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Widespread persistence of expanded East Antarctic glaciers in the southwest Ross Sea during the last deglaciation

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ABSTRACT

It has been suggested that the grounding line of the Last Glacial Maximum (LGM) ice sheet in the Ross Sea, Antarctica, receded in an approximately north-to-south pattern during the Holocene. An implication of this hypothesis is that geological evidence from the southwestern Ross Sea has been used widely to interpret retreat histories of the West Antarctic Ice Sheet (WAIS) across the wider Ross Sea embayment. Accurately constraining the timing and pattern of marine-based ice sheet retreat in this embayment is critical to understanding the drivers that may have triggered this event, and its contribution to rapid sea-level rise events. Here, we present new multibeam swath bathymetry data that identifies well-preserved glacial features indicating that thick (>700 m) marine-based ice derived from the East Antarctic Ice Sheet coastal outlet glaciers dominated the ice sheet input into the southwestern Ross Sea during the last phases of glaciation. Subglacial geomorphic features indicate that ice derived from present outlet glacier valleys in South Victoria Land flowed southeastward. This is more consistent with flowlines from model-based interpretations of an earlier retreat of the WAIS in the central Ross Sea than with previous land-based geological reconstructions. This implies that coastal records of deglaciation along the Transantarctic Mountains front record only the final phases of glacial retreat in the Ross Sea. Therefore, chronological data from the central embayment are required to accurately constrain the timing of large-scale glacial retreat in the Ross Sea and to identify the mechanisms that drove it.

INTRODUCTION

At the Last Glacial Maximum (LGM, ca. 20 ka), a marine-based ice sheet occupied the Ross Sea, Antarctica, and was grounded near to the continental shelf edge (Anderson et al., 2014). It has been proposed that the timing of deglaciation in South Victoria Land is a reliable indicator of glacial extent in the central regions of the Ross Sea (Hall et al., 2015). Provenance indicators in terrestrial moraines are interpreted as showing that LGM ice flowed from the central Ross Sea, around the north of Ross Island, and then southwest into McMurdo Sound (Denton and Marchant, 2000; Fig. 1). However, recent multibeam and sediment core studies suggest that the central Ross Sea embayment may have deglaciated first and that the coastal records may instead be recording ice sheet retreat from local outlet glaciers (Halberstadt et al., 2016; McKay et al., 2016). Thus, two leading hypotheses have emerged: (1) grounded ice sheets sourced from the central Ross Sea flowed toward the Transantarctic Mountains in South Victoria Land, and chronologies of retreat in South Victoria Land are representative of broader ice sheet retreat in the central Ross Sea (Fig. 1A); or (2) grounded ice flowed eastward from the Transantarctic Mountains outlet glaciers and southwards toward Ross Island and McMurdo Sound, with chronologies in South Victoria Land being representative of local outlet glacier retreat that may have significantly lagged retreat in the central Ross Sea (Fig. 1B). Here, we present new multibeam swath bathymetry data that can test these hypotheses by identifying the paleo–ice sheet flowlines in this critical region.

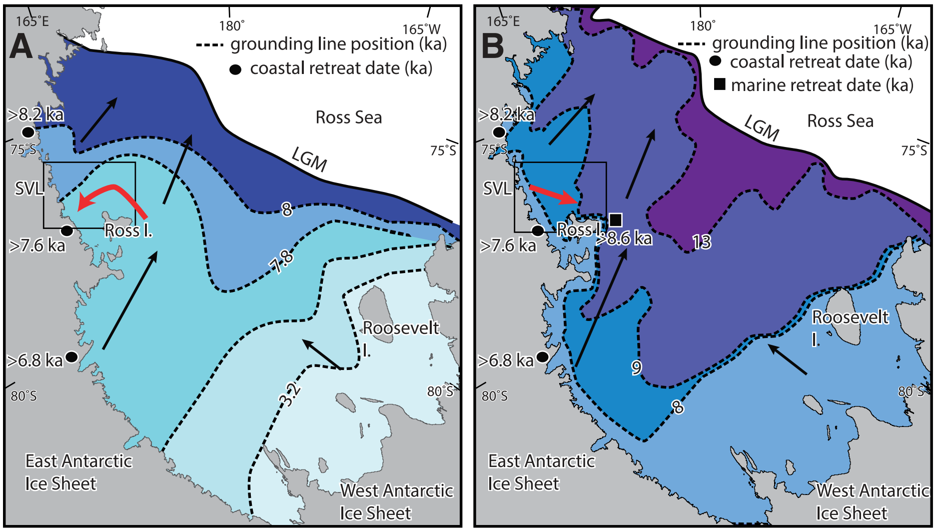

Figure 1. Two hypotheses for Ross Sea, Antarctica, grounding line retreat. A: Ice flowing from central Ross Sea toward South Victoria Land (SVL) coast (red arrow). Timing of retreat is constrained by geological data (black circles) in SVL and requires retreat throughout Holocene (Conway et al., 1999). B: Expansion of local SVL outlet glaciers (red arrow) during deglacial allows for earlier retreat in central Ross Sea. Timing of retreat is based on combined geological (black circles and square) and modeling constraints (McKay et al., 2016). Darker blue contour fill indicates earlier grounding line retreat (LGM—Last Glacial Maximum). Black rectangle shows location of Figure 2A.

METHODS

In the austral summer of A.D. 2012–2013 and 2014–2015, the Korea Polar Research Institute conducted swath bathymetric surveys in the southwest Ross Sea aboard the R/V *Araon*, equipped with a hull-mounted EM122 system. The data were processed using CARIS HIPS and SIPS software (http://www.caris.com/products/hips-sips/) and converted to a 15 m grid. Figure

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DR1 in the GSA Data Repository[1] shows these data overlain on existing regional seafloor bathymetry data previously reported by Greenwood et al. (2012) and Halberstadt et al. (2016) and obtained from the Marine Geoscience Data System (http://www.marine-geo.org).

GLACIAL GEOMORPHOLOGY OF THE SEAFLOOR

Megascale Glacial Lineations

Megascale glacial lineations (MSGLs) are curvilinear, parallel ridges that extend as much as several kilometers in length, are several meters in height, and have wavelengths of tens to hundreds of meters (Dowdeswell et al., 2008). They are interpreted to have formed as part of a deforming till beneath fast-flowing grounded ice and provide unequivocal evidence of former glacial flowlines. In this study, MSGLs are observed in the 700-m-deep bathymetric trough in Granite Harbor (Ross Sea), and the paleoflow orientation can be traced ~50 km offshore, where the lineations are aligned in a southwest-northeast direction near the mouth of the Mackay Glacier but have a WNW-ESE orientation further offshore (Fig. 2D). Near the mouth of the Mawson Glacier, MSGLs bifurcate around a distinct bathymetric high, indicating that a spreading grounded ice mass flowed from this glacier to the north and south (Fig. 2B). The southward-flowing lines can be traced >150 km offshore to the south where they are initially directed west-east before curving toward NNW-SSE and then a west-east direction north of Beaufort Island (Figs. 2C and 2E). MSGLs are also oriented northwest-southeast south of Beaufort Island, whereas further east they have a southwest-northeast orientation. To the immediate northeast of Ross Island, these MSGLs converge with the MSGLs to the east of Beaufort Island.

Grounding-Zone Wedges

Grounding-zone wedges (GZWs) have a characteristic asymmetric geometry that can be linked to the direction of ice flow, with the seafloor displaying a ramped profile with a steep slope on the lee side. The surface of the ramp on the stoss side is commonly superimposed by MSGLs, interpreted as deformation till deposited beneath a flowing ice sheet, while the crest of the GZW represents the location of a grounding line stillstand during retreat (Batchelor and Dowdeswell, 2015). To the east of the Mackay Glacier, there are a total of eight GZWs that can be traced into Granite Harbor. The GZW are generally <10 km wide, but their asymmetric geometry indicates that the final phase of grounded ice in this trough was characterized by an expanded Mackay Glacier. In the southern Drygalski Trough, southeast of the Mawson Glacier, GZWs are larger (>10 km in width) and more abundant. The ramped stoss sides of GZWs are all superimposed by MSGLs, oriented approximately perpendicular to GZW crests. The MSGLs can be traced from the Mawson Glacier >150 km offshore. They form a back-stepping pattern whereby the ramped structures are stacked up (Fig. 2E). Combined, these data indicate that the MSGLs and GZWs formed during a single phase of retreating ice flow and that the Mawson Glacier expanded toward the southeast at least 150 km offshore during the last phase of grounded ice in the deep bathymetric troughs.

Transverse Ridges

Transverse ridges, like GZWs, are oriented at approximate right angles to MSGLs, but they are lower-relief features, generally on the order of 1–2 m in amplitude and three to four orders of magnitude smaller in volume than GZWs. They display a repeating, rhythmic pattern, with wavelengths of tens to hundreds of meters, and are commonly interpreted as annual ice push features representative of a rapid phase of retreat (Shipp et al., 2002; Dowdeswell et al., 2008). In our study area, a series of these ridges overprinting MSGLs occur in the deepest regions of the southern Drygalski Trough. However, a lack of clear GZWs or other geomorphic features indicative of flow directions makes the flow direction and the relative timing of events in this area ambiguous. However, as these features overlie MGSLs in this trough, it is tentatively suggested they are the consequence of the ice sheet reaching flotation point in the deeper regions of the Drygalski Trough (~900 m water depth), while ice derived from the Mawson Glacier was still grounded and streaming in the shallower troughs (~700 m water depth).

Channels

Direct geomorphic features indicative of ice flow direction are lacking in McMurdo Sound, with channel systems dominating the seafloor bathymetry (Greenwood et al., 2012). In New Harbour, a deeply incised (~100 m deep and ~1 km wide) U-shaped channel system with a flat bottom and steep flank is identified (Fig. 2F). Near the coast, the channel cuts through a plateau that contains crudely streamlined bedforms, crag-and-tail features, and shallower bifurcating channels that are characteristic of subglacially eroded bedrock, which forms the seabed at this location (Pekar et al., 2013). The channel bifurcates as it passes into the deeper waters of McMurdo Sound, and a turbidity current origin for these channels, formed by cold, sediment-laden water, has been proposed (Greenwood et al., 2012). While modern-day turbidity current activity may occur in these channels, there is minimal evidence of the large sediment fan at the mouth of these channels that would be expected if formed exclusively by turbidity currents. Crudely defined back-stepping ridges are present on the plateau and are tentatively interpreted as proglacial moraine deposits of a retreating Ferrar Glacier, near the mouth of the canyon (Fig. 2F; Fig. DR4), further suggesting a subglacial origin for the channel. Such channels are common on inner continental shelf regions in West Antarctica and may represent inherited, time-transgressive features formed over numerous previous (i.e., pre-LGM) periods of grounded glaciers (Graham et al., 2009).

A lower-relief channel system converges in the northern part of McMurdo Sound and eventually grades into MSGLs to the south of Beaufort Island. These channels have undulating thalwegs and were likely formed subglacially (Greenwood et al., 2012). Although not a direct indicator of ice flow direction, meltwater channels on a flat seabed generally trend in the direction of ice sheet surface slope and thus ice flow direction (Shreve, 1972).

DISCUSSION

Although exact sea-level budgets are still unclear, glacial retreat in the Ross Sea was likely one of the largest Antarctic contributors to post-LGM sea-level rise and may have partially contributed to rapid sea-level rise events prior to the Holocene (Golledge et al., 2014). Terrestrial chronologies along the Transantarctic Mountains front in our study area of the southwest Ross Sea imply that the majority of glacial retreat in that region occurred in the Holocene (Denton and Marchant, 2000; Hall et al., 2004; Jones et al., 2015). Whether this established glacial retreat chronology is indicative of wider retreat in the Ross Sea (Fig. 1A) or local outlet glaciers (Fig. 1B) can be determined by assessment of the glacial flowlines to the immediate north of Ross Island (e.g., red arrows in Fig. 1). If the retreat history is that of local outlet glaciers, then the majority of retreat in the Ross Sea may have occurred prior to the Holocene, as suggested by comparisons of sediment core data and numerical models (Fig. 1B; Golledge et al., 2014; McKay et al., 2016)

Our new data of GZWs back-stepping into the mouths of Transantarctic Mountains glaciers indicate that East Antarctic Ice Sheet (EAIS) outlets flowed into the western Ross Sea and south toward Ross Island. This contrasts with earlier interpretations of subglacial landforms in this area that could not connect the MSGL-derived flowline orientations to their source regions (Greenwood et al., 2012). Consequently, in order to fit the terrestrial-based reconstruction, Greenwood et al. interpreted an initial phase of outlet glacier advance eastward out of the Transantarctic Mountains, before a complete reversal in direction with a more expansive northwestward flow of a central Ross Sea ice sheet

[1]GSA Data Repository item 2017117, supplemental figures and multibeam swath bathymetry map of the southwest Ross Sea from R/V *Araon* data and Marine Geoscience Data System, is available online at http://www.geosociety.org/datarepository/2017/ or on request from editing@geosociety.org.

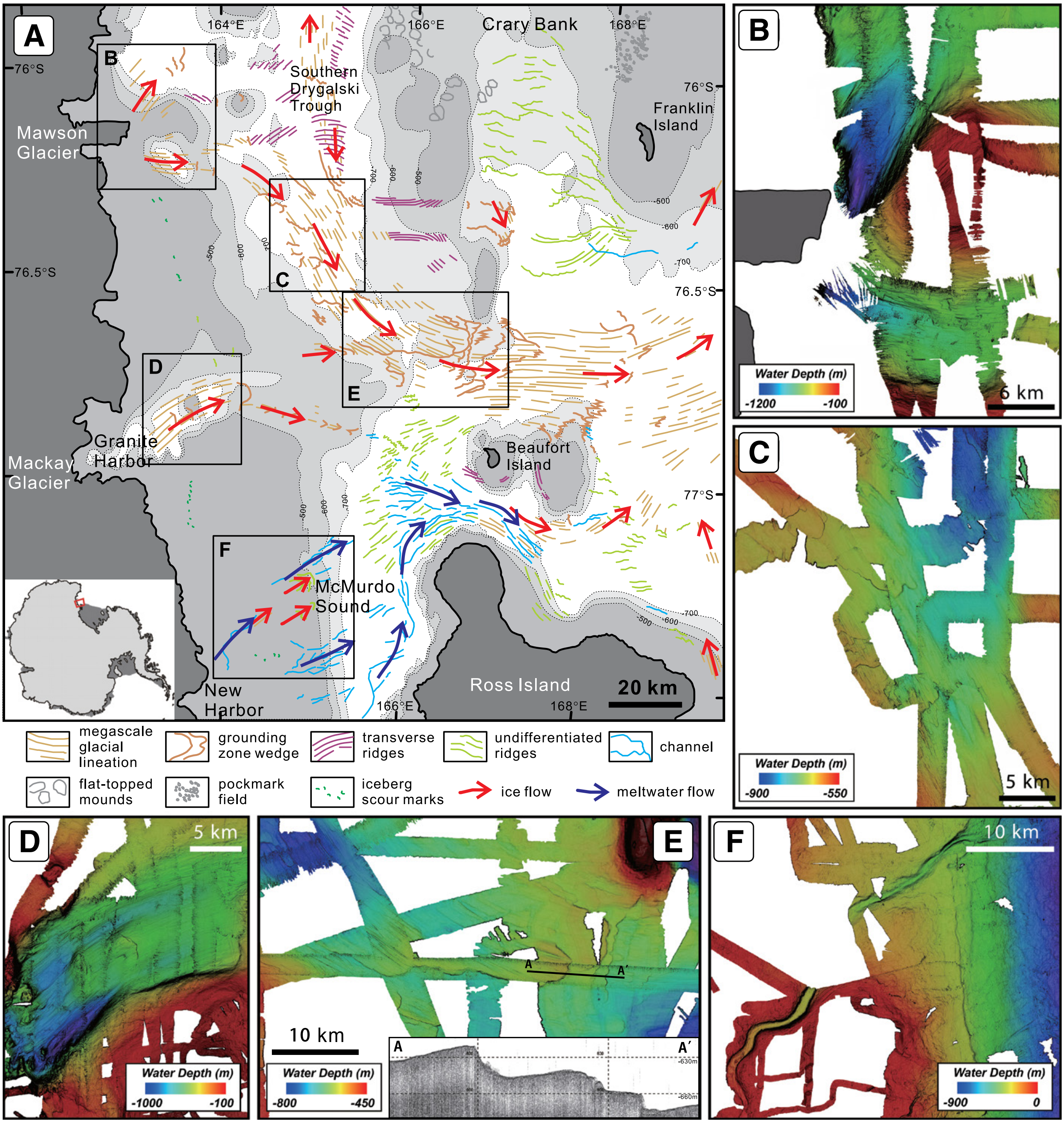

Figure 2. A: Mulitbeam bathymetry data and interpretations. A: Digitized glacial and interpreted flow direction of southwestern Ross Sea, Antarctica. Water depths (meters) are from Davey (2004). B: Bifurcation of past ice flow from Mawson Glacier around bathymetric high. C: Megascale glacial lineations (MSGLs) and grounding-zone wedges (GZWs) indicating southeast ice flow. D: MSGLs and GZWs in Granite Harbor. E: MSGLs and GZWs north of Beaufort Island indicating sinuous ice flow around Crary Bank, and 3.5 kHz seismic profile showing asymmetric GZWs. F: Flat-bottomed and steep-flanked canyon system in New Harbour.

toward the Transantarctic Mountains. Although we note that only the final stage of glacial flow is preserved in these bedforms, it is apparent that the MSGLs previously interpreted as formed by northwestward flow from central Ross Sea were actually formed from ice expanded from the Mawson Glacier, as evidenced by the back-stepping GZWs associated with the MGSLs (Fig. 2E). We see no evidence for major flowline switching to the north of Ross Island, and all of the subglacially formed features in this region can be explained by a relatively consistent ice flow direction, as shown in Figure 2.

Because the flow direction of an ice sheet is governed by its surface slope, the sinuous pattern of ice flow around bathymetric highs indicates a relatively low ice sheet slope that was strongly influenced by bathymetry rather than a large "overriding" ice sheet. Our data show that northward-flowing ice sourced from the central Ross Sea did not deflect the ice flow of EAIS outlet glaciers in the western Ross Sea, as has been interpreted from onshore provenance studies (Denton and Marchant, 2000).

During the later phases of glaciation in this region, these glaciers extended southwards at least 100 km from the present coast toward Ross Island and were >700 m thick. The persistence of ice masses derived from these outlets would have provided enough isostatic loading to influence the uplift rates derived from raised beach sequences along the coast of South Victoria Land, which constrain unloading to ca. 7.8 ka (Conway et al., 1999; Hall et al., 2004).

Cosmogenic nuclide data from nunataks on the margins of the Mackay Glacier indicate a rapid thinning of EAIS outlet glaciers at ca. 7 ka (Jones et al., 2015), modeled to be the result of marine ice sheet instability as the glacier rapidly retreated into an overdeepened trough from a bathymetric high ~70 km offshore. This thinning postdates sediment core evidence of retreat to the east of Ross Island by ca. 1.6 ka (McKay et al., 2016), indicating that the late glacial marine-based flowlines of the EAIS outlet glaciers into the southwest Ross Sea were largely independent of buttressing ice in the central Ross Embayment. Dating uncertainties may account for some of this offset, but these differences can be reconciled and highlight that glacier thinning histories should be fully integrated with detailed modeling and offshore sediment core chronologies when interpreting broader-scale ice sheet retreat dynamics.

Inferences of westward flow of ice from the central Ross Sea and then south into McMurdo Sound are irreconcilable with our data, requiring reassessment of provenance studies based on the distribution of anorthoclase phonolite (kenyte) erratics and coastal moraine mapping that are integral to that hypothesis (Fig. DR2). Cape Barne (western Ross Island) is unlikely to be the sole source for the kenyte as outcrops of this lithology are widespread on Mount Erebus (Ross Island) (Esser et al., 2004), while kenyte clasts noted at Cape Bird (Ross Island) (Denton and Marchant, 2000), at Black Island (Vella, 1969), and in ANDRILL (Antarctic Drilling Program) core AND-1B to the south of Ross Island (Fig. DR3) are incompatible with a single Cape Barnes source (Fig. DR2). Although there is significant potential for outcrops of this lithology to be currently ice covered, or for submarine outcrops in southern McMurdo Sound, these erratics can be explained with ice to the south of Ross Island flowing toward the Transantarctic Mountains while allowing for eastward flow from the Mackay and Mawson Glaciers to the north (Fig. DR2). This also allows constraints provided by the elevation of LGM glacial drift limits on Ross Island and the McMurdo Sound coastline (Denton and Marchant, 2000; Fig. DR2).

A complication regarding the kenyte erratic distribution is the possible presence of southwest-northeast–aligned back-stepping proglacial moraines on the shallow (<500 m water depth) bathymetric bank adjacent to New Harbour (Fig. 2F; Fig. DR4). However, two phases of ice flow in this region are compatible with the scenarios presented in Figure 1: (1) an earlier phase of ice flow directed from the Ross Island region during the glacial peak (i.e., delivering the kenyte erratics) with a minor Ferrar Glacier influence; followed by (2) a re-advance of the Ferrar Glacier system onto the shallow (<500 m water depth) bathymetric plateau in western McMurdo Sound, after grounded ice had retreated from the deeper sections of McMurdo Sound (Fig. DR2).

Our data demonstrate that the glacial chronologies in the southwest Ross Sea region record local EAIS outlet glacier retreat rather than widespread central Ross Sea retreat. As such, the central Ross Sea may have deglaciated several thousand years prior to the western Ross Sea, as is implied by marine data sets and numerical models (Fig. 1B; McKay et al., 2016; Halberstadt et al., 2016). In order to better constrain deglaciation of the central Ross Sea and its contribution to post-LGM sea-level rise events, reliable chronological data directly from that region are required, but such data are currently poorly resolved and subject to large dating uncertainties (Anderson et al., 2014).

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