*Highlights (for review)

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1. Glacial geomorphology and geochronology of South Georgia described from swath bathymetry

2. Consistent pattern of large scale submarine geomorphological features observed in fjords

3. Last Glacial Maximum restricted to inner fjords

4. Cross shelf troughs, and moraines document more extensive pre-LGM glaciations

5. Glacial history similar to that of central Patagonia

Glacial history of sub-Antarctic South Georgia based on the submarine geomorphology of its fjords

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Abstract

We present multibeam swath bathymetric surveys of the major fjords surrounding the sub-Antarctic island of South Georgia to characterise the glacial geomorphology and to identify the relative timings and extent of past glacial advance and retreat. Bathymetry data revealed a range of glacial features including terminal, retreat and truncated moraines, deep (distal) outer and shallow (proximal) inner basins and cross shelf troughs. These provide evidence of glacial advance and retreat through several glacial cycles. A relatively consistent pattern of large scale submarine geomorphological features was observed in the different fjords suggesting a similar response of margins of the island ice cap to past climate forcing. A relative chronology based on the relationships between the submarine features with their

radiocarbon and cosmogenic isotope dated terrestrial counterparts suggests that widely observed inner basin moraines date from the last major glacial advance or Last Glacial Maximum, while deep basin moraines may date from an earlier (pre-LGM) more extensive glaciation, which we speculate corresponds to MIS6. On the sides of the deep basin troughs a series of truncated moraines show ice advance positions from preceding glacial periods. The cross shelf troughs, and mid-trough moraines are interpreted as the product of much more extensive pre-LGM glaciations that predate the fjord geomorphology mapped here, thus possibly older than MIS6. This hypothesis would suggest that South Georgia followed a glacial history similar to that of central Patagonia (46°S) where a series of Pleistocene glaciations (of MIS 20 and younger) extended beyond LGM limits, with the most extensive glacial advance occurring at *c.* 1.1 Ma.

1. Introduction

South Georgia is situated between the Antarctic Peninsula and southernmost South America. Its glacial history has been studied for nearly a century (Gregory, 1915). The main research questions have focused on whether its glaciations are in phase or out of phase with the South American, Antarctic and northern hemisphere glaciations, defining the maximum ice extent during the last glacial cycle, and establishing a chronology for deglaciation and glacier fluctuations during the Holocene. All of these questions have the wider goal of improving our understanding of the mechanisms of climate change, both regionally and with respect to the phasing of climate changes between the hemispheres (Broecker, 1998), as well as improving understanding of the mechanisms of ice sheet decay and its impact on global sea levels (Sugden, 2009).

To date, glacial geomorphological research on South Georgia has focused on the terrestrial geomorphology which has established that an independent ice cap glaciated the island during the local Last Glacial Maximum (referred to hereafter simply as 'LGM') (Clapperton, 1971; Sugden and Clapperton, 1977; Clapperton and Sugden, 1988; Clapperton et al., 1989; Bentley et al., 2007). Most of the effort has been focussed on interpreting the glacial features in specific, and logistically more accessible, locations on the basis of comparative geomorphology and geomorphological mapping (Clapperton, 1971; Stone, 1974; Clapperton et al., 1989), radiocarbon-based geochronological models of glacial sediments (Gordon, 1987), combined radiocarbon and cosmogenic isotope dating of moraines (Bentley et al., 2007), the onset of sedimentation in lakes and peat bogs (Clapperton et al., 1989; Wasell, 1993; Rosqvist et al., 1999; Rosqvist and Schuber, 2003; Van der Putten et al., 2004; Van der Putten, 2008), and lichenometric studies (Roberts et al., 2010).

More recently the remarkable maximum extent of past glaciations around South Georgia has been revealed by a new compilation of bathymetric soundings from the continental shelf and surrounding waters. This has revealed large cross shelf glacial troughs, moraines and trough mouth fans on the shelf and slope at an unprecedented level of detail (Graham et al., 2008; Fretwell et al., 2009). These suggest that one or more glaciations have extended to the continental shelf break. Collectively, these studies have considerably advanced our understanding of the glacial history, but it is still not known whether at the LGM the ice cap extended to the edge of the continental shelf around South Georgia (Clapperton et al., 1989), or if the LGM was limited to the inner fjords as suggested both by the more recent mapping and dating of the onshore Late Glacial to Holocene moraines (Bentley et al., 2007), and by the deposition of lake sediments indicating ice free conditions from 18,572 cal. yrs BP (Rosqvist et al., 1999). The former theory would suggest that the glacial history of South Georgia is an analogue to the glacial record on the Antarctic Peninsula, where the ice sheet and its discharging glaciers extended to the shelf break at the LGM, and subsequently retreated in a stepwise pattern to the present. The latter theory would require the LGM to follow a glacial history similar to that of central Patagonia (46°S) where a series of Pleistocene glaciations (of MIS 20 and younger) extended beyond LGM limits (Rabassa, 2000), with the most extensive glacial advance occurring *c.* 1.1 Ma (Singer et al., 2004).

At present the accumulated data on the glacial geomorphology of South Georgia lacks a detailed examination of the submarine geomorphology of the inner fjords and bays which form the gateways to the prominent deep cross-shelf troughs. Such information can often provide exceptionally well-preserved evidence of glacial geomorphology that can be matched to the record on land. Fjords are glacially over-deepened, semienclosed marine basins, that often preserve evidence of environmental change in their geomorphology and sediments (Howe et al., 2010). Most fjords have been glaciated a number of times and many of those on South Georgia still possess a resident tidewater glacier (where the terminus is grounded below sea level (Cook et al., 2010)). The submarine geomorphology of many fjords can provide evidence of the advance and retreat of glaciers and in some cases the limits of former glaciations. Fjords can also accumulate sediment archives from which the timing of glaciation timing and post-glacial environmental changes can be deduced (Howe et al., 2010). The aim of this paper was therefore to carry out detailed marine geophysical surveys of the South Georgia fjords, to describe their geomorphology and from this, to interpret their glacial history. This fills an important gap between the recent studies of palaeo-ice sheet drainage on the continental shelf (Graham et al., 2008) and the glacial geomorphology and chronology of ice-cap deglaciation on land from the last glacial cycle (Bentley et al., 2007). From this data set a new chronology of glaciations on South Georgia is proposed together with a rationale for selecting sediment coring sites in the fjords to further test which theory regarding the deglacial chronology of South Georgia since the LGM is correct.

1.1 Study area

South Georgia (Fig. 1) has been described in detail in recent papers (Bentley et al., 2007; Gordon et al., 2008; Graham et al., 2008; Fretwell et al., 2009). The island is part of the North Scotia Ridge and lies ~350 km south of the Antarctic Polar Frontal Zone (54–55°S,36–38°W) (Fig. 1A). The most prominent relief consists of two mountain ranges that form an elongate NW-SE chain, 175 km-long and 2 to 35 km wide reaching up to 2935 m a.s.l (Fig. 1B). The mountains are heavily glaciated with series of ice fields feeding glaciers that terminate either on land or, more commonly, into the sea via steep sided bays and u-shaped fjords. These bays and fjords dissect the coastline to the north and south of the island and then extend into major glacial cross-shelf troughs which radiate 40-102 km out towards the edge of the continental shelf (Graham et al., 2008). The climate is maritime. Mean annual temperature at Grytviken, on the more sheltered north coast is c. 1.7 °C, with an annual precipitation at sea level of c.1395 mm, but is highly variable on account of the island's position near the Antarctic sea ice limit, the behaviour of the Antarctic Circumpolar Current and related deep water tongues, which influence the island to its east and north, and frequent depressions driven by the southern hemisphere westerly winds. These physiographic conditions result in a highly sensitive glaciological regime that has been shown to respond rapidly to changes in temperature and precipitation (Gordon et al., 2008; Cook et al., 2010). The most deglaciated areas are the peninsulas on the north coast. These are where most terrestrial studies have been carried out to-date.

2. Methods

Multibeam swath bathymetric surveys of selected fjords were carried out in 2005 and 2006 using a high-resolution shallow-water Kongsberg EM710S multibeam echo sounder on HMS *Endurance*. We combined these new data sets with existing data collected using a deep-water Kongsberg EM120 multibeam echo sounder on various cruises of the RRS *James Clark Ross* to the South Georgia region. Both echo sounders are 1 x 1° resolution systems; the EM710S acquires 400 soundings per swath at 70-100 kHz, while the EM120 acquires data across a fan of 191 beams at

11.25–12.75 kHz. Practical port- and starboard-side angles of up to ~68° provided a sea-floor coverage of c. 4-5 times water depth. Data from the former are archived at the UK Hydrographic Office, and for the latter in the NERC Polar Data Centre. All multibeam data were ping-edited and gridded together using tools in the UNIX-based MB-System (Caress & Chayes 2006, http://www.ldeo.columbia.edu/res/pi/MB-System). Navigational data were recorded using differential GPS receivers. Sub-bottom topographic parametric sonar (TOPAS) data were acquired in Cumberland Bay, on the north coast of South Georgia (Fig. 1A), during cruise JR224 of the RRS *James Clark Ross*, using a Kongsberg Simrad TOPAS PS018 sub-bottom profiler operated in 'chirp' mode. Because such data have not been collected routinely in previous cruises to the South Georgia shelf, sub-bottom data were limited to only a small number of transects in this single fjord.

Cleaned data sets were gridded at high resolution to enhance the imaging of subtle submarine features. For most of the study area, we produced gridded datasets with cell sizes ranging from 4-10 m, suitable for the range of water depths encountered in the fjord regions (50-300 metres). Two of the bathymetric grids (Drygalski Fjord and King Haakon Fjord) were derived from existing gridded single-beam surveys, using legacy data provided by UK Hydrographic Office. Consequently, bathymetric resolution is lower in these areas compared to the fjords to the north of the island (>12-15 m). Nevertheless, glacial geomorphic features are still distinguishable on these datasets.

Vertical accuracy of both the multibeam and singlebeam systems are dependent on acquisition factors, but in shallow depths uncertainty normally equates to better than 1 metre (0.2% of the water depth across the entire swath). Bathymetric data are presented as plan and oblique shaded-relief images to differentiate the major sea-floor landforms.

Cross sections were taken through key features such as moraines, fjord basins, and debris cones. The offshore data were combined with near-shore satellite images of South Georgia (a compilation of SIO, NOAA, U.S. Navy, NGA and GEBCO sources) and with previously published onshore geomorphological maps (Bentley et al., 2007) (see figures in Appendix A) to highlight the relationships between the submarine fjord, and known terrestrial geomorphology.

3. Results

Surveys of the fjords that dominate the South Georgia coastline were carried out on the major inlets along the northern coast of the islands, together with accessible fjords on the south west and east coasts. The survey regions are shown as numbered boxes on a regional bathymetric map of the South Georgia continental shelf (Fig. 1, Fretwell et al., 2009). This shows the relationship of the surveyed fjords to the trough systems on the continental shelf. The submarine surveys revealed a range of glacial land forms from which the interrelationships between different features in each fjord could be examined. The results of the individual fjord surveys are described below.

3.1 Royal Bay

Royal Bay (Fig. 2) is a 241 m deep fjord, occupied until recently by the combined Ross/Hindle Glaciers, which have now divided and discharge separately into the bay from the south and the west (Fig. 2A). The bay is also fringed by a minor tidewater glacier, the Weddell Glacier that discharges into it from the south (located south of the red star in Fig. 2A). The Weddell Glacier terminates in a small embayment partially enclosed by a terminal moraine or shingle spit formed by reworking of glacial deposits. The fjord is approximately 12 km long and broadens in width seaward from 4 to 7.5 km before it extends beyond the headlands of Harcourt Island to the north and Cape Charlotte to the south (Fig. 2). The fjord consists of a relatively shallow inner basin whose modern-day topography is likely the result of a high sediment flux at the glacier terminus. The inner basin extends eastwards to a prominent c. 10-25 m-high transverse moraine ridge which has been partially breached on its northern side and towards the centre of the fjord (Fig. 2F). The top of the ridge, and the breaches, are interpreted to have been shaped by past interactions with icebergs shed from the nearby tidewater glacier fronts, likely when the glaciers were grounded in greater water depths, in a more advanced position. The unusual surface morphology on the steep distal flank of the moraine is also reminiscent of features composed of stacked thrust blocks, and suggests that the moraine may have formed by the thrusting and deformation of fjord sediments as the glacier advanced to this moraine limit. Beyond the inner basin moraine, the fjord extends into a deep smooth-bottomed, probably sediment-filled deep basin. On the north side of this deep outer basin are four clear promontories, which are interpreted as truncated moraines. It is possible that they are matched by the similar but less distinct features on the southern flank of the trough (Fig. 2C, D). Hummocky lobes at the foot of some of these truncated features a considered the result of rock fall which could have occurred after the last glacier terminus in the deep trough retreated landward of these moraines. Other notable features in the fjord are a relict meltwater channel that probably issued from a subglacial conduit at the northern part of the Ross Glacier front in the recent past, forming a chute with levees, carved into the seaward flank of the fjord floor where it shallows towards the coast (perhaps representing another moraine ridge near the terminus of the glacier, or the fjord bedrock) (Fig. 2E, 3). Seaward of the chute are a series of small, slightly sinuous ridges and intervening channels, oriented broadly parallel to the modern glacial front. There are several possible interpretations for these features: they may be a series of abandoned channels which together have discharged sediment gravity flows into the inner basin, their morphology reflecting sediment creep and deflection to the south by the Coriolis Effect (Fig. 3). Alternatively, the ridges can be interpreted as a series of small recessional moraines, stacked behind a curvi-linear ridge that is a larger end moraine. In either case, there appears to be evidence in Royal Bay for active or recently-active subglacial fluvial transport, including a possible esker ridge system that lies immediately south of the small ridge set (Fig. 3). Rapid sedimentation from the jet and plume as a subglacial meltwater channel issues from the grounding line is a common process in temperate and sub-polar, glacier-influenced fjords (Pfirman and Solheim, 1989; Powell and Alley, 1997; Ó Cofaigh and J.A., 2001) and is the most likely source of the sediments that fill both the inner and outer fjord basins.

3.2 Cumberland Bay East

The Cumberland Bay complex is the largest fjord system on South Georgia and is the outlet for the major glaciers of the Allardyce Range and the Kohl Plateau Ice Field. Cumberland Bay East (Fig. 4) is approximately 15 km long, 3-5 km wide and up to

270 m deep, extending from the terminus of the Nordenskjöld Glacier to Sappho Point where it merges with Cumberland Bay West and connects to the head of a prominent cross shelf trough (Fig. 1, 4A). It consists of one principal fjord with two tributary fjords: Moraine Fjord and King Edward Cove (KEC on Fig. 4A). Moraine Fjord is a 6 km long re-entrant and the outlet for two tidewater glaciers, the Hamberg Glacier and Harker Glacier whilst King Edward Cove is not currently glacierised. The mouth of Moraine Fjord is enclosed by an arcuate submarine terminal moraine, most likely an extension of a laterofrontal moraine complex described by Bentley et al. (2007) whose large boulders and kelp beds are exposed at low tide, whilst King Edward Cove is partially enclosed by a shingle spit: King Edward Point. Like Royal Bay, Cumberland Bay East consists of a relatively shallow inner basin terminating in a prominent inner basin moraine which is well-preserved on the north side but has multiple breaches in the centre of the fjord (Fig. 4B). Because of their highly random orientations these breaches are likely to have been caused by iceberg ploughing. Ploughing of the sediment by icebergs is evident in circular grounding pits and chaotic scours that are present in water shallower than ~220 m depth, near the terminus of the Nordenskjöld Glacier. Because the sea-floor deepens slightly away from the coast here, the scours can only feasibly have formed during episodes of terminus retreat from a more extensive position. As is the case with Royal Bay, the fjord deepens seaward to an outer basin 270 m deep, immediately seaward of the inner basin moraine. Again, there are a series of potential truncated moraines or submarine bedrock promontories, one of which lies approximately 1 km northeast of King Edward Cove (Fig. 4A), and is likely a relict moraine formed by an extended Hamberg/Harker Glacier occupying Moraine Fjord. At the mouth of the fjord there is a second moraine marking the outer limit of the deep basin. This appears partly

eroded and breached near the centre of the fjord, although well preserved otherwise (Fig. 4C). There is a series of topographic highs between this moraine and Barff Point (Right Whale Rocks) which may be truncated moraines, and an unusual, discontinuous sea-bed high landward of the moraine, which is possibly a remnant moraine owing to the fact that it shares a cross-profile similar to that of the outer-basin moraine (Fig. 4D, 4E). Other notable features on land are the outwash from the fjord valley system of the Hamberg 'valley' and Moraine Fjord, separated by a moraine complex, Zenker Ridge, which formed along the northwest margin of the expanded Harker Glacier and extended offshore from the mouth of Moraine Fjord. The adjacent Hamberg Valley (HV on Fig 4A) has most likely been formed by a fjord becoming infilled with glaciofluvial sediment to above sea level, assisted by post glacial isostatic rebound and relative sea level fall. The floor of this paraglacial coastal valley, Hesterletten (HS on Fig 4 A), comprises reworked glacigenic sediment with a prograding fjord head delta and braided river system with a trunk stream that has discharged sediments into Cumberland Bay East via turbidity currents and sediment plumes. These sediments extend up to 3 km into the bay. Multiple slope failures can be seen in this reworked glacigenic sediment immediately seaward of the Hamberg Valley. Small slope failures are also present at various locations along the margins of Cumberland Bay East where a deep sedimentary infill is evident on TOPAS sub-bottom profiler data (e.g. Fig. 4E).

3.3 Cumberland Bay West

Cumberland Bay West (Fig. 5) is the outlet for the Neumayer and Geikie glaciers and the heavily debris covered Lyell Glacier. All three are tidewater glaciers with the Neumayer Glacier discharging directly into Cumberland Bay West and the Lyell and

Geikie Glaciers discharging into tributary fjords, Harpon Bay and Mercer Bay, which are both partially enclosed by moraines exposed as kelp beds at low tide. Cumberland Bay West is approximately 18 km long and 2.5-5 km wide and up to 265 m deep, extending to Mai Point beyond which it merges with Cumberland Bay East (Fig 4A). Mapping of the fjord did not extend to the glacier fronts so we did not identify a shallow inner basin moraine, although from Admiralty Chart 3597 (South Georgia) and the compilation data in Fig 1a., it is possible that it may occur just south of Carlita Bay where Bentley et al. (2007) document a series of moraines associated with an earlier advance of the Neumayer Glacier (Appendix Fig. A2). From the survey limits, the fjord deepens seaward past a series of up to four submerged promontories, possibly truncated moraines, to a heavily eroded outer moraine which shares a similar profile to the outer basin moraine in Cumberland Bay East (Fig. 5C), and is eroded away on the central and southern parts of the fjord (Fig. 5B). Other notable features are debris cones or moulin kames, interpreted to have formed where sediment-laden water and/or supraglacial debris has drained through or melted out of sink holes in the floating glacier when it occupied a more advanced position in the fjord. There is also a possible medial moraine extending seaward from Middle Head (Fig. 5A).

3.4 Stromness Bay and Husvik Bay

Stromness Bay and Husvik Bay (Fig. 6) are two shallow fjords 6-8 km long (measured to the deep basin moraine, Fig. 6B), up to 2.5 km wide and approximately 50-160 m deep, separated by Tonsberg Point (Fig. 6A). Tidewater glaciers are absent from these fjords, which are currently amongst the most deglaciated parts of the island. As with the other fjords the general pattern of a shallow inner basin terminating in a shallow, flat-topped moraine is repeated. In this case the inner basin consists of a complex of basins that have originated from earlier glaciers occupying the three major glacial valleys feeding into Leith, Stromness and Husvik Bays. The inner basin moraine is located just beyond Tonsberg Point in Husvik Bay and immediately south of Black Rocks in Stromness Bay (Fig. 6C). This observation suggests formation by two independent glaciers, because the inner basin moraines do not form one continuous ice-marginal limit. The moraine in Stromness Bay has a deep breech in the centre of the fjord. Three lateral or frontal moraines derived from valley glaciers in Leith and Husvik harbours are present between Berntson Ridge and Grass Island and similar features are present in Husvik Bay. Elsewhere it is difficult to separate moraines from bedrock features. From terrestrial geomorphological studies Bentley et al (2007) describe the series of prominent inset lateral moraines that document the recession of a fjord-based glacier along the south shore of Husvik Bay. The most extensive of these (Bentley et al's. Limit I) was mapped on both sides of the bay with further retreat positions marked by limits II and III and glacially abraded bedrock (see Appendix Fig. A3, parts A and B). Submarine evidence of the extensive Limit I retreat position appears to be evident in close inspection of the detailed bathymetry of the bay (Fig. 6D and Appendix Fig. A3, parts A and B), but its subtle sea-floor expression suggests that the inner basin retreat moraines have been at least partially buried by high sediment flux from the former tidewater glaciers, and perhaps more recently by inflowing sediment-laden rivers. The landward extent of our multibeam dataset also hints at resolving the sea-floor expression of retreat Limit III (Fig 6A), but not Limit II. The three lateral or frontal moraines mapped at the sea bed between the tip of Berntson Ridge and Grass Island may correlate with the three retreat limits (I-III) recorded by Bentley et al. (2007) in Husvik Harbour. This interpretation would only be possible if the moraines were derived from the

Stromness Valley glacier rather than having formed at the juncture of the Leith and Stromness valley glaciers, which would suggest a more complex glacial history. Seaward of the inner basins and inner basin moraines the fjords merge into two apparently distinct deeper basins, with noticeably different water depths (marked X and Y on Fig 6A), that extend to the mouth of the fjord where there is a deep basin moraine east of Framnaes Point (Fig. 6B), whose crest appears to lie deeper on the Stromness (N) side of the merged fjord. Although they share a similar limit, these may be two separate moraines. The difference in their ridge height probably reflects the separation of basins in this part of the fjord and the formation of moraines by individual glaciers. While bathymetry does deepen seaward offshore from the deep basin moraine, unlike the other fjords, the outlet of Stromness Bay and Husvik Bay does not obviously feed into a cross-shelf trough (Fig. 1).

3.5 Antarctic Bay

Antarctic Bay is a steep sided fjord, formed by the Crean Glacier, which remains a significant tidewater outlet today (Fig. 7). The fjord is 8.5 km long and 2-2.5 km wide, extending past Morse Point into one of the glacial troughs on the continental shelf. Although bathymetric coverage is low, the data suggest the presence of a shallow (30-150m deep) inner basin terminating in a moraine complex, comprising at least three arcuate ice-marginal limits, seaward of which there is a deeper (200 m) outer basin (Fig. 7B, 7C). These limits are more or less consistent with terrestrial moraines on the west coast of the bay (Appendix Fig A4) that mark an expanded position of the glaciers in the fjord but which have not yet been dated (Bentley et al., 2007). The inner basin floor behind the three moraines is characterised by at least two elongated ridges, one of which appears slightly sinuous (Fig 7A). These may have been streamlined directly by the flow of grounded ice, or else comprise eskers recording phases of meltwater deposition in subglacial tunnels near to the ice margin.

3.6 Possession Bay

Possession Bay is the outlet for the Purvis Glacier and a number of other tidewater glaciers and ice fields (Fig. 8). The fjord is ~8 km long and up to 4 km wide (Fig. 7A). It has a relatively shallow inner basin terminating in a prominent moraine which is visible at low tide (Fig. 8C, 8D). The moraine sits in a very similar fjord position to the inner basin moraine mapped in the adjacent Antarctic Bay; marked ‘outer moraine reef’ on Admiralty Chart 3585 (Harbours and Anchorages in South Georgia). The inner basin moraine is consistent with a mapped position of a suite of onshore moraines on the south east shore of Possession Bay (Bentley et al., 2007, Appendix Fig. A5). The inner basin also exhibits a number of smaller retreat moraines (marked with arrows) that record ice retreat to modern glacial extents (Fig. 8C). Beyond the inner basin is a ~4 km-diameter, 350 m deep basin bounded on its northern side by a 60 m high, relatively well-preserved arcuate deep basin moraine (Fig. 8A, 8B), situated 2 km north east of Black Head. Several lateral moraines are found farther north still of the deep basin moraine, interpreted to have formed as medial features between ice flowing out of Prince Olav Harbour and Possession Bay itself (Fig. 8A).

3.7 King Haakon Bay

King Haakon Bay was the only fjord surveyed on the south coast of South Georgia in this study. It is one of the narrowest and longest fjords, being ~13 km long, up to ~3 km wide and relatively shallow at up to 160 m deep (Fig. 9). It is the outlet for the Briggs Glacier, a major tidewater glacier which discharges from the east (Fig. 9A), and a number of smaller tributary glaciers. The bathymetry data show a shallow inner basin terminating in a 50-110 m high moraine, followed by a deeper basin offshore. The deep basin bifurcates seaward around McCarthy Island, and shallows to 40-50 m to the south. Linear features behind the moraine in the inner basin are evidence of medial moraines or streamlined subglacially-formed ridges which may be analogous to the medial moraine previously described from behind Husvik whaling station in Husvik Bay; part of the same sequence that forms the Husvik Bay inner basin moraine (Figs. 9A, 9B) (Limit III, Bentley et al., 2007). A number of smaller, minor arcuate moraines, probably formed during recent phases of readvance or retreat, mark the innermost 3 km of the basin where the fjord narrows towards the glacier front (Figs 9A, 9C).

3.8 Drygalski Fjord

Drygalski Fjord is the only major inlet at the south-eastern extremity of South Georgia (Fig. 10). Like King Haakon Bay it is narrow and long, extending ~12 km from the entrance at Nattriss Head to the tidewater termini of the Risting and Jenkins Glaciers. The fjord is 1-3 km wide (mostly <2 km), with a maximum depth of 220 m. A number of tributary glaciers feed the fjord. The bathymetry survey reveals a large shallower inner basin with a sinuously carved, flat-bottomed floor. Notably, the deepest part of the basin extends to the present-day front of the Risting Glacier, whereas the tributary connecting the fjord to Jenkins Glacier is surprisingly shallow, suggesting that the Risting Glacier has been the dominant erosional system in the fjord's evolution. A marked inner basin moraine connects to the headland west of the entrance to Larsen Harbour, forming a pronounced loop marking a former ice-marginal limit at the fjord mouth. Erosional grooves, probably subglacial in origin, characterise the backslope of the moraine (Fig. 10B, black arrows), which has a 'wedge'-like asymmetric profile similar to that of the inner basin moraines in Cumberland Bay East and West (Fig. 10C). This is one of the largest fjord moraines in South Georgia. Beyond the moraine, the fjord bathymetry deepens to a <310-m deep basin that extends south east and merges into a south westward trending cross-shelf trough terminating in a deep basin moraine (see Fig 1 for its location). At least three smaller moraines are observed stretching laterally across the innermost part of the fjord, recording recent advance or retreat limits of the Risting and Jenkins Glaciers (black arrows, Fig. 10A). Admiralty Chart 3585 (Harbours and Anchorages in South Georgia) shows that Larsen Harbour has its own shallow inner basin terminating in a moraine, marked Fairway Rock, and a series of possible truncated moraines before it meets Drygalski Fjord.

4. Discussion

Despite the different lengths, widths and orientations of the fjords surveyed, a relatively consistent pattern of large scale submarine geomorphological features has emerged (Table 1). In particular, the majority of the fjords have a shallow inner basin bounded by an inner basin moraine, a marked drop seaward into a deep basin with a corresponding deep basin moraine at the outer limits of the fjord. Some fjords have evidence of truncated moraines along the flanks of the deep basins. The outlets of all the fjords are aligned with cross-shelf troughs (Fig. 1), with the exception of Husvik and Stromness Bays. Most fjords are U- shaped with steep valley sides.

4.1 Relative ages of the glacial geomorphological features

Using a combination of previously published terrestrial radiocarbon, and cosmogenic isotope exposure age constraints, together with the stratigraphic relationships between the geomorphological features it is possible to reconstruct a relative glacial chronology (Table 1; Fig. 11). According to analyses of the terrestrial glacial geomorphology Clapperton (1971) and Bentley et al. (2007) found that all moraines in the Stromness Bay and Cumberland Bay East and West are confined to the inner fjords, whilst the outer headlands are devoid of major onshore depositional landforms. In Cumberland Bay East, Antarctic Bay and possibly Possession Bay the most seaward of the terrestrial moraines mapped by Bentley et al. (2007) coincide with the position of the submarine inner fjord moraines (Appendix Figs. A1, A4, A5). Bentley et al (2007) attempted to date this feature in Cumberland Bay East at Moraine Fjord (Fig. 4 and Appendix Fig. A1), but the ^{10}Be age had an unacceptably large error (GRE5, 12,900 ± 7800). These inner basin moraines have a cross section that, in comparison with conceptual models of tidewater glacier sedimentation (Powell, 2003, Figs. 13.7 & 13.17) suggests they are push moraine banks formed at an advancing grounding line. Their characteristics including profile asymmetry, generally rounded crests, as well as evidence, in some examples, of thrust-blocks within the moraine belt (e.g. Fig. 2), are all diagnostic of bull-dozed moraine banks. In combination with their size, at 10s of metres high, the moraines are therefore taken as indicators of a maximum grounding line advance rather than moraines formed during retreat from an otherwise more expansive glacial extent. Given the preservation of these features, it is high unlikely that these moraines have been overridden since their formation because any subsequent advance would have presumably cannibalised any existing sediment bodies. Glacial retreat in the inner basins has likely been accompanied by large volumes of glacimarine sediment deposition which has accumulated behind the inner moraine contributing to inner basin moraine profiles that have an asymmetric morphology rising gradually 20-100 m to a moraine crest then descending steeply 30-160 m into the deep basin on the seaward side. The difference between the depth of the shallow inner, and deep outer basins can therefore be attributed to a high sediment flux between the glacier termini and the inner basin moraines, coupled with rapidly shallowing underlying basement rocks. In those surveys with exceptional sea-floor detail (e.g. Royal Bay, Cumberland Bay East) these accumulations of inner-basin sediments are characterised by a range of sedimentary features including sediment gravity flows, debris fans and slope failures, all of which can be associated with high sediment supply. At some sites (e.g. Royal Bay) the inner moraines may have been partially breached and subsequent debris flows have created debris fans which overlie older glacial deposits. However in general debris fans are absent from the deep basins with the exception of sites where tributary glaciers discharge into the fjords, for example where Moraine Fjord and the Hamberg Valley discharge into Cumberland Bay East.

The large volume of glacial sediments in the inner basins appears to have, in some cases, buried any evidence of retreat moraines in the inner basins, and these latter features appear to be better preserved on land for example in Husvik Bay and Cumberland West Bay (Clapperton et al., 1989; Bentley et al., 2007) (Appendix Figs. A2,A3). Some potential evidence of inner basin retreat moraines however was found in Cumberland Bay East (Fig. 4), as well as in the innermost parts of Husvik Bay, Antarctic Bay, Possession Bay, King Haakon Bay, and Drygalski Fjord. The terrestrial moraines in these inner basin regions are interpreted as marking the oldest mapped ice advance on South Georgia and have cosmogenic ^{10}Be exposure ages of between 14.2 and 10.6 ka BP, mean 12.2 ± 1.5 ka BP, based on data from the Husvik medial moraine (Bentley et al., 2007, 'category a' moraines) (Appendix Fig. A3). These ‘category a’ moraines have been correlated on geomorphological grounds with the oldest terrestrial moraine ridges in Antarctic Bay, Possession Bay and Moraine Fjord (Zenker Ridge) (Appendix Figs. A4, A5, A1, respectively). If these dates are correct, this suggests that glacier retreat from the inner basin moraine took place during the warming that followed the Antarctic Cold Reversal; the abrupt cooling in Antarctica which occurred between 14,540 and 12,760 years ago and is associated with glacier expansions as far north as 44° S (Putnam et al., 2010). Landward of these moraines is a second set of moraines documenting a mid-Holocene advance at 3600 ± 1100 yr BP (Bentley et al., 2007, 'category b' moraines) (Appendix Fig. A1). In some areas this advance approached nearly to the ‘category a’ limits. If the LGM on South Georgia was restricted to the inner fjords, as suggested by Bentley et al. (2007) then the inner basin fjord moraines would represent the maximum grounding lines (Fig. 11). The asymmetry between the position of the inner basin moraines in Husvik and Stromness Bays (Fig. 6 and Appendix Fig. A3) would place Tonsberg Point in a favourable position to avoid overriding glacial ice and may explain why 18.6 ka lake sediments are found there (Rosqvist et al., 1999; Rosqvist and Schuber, 2003).

We rule out a Little Ice Age (LIA) date for the inner basin moraines because this would be inconsistent with the available cosmogenic and radiocarbon age constraints. In addition the LIA, or at least the most recent advance, has been shown as a relatively minor advance of the higher mountain glaciers (Clapperton, 1971; Roberts et al., 2010). In Royal Bay, Gordon and Timmins (1992) also interpreted very minor readvance of the Ross Glacier during the LIA, based on the presence of heavily vegetated shore-side moraines, which lie just beyond the 20th Century glacier limit.

All the fjords in this study have a deep basin, a majority have a deep basin moraine and between 5 and 7 have features which might be interpreted as truncated moraines along the flanks of the deep basin, because they apparently do not have a bedrock control (Fig. 11). Deep basin moraines can also be seen in other fjords not surveyed in this study, such as the major submarine fjord which discharges from the west side of the Bay of Isles (Fig. 1, circled). There is little evidence of events coinciding with the formation of the deep basin moraines being preserved on land. Instead the coastal areas adjacent to the deep basin moraines contain only patchy degraded till veneers and a very limited number of glacial erratics of unknown age (Bentley et al., 2007). Based on this weathering and a proposed morphological distinction between last glaciation and older landforms (Bentley et al., 2007), our interpretation is that the deep basin moraine may represent an older pre-LGM glaciation; the simplest interpretation being that it is the penultimate MIS6 glacial limit in the fjords (Fig. 11). Where it is well preserved, it shares a similar cross-section to the inner basin moraine, with an asymmetric morphology rising gradually 25-60 m to a moraine crest then descending steeply 40-90 m on the seaward side. Good examples of this are found at the mouth of Cumberland Bay East and Possession Bay and similar features have been described from the southern Chilean fjords (Fig. 7B in Dowdeswell and Vásquez, 2013). Not all are well preserved, for example in Cumberland West Bay the moraine is breached on its eastern side, possibly by iceberg scouring or a readvance of the combined Neumayer, Geikie and Lyell Glaciers, although the latter is less likely as it should have removed the entire moraine, at least in the central part of the fjord.

Features inferred to be truncated moraines, where present, are usually located along the sides of the deep basins (Fig. 11). These are interpreted as recording a series of successive glacial advances that pre-date the deep basin moraine. Seaward of the deep basin moraine most of the fjords merge with 250-380 m deep cross shelf troughs that vary between 40-102 km in length and 2-5 km wide in the inner shelf to 12-26 km wide on the middle and outer shelf (Graham et al., 2008) (Fig. 1). These also have broadly similar cross sections to those seen in the fjords, in particular several mid-trough moraines (Fig 5a in Graham et al., 2008) which mark the position of one glacial advance, and more distal moraines and at least one trough mouth fan on the shelf edge which mark a series of older and maximum glaciation(s). However, because of the less well defined and rounded nature of many of these moraines our interpretation is that the outer parts of these troughs were not ice-filled at the LGM, and instead moraines mark a series of older glaciation(s). The troughs themselves are likely to have formed since the Late Miocene and thus glaciations may be as old as the early Pleistocene, and more similar to those seen off the coast of Patagonia (Rabassa, 2000; Singer et al., 2004). Older terrestrial rock platforms e.g. at c. 21 m in Harpon Bay and 24 m in Carlita Bay (Bentley et al., 2007, p.655), that are overprinted by later moraines may reflect the glacioisostatic depression from these continental shelf glaciations. Similar altitude terrerestrial rock platforms have been observed elsewhere between 2-3.5 and 5.5-7.5 m above sea level (Adie, 1964; Stone, 1974).

The apparent absence of glacial lineations, streamlined bedforms, drumlins and other flow-parallel features in the fjords, as found for example in Marguerite Bay (Ó Cofaigh et al., 2005) on the Antarctic Peninsula, some of the Southern Chilean fjords

(Dowdeswell and Vásquez, 2013) and at the mouth of the Kongsfjorden-Krossfjorden system in Svalbard (MacLachlan et al., 2010), suggests that the features have been buried by post-glacial sedimentation via turbid meltwater plumes from glaciers and sediment delivery from icebergs which can discharge high volumes of sediment into the fjord environment. In a previous study, Graham et al. (2008) showed evidence for drumlinised topography on part of the South Georgia continental shelf where sediments presumably thin out or are absent. Furthermore, towards the mouths of the fjords in both Drygalski Fjord and King Hakkon Bay there is some indication in the bathymetry that exposed bedrock or basin sediments have been streamlined by past ice flow, while large moraines attest to significant delivery of subglacial sediment. Thus, while there is no clear evidence for full ice-stream style drainage, it remains possible that several or more glaciers that drained the former South Georgia ice cap were fast-flowing, and actively eroded and modified their bed.

4.2 Regional significance

Collectively the data presented here suggest that LGM was limited to the inner fjords as implied by Bentley et al. (2007) . This might imply a degree of sea level control on glacier extent, with the lower LGM sea level resulting in some of the glacier fronts being grounded on land within the inner basins. This is supported by studies of recent glacial retreat in Greenland which has shown that marine-terminating outlet glaciers have thinned more rapidly than land-terminating outlet glaciers (Sole et al., 2008). Thus in situations where the glaciers were grounded on land they may not have advanced beyond the inner basin moraines.

Another factor resulting in the limited glacial extent at the LGM could be that the glaciers were deprived of moisture by the more extensive sea ice during the later stages of the last glacial (Allen et al., 2011; Collins et al., 2012). This is a common feature of sub-Antarctic islands where the combination of sea ice further north and strong winds increased aridity (Hodgson et al., 0000; Bentley et al., 2007) – hence most peat and lake sequences in the sub-Antarctic region only start to accumulate in the early to mid-Holocene (Van de Putten and Verbruggen, 2005; Van de Putten, 2008), with occasional exceptions between 19000 cal yr BP and the start of the Holocene (Selkirk et al., 1988; Keenan 1995; Rosqvist et al., 1999). Patagonian climate, east of the Andes was also arid at this time (Recasens et al., 2011) due, in part to the same factors, together with the rain shadow effect of the mountains.

In addition to changes in sea ice extent, reduced moisture delivery is a product of a northward shift of the Southern Hemisphere westerly winds. One simplified study with a general circulation model (Toggweiler et al., 2006) suggests that the belt of the Southern Hemisphere westerly winds may move northward towards the Equator during cold periods (and vice versa). This would suggest that moisture supply seems to be a major factor in the mass balance of the South Georgia glaciers (Bentley et al., 2007; Gordon et al., 2008), with insolation and aspect being of lesser importance. Unravelling the sequence and extent of South Georgia (and other subantarctic) glaciations could therefore provide important information on long term changes in the position of the Southern Hemisphere Westerlies (moisture supply from subtropical air masses) and changes in glacial sea ice extent (aridity).

An alternative hypothesis is that over many glacial cycles, the glacial erosion of the alpine valleys and fjords has been sufficient to reduce the length of glaciers in the most recent cycle because theoretically glacier length can scale linearly with erosion depth (Anderson et al. 2012). In such cases there are often earlier moraines deposited well beyond the LGM limits. These are referred to by Anderson et al. (2012) as 'far-flung' moraines. This suggests that the glacially modified landscape, rather than a different climate, may be capable of explaining at least some of the earlier more extensive glacier extents, but this hypotheses has yet to be tested in detail..

Biological studies of the South Georgia continental shelf have shown that it is a hotspot for biodiversity; a possible result of it being an ice free refuge for the biota through several glacial cycles (Barnes et al., 2011; Hogg et al., 2011). Terrestrial glacial refuges were also present for endemic birds on the island with molecular biological data pointing to divergence of the South Georgia Pintail (*Anas georgica georgica*) from the neighbouring Argentinian population of yellow-billed pintails (*A. georgica spinicauda*) prior to the Last Glacial Maximum (McCracken et al. 2013). Therefore better dating of the shelf sediments and geomorphological features will provide a temporal context to the emerging evolutionary history of the Antarctic and Southern Ocean biota. Thus, the need for a robust glacial chronology extends beyond fields of geoscience and palaeoclimate studies.

4.3 Future work

South Georgia's location at the heart of the Southern Ocean, means that the phase relationships, forcing, and magnitude of glacial events on the island and its adjoining shelf are likely to provide crucial insights into how climate has fluctuated through time, enabling correlation of records regionally (to South America and the Antarctic Peninsula), and with climatic and ice sheet variability at the global scale. Therefore it is important to do further work to establish whether the South Georgia glaciers were indeed grounded in their inner fjords at the LGM (Bentley et al., 2007), or extended onto the continental shelf, or indeed reached the continental shelf break (Graham et al., 2008). In order to determine this, sampling of sediments either side of the inner basin, deep basin and mid-shelf moraines is required. Specifically, by dating the sediments and showing that they are glacimarine or fully open marine would provide a minimum constraint on deglaciation, and dating material within or below tills would provide maximum constraints. TOPAS (0.5-5 kHz) sub-bottom profiler data from Cumberland Bay shows cross-sections of the outer basin moraine as well as the deep basin landward of this feature (Fig. 4E). Both features are draped with sediments. The chaotic unit at the base of the outer basin has an acoustic signature that is normally associated with diamicton, such as glacial till, but it is not present, or not resolved, in sedimentary basins on the seaward side of the moraine. Sediment coring will help define whether this unit is indeed the LGM till. This hypothesis will be tested in future work that will also involve dating the glacigenic sequence beyond the outer moraines.

Further shallow water seismic surveys (e.g. Fig 4E) would also be advantageous to map the basic depositional architecture of the sediment facies within these moraines and to compare them with sedimentological models (e.g. Fig. 13.17 in Powell, 2003) and terrestrial evidence. Previous studies in sub-polar and polar fjords have found that sediment can be preserved from several glacial episodes (Barrett and Hambrey, 1992) and studies of Antarctic Peninsula Fjords have shown the presence of distinct interglacial sequences comprising diatomaceous sediments in spring and summer and an enhanced terrigenous sediment supply in winter (Allen et al., 2010). If this is the case at South Georgia then it may be possible to reconstruct the limits of several previous glaciations and glacial advances. For the oldest glaciations the relative chronology could be established by extracting marine sediment cores from the trough mouth fans at the end of the cross shelf troughs and farther down the slope on sediment drift bodies. The potential of the former features has been previously recognised (Graham et al., 2008). The conclusion of Clapperton and Sugden (1988), that ‘much of the evidence on which the chronology of glacier fluctuations in South America and Antarctica is based appears to be tenuous and, in places, highly ambiguous’ still applies to South Georgia today but could be rapidly addressed by a marine geological coring programme.

5. Conclusions

Mapping of the submarine geomorphology in nine of South Georgia’s innermost fjords has revealed a relatively consistent pattern of submarine geomorphological features. These include a shallow inner basin bounded by an inner basin moraine, a deep basin, and a deep basin moraine at the outer limits of the fjords. Some fjords have evidence of truncated moraines in the deep basins. The outlets of all the fjords were aligned with cross-shelf troughs, with the exception of Husvik and Stromness Bays.

A relative chronology based on existing terrestrial evidence suggests that the inner basin moraines date from the last major glacial advance (LGM), and the deep basin moraines from an earlier glaciation, possibly MIS 6. On the sides of the deep basin trough a series of truncated moraines show ice advance positions from preceding periods. Based on the existing chronological constraints the cross shelf troughs, and mid-trough moraines are interpreted as the product of glaciations that pre-date the LGM.

LGM glaciers persisted until the end of the Antarctic Cold Reversal and then retreated during the Holocene, punctuated by a series of readvances towards the LGM limit (cf. Clapperton, 1971; Bentley et al., 2007).

If correct, the relative stratigraphic relationships between the various geomorphological features and previously published age constraints suggest that the glacial history of South Georgia is more similar to that of Southernmost South America where a series of Pleistocene glaciations (of MIS 20 and younger) extended beyond LGM limits in Patagonia (Rabassa, 2000; Coronato et al., 2004), with the most extensive glacial advance occurring *c.* 1.1 Ma (Singer et al., 2004). Further marine geological records are required to test this interpretation.

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Table

Table 1. Presence and number of key submarine glacial geomorphological features identified in the South Georgia fjords from swath bathymetric and bathymetric soundings. Age constraints for these features are based on a combination of terrestrial age constraints (radiocarbon dates and cosmogenic isotope dating) and the relative geochronological relationships between various terrestrial and submarine features (see Appendix A figures). *located in the inner basin based on terrestrial evidence. †circled on Fig. 1.

Figure captions

Figure 1A. Topographic and bathymetric compilation of South Georgia and its continental shelf (223 m cell size grid, UTM Zone 24S projection) compiled from a variety of data sources including, multibeam swath and single-beam bathymetry data (Graham et al., 2008; Fretwell et al., 2009). Note the aligned trough systems widening from the fjords towards the outer shelf, converging tributaries, banked shelf edge features, well-defined shape of the continental margin, and radial distribution of troughs north and south of the island. Hillshade of DEM of South Georgia supplied by P. Fretwell, BAS. Locations of Figures 2-9 are shown as inset boxes. Circles highlight the deep basins at Bay of Isles (northwest coast) and Drygalski Fjord (east coast). Inset map shows the wider regional location of South Georgia with grey shading indicating water depths <500m. Oceanographic boundaries indicated are the Polar

Front, the Sub-Antarctic Front (SAF) and the southern Antarctic Circumpolar Current Front (SACCF).

Figure 1B. Oblique aerial photograph along the heavily glaciated south coast of South Georgia facing west from near the head of Drygalski Fjord.

Figure 2. Multibeam swath bathymetry and geomorphological features of Royal Bay, South Georgia. Inset boxes show (B) a cross section along the fjord, (C) an enlarged image of the truncated ridges or moraines, (D) cross-section of the truncated ridges or moraines (E) an enlarged image of the inner basin, and (F) an enlarged image of the inner basin moraine.

Figure 3. Oblique perspective image of multibeam swath bathymetry from the inner basin, Royal Bay, showing sea-floor geomorphic features including sets of small ridges and an active or recently-active meltwater gully. Glacier flow, today, is towards the reader. Image is approximately 3 km across in the forefield.

Figure 4. Multibeam swath bathymetry of Cumberland Bay East, South Georgia. HV: Hamburg Valley; HS: Hestesletten; KEC: King Edward Cove. Inset boxes show (B) an enlarged image of the inner basin and inner basin moraine, (C) an enlarged image of the outer basin moraine, (D) a cross section along the fjord and (E) a TOPAS sub-bottom profile collected on the RRS *James Clark Ross* cruise JR224 shows cross-sections of both the outer deep basin moraine as well as the second remnant moraine landward of this feature.

Figure 5. Multibeam swath bathymetry of Cumberland Bay West, South Georgia. Inset boxes show (B) an enlarged image and (C) a cross section of the partially preserved outer basin moraine, and (D) a cross section of the inner basin.

Figure 6 (upper panel). Multibeam swath bathymetry and geomorphological features of Stromness and Husvik Bays, South Georgia. Inset boxes show (B) a cross section of the inner basin moraine and (C) a cross section of the outer deep basin moraine.

Fig 6 (lower panel). Oblique aerial photograph of Husvik Bay and Tonsberg Point facing approximately south west. HMS *Endurance* is present in Husvik Harbour (to the right of the image) for scale.

Figure 7. Multibeam swath bathymetry and geomorphological features of Antarctic Bay, South Georgia. Inset boxes show (B) an enlarged image and (C) cross-section of the moraine complex at the seaward end of the inner basin, comprising at least three ice-marginal limits.

Figure 8. Multibeam swath bathymetry and geomorphological features of Possession Bay, South Georgia. Inset boxes show (B) an enlarged image of the deep basin moraine, (C) an enlarged image of the inner basin moraine, and (D) a cross section of the deep basin and deep basin moraine.

Figure 9. Multibeam swath bathymetry and geomorphological features of King Haakon Bay, South Georgia. Inset boxes show (B) a transverse cross-section of the medial moraines and (C) a cross section along the fjord.

Figure 10. Multibeam swath bathymetry and geomorphological features of Drygalski Fjord, South Georgia. Inset boxes show (B) an enlarged image of the inner basin moraine showing the erosional grooves that characterise the back slope of the moraine (black arrows) and (C) a cross section of the inner basin moraine.

Figure 11. Cross-section schematic of a typical South Georgia glaciated fjord, showing main geomorphic features, correlation to onshore chronological constraints, and inferred ages from this study. In our model, features seaward of the deep basin moraine on the continental shelf (not shown) are proposed as older than the penultimate glacial episode, MIS6. [a] this study; [b] ages from terrestrial studies of Bentley et al. (2007) and Rosqvist et al. (1999).

Appendix A

Appendix A contains figures showing the detailed submarine geomorphology of the South Georgia fjords spliced together with the terrestrial glacial geomorphological maps of Bentley et al. (2007), to illustrate the goemorphological and chronological relationships between these datasets .

Appendix Figure A1. Multibeam swath bathymetry of Cumberland Bay East, South Georgia combined with Figures 7a (west coastline); 7b (Szielasko Valley); and 7c (Lower Sorling Valley) from Bentley et al (2007). The west coastline includes a number of lateral moraines of the formerly more expansive Nordenskjöld Glacier which may be related to the prominent inner basin moraine in the fjord. These onshore lateral moraines are not dated but the inner basin moraine in the fjord can be correlated based on geomorphological evidence to the inner basin moraine at the entrance to Moraine Fjord, 2 km to the west (see Fig. 4). A cosmogenic isotope date for this feature (GRE5, Bentley et al. 2007) had an unacceptably large error of 12900 ± 7800 yr BP so does not provide a reliable age constraint for these moraines.The moraine from which sample GRE5 was collected has also been correlated on goeomorphological grounds with the Husvik medial moraine which had a weighted mean cosmogeinc isotope age of 12200 ± 1500 yr BP.

Appendix Figure A2. Multibeam swath bathymetry of Cumberland Bay West, South Georgia combined with Figures 8a (Mercer Bay, Harpon Bay and Sphagnum Valley); 8b (Carlita Bay); 8c (Enten Bay); and the lower part of Figure 10b from Bentley et al (2007). Although a shallow inner basin is not present on this image it is possible that it may occur just south of Carlita Bay where Fig. 8b of Bentley et al. (2007) documents a series of moraines and lake shorelines associated with an advance of the Neumayer Glacier. These are undated.

Appendix Figure A3. Multibeam swath bathymetry of Stromness (upper image) and Husvik (lower image) Harbours combined with Figure 18 of Bentley et al (2007) which shows an overview of the geomorphology of Husvik Harbour, its major moraine locations and interpreted ice marginal positions (I-III) that document significant still stands during overall recession from the centre of the fjord. Combined, these figures show the relationship between the onshore and offshore glacial geomorphology including features from which age constraints from cosmogenic isotope exposure age dating and the onset of lake sedimentation are available. Radiocarbon ages from Block Lake and a soil profile south of Limit III are reported as the mean of the two-sigma range, calibrated using Calib 14C program v7.0 and the SHcal13 calibration curve.The terrestrial moraines in the inner basin of Husvik Harbour are interpreted as marking the oldest mapped ice advance on South Georgia based on a cosmogenic ^{10}Be exposure ages of between 14.2 and 10.6 ka BP, mean 12.2 ± 1.5 ka BP, from the Husvik medial moraine (Bentley et al., 2007, 'category a' moraine). These ‘category a’ moraines have been correlated on geomorphological grounds with the oldest terrestrial moraine ridges in Antarctic Bay, Possession Bay and Moraine Fjord (Zenker Ridge) to the west of Cumberland Bay East (Appendix Figs. A4, A5, and A1, respectively).

Appendix Figure A4. Multibeam swath bathymetry of Antarctic Bay combined with Figure 14 of Bentley et al (2007) which is a geomorphological map of the west shore of Antarctic Bay. The oldest of the terrestrial moraines is a ‘category a’ moraines correlated on geomorphological grounds with the oldest terrestrial moraine ridges in Husvik Harbour Possession Bay and Moraine Fjord (Zenker Ridge) to the west of Cumberland Bay East (Appendix Figs. A3, A5, and A1, respectively).

Appendix Figure A5. Multibeam swath bathymetry of Possession Bay combined with Figure 16a of Bentley et al (2007) which is a geomorphological map of the valley on the south east shore of Possession Bay. This shows the outermost of a series of latero-frontal terrestrial moraine loops deposited by mountain ice to the south coalescing with the outer laterofrontal moraines of the former fjord ice and a prominent inner basin moraine in the fjord. This is a ‘category a’ moraine correlated on geomorphological grounds with the oldest terrestrial moraine ridges in Husvik

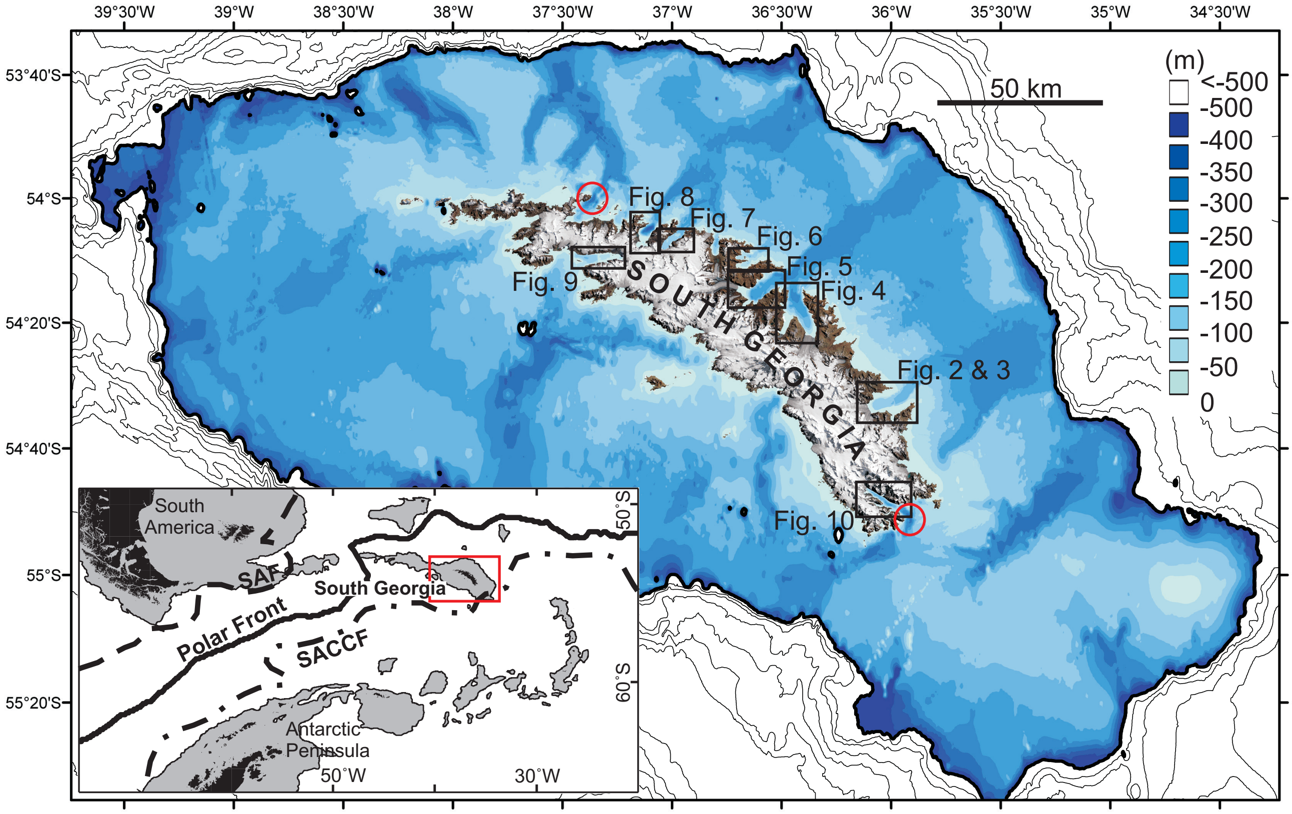
Harbour, Antarctic Bay and Moraine Fjord (Zenker Ridge) to the west of Cumberland Bay East (Appendix Figs. A3, A4, and A1, respectively).

Table 1

Submarine glacial landforms	Royal Bay	Cumberland Bay East	Cumberland Bay West	Husvik Bay	Stromness Bay	Antarctic Bay	Possession Bay	King Haakon Bay	Drygalski Fjord	Age constraints based on terrestrial evidence
Inner basin	1	1	?	1	1	1	1	1	1	≤14.2 – 10.6 ka
Inner basin moraine	1	1	?	1	1	1	1	1	1	>14.2–10.6 ka >18.6 ka / LGM
Deep basin	1	1	1	1	1	1	1	1	1	<MIS 6
Deep basin moraine	?	1	?	1	1	0	1	?	1†	Earlier glaciation (MIS 6?)
Deep basin Truncated moraines/promontories	4	3-4	2-4	1*	1	2	0	0	?	>MIS6
Cross shelf trough	1	1	1	0	0	1	1	1	1	>>MIS6

Table 1

*Figure



Figures & locations			
	Figs. 2 & 3: *Royal Bay*	Fig. 6: *Stromness/Husvik Bays*	Fig. 9: *King Haakon Bay*
	Fig. 4: *Cumberland Bay East*	Fig. 7: *Antarctic Bay*	Fig. 10: *Drygalski Fjord*
	Fig. 5: *Cumberland Bay West*	Fig. 8: *Possession Bay*	

Figure 1, Hodgson et al.

*Figure 1B
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*Figure 2

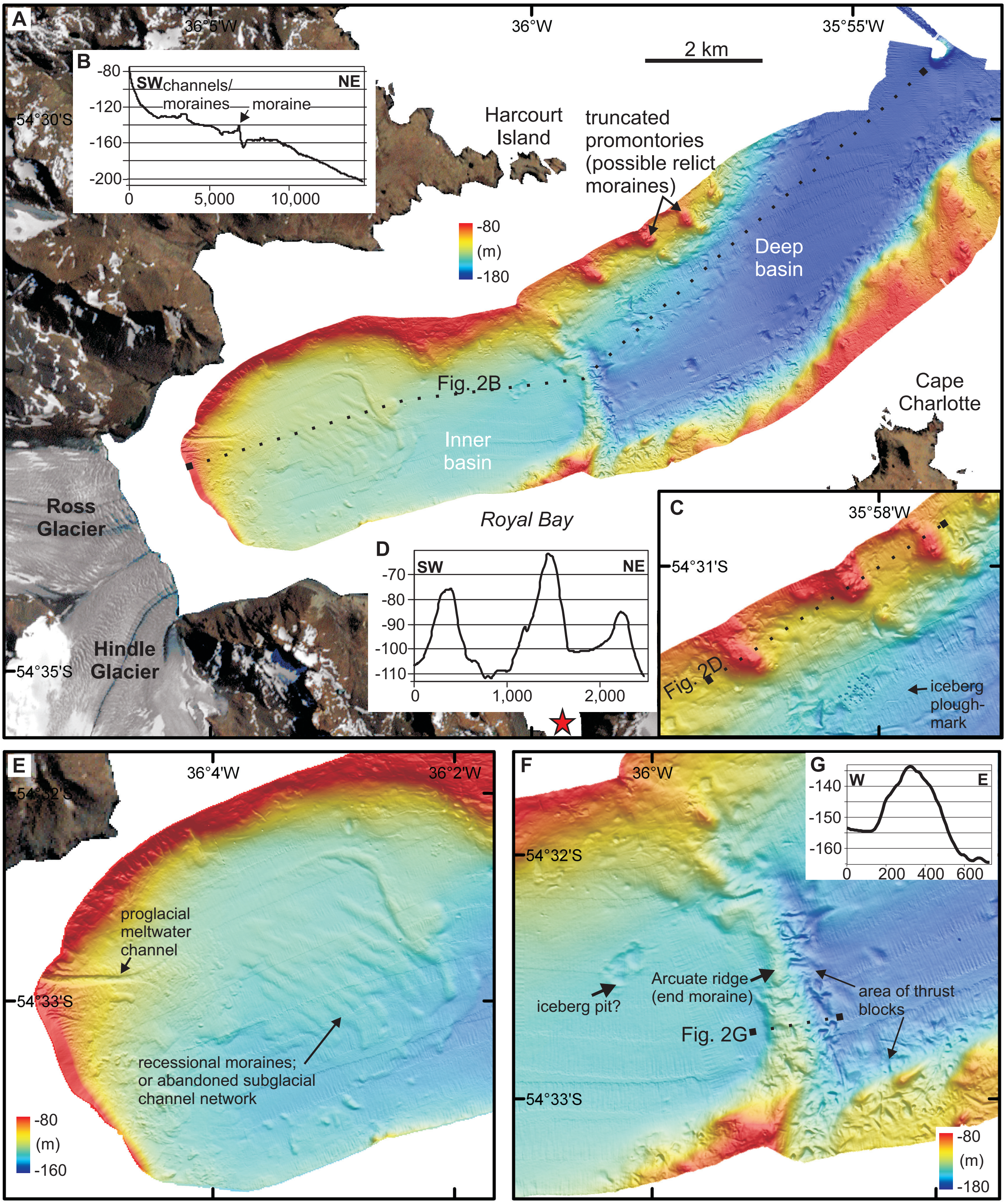


Figure 2. Hodgson et al.

***Figure 3**

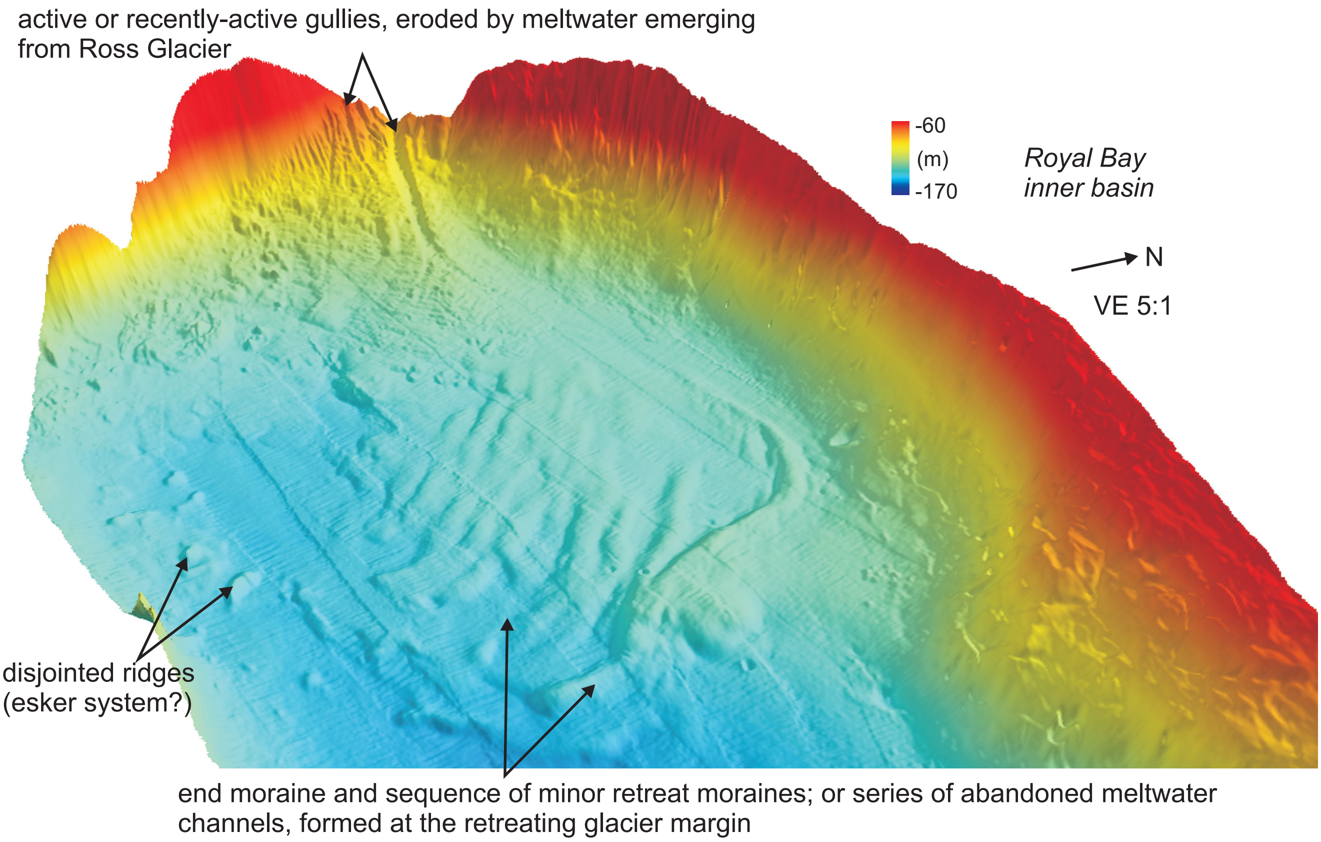


Figure 3. Hodgson et al.

*Figure 4

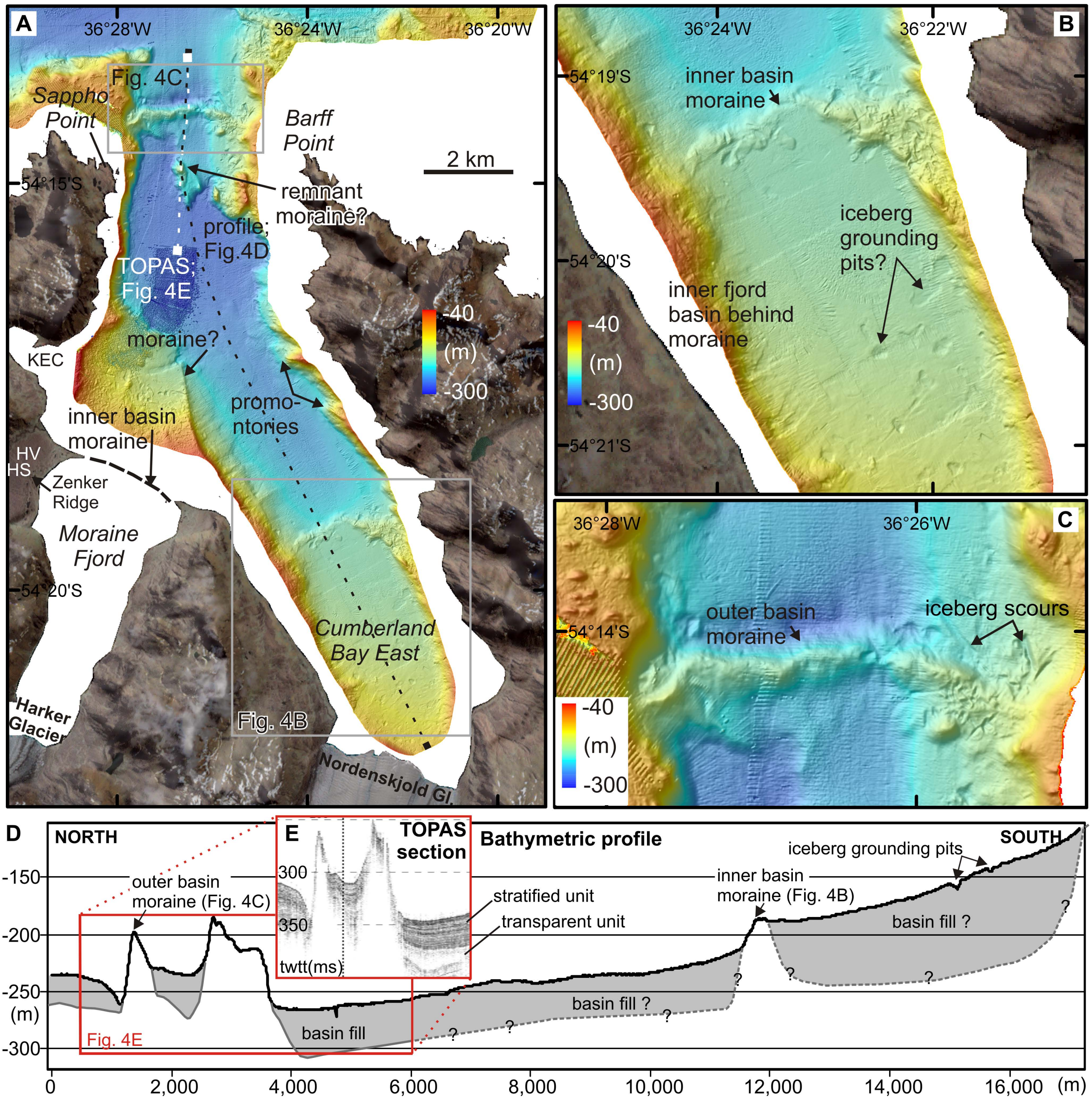


Figure 4, Hodgson et al.

***Figure 5**

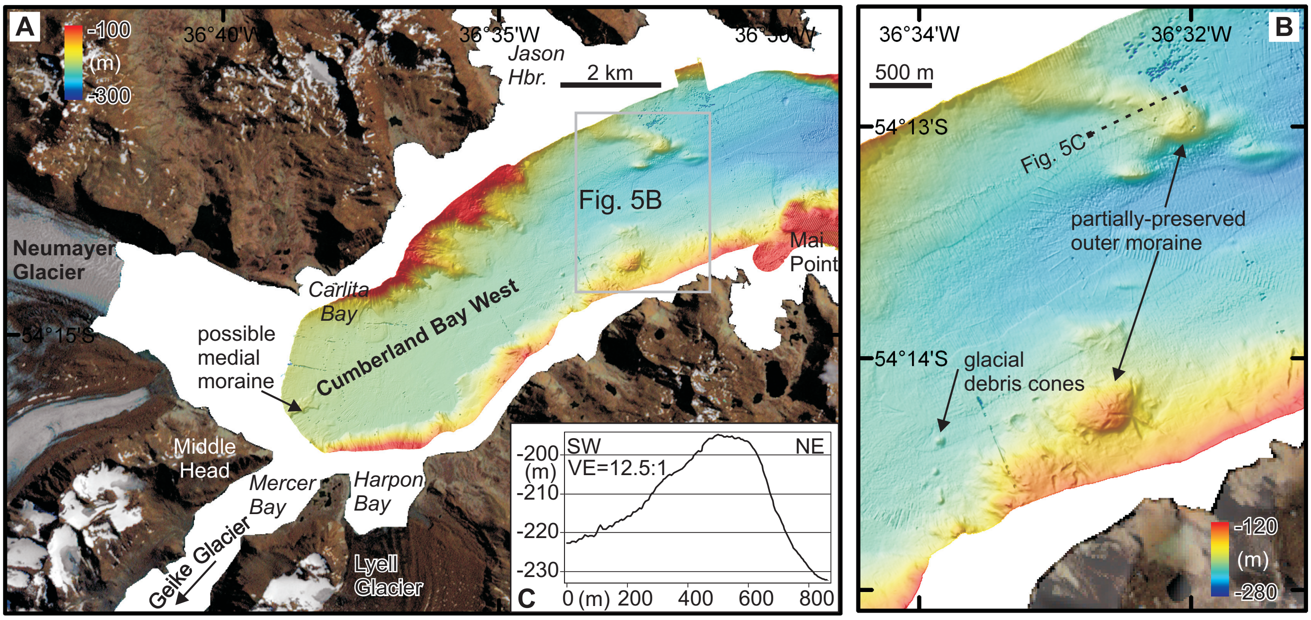


Figure 5, Hodgson et al.

***Figure 6A**

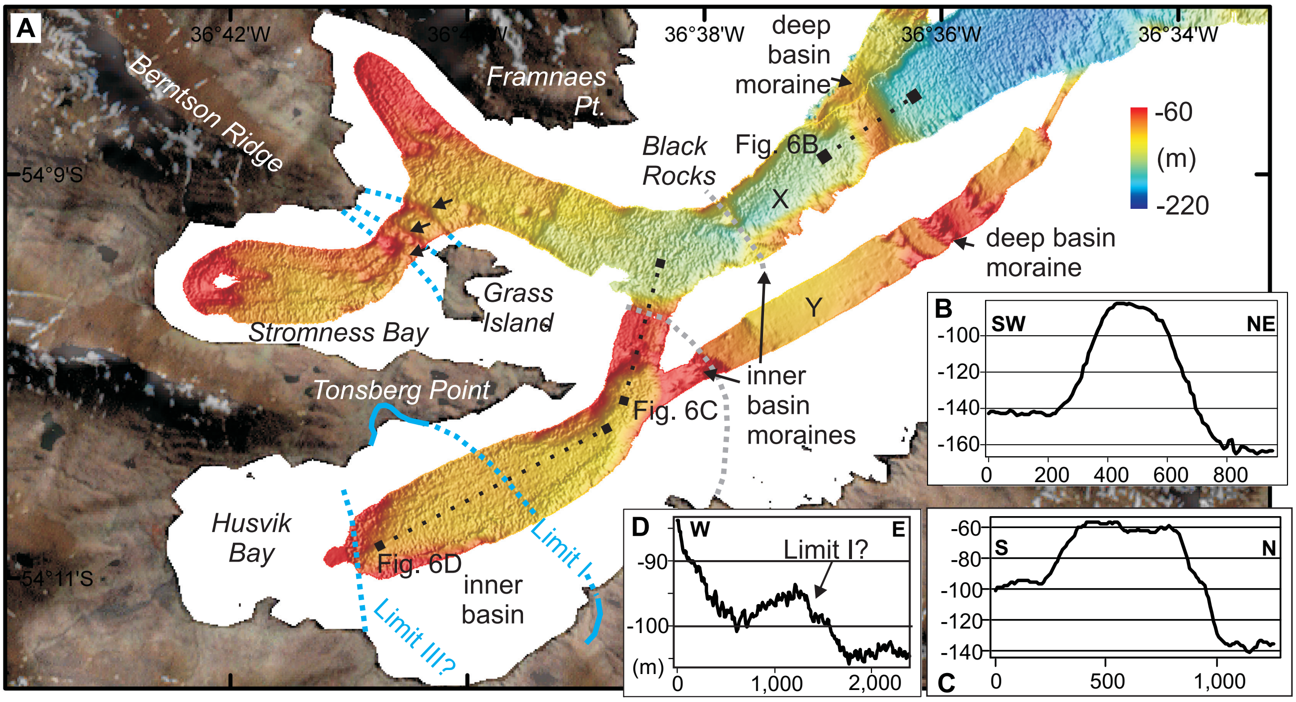


Figure 6, Hodgson et al.

***Figure 6B**
Click here to download high resolution image

***Figure 7**

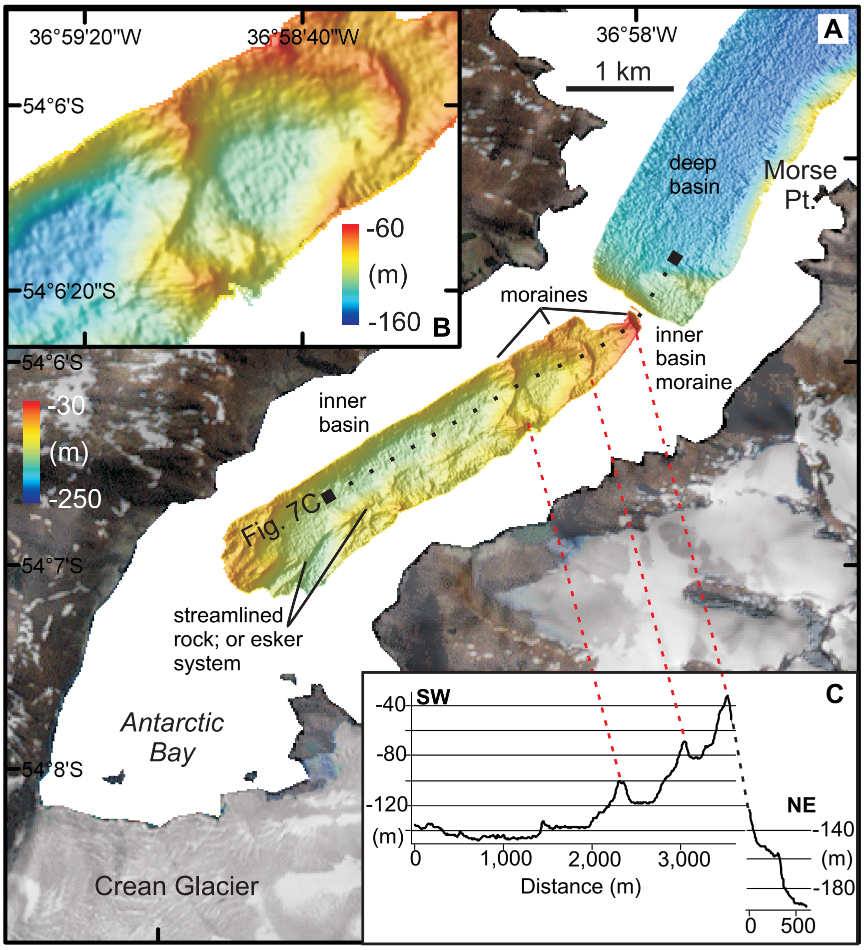


Figure 7, Hodgson et al.

***Figure 8**

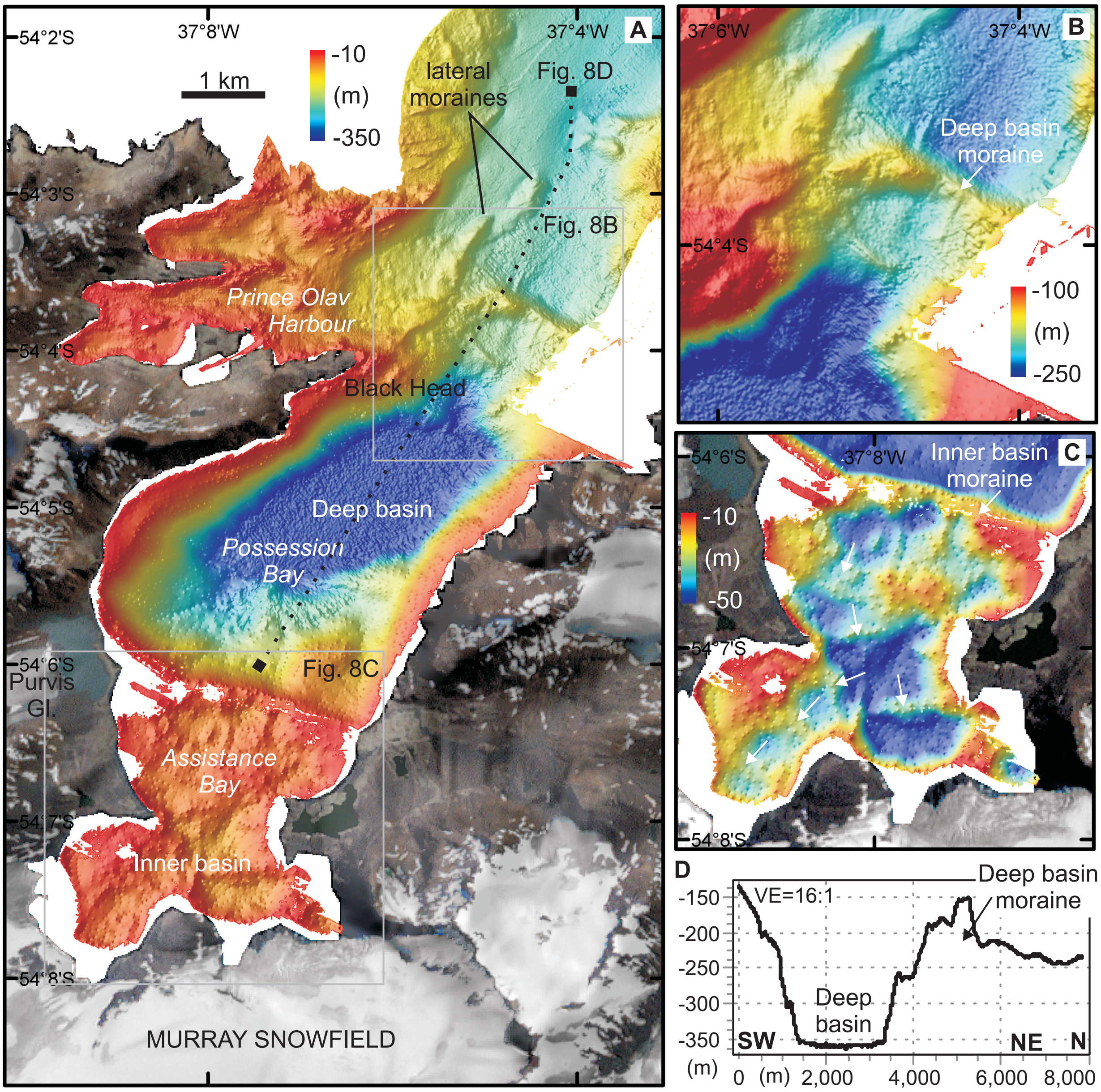


Figure 8, Hodgson et al.

*Figure

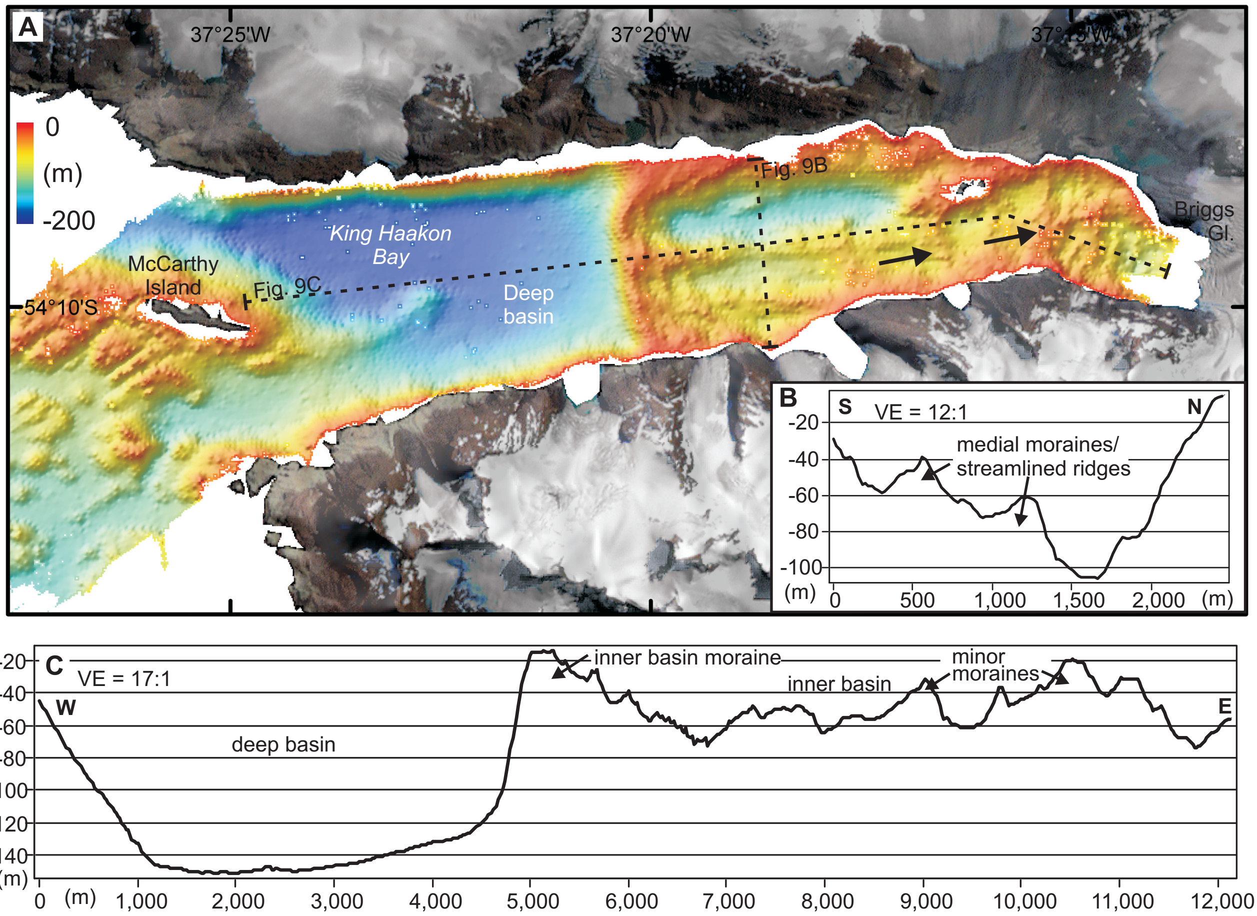


Figure 9, Hodgson et al.

*Figure 10**

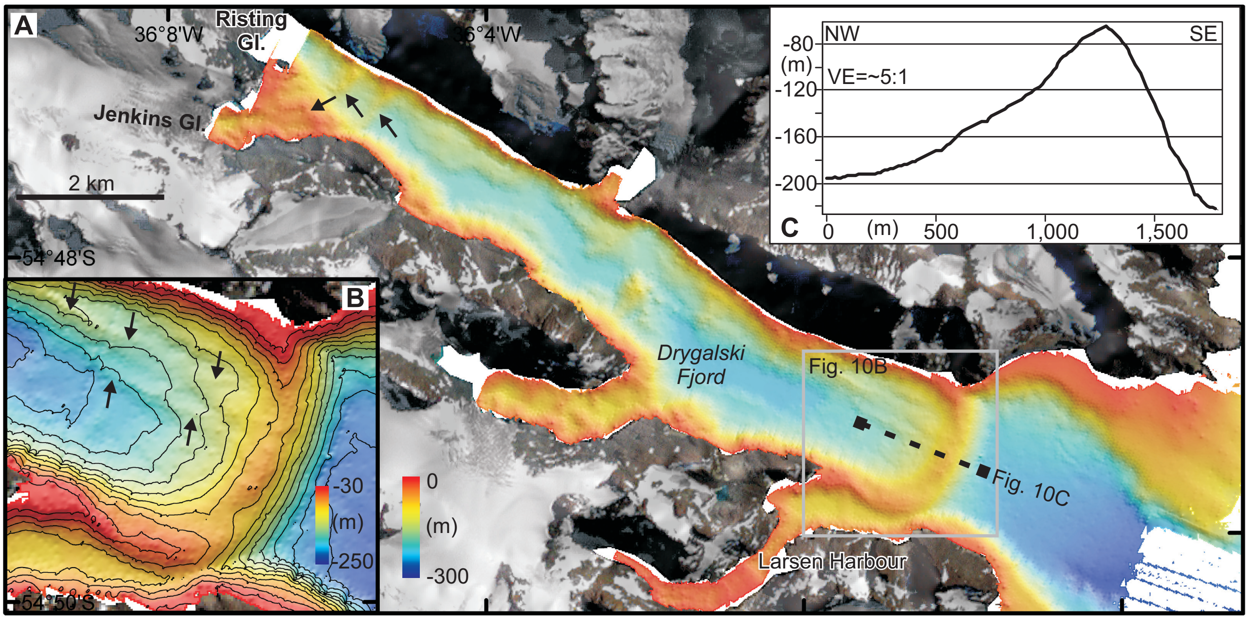


Figure 10. Hodgson et al.

*Figure 11

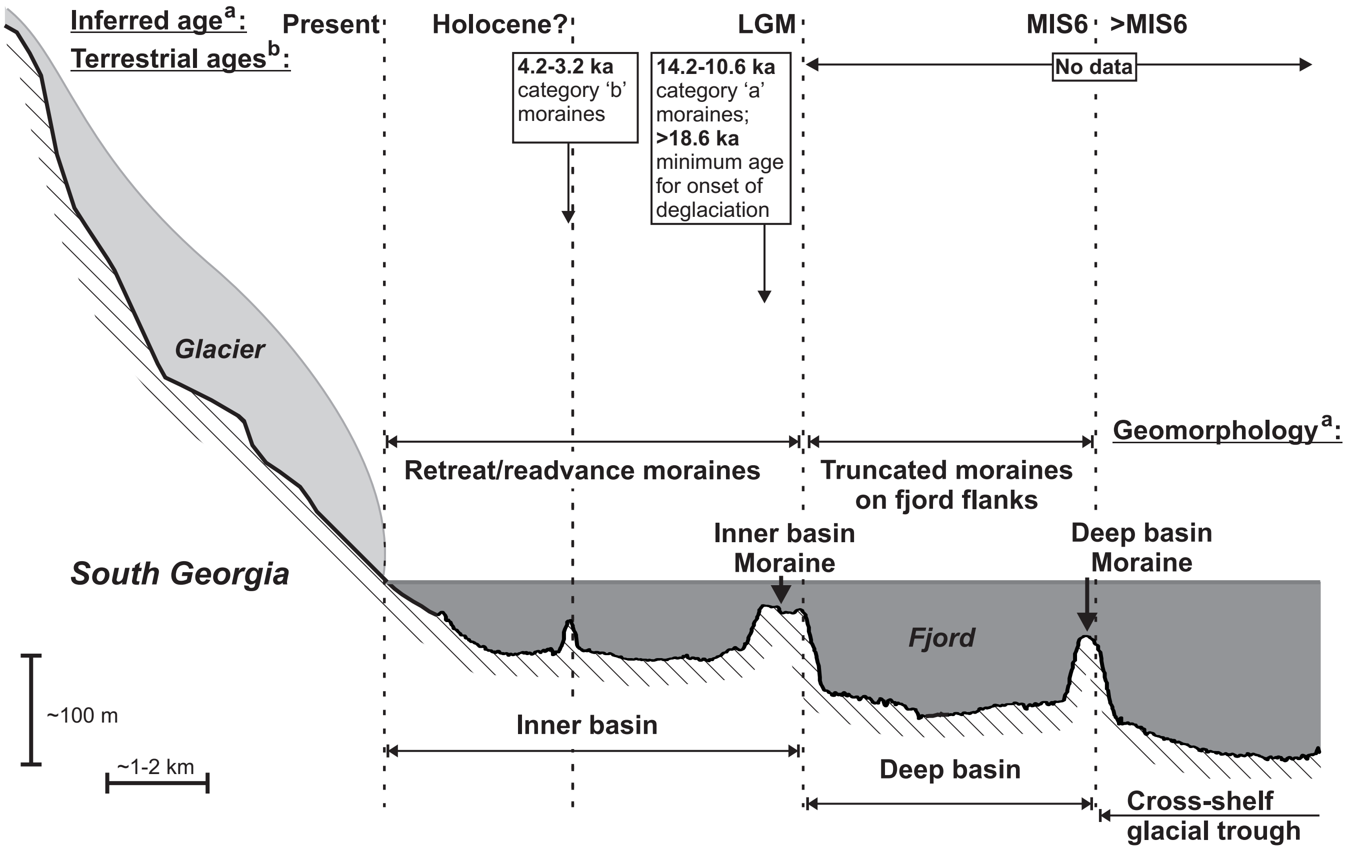
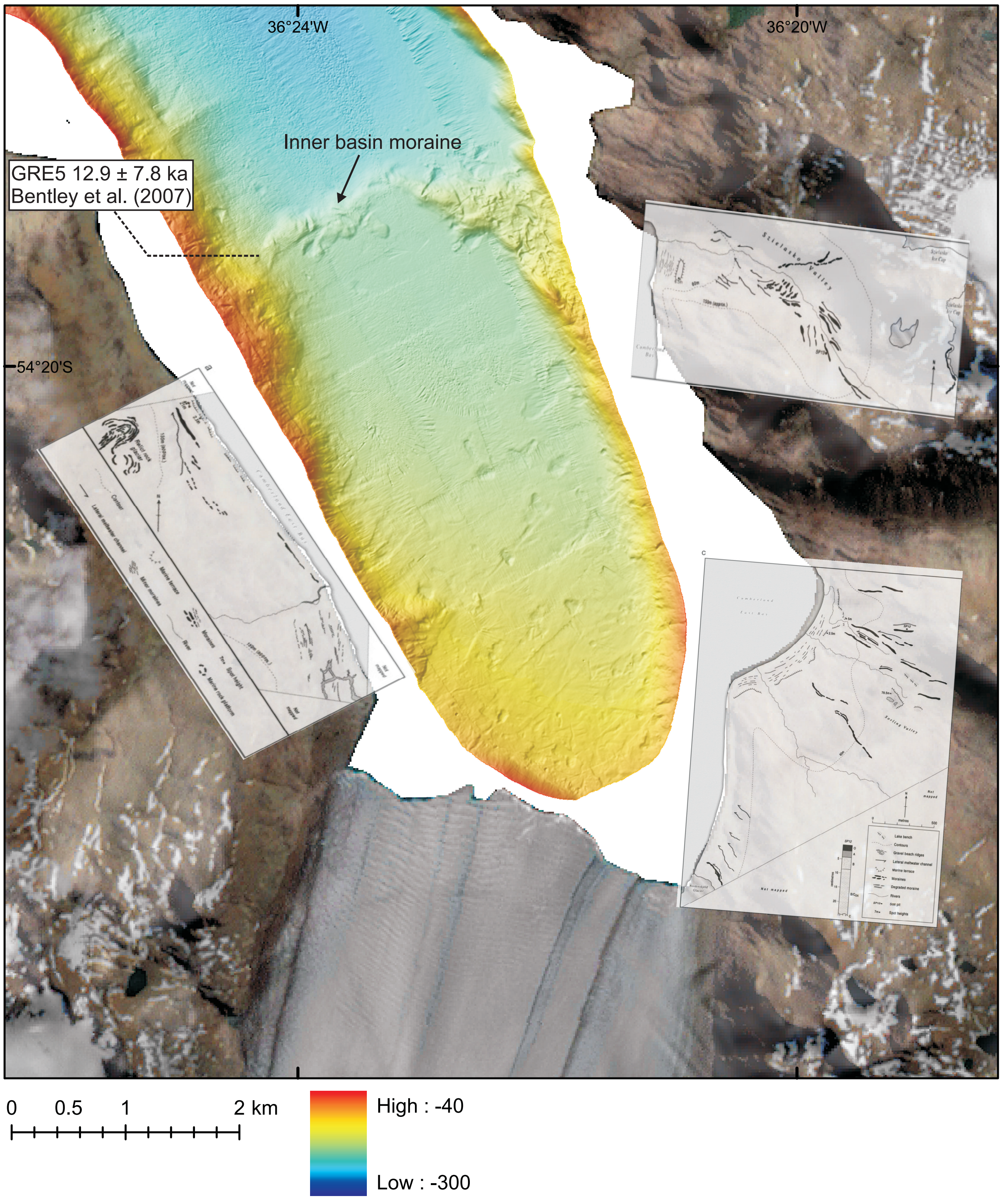


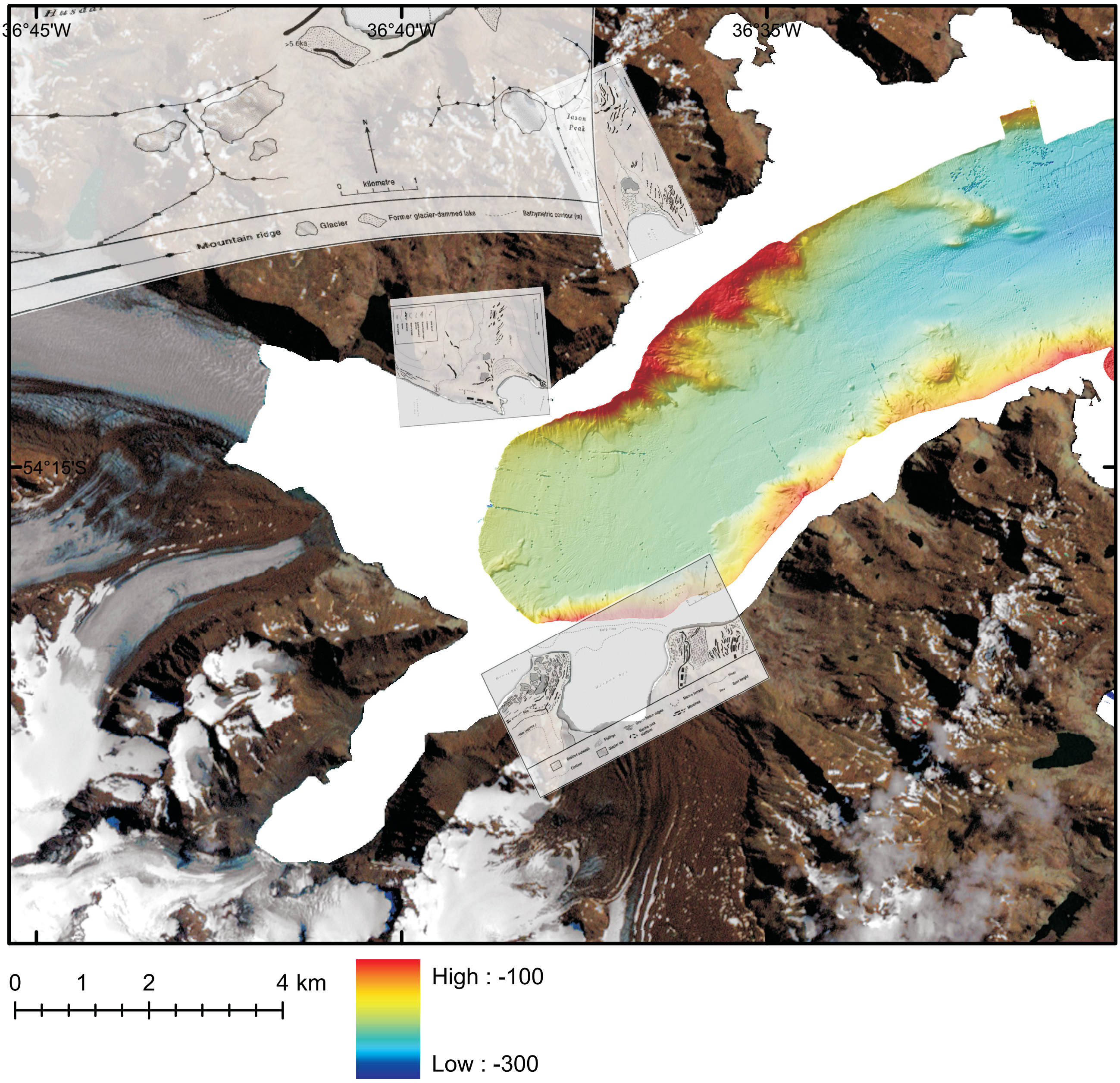
Figure 11, Hodgson et al.

***Figure Appendix A1**



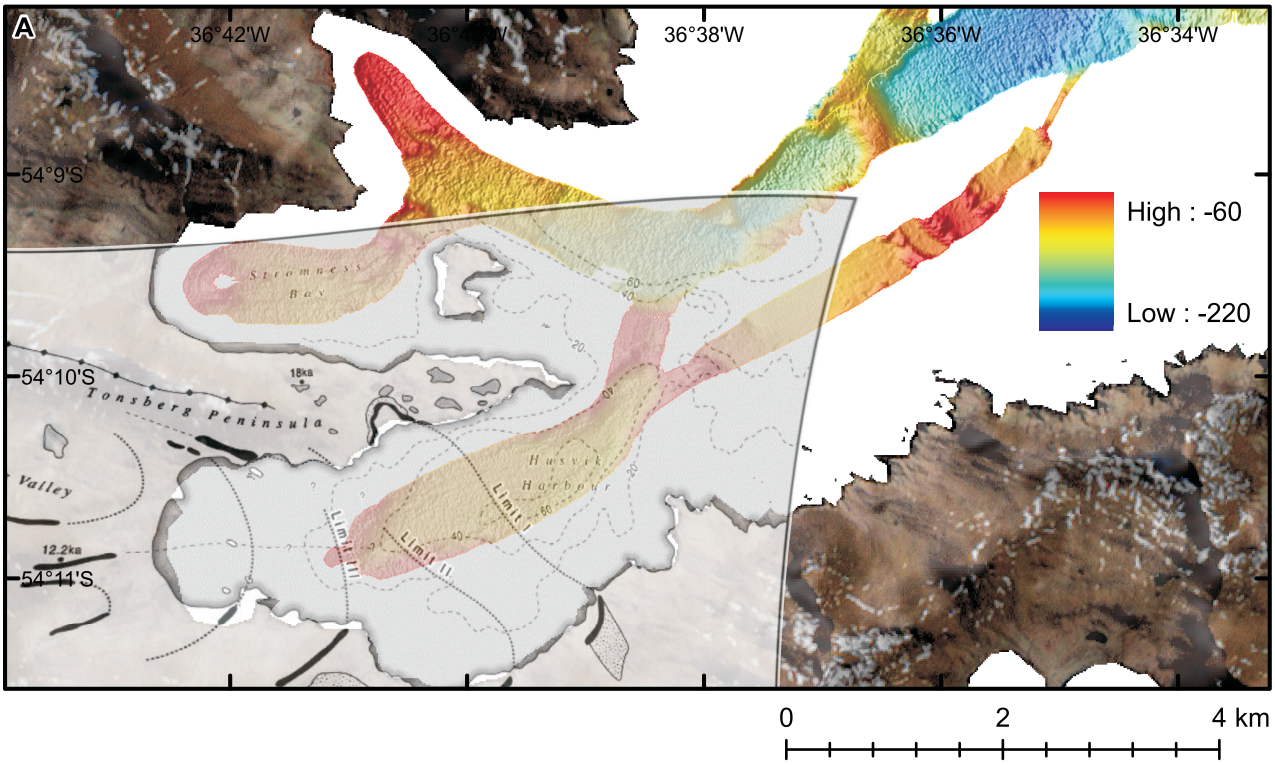
Appendix Figure A1

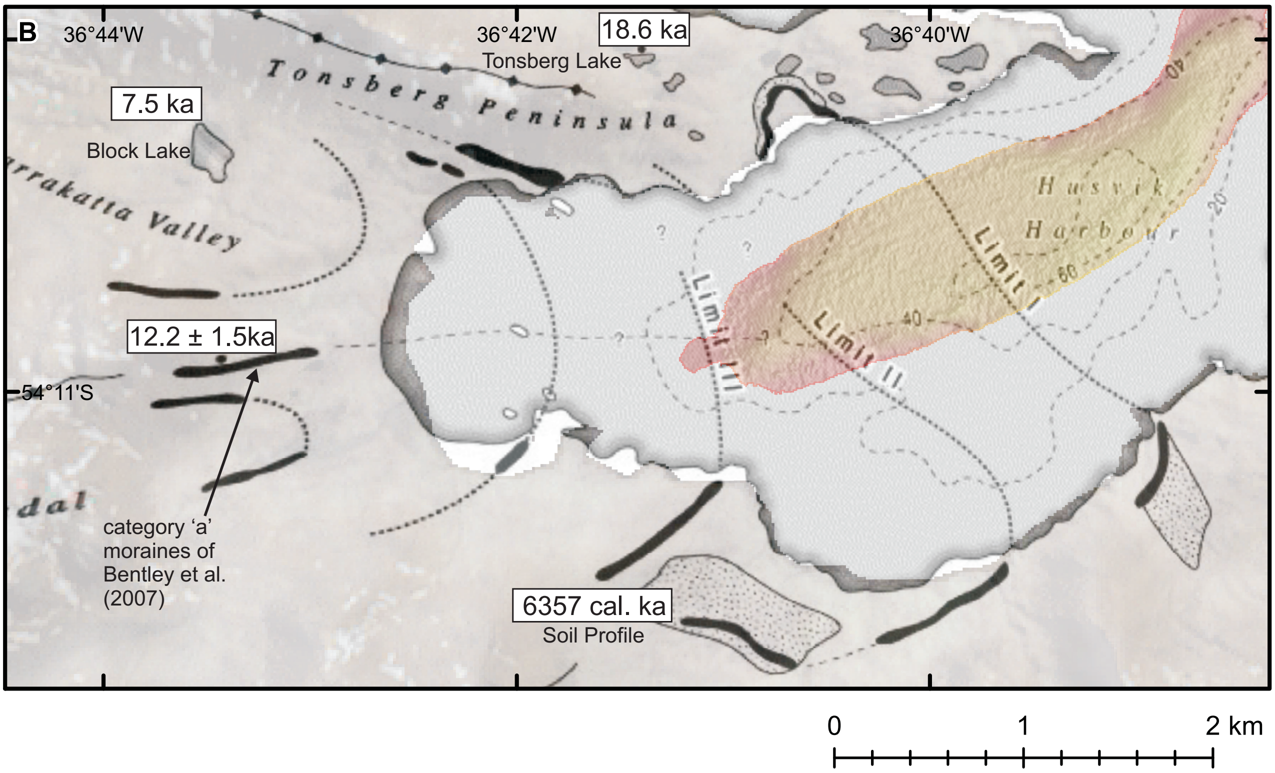
***Figure Appendix A2**



Appendix Figure A2

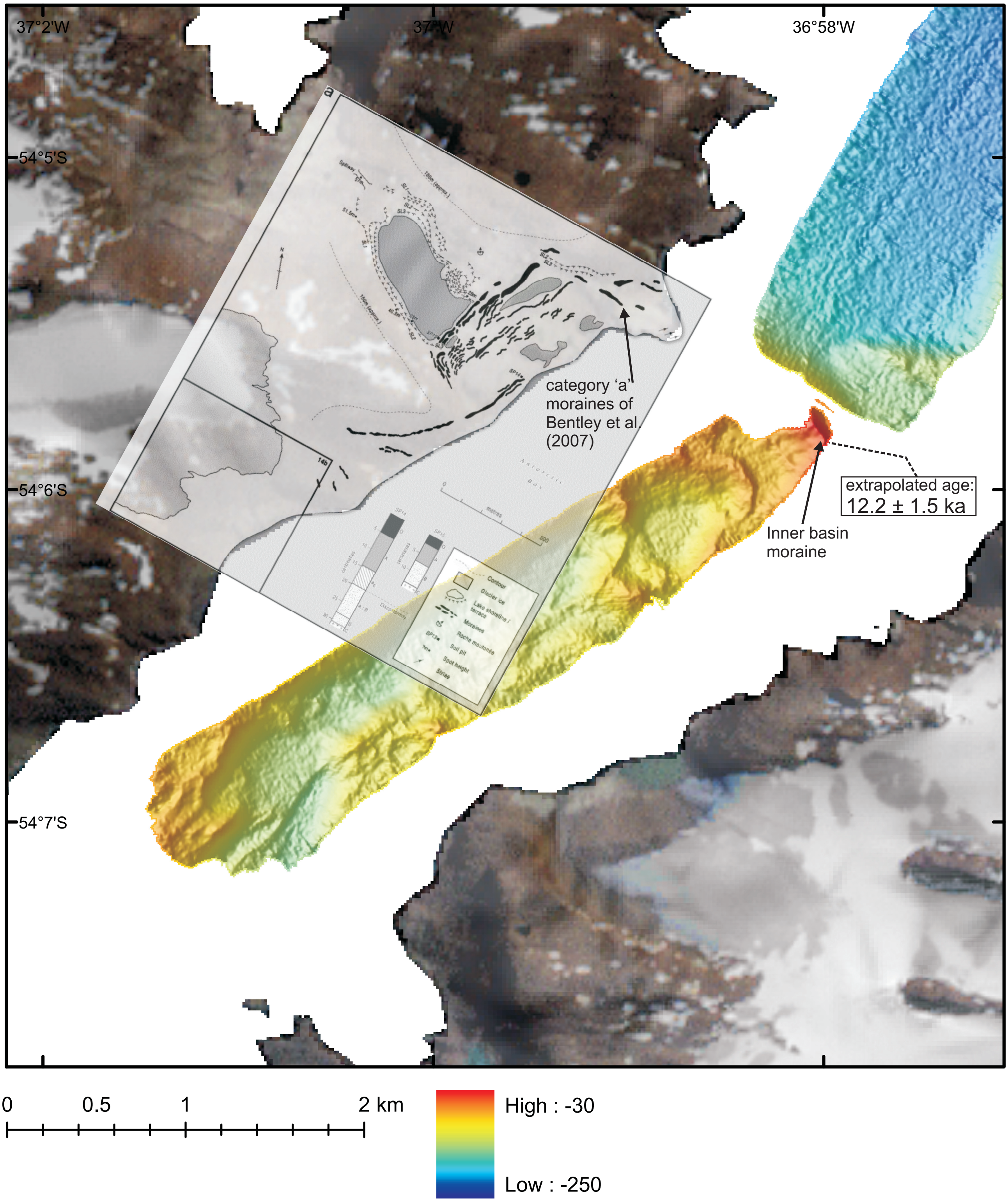
*Figure Appendix A3**





Appendix Figure A3

***Figure Appendix A4**



Appendix Figure A4

*Figure Appendix A5

Appendix Figure A5.