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A new bathymetric compilation highlighting extensive paleo–ice sheet drainage on the continental shelf, South Georgia, sub-Antarctica

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[1] A grid derived from a new compilation of marine echo-sounding data sets has allowed us to visualize and map the geomorphology of the entire continental shelf around South Georgia at an unprecedented level of detail. The grid is the first continuous bathymetric data set covering South Georgia to include multibeam swath bathymetry and represent them at a subkilometer resolution. Large and previously undescribed glacially eroded troughs, linked to South Georgia's modern-day fjords, radiate from the island, marking the former pathways of large outlet glaciers and ice streams. A tectonic or geological influence is apparent for the major troughs, where glaciers have exploited structural weaknesses on the continental block. Bed forms lining the troughs give some first insights into glacial dynamics within the troughs, suggesting arteries of fast flowing ice occupied these topographic depressions in the past and operated over both bedrock and sedimentary substrates. On the outer shelf and within the troughs, large ridges and banks are also common, interpreted as terminal, lateral, and recessional moraines marking former positions of ice sheets on the shelf and their subsequent reorganization during deglaciation. A small trough mouth fan has developed at the mouth of at least one of the cross-shelf troughs, demonstrating a focused sediment delivery to the margin. Slides and slide scars are also present on parts of the margin, showing that margin stability, perhaps also related to glaciation, has been an important factor in depositional processes on the continental slope.

Implications of the new observations are that ice sheets have been more extensive on South Georgia than any previous studies have reported. Their age may date back to late Miocene times, and evolution of the shelf system has probably involved numerous late Cenozoic glacial episodes. However, relatively fresh seafloor geomorphology coupled with evidence from other maritime-Antarctic islands (Heard Island and Kerguelen Island) indicating extensive glaciation at the Last Glacial Maximum raises the possibility that the extent of sub-Antarctic glaciation for the Last Glacial period has, until now, been underestimated.

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1. Introduction

[2] An increasingly important question in the sub-Antarctic is, what was the maximum ice extent during the last glacial cycle? The question is critical because the varying size of maritime-Antarctic ice sheets reflect past changes in climatic gradients and provide constraints on relative sea level, glacial isostasy and ice sheet/glacier fluctuations. Isolated in the Southern Ocean and as one of the largest sub-Antarctic islands, South Georgia has a particularly long history of glacial geological investigation, motivated by terrestrial geomorphological evidence that an independent ice sheet glaciated the island during the Last Glacial Maximum (LGM) [*Clapperton*, 1971, 1990; *Bentley et al.*, 2007a]. However, longer-term knowledge of the island's ice sheets (in terms of size, extents, configurations and sensitivity) is lacking. This can be attributed to the fact that nearly all late Quaternary investigations to date have focused upon terrestrial sites, with specific research foci centered on onshore geomorphological mapping [*Clapperton*, 1971, 1990; *Clapperton et al.*, 1989; *Bentley et al.*, 2007a], paleolimnological studies [*Wasell*, 1993; *Rosqvist et al.*, 1999; *Van der Putten and Verbruggen*, 2005], radiocarbon-based geochronological models of glacial sediments [*Gordon*, 1987] and, more recently, surface exposure age (cosmogenic isotope) dating of moraines formed during the last deglaciation [*Bentley et al.*, 2007a].

[3] In contrast, there have been no comparative studies to understand the offshore glacial geomorphology and marine sedimentary environments around South Georgia; such records harbor the potential to reveal detail on LGM or pre-LGM ice sheet configurations. Yet, despite frequent visits to the island and its surrounding seas, no sediment cores and relatively few subbottom acoustic data have been recovered from the South Georgia continental shelf. As a result, there is still debate over the extent and thickness of former ice sheets that covered South Georgia and, in particular, the last major (late Quaternary, Marine Isotope Stage 2) ice cap.

[4] In terms of LGM ice sheet limits, two general models currently exist: the first invoking that ice sheets extended to the edge of the continental shelf around South Georgia at the LGM [*Clapperton et al.*, 1989], the other proposing a more restricted LGM limit at inner fjord limits based on recent mapping and dating of the onshore Late Glacial to Holocene moraines [*Bentley et al.*, 2007a]. The "extensive LGM model" lacks geological data on the continental shelf to support it. By contrast, although the "restricted model" is supported by radiocarbon dating from lake basal sediments indicating ice free landscapes from 18.6 ka B.P. onward [*Bentley et al.*, 2007a; *Rosqvist et al.*, 1999], it has recently been the subject of some debate [*Van der Putten and Verbruggen*, 2007; *Bentley et al.*, 2007b]. If a restricted LGM limit is correct, then glacial "channels," which are known to extend offshore South Georgia in some areas [*Simpson and Griffiths*, 1982], would predate the LGM and might have formed during one or more of the series of Pleistocene glaciations (of MIS 20 and younger) that extended beyond LGM limits in Patagonia [*Rabassa et al.*, 2000]. How-

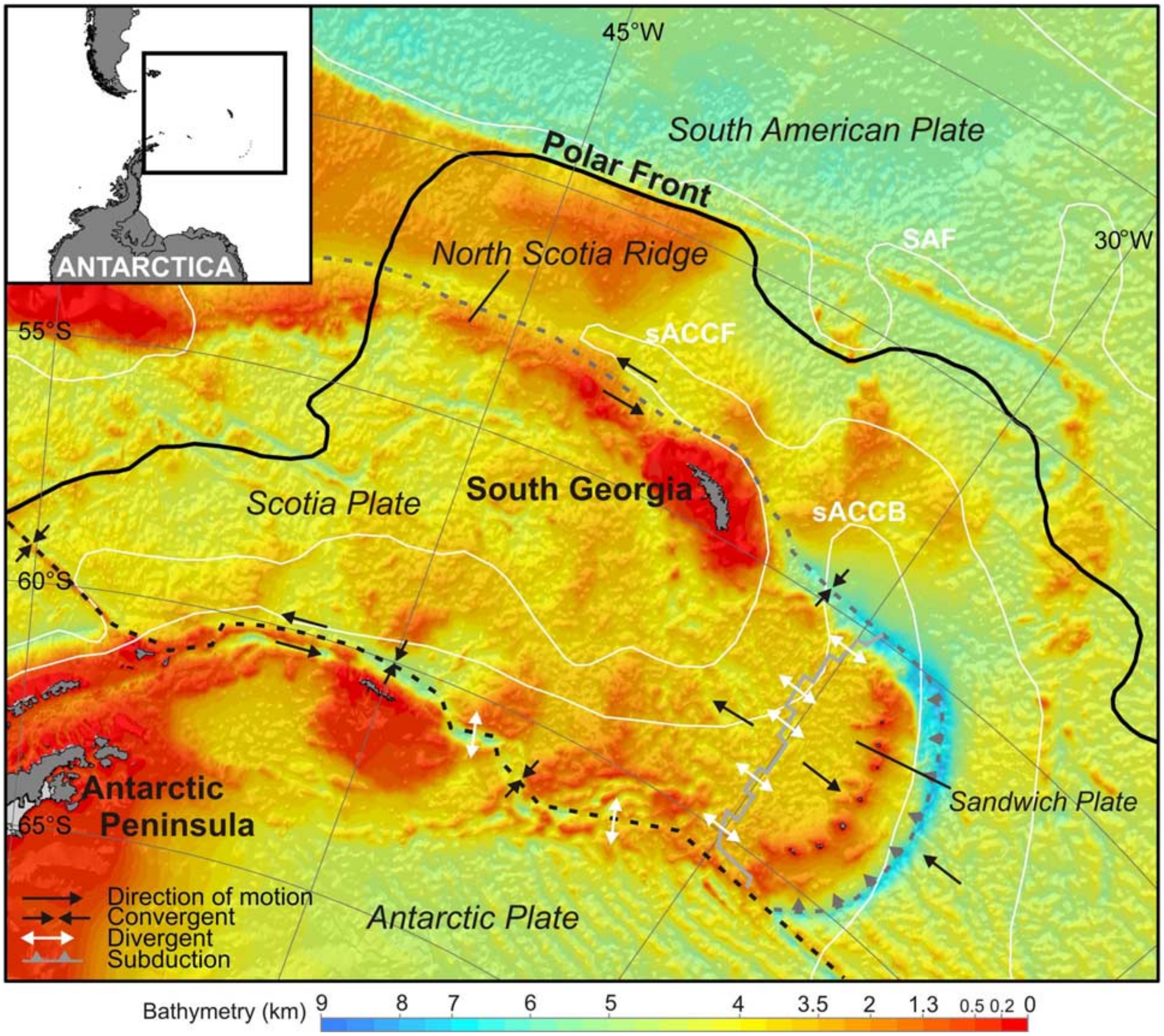

Figure 1. Regional location map and setting of South Georgia. The island forms part of the Scotia arc and lies at the boundary between the South American and Scotia plates. Position of the Polar Front and other oceanic fronts illustrated. sACCF/sACCB, southern Antarctic Circumpolar Current Front/Boundary; sAF, sub-Antarctic Front. Polar stereographic projection.

ever, in the absence of offshore data to test these models further, including marine sediment cores where the transition between glacial diamicton and biogenic sediments can be dated, both views remain plausible within the existing lines of evidence for South Georgia glaciation.

[5] Here, we present a new compilation of bathymetric soundings from the South Georgia continental shelf and surrounding waters, which reveals the glacial geomorphology of the shelf and slope at an unprecedented level of detail. Using the new compilation we are able to visualize the large-scale geomorphology, and smaller three-dimensional geomorphic elements of the submarine landscape. In particular, the new data set provides evidence of the former drainage patterns in past ice sheets on South Georgia, allowing preliminary interpretations to be made concerning past ice sheet extents and glaciodynamics. We show that past glaciations of South Georgia were extensive [cf. *Clapperton et al.*, 1989].

2. Tectonic and Physiographic Setting

[6] South Georgia is the largest island of the Scotia arc, situated in the northeastern Scotia Sea (Figure 1) [*MacDonald and Storey*, 1987]. It com-

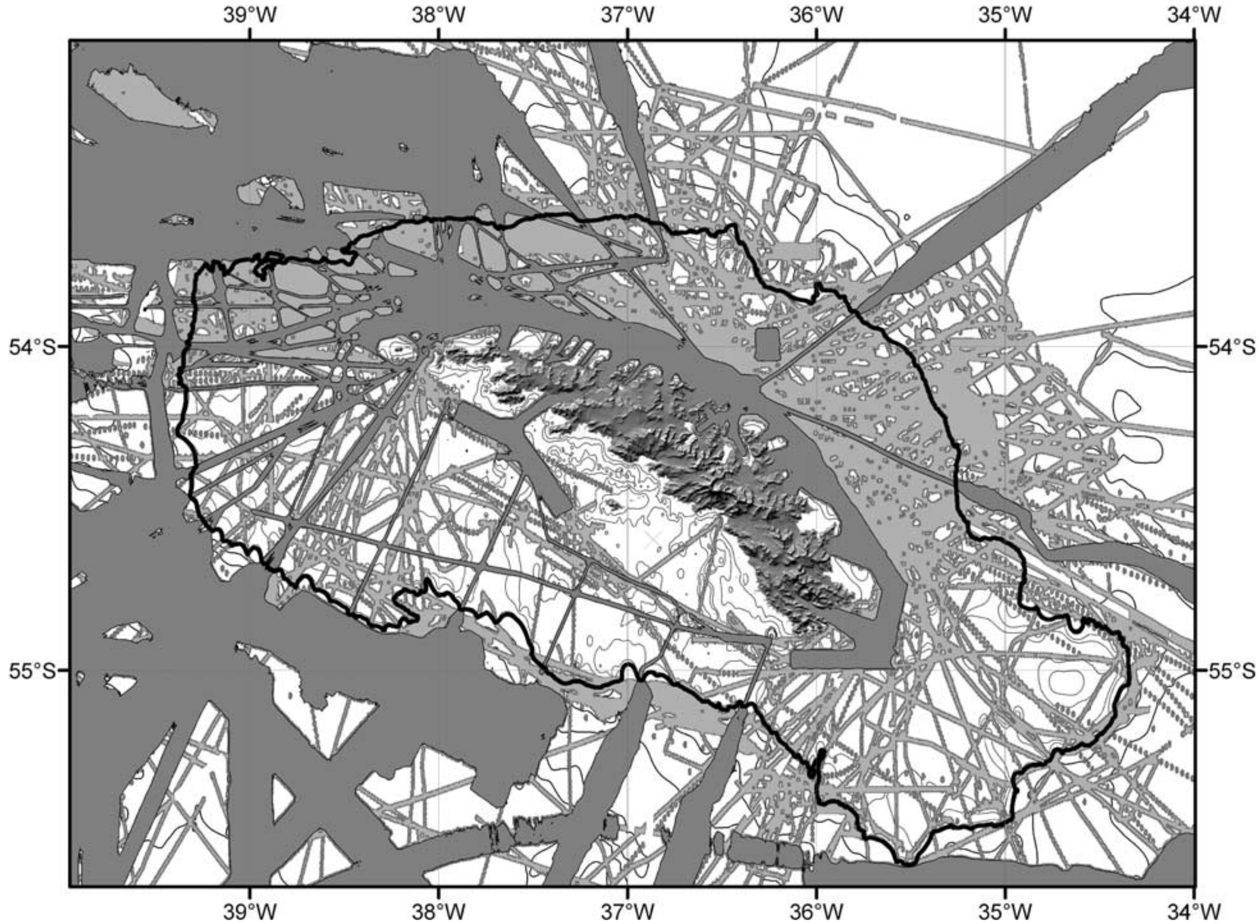

Figure 2. Data distribution map for the South Georgia bathymetric compilation. Areas of primary, multibeam swath bathymetric data (dark gray), and secondary older multibeam swath, BAS, Hydrographic Office and Fisheries single-beam data (light gray) are shown. Black line defines approximate edge of the continental shelf. WGS84 Mercator projection.

prises one of a series of islands and submarine ridges, which together characterize the North Scotia Ridge, a tectonically active, complex, and convergent boundary which accommodates sinistral strike-slip motion between the South American and Scotia plates [*Cunningham et al.*, 1998]. South Georgia's ongoing tectonic history is important to ice sheet development in sub-Antarctica for two reasons: (1) The island may still be uplifting owing to oblique convergence between the South American and Scotia plates, although its overall history of uplift is still poorly known. (2) The island has probably maintained its present position, relative to the South American plate, since the late Miocene when seafloor spreading in the West Scotia ridge and in the Central Scotia Sea ceased [*Barker and Hill*, 1981; *Maldonado et al.*, 2006]. Thus, it has been a stable site for potential glaciation since ~6.4 Ma.

[7] Present-day South Georgia lies ~350 km south of the mean position of the Polar Frontal Zone (Figure 1). Two main NW–SE trending mountain ranges (the Allardyce and Salvesen ranges), divide the 175 km-long island to the north and south by a relief of up to 2960 m (above sea level). Accordingly, modern topography has a strong orographic control, which in turn influences precipitation patterns over South Georgia. Sea surface temperatures exhibit strong and persistent gradients north-south (with latitude) either side of the island, while Antarctic sea ice limits also fluctuate between the southern and northern extents of the island [*Bentley et al.*, 2007a]. Precipitation, temperature and ocean circulation show strong gradients and high variability around South Georgia, often exhibiting interannual changes or anomalies, and hence significantly perturb environmental conditions there [*Meredith et al.*, 2003]. In particular, environmental conditions are closely connected to the behavior

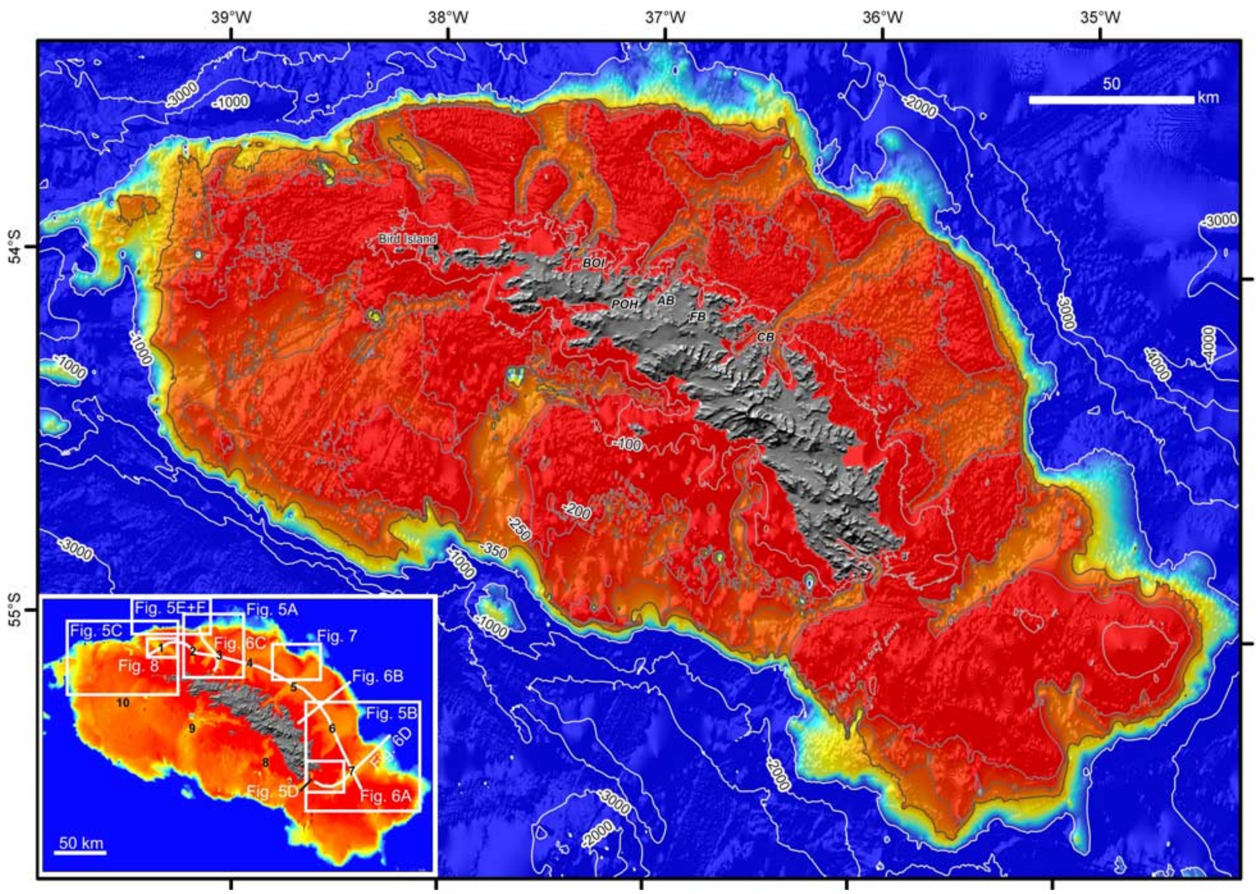

Figure 3. Newly compiled bathymetric map of the South Georgia continental shelf (223 m cell size grid, UTM Zone 24S projection). Note the aligned trough systems widening from fjordal areas toward the outer shelf, converging tributaries, banked shelf edge features, well-defined shape of the continental margin, and distribution of troughs north and south of the island. Contours on the shelf are at 350, 200, and 100 m. Color bar is skewed toward these water depths on the shelf. Hillshade of DEM of South Georgia from P. Fretwell. Locations of Figures 4–8 shown inset. Numbered troughs (in black) relate to the statistics in Table 1 and to references in the text. BOI, Bay of Isles; POH, Prince Olav Harbour; AB, Antarctica Bay; FB, Fortuna Bay; CB, Cumberland Bay.

of the Antarctic Circumpolar Current and related deep water tongues, which wrap around the island to its east and north (Figure 1). They provide influxes of heat to the waters around South Georgia and have been shown to affect local climate, from the deeper ocean onto the shelf [*Meredith et al.*, 2003].

[8] In combination these physiographic conditions result in a highly sensitive maritime glaciological regime on South Georgia. Ice fields now occupy the central spine of South Georgia, from which glaciers radiate; most extending down through glacial valleys as tidewater glaciers of the modern coastline [*Gordon et al.*, 2008]. Suites of moraines on the island's lowlands, particularly along the northeast coast, demonstrate former limits of glaciers and ice sheets [*Bentley et al.*, 2007a]. Trimlines provide evidence of phases of more extensive ice sheet growth at higher elevations [*Clapperton et al.*, 1989]. Glaciers have also carved out relatively deep fjords along the South Georgia coastline and, farther offshore *Simpson and Griffiths* [1982] previously identified several seabed "channels," which extend from the modern-day fjords and attributed their presence to glacial activity. Prior to this study, these were the only observations of continental shelf geomorphology offshore South Georgia.

3. Data Compilation

[9] We constructed a subkilometer-scale bathymetric compilation grid to characterize the geomorphology of the South Georgia shelf (Figure 2). The new seafloor bathymetric grid (Figure 3) was

Table 1. Data Sets Used in the South Georgia Bathymetric Compilation

Survey ID	Data Type	Year	Reference/Source
JR167/168	Kongsberg EM120 multibeam	2007	BAS
JR100	Kongsberg EK60 echo sounder	2003	BAS
JR103	Kongsberg EM120 multibeam	2003	BAS
JR107	Kongsberg EM120 multibeam	2004	BAS
JR109	Kongsberg EM120 multibeam	2004	BAS
JR114/121	Kongsberg EM120 multibeam	2005	BAS
JR116	Kongsberg EM120 multibeam	2004	BAS
JR149	Kongsberg EM120 multibeam	2006	BAS
JR60	-	-	BAS
JR69	Kongsberg EM120 multibeam	2001	BAS
JR72	Kongsberg EM120 multibeam/EK500 echo sounder	2002	BAS
JR82	Kongsberg EK60 echo sounder	2003	BAS
JR92	Kongsberg EK60 echo sounder	2003	BAS
JR93	Kongsberg EM120 multibeam	2003	BAS
JR134	Kongsberg EM120 multibeam	2005	BAS
JR77/78	Kongsberg EM120 multibeam	2004	BAS
BAS/UK Hydrographic Office tracks	Kongsberg EA600 single-beam	-	UKHO
HO chart no. 3596	soundings from scanned charts	-	UKHO
HO chart no. 3597	soundings from scanned charts	-	UKHO
Fisheries data	single-beam echo sounders (FV Argos Helena, FPV Dorada)	2003/04	-
GEBCO database	global bathymetric compilation	2003	*GEBCO* [2003]

produced from a number of different data sources (Table 1 and Figure 2). These included the following: a collation of BAS multibeam echo-sounding data acquired over several years aboard the RRS *James Clark Ross*; older BAS single-beam echo-sounding data; Hydrographic Office single-beam acoustic and swath bathymetric data; various fisheries echo sounder data sets; and GEBCO bathymetric data for areas lacking higher-resolution coverage [*GEBCO*, 2003].

[10] Multibeam data were cleaned and compiled using MB software, and subsequently gridded using the TopoGrid program in ArcGIS 9.2 with a "natural neighbor" gridding algorithm [cf. *Nitsche et al.*, 2007]. The investigated area covers a region of continental shelf and slope spanning 320 by 160 km (>50,000 km^2) in size. Lateral resolution of the bathymetric grid (cell size) is 223 m (equivalent to 0.002 decimal degrees of latitude at 54°S, 37°W), providing good spatial resolution for the interpretation of large-scale glacial geomorphological features, but falling below the quality of data typically required for more detailed geomorphic analyses (e.g., from multibeam data, optimal spatial resolution on shallow shelves of 10–20 m).

[11] Relatively few artifacts are present on the compiled bathymetric map (Figure 3), but where present these include unrealistically deep holes, coherent patches of noise and edge effects, all of which probably result from less reliable outer beams of multibeam swaths, or gaps in the data coverage. For the most part, data coverage is good on the continental shelf. However, the varying distribution of multibeam swath data means there is a bias toward resolving features to the north of South Georgia.

[12] Given the comparatively coarse resolution of our data set we supplemented interpretation of the regional grid by examining some higher-resolution multibeam swath bathymetric data (Kongsberg Simrad EM120 data comprising water velocity profile-corrected and unedited swaths, gridded with a 30–50 m cell size) from selected areas of the continental shelf. We also utilized information from the Olex global bathymetric database, a form of single-beam echo sounder used commonly by commercial fishing vessels, and employed recently in the mapping of offshore portions of the last British Ice Sheet [*Bradwell et al.*, 2008]. The data set comprises gridded point data, with a 5 m cell size, 1 m vertical resolution, and a positional accuracy better than 10 m. Both data sources served to provide more detailed geomorphological records of paleo–ice flow.

4. Results

[13] Our new bathymetric grid affords significant improvements upon older bathymetric maps of the broad continental shelf around South Georgia

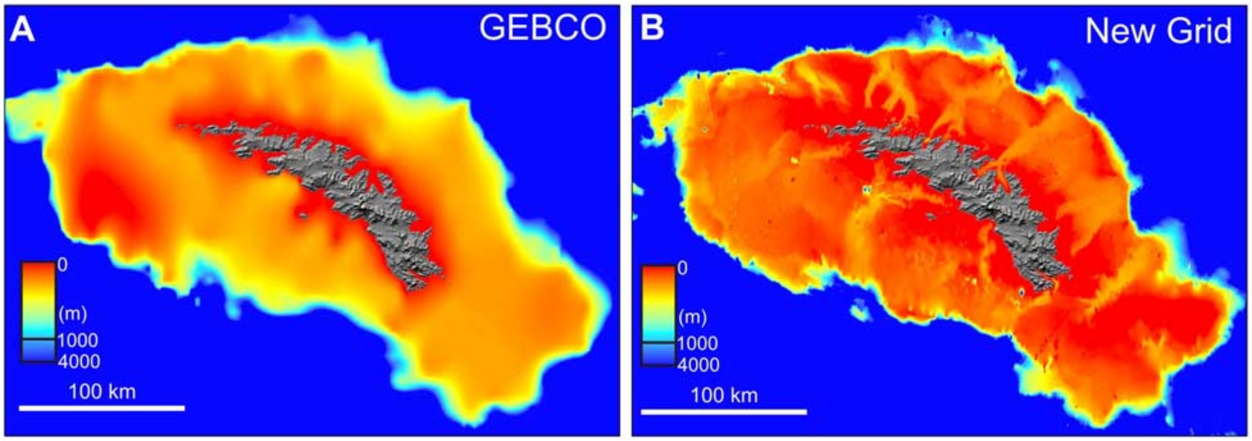

Figure 4. Comparison of (a) GEBCO shelf bathymetric grid against (b) the new BAS bathymetric compilation. Note the level of detail provided by the new compilation.

(Figure 4). The new map reveals (1) shallower water depths on the shelf than the previous average, (2) subtle differences in the shape of the shelf and margin and (3) more detailed representation of geomorphic features on the shelf (Figures 3 and 4). We describe these geomorphic elements herein.

4.1. Trough Systems

[14] The most prominent large-scale geomorphic features on the seafloor around South Georgia are a series of long and relatively deep cross-shelf troughs (250–380 m water depth), with intervening shallower banks (<80–200 m water depth), which extend from the modern-day fjords toward the shelf edge (Figures 3, 5a, 5b, and 6 and Table 2). At least ten separate trough systems are identified around South Georgia, seven of which discharge to the north of the island, and three to the south (Figures 3, 5, and 6a). The pattern of troughs is more or less radial from the present landmass, but with a strong sense of drainage to the north of the island and less well defined drainage pathways south of South Georgia (Figure 3); this discrepancy could be related, in part, to the lower density of data there. Troughs measure between 2 and 5 km wide in the inner shelf and fjords, widening to 12–26 km on the middle to outer shelf. They vary between ~40–102 km in length and have maximum amplitudes ranging from relatively shallow (~80 m) up to ~250 m (Table 2). Along the troughs, depths tend to decrease very gradually seaward (compare to troughs offshore West Antarctica [*Nitsche et al.*, 2007]) At times of glacial maxima, assuming eustatic falls of ~127 m (max. estimate) [*CLIMAP Project Members*, 1981; *Fairbanks*, 1989; *Lambeck et al.*, 2002] at least part of this shelf area would have been emergent, although in practice ice sheet loading may have kept virtually the entire shelf below sea level.

[15] Many of the troughs are fed by more than one tributary, these often converging in the inner shelf areas (Figures 3, 4, and 5a). Good examples visualized on the new data set north of the island include a 68 km-long convergent system, which feeds from Prince Olav Harbour, Antarctic Bay and Fortuna Bay (Trough 4; Figure 3 inset). A 50 km-long trough also connects three large converging tributaries north of the Bay of Isles (Troughs 2 and 3, Figure 3 inset and Figure 5a), and a 40 km-long trough is formed by converging tributaries north of Bird Island (Trough 1, Figure 3 inset and Figure 5c). To the south of South Georgia, groups of 2–3 troughs extend from fjord outlets and typically converge on the inner shelf to form broader troughs seaward (Figure 3 and Table 1).

[16] Cross-profiles of all the troughs show that they are normally u-shaped, with steep valley sides and flat bottoms (Figure 6a). In between the troughs, shelf profiles show reverse gradient slopes with characteristically deep inner to midshelf bathymetry, and shallow, positive-relief banks at the outer shelf (Figure 6b). By contrast, the long axis profiles of several of the troughs are relatively flat, except for in the fjords where isolated depressions occur as a result of overdeepening, most likely by local glacier erosion, or on the inner shelf where raised bedrock platforms are encountered (Figures 6c and 6d).

[17] On the basis of their distinct profiles, cross-shelf alignment, radial drainage pattern, and con-

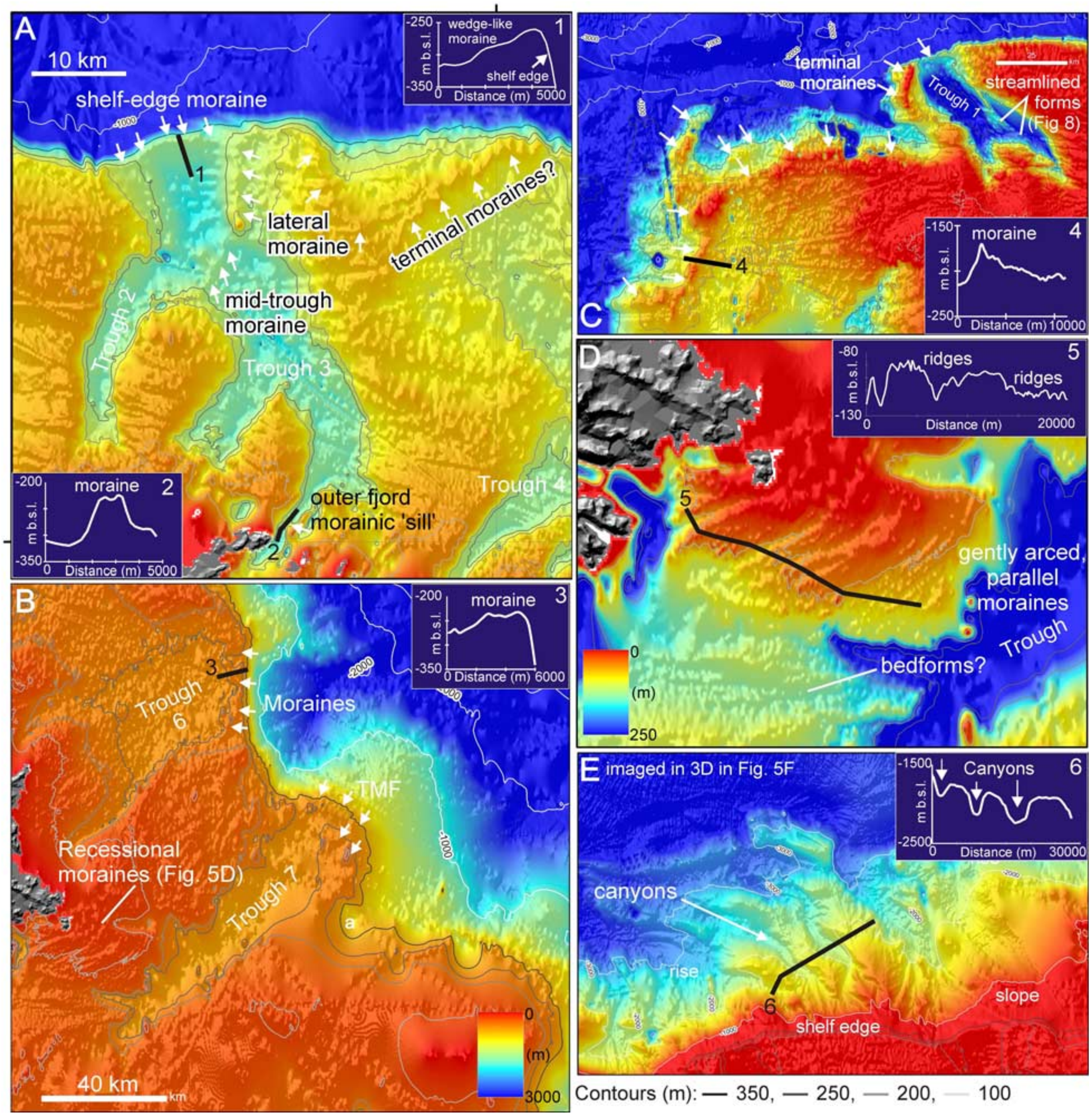

Figure 5. (a–e) Planform details of seafloor bathymetry from selected areas of the South Georgia continental shelf. A variety of convergent seabed troughs, ridges and banks (moraines, arrowed), a slope trough mouth fan (TMF), gullies, and canyons are imaged. See Figure 3 inset for locations. (f) Three-dimensional scene of large canyons (C) extending down the continental slope and rise to the abyssal plain, northwest of South Georgia. Note the channels are separated by large sediment lobes (L). They are interpreted as contourite or debris flow features, interspersed with small sediment drifts. See Figure 3 inset and Figure 5e for location.

nection to modern upstream glaciers, we interpret the troughs as features formed by glacial erosion. Although we have little data on the seafloor lithologies, on the basis of the trough morphology, seafloor profiles, and older geophysical surveys of the shelf it is likely that Mesozoic sedimentary and volcanic rocks (that outcrop onshore) extend beneath the inner shelf. Cenozoic sediments form the outer parts of the continental shelf [*Simpson and Griffiths*, 1982].

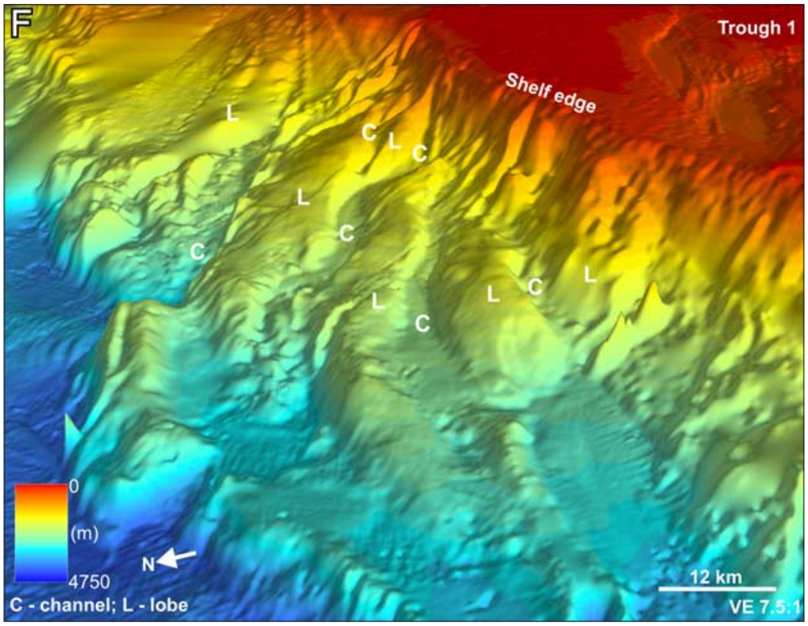

Figure 5. (continued)

4.2. Moraines

[18] Large straight to arcuate ridges and banks are visualized in three situations on the South Georgia continental shelf, superimposed on the trough morphology: (1) at the seaward limit of seven of the cross-shelf troughs, (2) along the axis of at least four of the shelf troughs, and (3) on areas of seafloor between trough features north of South Georgia (Figures 5a, 5b, 5c, and 5d). These range in size from large shelf edge "banks" to smaller ridges, with widths of 1–12 km and lengths from a few km up to ~36 km. Ridges have a subtle relief, from a few meters up to >75 m height (e.g., Figure 5, Profiles 2 and 4). Profiles which extend down the trough axes and between troughs highlight these ridges clearly, at both midshelf positions, and shelf edge extents (Figures 6b and 6c).

[19] Shelf-edge ridges, which cross the mouths of several glacial troughs northwest of the island have arcuate geometries, gentle proximal slopes and steeper distal flanks which are continuous with the shelf break. The landward steepening of the trough axis gradient in these areas produces a characteristic asymmetric wedge-like cross-profile (e.g., Figures 5a and 5b, Profiles 1 and 3; see also Figure 6c). We interpret such shelf-edge ridges as ice-proximal grounding line (terminal) moraines, or grounding zone wedges, formed as depositional bodies at marine-based ice sheet margins on the basis of their geometry, size, distinct positive relief and association with glacial troughs [*Hambrey*, 1995; cf. *Bart and Anderson*, 1997; *Shipp et al.*, 2002; *Shaw et al.*, 2006; *Ottesen et al.*, 2007]. Some of the best examples of shelf ridges occur west of South Georgia, where large plateaus of troughless continental shelf are bounded toward the shelf edge by distinct strings of arcuate ridges and banks (Figure 5c). Their profiles, peaked crests and geometry indicate that they are also terminal moraines (Figure 5c, profile 4).

[20] On higher-resolution Olex bathymetry from areas between troughs 4 and 5 (Figure 3 inset), we also image large banks at the shelf edge, up to 15 km long, 4 km wide and several tens of meters high (Figure 7). The improved spatial resolution of the Olex data set reveals that the shelf edge banks here are draped and surrounded by a number of shorter, lobate to long, arcuate to curvilinear ridges (Figure 7). Their arrangement is complex, and most have a shelf-strike orientation (~2.5–10 km long, ~10–30 m high, ~500–950 m wide). Some of the most distal (seaward positioned) ridges are also truncated by better preserved landward positioned ridges (e.g., Figure 7b). We interpret the ridges as typical high-latitude margin ice sheet end moraines [e.g., *Stoker and Holmes*, 1991; *Bradwell et al.*, 2008], and attribute their formation to a number of individual oscillatory episodes of ice sheet activity offshore South Georgia. Our observations also imply at least two generations of moraine formation, and consequently, that the seafloor has been subject to repeated grounding line advances, or

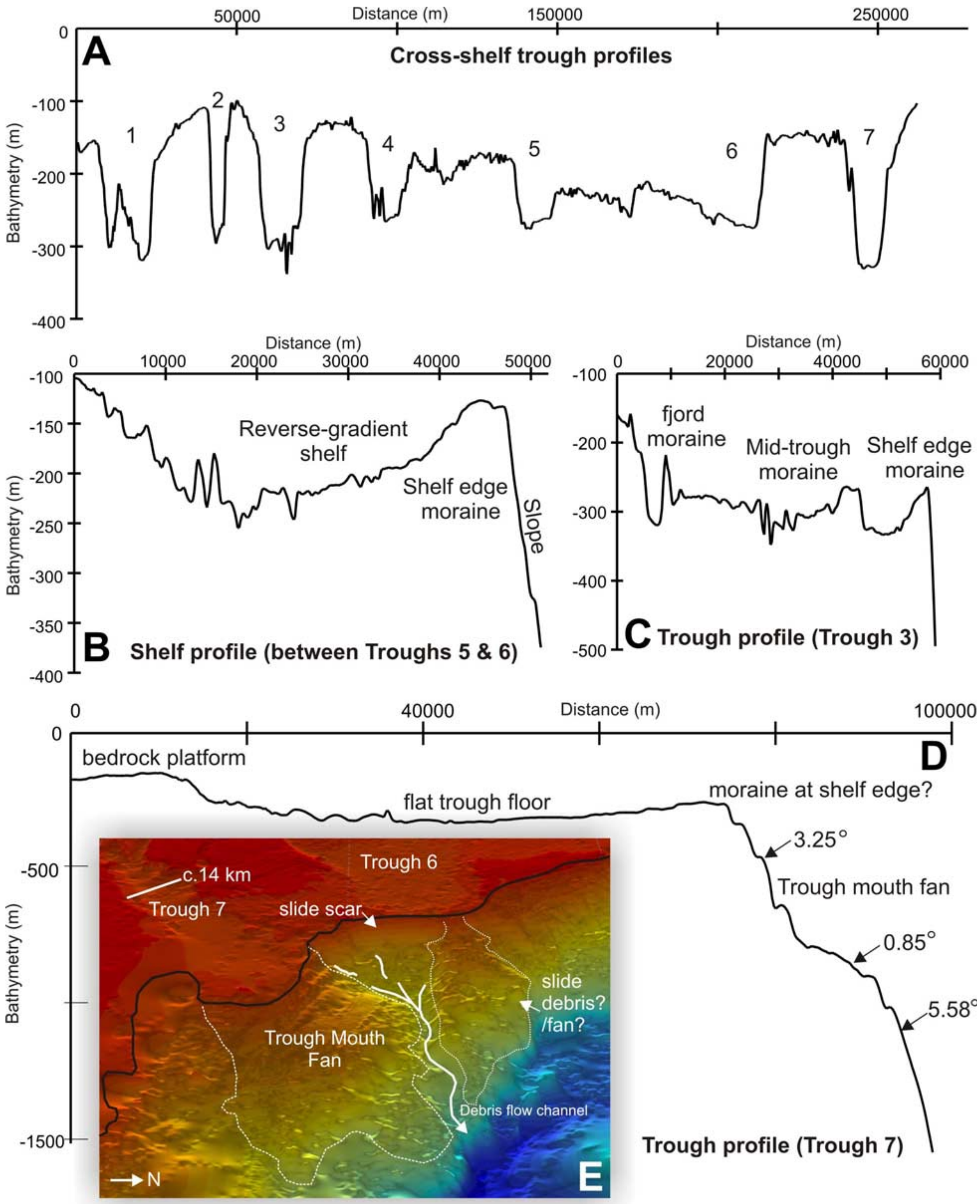

Figure 6. Seafloor profiles of the continental shelf around South Georgia illustrating (a) a series of u-shaped cross-shelf troughs north of the island, labeled Troughs 1–7; (b–d) reverse gradient cross-shelf profiles with moraines at midtrough and shelf edge positions; (d and e) a trough mouth fan at the seaward extent of one of the glacial troughs. Slides and debris flow channels have also influenced the part of the margin near the trough mouth fan, imaged in a 3-D scene in Figure 6e. See Figure 3 inset for locations.

Table 2. Characteristics of Cross-Shelf Troughs, Offshore South Georgia[a]

Trough (Map Reference, Figure 3 inset)	Max. Length (km)	Trough Widths (min-max, km)	Max. Amplitude (m)	Number of Tributaries
1	40	2–13	180	2
2/3	50	2–15	250	3–4
4	68	3–12	90	>3
5	69	4–12	100	2
6	47	5–26	150	2
7	69	2–15	165	>3
8	71	2–16	200	>2
9	102	2–20	190	>2
10	57	2–12	80	2

[a] See Figure 3 inset for locations.

readvances, toward the shelf edge in the past. It remains uncertain whether these advances occurred during successive cycles of glaciation, or during the course of a single glacial episode. A series of smaller ridges in parallel sets (5–6 m high, 1–2 km length, 200–300 m wide), which occurs between the larger ridges, also resemble the form of "De Geer" moraines (Figure 7). Characterized by their flow-transverse orientation, slightly arcuate to anastomosing form, and occurrence in parallel clusters [*Lundqvist*, 2000], such ridges are usually indicative of short pauses in a marine-based grounding line during ice sheet retreat [e.g., *Todd et al.*, 2007]. Their formation is believed to result from the deposition of subglacially advected material, associated with a deforming ice sheet bed [*Linden and Møller*, 2005].

[21] Less well defined "sills" occur across the centers of troughs in the middle shelf and fjord areas (Figures 5a and 6c). In contrast to the shelf-edge moraines, these ridges are generally smaller and have symmetric cross-profiles with more rounded crests (e.g., Figures 5a, profile 2, and Figure 6c). Although limited by the data resolution, we consider these likely candidates for morainic landforms formed under two possible scenarios: (1) during smaller readvances of the ice sheet in the troughs during a longer-term phase of deglaciation or (2) as stillstands of the ice margin during a continuous deglaciation [cf. *Bradwell et al.*, 2008]. These interpretations are based on the ridge geometries (parallel to the shelf break and perpendicular to radial trough orientations) as well as positive seafloor relief (Figure 6c). Examples of moraines lining cross-shelf troughs and forming sills at the mouths of glacial fjords are numerous [e.g., *Davies et al.*, 1997].

[22] A lone trough-mouth lateral ridge is also identified parallel to the long axis of a single trough aligned across the shelf northward of the Bay of Isles (Troughs 2 and 3, Figure 3 inset and Figure 5a). Owing to its cross-shelf alignment, straight form and pointed crest the ridge is interpreted as a lateral moraine formed at the shear margin of a glacier which once occupied the trough (Figure 5a; compare to example given by *Bartek et al.* [1997]).

[23] Finally, closer to the modern shoreline, east of South Georgia, an assemblage of arcuate ridges is well imaged over a shallow part of the seafloor (Figure 5d). This group comprises gently arced ridges measuring 350–1000 m in width, with lengths between 2 and 13 km and a relief of 3–15 m. Cross-profiles of the ridges show a rugged and ridged seafloor expression (Figure 5d, profile 5). The ridges are likely to be recessional moraines; depositional features formed during progressive ice margin retreat or by fluctuations of a relatively slower moving part of the paleo–ice sheet [cf. *Shaw et al.*, 2006; *Ottesen et al.*, 2007; *Todd et al.*, 2007]. They follow the general trend of the coastline in parallel sets, and are found adjacent to smaller fjordal outlets where modern glaciers currently reside (Figure 5d).

4.3. Shelf Margin Morphology and Features

[24] On the slope of the continental block, northeast of the recessional moraines, one part of the margin is clearly lobate in form, covering an area of seafloor ~380 km^2 in size, and situated at the mouth of one of the most prominent cross-shelf troughs (Figures 5b and 6e). Judging by the convex shape of the continental margin, low-angle slope profile (0.85° on part of the upper surface, <6° on lower slope), and the smooth, arcuate slope and rise in this area, the feature is interpreted as a small

Figure 7. Planform images of Olex echo sounder bathymetry data for an area north of South Georgia, between Troughs 4 and 5. (a and b) Two planview visualizations of large sedimentary banked moraines and arcuate ridges. (c) Arbitrary cross-sectional profile [X-X′] through 5 of the main ridges and smaller "De Geer" moraines. (d) Sketch interpretation of the large banks and superimposed moraines. Horizontal datum is WGS84; vertical reference is equinoctial spring low water.

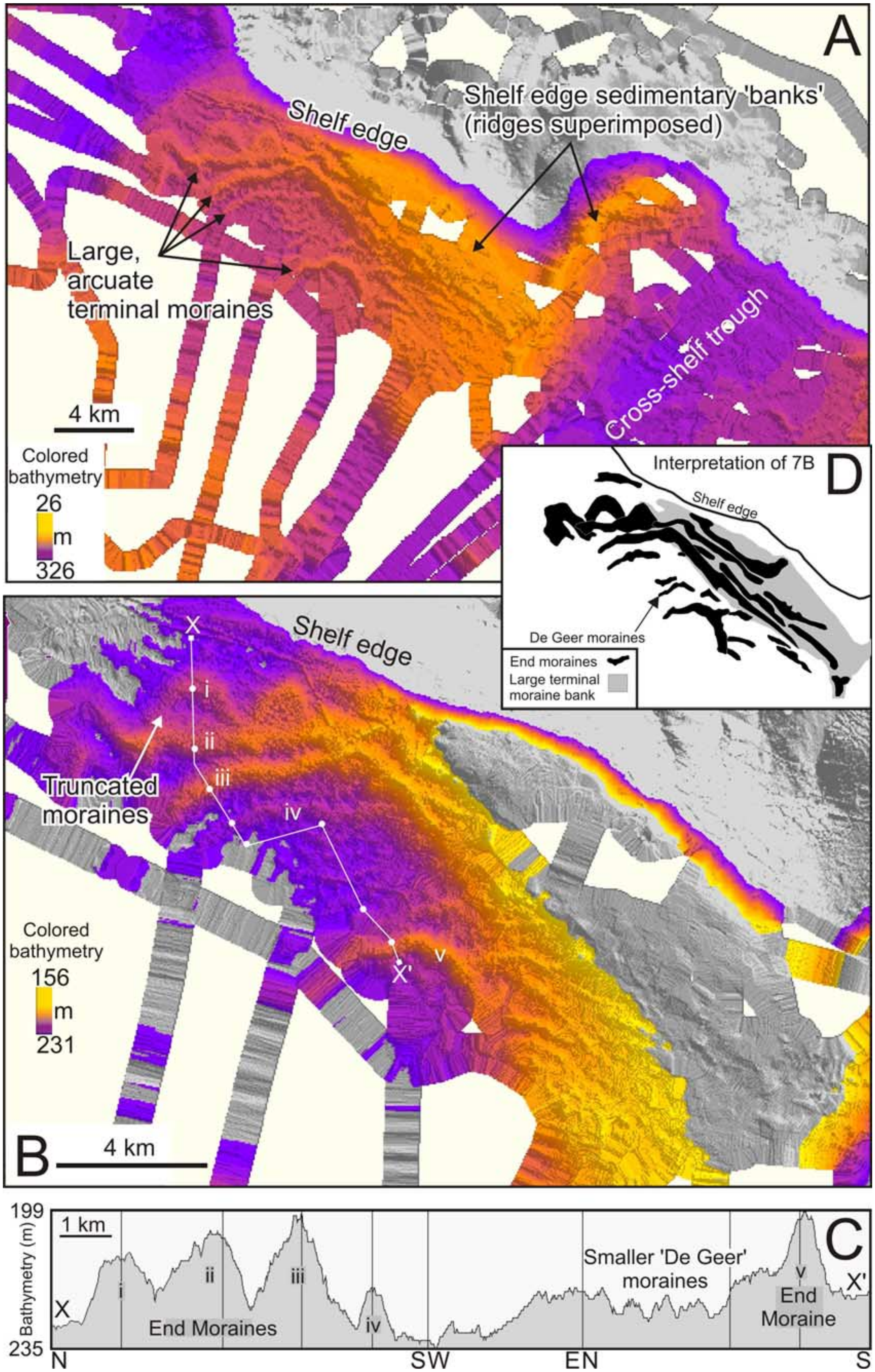
A
Shelf edge
Shelf edge sedimentary 'banks'
(ridges superimposed)
Large,
arcuate
terminal moraines
Cross-shelf trough
4 km
Colored
bathymetry
26
m
326
D
Interpretation of 7B
Shelf edge
De Geer moraines
End moraines
Large terminal
moraine bank
B
Shelf edge
X
i
ii
iii
iv
v
X'
Truncated
moraines
Colored
bathymetry
156
m
231
4 km
C
199
235
Bathymetry (m)
1 km
X
i
ii
iii
iv
End Moraines
Smaller 'De Geer'
moraines
v
End
Moraine
X'
N
SW
EN
S

Figure 7

trough mouth fan, formed by focused delivery of sediment to the shelf margin (Figures 6d and 6e) [*Stoker*, 1995; *Vorren and Laberg*, 1997]. Trough mouth fans are normally formed of prograded and stacked sequences of glacigenic debris flows sourced from the front of ice streams, which occupy cross-shelf troughs [e.g., *Cooper et al.*, 1991; *Vorren et al.*, 1998]. The bulge visualized in the seafloor contours (e.g., Figure 5b) can be explained by the presence of built out fan material and is typical of large glacial fans of the Northern European continental margin (e.g., Byørnøya Fan [*Hjelstuen et al.*, 2007]).

[25] Other sedimentary mounds occur on the lower slope and rise in the same area (Figure 6e). These may represent additional trough mouth fans or slide bodies derived from margin deposits, as suggested by their long-axis profile, planform geometry, and by the presence of slide scar headwalls at the shelf break adjacent to large sedimentary accumulations (Figure 6e). Channels are also carved through and around these deposits, probably reflecting the downslope movement of sediment and water in debris flows or turbidity currents (arrowed in Figure 6e) [*Pudsey*, 2000; *Dowdeswell et al.*, 2004].

[26] Canyons and gullies also dominate the seafloor morphology on the slope and continental rise in at least two places offshore South Georgia (Figures 5e and 5f). Large, gently sinuous to straight canyons extend for >30 km in the best examples (northwest of the island), where they are more than 2–3 km wide, with amplitudes of 100–450 m. We interpret their morphology as having formed by the interaction of turbidity currents and contour currents. Smaller erosional gullies also incise the flanks of the canyons and intervening highs (Figure 5e). Large lobate mounds imaged between channels may be drifts formed by the entrainment of fine-grained components of turbidity currents or via downslope debris flows (Figure 5f) [cf. *Nitsche et al.*, 2000]. The evidence presented here is strongly suggestive of the presence of mobile sediment on the outer shelf and margin around South Georgia, indicating that marginal features are formed of unconsolidated sediments as opposed to harder bedrock.

4.4. Bed Forms

[27] Glacial bed forms on the shelf are generally poorly resolved on the regional bathymetric grid, at or near the spatial resolution of the data set (at 223 m). Multibeam swath bathymetric data used in the compilation of our grid reveal more detailed imagery of the seafloor in one of the cross-shelf troughs northwest of South Georgia (Trough 1, Figure 3 inset; Figure 8, 30–50 m cell size). Here, we identify an assemblage of short, slightly attenuated to highly elongate and streamlined bed forms, oriented along the main axis of the cross-shelf trough at the seabed. They have lengths of ~0.4–10 km, widths < 250–500 m, heights < 20 m, and length:width ratios up to a maximum of ~24:1. Highs surrounding the trough also exhibit streamlined grooves, which align with the bed forms within the trough itself (Figure 8). The longest and most elongate features occur seaward in the center of the trough, while shorter forms lie landward at the mouths of tributaries and at the tributary confluence (Figure 8). Several of the bed forms are also continuous across a well-imaged midtrough moraine, which sits transversely across the trough axis on the midshelf.

[28] On the basis of their geometry and form we interpret the bed forms as subglacial drumlins and lineations, characteristic of formation in a sub–ice sheet environment via a combination of glacial erosion, subglacial sediment deformation and deposition [cf. *Shipp et al.*, 2002]. It is unlikely that elongate drumlins and lineations are formed under areas of ice sheets that are moving slowly [*Andreassen et al.*, 2008]. Instead, there is now a general consensus that drumlins and attenuated lineations form key components of ice stream land systems, and typically characterize increasing downstream velocities in paleo–ice stream pathways [*Wellner et al.*, 2001; *Ó Cofaigh et al.*, 2002; *Anderson and Oakes-Fretwell*, 2008; *Ottesen et al.*, 2008]. Therefore, we consider their identification here as consistent with interpretations of former, relatively fast flowing or accelerating ice within the trough [*Stokes and Clark*, 1999].

5. Paleo–Ice Sheet Drainage and Shelf Evolution

[29] Imaged here for the first time, the trough-bank morphology of the South Georgia continental shelf and associated geomorphic features (streamlined bed forms, moraines, trough mouth fans) are all hallmarks of a heavily glacially influenced seafloor (Figure 9). They indicate that glacial deposition and erosion has been a major influence over the development and current form of the South Georgia continental shelf and margin. The trough systems demonstrate the presence of widespread grounded ice on the shelf, probably on more than

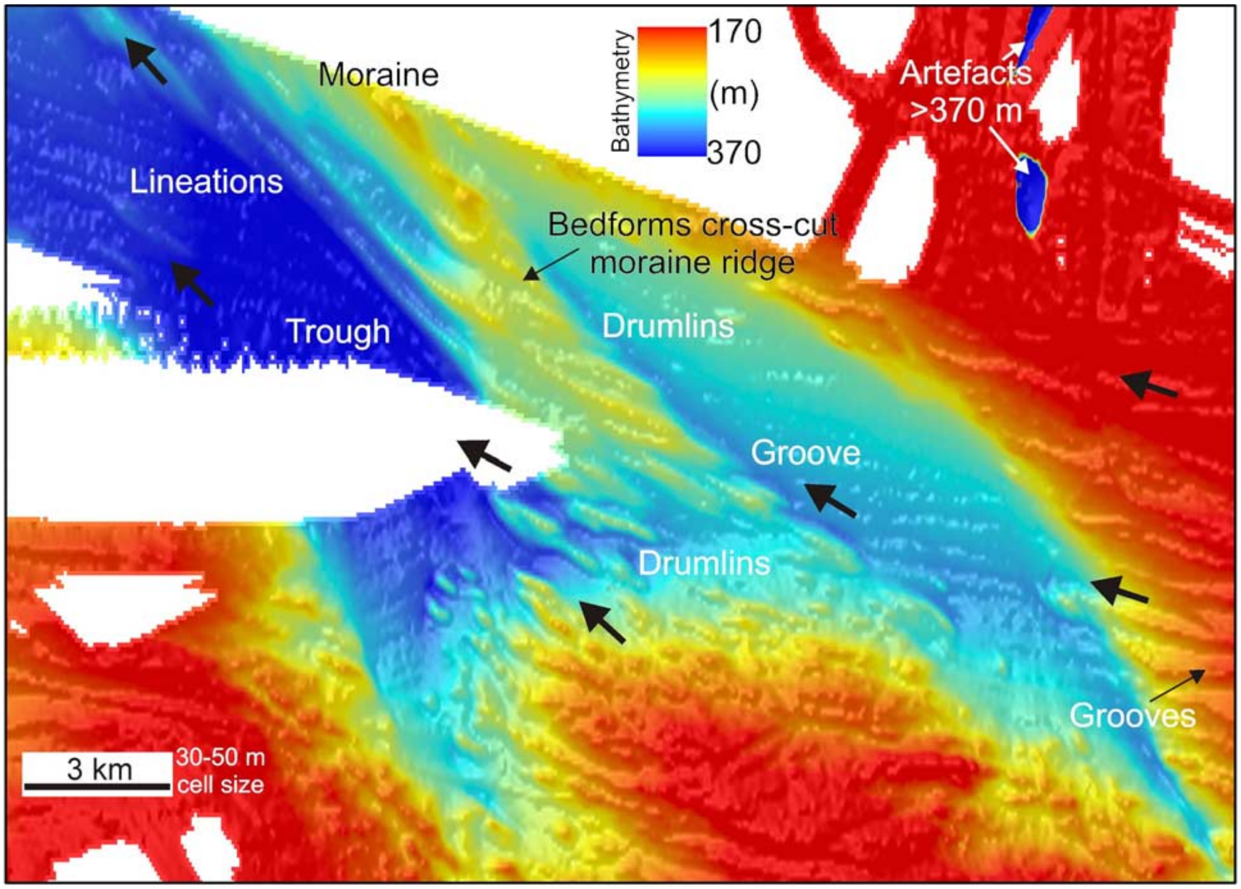

Figure 8. Unedited, water-velocity corrected multibeam swath bathymetric data from a glacial trough (Trough 1) northwest of South Georgia. Crudely streamlined bedrock characterizes the tributary areas, while the trough confluence is lined with elongate drumlins. Seaward of the confluence, several highly elongate lineations are imaged on the trough floor. Black arrows depict interpreted ice flow direction. Grid cell size 30–50 m (0.0008 degrees). Mercator projection. See Figure 3 inset for location.

one occasion, having formed via a combination of focused glacial erosion (in the troughs) and slower erosion/aggradation on intervening shallower banks. Suites of moraines and sedimentary banks also indicate that at least one previous ice sheet has been extensive on the South Georgia continental shelf, extending to the shelf edge in at least several locations, where it formed ice marginal landforms. The most prominent ridges at the shelf edge are characteristic of terminal moraines that record pinning points and depositional centers at the maximum extent of grounded ice limits (Figures 7 and 9). Smaller midshelf moraines record deglacial stages or previous terminal limits of one or more former ice sheets. Furthermore, the trough systems we image on the bathymetric data are consistent with an ice sheet whose glacidynamics were controlled by radial arteries of topographically controlled, faster flowing ice in the form of large outlet glaciers or ice streams (Figure 9). Cross-shelf troughs are well-known focal areas for ice flow convergence and acceleration in the Antarctic, and northern hemisphere, midlatitude Quaternary ice sheets [e.g., *Canals et al.*, 2002; *Ottesen et al.*, 2005]. Bed form evidence within one of the troughs, in the form of elongate lineations, with length:width ratios of >10:1 (up to 24:1 in our study), is widely regarded as being indicative of faster flowing elements in grounded paleo–ice sheets [*Stokes and Clark*, 1999; *Wellner et al.*, 2005; *Ó Cofaigh et al.*, 2002, 2005; *Mosola and Anderson*, 2006]. Drumlins which occur landward of these lineations also support a concept that the last paleo–ice sheets to cross the shelf were accelerating as they did so, within the troughs [*Wellner et al.*, 2001; *Ó Cofaigh et al.*, 2002]. This observation is supported by the convergence of glacial tributaries on the middle shelf which further

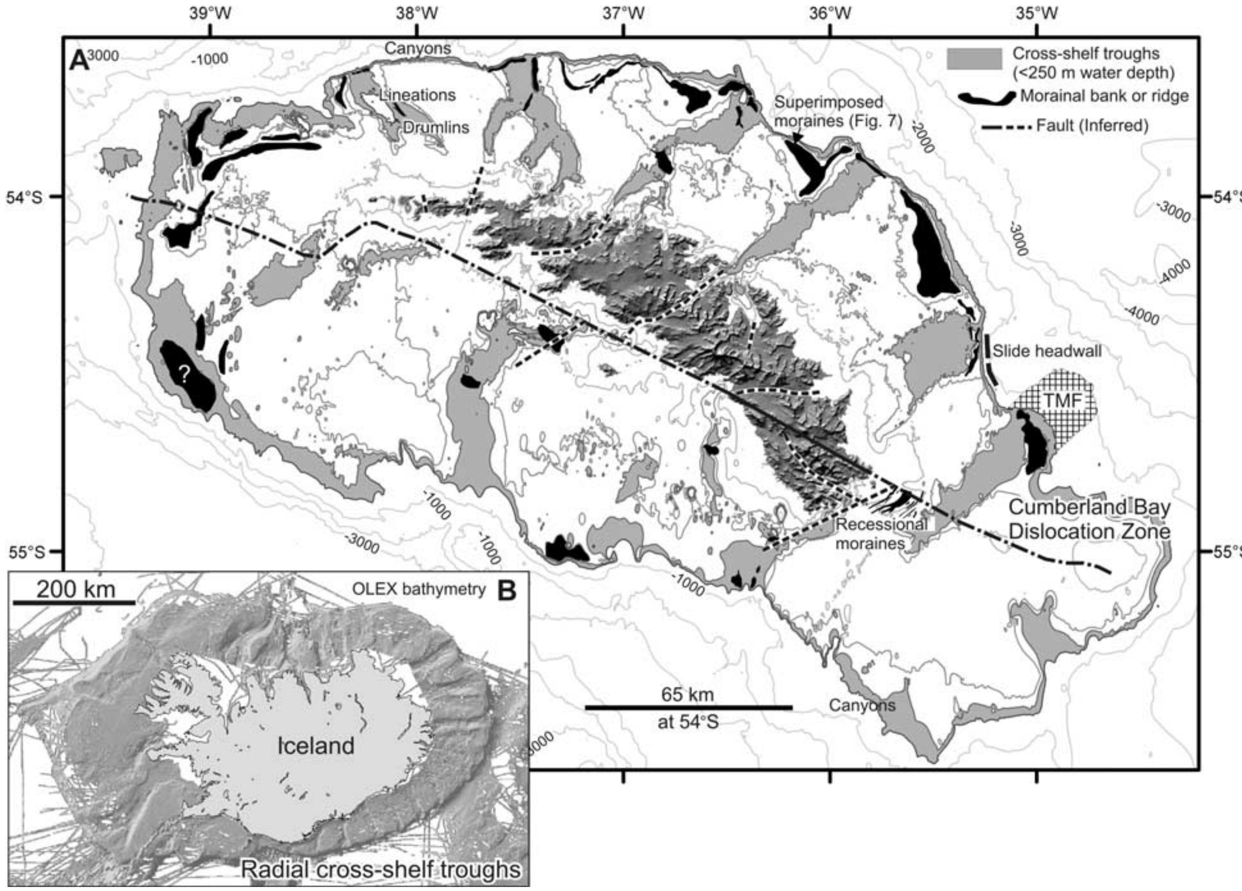

Figure 9. (a) Summary of geomorphic interpretations from the new bathymetric grid. Black polygons are features interpreted as moraines which reside at the seafloor on the continental shelf. Grayed areas depict fast flow outlets along cross-shelf troughs (note parts of the margin also shaded owing to similar water depths). Geological structures are also illustrated; the troughs show a strong association with the location of major faults extending from the west-east dislocation zone. TMF, trough mouth fan. (b) Olex echo sounder data set for the Icelandic continental shelf showing bathymetry characterized by radial, glacial cross-shelf troughs.

implies accelerating paleo–ice sheet conditions for some of the cross-shelf troughs. Given that these bed forms also crosscut midtrough moraines (Figure 8), and that other shelf-edge moraines overprint one another (Figure 7), we propose a minimum of two grounding line advances over the shelf in the past.

[30] The continental margin itself has likely been extended and enlarged through progradation as a result of ice sheets feeding sediment onto the shelf, and focusing sediment delivery along fast flow arteries. Indeed, several glacial episodes have probably served to overdeepen the troughs on the shelf thereby accentuating the pathways for ice drainage along these routes. In the absence of a chronology to constrain the age of trough morphology, it is acknowledged that this drainage evolution may have begun pre-Quaternary, given that South Georgia has been a stable site for glaciation since its pinning by Shag Rocks Passage at ~6 Ma [*Barker and Hill*, 1981]. In this setting south of the polar front, with a high relief, and in maritime conditions with continually high precipitation rates, we would expect the island to be consistently colder than South America during glacial episodes. On this basis, South Georgia should possess a glacial history at least comparable with that of Patagonia, where glaciation began in the Late Miocene [*Rabassa et al.*, 2005].

[31] The single trough mouth fan identified offshore eastern South Georgia is a probable concentrated sink for the sediment carried by a former glacial outlet (Figure 9); its existence downstream from a cross-shelf trough, coupled with streamlined bed form evidence elsewhere strongly suggests the repeated presence of former ice streams in South

Georgia ice sheets. The fan thus constitutes a potential locus for an extended sedimentary archive of ice movements offshore South Georgia. Other cross-shelf troughs imaged on the new bathymetry may also be associated with additional trough mouth fans but if so, the current bathymetric data are insufficiently detailed to reveal them.

[32] Elsewhere on the margin, canyons, gullies, and sediment drifts reveal that downslope and along-slope processes have been active on the South Georgia continental slope and rise. Channels and sediment mounds imaged in the new bathymetry are linked tentatively to sediment transport to the margin (through meltwater plumes, turbidites and debris flows) perhaps during glacial episodes. The form and orientation of the channel/drift systems are also likely to be influenced to some degree by fluxes of a Weddell Sea derived bottom current, which flows along the base of the continental slope and rise toward the Argentine Basin to the northwest (Figure 1) [*Locarnini et al.*, 1993; *Cunningham and Barker*, 1996]. In contrast, slides and their headwalls imaged in our bathymetric grid might relate to mass wasting events as a result of lowered margin stability through rapid deposition on the upper continental slope during glacial stages.

6. Controls on Trough Systems and Ice Sheet Configurations

[33] Morphologically, the orientation of many of the cross-shelf troughs, particularly north of South Georgia show a consistent NE–SW pattern (Figure 9a), revealing a hitherto unrecognized structural control on glacial drainage, as nearly all of the cross-shelf troughs follow structural geological elements of the continental block (Figure 9a). Our correlation of terrestrially mapped faults with troughs extending offshore of South Georgia show that past ice streams have exploited weaknesses in the bedrock structure (mainly cross-faults extending away from the Cumberland Bay Dislocation Zone, Figure 9) and hence that their locality, as well as straight geometry, has been directly influenced by the bedrock geology. Ice stream troughs on the circum-Antarctic shelves are often tectonically controlled (e.g., Amery Trough [*Cooper et al.*, 1991]) and the loci of many modern Antarctic ice streams are known to be controlled by subglacial geology [*Bell et al.*, 1998; *Anandakrishnan et al.*, 1998]. Because the ice streams that drained ice away from the island are also interpreted to have crossed both bedrock and sedimentary substrate, increasingly erodible substrates seaward of South Georgia may be partly responsible for past ice flow velocities and ice stream initiation in paleo–ice sheets on South Georgia [*Wellner et al.*, 2001]. Rapid flow of ice in ice streams has been shown to originate via basal sliding and deformation of a subglacial till layer [*Alley et al.*, 1986; *Kamb*, 2001; *Ó Cofaigh et al.*, 2005]. Soft shelf sediments and their availability would therefore allow for fast flow in South Georgia's ice sheets and facilitate the high sediment supply required in order to maintain high flow rates in their ice streams.

[34] South Georgia's geology and its effect on physiography has also served to influence its patterns of glacierization; recent studies have shown that glacier mass balance exhibits a strong north-south gradient over the island today [*Gordon et al.*, 2008]. Accordingly, the spatial patterns of paleo-ice stream troughs on the shelf demonstrate a similar bias toward the north of South Georgia where troughs are more numerous and well-defined, and where moraines are well developed. Possible explanations for this spatial arrangement may be increased solar radiation on the northern side of the paleo–ice sheet, increasing surface melt and water supply to the ice sheet bed, thereby enhancing northerly ice flow. Alternatively, past variations in ocean temperature (and hence air temperature and ice surface temperature) and precipitation patterns may have influenced ice sheet mass balance across the north-south divide, with a less active erosive environment south of the island, and a focused glacial discharge to the north. The well-formed shelf edge moraines north of the island can be best explained as a consequence of rapid basal melting through interaction with relatively warm Circumpolar Deep Water, tongues of which encircle the continental block east and north of South Georgia today (Figure 1). In turn, the absence of similar moraines south of the island may be attributable to the bias in multibeam data coverage toward the north of the island (Figure 2).

7. Analogues and Implications for Last Glacial Maximum Glaciation

[35] Considering the newly discovered ice drainage patterns presented here, we suggest possible comparisons with suitable analogs from other maritime glaciated subpolar islands. Icelandic glaciations during the Quaternary have been especially well studied in recent years [*Andrews*, 2008], and the offshore domains surrounding Iceland are relatively well understood. The region therefore lends

strong support to our interpretation of extensive paleoglaciations in South Georgia, on the basis that their analogous topographic and environmental settings leads one to expect similarities in their past glacial regimes.

[36] Both regions share physiographic characteristics, being maritime glaciated areas strongly influenced by the movement of polar frontal zones and oceanographic changes. Similar maritime and climatic conditions suggest that the degree and scale of ice sheet growth and decay is likely to have been comparable in both localities, with extensive offshore ice sheets documented on the Icelandic continental shelf since the late Pliocene [*Ingólfsson*, 1991].

[37] We use Olex echo sounder bathymetry recently compiled for the Icelandic shelf to demonstrate that South Georgian ice sheets had a similar radial patterns of shelf drainage to those in Icelandic glacial configurations (up to 18 shelf troughs have been reported from Iceland [*Andrews et al.*, 2000]), implying that paleo–ice sheets on respective shelves were controlled at their maximum extents by drainage along topographically controlled outlet glaciers (Figure 9b). We also recognize a strong potential in each region for the development of ice streams due to high precipitation (at relatively warm temperatures) as a result of their comparable maritime settings, producing mainly wet-based glacial systems with high net-balance gradients [*Canals et al.*, 2002]. Furthermore, high budget gradients, which are common to maritime ice sheets, will produce significant rates of subglacial erosion [*Hooke*, 2005], consistent with the observation of eroded troughs on both shelves today. Additionally, the outer continental shelf and termini of Icelandic cross-shelf troughs are characterized by large moraines, similar to those imaged around South Georgia in this study, while numerous ridges and ice margin pinning points also characterize areas of the continental shelf landward of the Icelandic shelf break [*Andrews et al.*, 2000; *Bingham et al.*, 2003].

[38] In view of these similarities we again pose the question, what was the extent of the LGM ice sheet in sub-Antarctica? Recent work in Iceland has indicated an extensive LGM ice sheet on the continental shelf [*Andrews et al.*, 2000], contrary to earlier investigations that interpreted a restricted LGM ice sheet with a largely pre-LGM shelf geomorphology [*Hjort et al.*, 1985]. Although there is no direct evidence for any similar extensive marine ice sheet operating during the LGM in South Georgia, the possibility of an expansive glaciation during the LGM is supported by our data. The existence of subglacial bed forms in at least one trough demonstrates that ice sheet activity has been extensive relatively recently, generally unaffected by subsequent erosion or burial, within the constraints of our data resolution. Also, the preservation of shelf-residing moraines, akin to other high-latitude examples, supports a record of reorganization and oscillation of the ice sheet and its fronts during deglaciation (e.g., recessional and terminal moraines, Figures 5d and 7). On many continental shelves similarly exposed ice marginal features relate to young ice sheet events interacting with the seabed [e.g., *Bradwell et al.*, 2008], while older features are generally removed or buried [*Nygård et al.*, 2004]. In support of a young age for the moraines, if we assume typical average sedimentation rates for the South Georgia outer continental shelf of anywhere from 5 to 800 cm/ka (sensu minimum sedimentation rates for postglacial times on the Norwegian glaciated shelf [e.g., *Rise et al.*, 2008]), then we would expect features with amplitudes of tens of meters (i.e., moraines and bed forms) to be completely buried within only a few tens to hundreds of kiloyears or less. Thus, these simple estimates suggest strongly that the newly visualized outer shelf geomorphology relates to relatively recent phases of offshore glaciation.

[39] While an extensive LGM interpretation would contradict the recent work of *Bentley et al.* [2007a], who suggested that moraines lining the South Georgia coastline record a terminal limit of the ice sheet, it could be considered that terrestrially mapped moraines are in fact stillstand or readvance margins of a post-LGM ice sheet, formed subsequent to the maximum extension of the ice sheet onto the shelf (compare to Patagonian Ice Sheet readvances from 15 to 10 ^{14}C ka B.P. [*Rabassa et al.*, 2005]). Indeed, the oldest of the moraines mapped by *Bentley et al.* [2007a] (younger than 14.1 ka B.P.) postdates the range of accepted timings for LGM global ice sheet volume by 7–12 ka (LGM at ∼26–21 ka B.P. [*Peltier and Fairbanks*, 2006]) and surpasses the LGM in neighboring Patagonia by ∼11 ka, where a period of maximum extent is recorded at ∼25 ka B.P. on the basis of ^{10}Be dates from terminal moraines [*Kaplan et al.*, 2008]. Both chronologies allow for an extensive shelf glaciation and retreat to Late Glacial coastal limits. The combination of environmentally sensitive glaciers and the reverse-slope morphology of the continental shelf would also allow for dynamic and rapid advance, and retreat of

shelf ice through mechanisms which, for the most part, are understood for the Icelandic and West Antarctic Ice Sheets [*Hubbard et al.*, 2006; *Schoof*, 2007].

[40] Ultimately, the geomorphic record offshore South Georgia requires age constraints and further detailed marine investigation is therefore needed. If smaller subglacial bed forms and moraines are formed in bedrock or on a relict sedimentary terrain then they may be of indeterminate pre-LGM age (compare to offshore Patagonian moraines [*Kaplan et al.*, 2008] or relict ice scours offshore Greenland described by *Syvitski et al.* [2001]). However, taking into account (1) that other maritime Antarctic Islands (Heard Island and Kerguelen Island) which lie within the Polar Front have been identified as possible areas of former extensive LGM glaciation, on the basis of depositional grounding zone features which occupy areas of shallow water around these isles [*Balco*, 2007]; (2) that a large Patagonian ice sheet developed at the LGM in southern South America, a locality that shares strong geological, environmental and glaciological influences with the sub-Antarctic regions [*Hall*, 2004]; and (3) that geomorphic observations from our new data set favor recent glacial activity, there is a distinct possibility that ice caps of much greater extent could have existed across many of the sub-Antarctic islands at the LGM. If true then the significance of glaciation in these regions may have, until now, been notably underestimated.

8. Conclusions

[41] 1. A subkilometer-resolution compilation grid of bathymetric data has revealed hitherto unseen detail concerning the drainage patterns and glaciated character of the South Georgia continental shelf.

[42] 2. The presence of glacially formed cross-shelf troughs and ice sheet terminal moraines indicates that a South Georgian ice sheet extended to the shelf break at least once, and probably numerous times, in the past.

[43] 3. Fast flowing outlet glaciers or ice streams formed the main drainage pattern of past ice sheets on the shelf and were influenced by the structural framework and maritime setting.

[44] 4. The age of the shelf geomorphology documented on the new bathymetric grid remains open to interpretation, potentially reflecting glaciation from late Miocene times onward. An extensive LGM glaciation of South Georgia is feasible, but such a hypothesis remains untested, and calls for a well-dated sequence of sediment cores.

[45] 5. Our observations from this new data set are only preliminary and require a more thorough interrogation supplemented with further marine geophysical (high resolution seismic) and geological (offshore coring) investigation of the South Georgia shelf and fjords.

[46] An up-to-date version of the bathymetric grid used in this paper is available online at http://www.antarctica.ac.uk/bas_research/data/online_resources/sgbd/.

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