history, and influenced strongly by the bedrock geology (e.g. Graham *et al.* 2009). The bedrock landforms include an extensive network of subglacial meltwater channels recording channelised meltwater flow in this zone (Anderson & Fretwell 2008).

Drumlins and crag-and-tail bedforms have been interpreted to indicate the onset-zone of fast ice-stream flow (e.g. Wellner *et al.* 2001). These landforms occur on the mid-shelf where there is a change from rough bedrock to smooth unconsolidated sediment on the outer shelf and ice is converging into the main trough from surrounding tributaries (Fig. 4b). Thus, some of these landforms may be related to ice-flow acceleration, when ice was streaming out to the shelf edge at the LGM. If this was the area of onset of streaming, its position seems to have been controlled by the geometry of Marguerite Bay, the underlying geology and its roughness (e.g. Graham *et al.* 2009; Winsborrow *et al.* 2010).

The landforms in glacial sediments on the outer shelf (Fig. 4b) indicate deformation of water-saturated sediments at a former ice-stream bed (Dowdeswell *et al*. 2004a; Ó Cofaigh et al. 2005) and probably record the final phase of deglaciation (Livingstone *et al.* 2016). The absence of meltwater landforms on the outer shelf may indicate water flow through small canals below the resolution of the data, flow in a dynamic network where channels are constantly evolving due to creep closure, and/or Darcian flow through the sediment. Certainly, compared to the large meltwater channel networks on the inner shelf that were probably carved over a long period of time, the landforms on the outer shelf represent an entirely separate temporal signature. In water depths shallower than about 300–500 m the glacial-landform record is heavily reworked by iceberg ploughmarks. This has made it difficult to identify landforms towards the outer-shelf edge and in the inter-ice stream regions to either side of the trough where flow was slower.

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Fig. 1: Regional bathymetry and shelf architecture of the Marguerite Trough shelf-slope system, Antarctic Peninsula. The location of subsequent figures is shown. (**a**) Multibeam-bathymetric coverage of the Marguerite Trough system. Light grey is grounded ice; dark grey is floating ice; (a) is located as a red box on the inset location map of the Antarctic Peninsula. AP, Antarctic Peninsula. Regional bathymetry from IBCAO v. 3. Arrows denote perspective of oblique views in Figs. 2a and 3a. (**b**) 130-km long dip seismic-reflection profile showing Antarctic Peninsula continental-shelf architecture comprising the transition from crystalline bedrock to sediment, the mid-shelf high and Marguerite Trough.

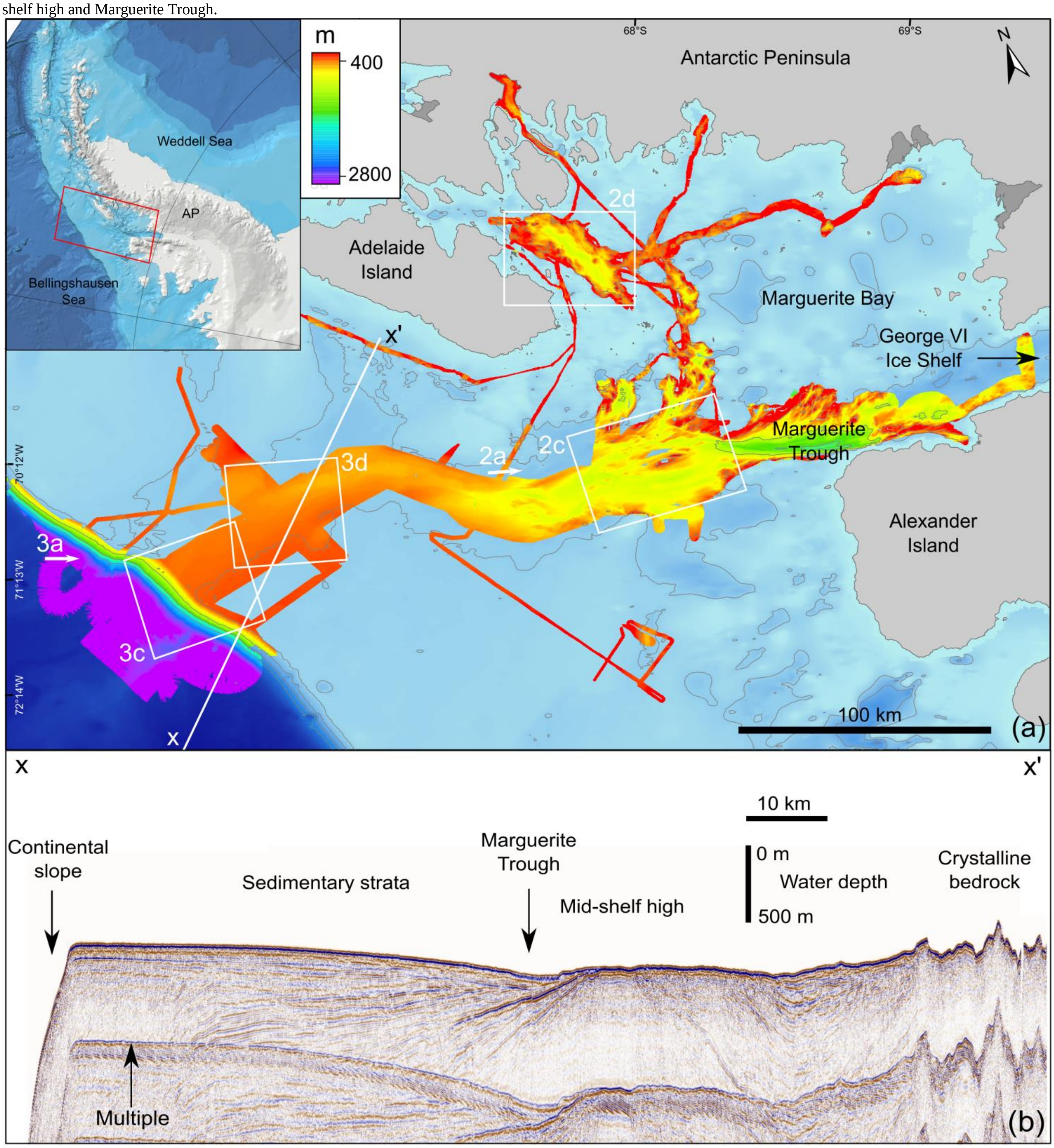

Fig. 2: Marine-geophysical data from the inner and mid parts of the Marguerite Trough system. (**a**) Oblique view looking roughly SW towards the main trough across the complex mid-shelf. This encompasses the transition from crystalline bedrock to sediment and shows a wide range of landforms including crag-and-tails, streamlined bedrock, drumlins, meltwater channels and lineations. (**b**) 3.5 kHz sub-bottom profile across a drumlin with a crescentic scour at its stoss side shown in (c). The profile also shows the transition from smooth sedimentary substrate to more rugged bedrock. (**c**) Sun-illuminated multibeam-bathymetric image showing the complex arrangement of landforms on the mid shelf. (**d**) An isolated basin on the inner shelf containing crag-and-tails and meltwater channels.

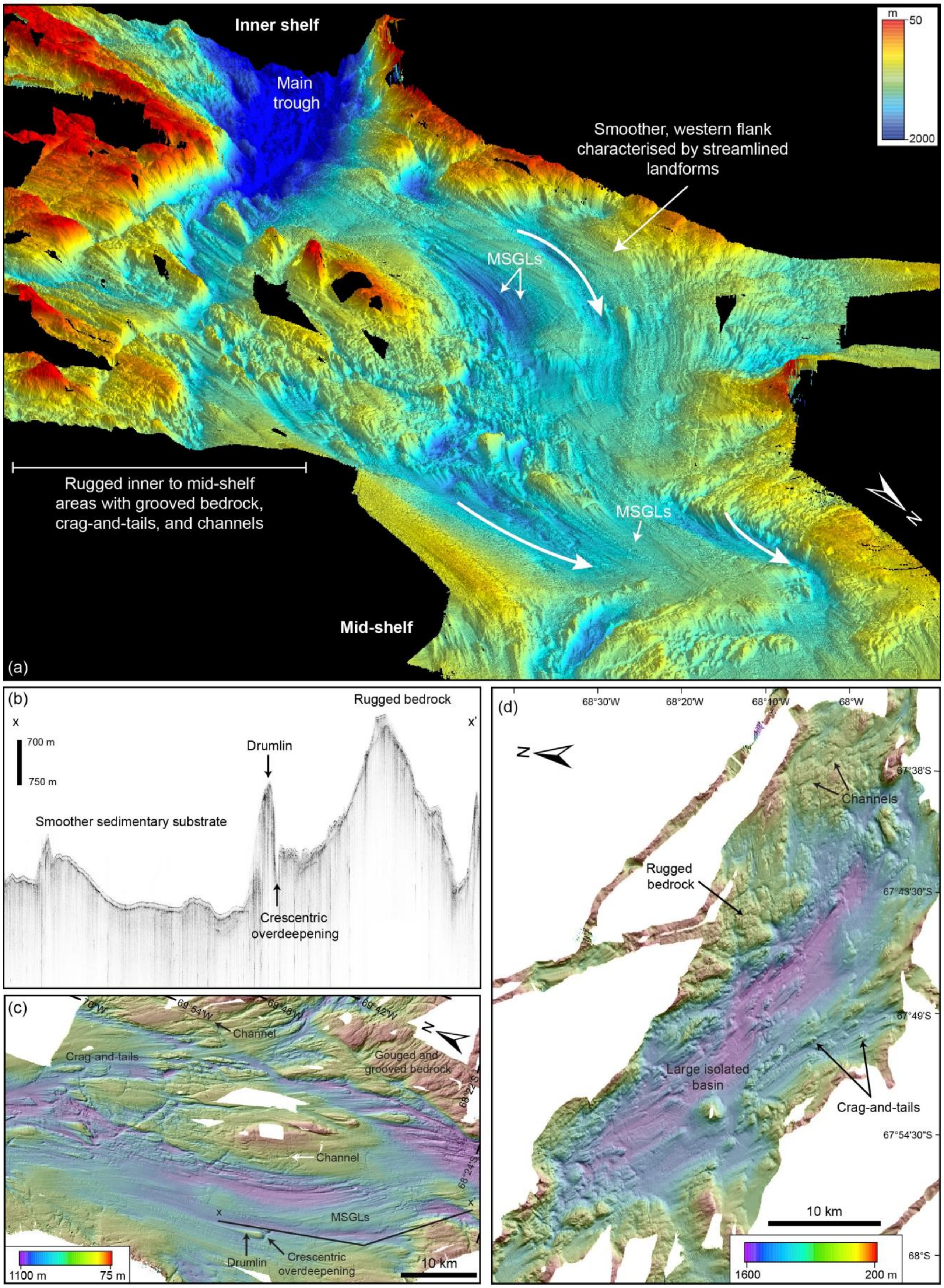

Fig. 3: Marine-geophysical data from the outer part of the Marguerite Trough system. (**a**) Oblique view looking roughly southwards across the outer shelf of Marguerite Trough. (**b**) 3.5 kHz sub-bottom profile shown in (c), displaying MSGLs in an acoustically transparent unit comprising low shear strength, matrix-supported diamict on the outer shelf, and the steep continental slope. (**c**) Sun-illuminated multibeam-bathymetric image showing MSGLs and iceberg-ploughed terrain on the outer shelf and gullies on the continental slope. (**d**) Sun-illuminated multibeam-bathymetric image showing MSGLs and GZWs on the outer shelf. (**e**) 3.5 kHz sub-bottom profile showing MSGLs and GZWs on the outer shelf, shown in (d). Note the wedge-like shape of the GZWs and the smooth basal reflector that underlies the MSGLs.

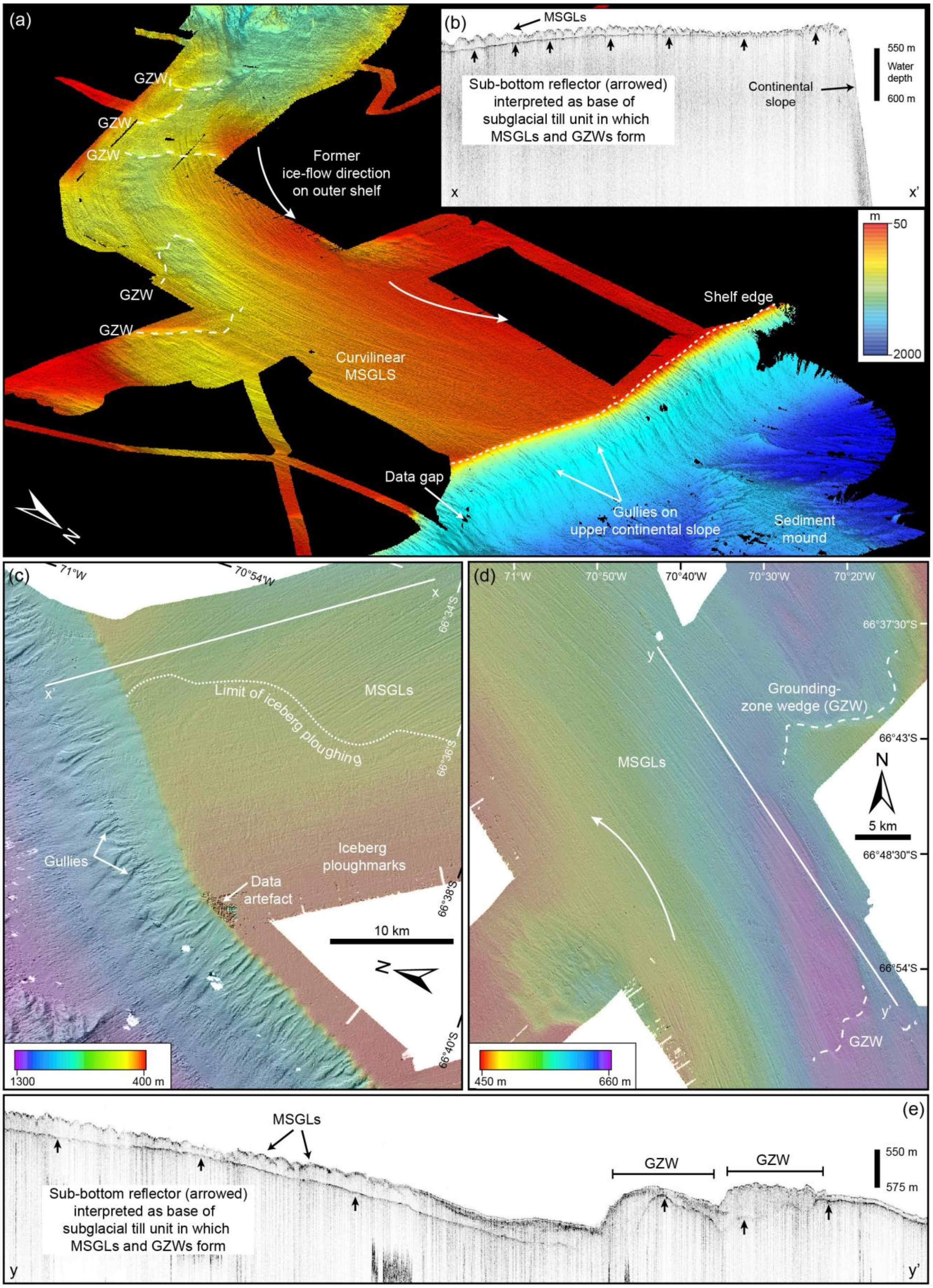

Fig. 4: (**a**) Summary diagram of the distribution pattern of submarine landforms in the Marguerite Trough shelf-slope system, Antarctic Peninsula (based on Livingstone *et al*. 2013). (**b**) Schematic landform-assemblage model for a shelf-slope sedimentary system in the Antarctic Peninsula.