Antarctic marine ice-sheet retreat in the Ross Sea during the early Holocene

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ABSTRACT

Geological constraints on the timing of retreat of the Last Glacial Maximum (LGM) Antarctic Ice Sheets provide critical insights into the processes controlling marine-based ice-sheet retreat. The over-deepened, landward-sloping bathymetry of Antarctica's continental shelves is an ideal configuration for marine ice-sheet instability, with the potential for past and future ice-sheet collapse and accelerated sea-level rise. However, the chronology of retreat of the LGM ice sheet in the Ross Sea is largely constrained by imprecise radiocarbon chronology of bulk marine sediments or by coastal records that offer more reliable dating techniques but which may be influenced by local piedmont glaciers derived from East Antarctic outlet glaciers. Consequently, these coastal records may be ambiguous in the broader context of retreat in the central regions of the Ross Sea. Here, we present a sedimentary facies succession and foraminifera-based radiocarbon chronology from within the Ross Sea embayment that indicates glacial retreat and open-marine conditions to the east of Ross Island before 8.6 cal. (calibrated) kyr B.P., at least 1 k.y. earlier than indicated by terrestrial records in McMurdo Sound. Comparing these data to new modeling experiments, we hypothesize that marine-based ice-sheet retreat was triggered by oceanic forcings along most of the Pacific Ocean coastline of Antarctica, but continued Holocene retreat into the inner shelf region of the Ross Sea occurred primarily as a consequence of bathymetric controls on marine ice-sheet instability.

INTRODUCTION

During the Last Glacial Maximum (LGM), marine-based ice sheets expanded across Antarctica's continental shelves (Bentley et al., 2014). Subsequent retreat of the largely marine-based sectors of the Antarctic Ice Sheet contributed 10–18 m to eustatic sea-level rise, with the greatest loss of mass occurring in the Ross and Weddell Sea regions (Denton and Hughes, 2002; Pollard and DeConto, 2009; Golledge et al., 2014). However, the timing and pattern of post-LGM ice-sheet retreat in Antarctica is ambiguous, and in many areas not well constrained. This is largely due to the well-documented difficulties in reliably dating marine deposits by ^{14}C due to the very poor preservation of $CaCO_3$ in the corrosive waters around Antarctica (Anderson et al., 2014). Most chronologies from marine sediments in the Ross Sea are based on ^{14}C ages from acid insoluble organic (AIO) residues extracted from bulk sediments, but these inherently overestimate the age of glacial retreat due to pervasive reworking and incorporation of older carbon (Andrews et al., 1999). Even when precise ages can be obtained, processes such as subglacial reworking, bioturbation, sediment gravity flows, and winnowing that mix sediment of various ages act to bias the age either toward a younger or older value depending on the nature of mixing.

For the Ross Sea, it has been hypothesized that post-LGM retreat was characterized by a "swinging gate" pattern of retreat, whereby the grounding line receded southward along the Transantarctic Mountains (at its western margin) at a relatively constant rate through the Holocene, and at its eastern margin retreat was slower and became "hinged" near Roosevelt Island by the late Holocene (ca. 3.2 kyr B.P.) (Conway et al., 1999). However, there are significant uncertainties in the chronologies that underpin this interpretation, in particular a lack of reliable age control from more central regions of the inner Ross Sea (Anderson et al., 2014). Here, we report a lithofacies-based retreat history constrained by in situ foraminifera-based ^{14}C dates from cores collected east of Ross Island (site CH-2; Fig. 1). The site is ideally located to assess the timing of major mass balance changes of the LGM marine-based ice sheets, as it is located within the paleo-drainage path of the Byrd and Darwin Glaciers, which were major contributors to the ice sheets draining into the Ross Sea at the LGM (Denton and Hughes, 2002; Licht et al., 2005).

METHODS

During the Antarctic Geological Drilling (ANDRILL) site survey in 2010–2011, a hot-water-drill access hole was made through the Ross Ice Shelf at Coulman High site 2 (CH-2; 77°34.9′S 171°30.4′E), ~60 km east of Ross Island. Currently, this site lies beneath the modern-day active "calving line zone" of the Ross Ice Shelf (ice shelf thickness of 273 m and water depth of 862 m), where the last major calving event occurred in 2002 (Table DR1 in the GSA Data Repository[1]). Two cores from this site are examined in this paper, CH-GC-07 and CH-GC-08, with magnetic susceptibility and wet bulk density obtained by a multisensor core logging tool (Fig. 2). Discrete sediment samples were analyzed for water content, total organic carbon (TOC), and grain size. Grain-size samples were treated with 10% H_2O_2 and 1 M NaOH to remove organic and biogenic silica, and the <150 µm fraction was analyzed on a laser diffraction particle sizer. The >150 µm fraction was dry-sieved at 500 µm and 2000 µm and weighed. Diatom abundance (including fragments) and biogenic opal were determined using the methods of Konfirst et al. (2012) and Müller and Schneider (1993), respectively. Core CH-GC-07 was sampled exclusively for foraminifera in order to obtain larger sample sizes from the whole core round.

RESULTS AND DISCUSSION

Facies Analysis and Radiocarbon Chronology

Core descriptions and X-ray images show a near-identical stratigraphy from both cores collected at site CH-2 (Fig. 2; Fig. DR1 and Table DR1 in the Data Repository), and contain a facies succession consistent with a well-established glacial retreat model from a subglacial to proximal ice-sheet grounding line setting into an ice-shelf calving line environment in the Ross Sea (Domack et al., 1999; McKay et al., 2008; Table DR1). Muddy diamict (facies Dm) that occurs at the base of this succession is overlain by a weakly stratified muddy diamict (facies Ds) with common granule-sized mud/diamict intraclasts. Clast lithologies in the diamicts include foliated and/or mylonitic granitoids, biotite schists, and marble, consistent with a Transantarctic Mountains source between the Skelton and Byrd Glaciers (Licht et al., 2005; Talarico et al., 2012) (Fig. 1; Table DR1). The presence of these clasts suggests subglacial transport and deposition in a grounding line–proximal depositional setting.

[1]GSA Data Repository item 2016002, Table DR1 (facies descriptions), Table DR2 (radiocarbon dates), Tables DR3–DR5 (sedimentary, geochemical, and physical properties), Figure DR1 (facies images), and model methods and supplementary references, is available online at www.geosociety.org/pubs/ft2016.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

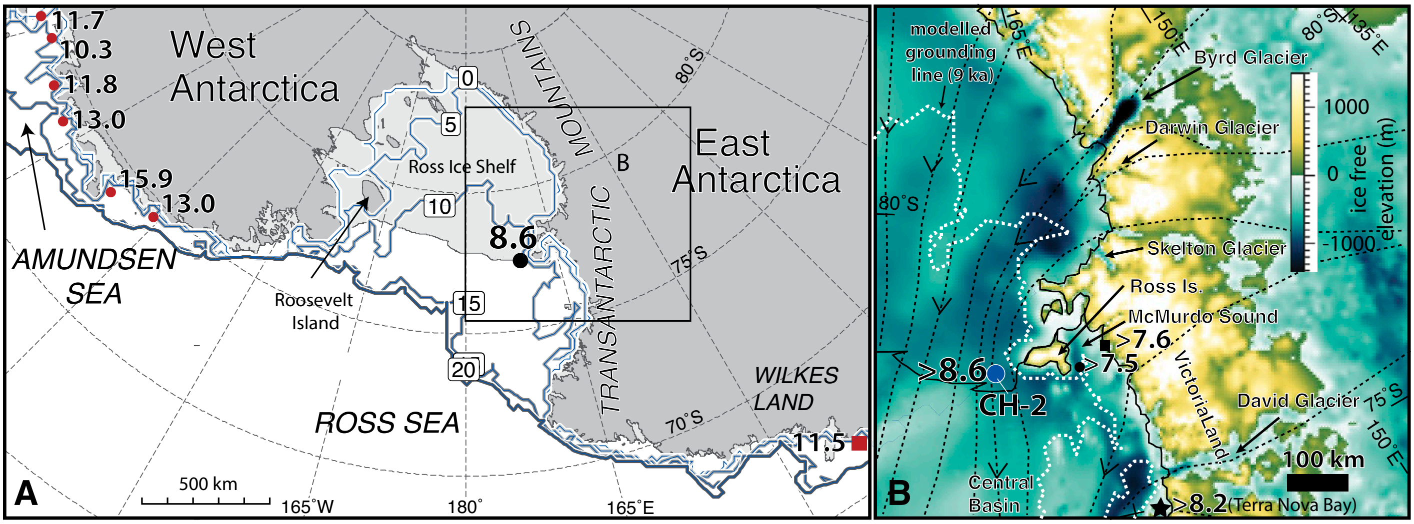

Figure 1. A: Location map showing modeled (blue lines) post–Last Glacial Maximum (LGM) grounding line retreat (at 5 k.y. intervals; ages are kyr B.P.). Modern-day grounding line positions were established in Amundsen Sea (Hillenbrand et al., 2013) and Wilkes Land (Mackintosh et al., 2014) prior to the Holocene. B: LGM ice flow (black dotted lines, after Denton and Hughes, 2002) at Coulman High site 2 (CH-2) location (blue dot) was from Darwin and Byrd Glaciers. Modeled retreat at 9 ka (white dotted line) occurred at CH-2 prior to sites along Victoria Land coast. Calibrated ^{14}C ages (in kyr B.P.) of foraminifera at CH-2 (blue dot), raised beaches along Scott Coast (black square; Hall et al., 2004) and Terra Nova Bay (black star; Baroni and Hall, 2004), and a reworked shell in McMurdo Sound (black dot; Licht et al., 1996) provide minimum constraints for local grounding line retreat. Ice-free topography and bathymetry from Fretwell et al. (2013).

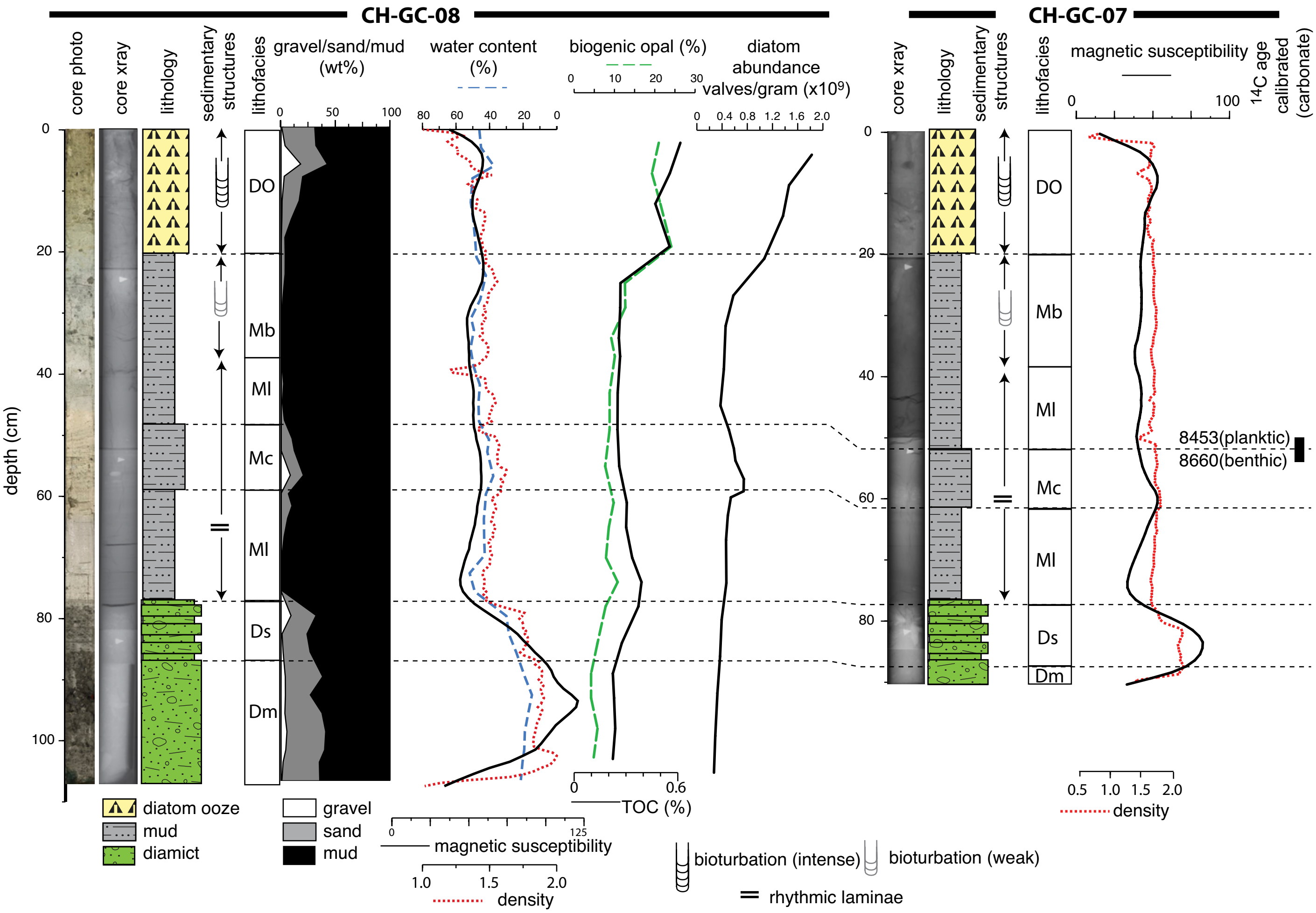

Figure 2. Stratigraphic logs and images of cores collected at Coulman High site 2, Ross Sea, Antarctica. A total of six facies were identified: Diatom ooze (DO), bioturbated mudstone (Mb), laminated mudstone (Ml), laminated mudstone with clasts (Mc), stratified diamict (Ds), and massive diamict (Dm). TOC—total organic carbon. Corrected and calibrated ^{14}C dates from foraminifera core CH-GC-07 are shown (black box; Table DR2 [see footnote 1]).

The diamict facies pass up into a mud with subtle, rhythmic, submillimeter-scale to millimeter-scale laminae (facies Ml; Fig. 2; Fig. DR1). This interval lacks clasts in the basal 20 cm, but passes up into a diatom-bearing (0.74×10^9 valves/g) mud with common clasts (facies Mc). Clasts in this facies are of similar lithologies to those of facies Dm and Ds, but do not contain the biotite schists observed in the basal diamict, and instead were likely transported by ice rafting from Victoria Land (Table DR1). Importantly, this interval is also characterized by common, well-preserved planktonic and benthic foraminifera (54–50 cm in core CH-GC-07; Fig. 2) that are otherwise absent in the core below 23 cm. We obtained separate ^{14}C dates for these planktonic (100 specimens) and benthic (340 specimens) foraminifera assemblages, which provided corrected and calibrated ^{14}C ages of 8391 ± 180 cal. yr B.P. and 8616 ± 242 cal. yr B.P., respectively (Table DR2). Bulk sediment AIO dates obtained from facies Ml and MC were all older than 26,100 ^{14}C yr B.P. This offset between the carbonate and AIO residues indicates significant input of reworked, pre-LGM carbon relative to autochthonous carbon. Although diatoms or foraminifera can be advected significant distances beneath an ice shelf, gravel clasts cannot (Domack et al., 1999; McKay et al., 2008). Thus, the combination of increased diatom abundance, gravel (ice-rafted debris), and planktonic and benthic foraminifera within the laminated muds is indicative of a short period of open water over the core site. The deposition of rhythmically laminated terrigenous mud pre-and post-deposition of this interval, alongside significant input of pre-LGM carbon, suggests (1) a grounding line–derived terrigenous sediment supply (i.e., reworked LGM till) and (2) the presence of grounding line–proximal (i.e., tidal-influenced) currents (Holland, 2008).

The presence of the combined planktonic and benthic assemblage of the same age and the preservation of the fine rhythmic laminae effectively rule out significant post-depositional reworking and mixing of different foraminifera ages via sediment gravity flows or bioturbation. Similar subtle but rhythmic laminae in other Antarctic glacial retreat sequences are commonly interpreted as resulting from tidally regulated traction currents or sediment delivery by meltwater plumes originating from a glacier terminus, both of which point toward relative proximity to the grounding line during the deposition of this unit (Domack and Williams, 1990). The uniform, highly rhythmic nature of the laminae and lack of obvious grading suggest that the laminae are not turbidites, although tidal-current reworking of turbidites is possible. They also differ from the meltwater plumites previously documented in glacial settings with large volumes of subglacial meltwater discharge, as the unit is comparatively thin and there is no visual size sorting defining the laminae (McKay et al., 2009).

The absence of significant terrigenous sedimentation in the modern ice-shelf environment (discussed later) supports the interpretation that the foraminifera-bearing laminated muds were deposited in proximity to the ice-sheet grounding line during glacial retreat. However, determining how proximal remains difficult to quantify given a lack of modern sedimentary process studies from beneath large ice shelves such as the Ross Ice Shelf. Consequently, our foraminifera-based age constraint can only confirm that the grounding line migrated past this site sometime prior to 8.6 cal. kyr B.P., rather than provide an exact timing. Although the absence of bioturbation and persistence of terrigenous sediment indicate that there were probably still grounding-line influences at this time, it is possible that the migration of the grounding line past the site may have occurred some significant amount of time earlier, particularly if deposition below the dated interval was condensed or not continuous.

The laminated muds pass upward into a weakly bioturbated mud (facies Mb; Fig. 2). The presence of bioturbation is likely the combined result of decreasing terrigenous sedimentation and increased benthic activity as the grounding line migrated away from the core site. The top of the facies succession is characterized by a thin (<20 cm) intensely bioturbated diatom ooze (facies DO) with abundant clasts and common foraminifera. The thin nature of this diatom ooze in combination with the abundant presence of clasts suggests that this is a condensed unit resulting from cessation of grounding line–derived sediment input (Table DR1). This interval is interpreted as representing essentially the same conditions found today at the core site—calving line–proximal ice shelf with periods of seasonally open water with ice rafting.

Ice-Sheet Grounding Line Migration

The minimum age constraint of 8.6 ± 0.2 cal. kyr B.P. we have obtained for grounding line migration is ~400 yr older than the oldest radiocarbon ages (ca. 8.2 cal. kyr B.P.) from shells, penguin bones, and guano in raised beaches in Terra Nova Bay (Fig. 1B). However, Terra Nova Bay is located 300 km to the north of the Coulman High site (Baroni and Hall, 2004) and may have been overridden by a large lobe of ice sourced from the East Antarctic Ice Sheet that at the LGM flowed into western Ross Sea basins via the David Glacier (Pollard and DeConto, 2009; Golledge et al., 2013). The difference in age between these two sites probably represents the lagged retreat of residual piedmont glaciers, ice shelves, and multi-year sea ice at coastal sites in the western Ross Sea (Fig. 1; Greenwood et al., 2012). By contrast, geological and modeling reconstructions place the Coulman High coring site in the paleo-glacial flow path of ice from the Byrd and Darwin Glaciers to the south that flowed northward into the Central Basin (including the Joides) and Challenger Basin (further to the east) and which contributed significantly to the grounded ice sheet in the central Ross Embayment (Denton and Hughes, 2002; Licht et al., 2005; Pollard and DeConto, 2009; Golledge et al., 2013) (Fig. 1).

Our age is ~1.3 k.y. younger than the previous estimate of first open-water conditions immediately north of Ross Island of ca. 10 cal. kyr B.P. (8.9 ^{14}C kyr B.P.) obtained from bulk sediment AIO residue in the nearby DF80-189 core by McKay et al. (2008). However, AIO ages are subject to large uncertainties due to reworking (Andrews et al., 1999), and in the context of more reliable ^{14}C ages of glacial retreat within McMurdo Sound (Fig. 1B), these estimates of glacial retreat occurring at ca.10 ka have rightly been called into question, with relative sea-level curves indicating final retreat in McMurdo Sound occurring at 7.5 cal. kyr B.P. (Hall et al., 2004), >1 k.y. after the retreat to the east of Ross Island at site CH-2 (Fig. 1B).

The implication of our new data is that ice lingering in the coastal regions of South Victoria Land was not fed by a marine ice sheet to the east of Ross Island, at least during the late deglacial stage of retreat (i.e., post–8.6 ka), a pattern that is also consistent with our numerical model (Fig. 1B). Consequently, the retreat records from coastal regions in South Victoria Land should not be used as an absolute basis for constraining glacial retreat within the broader Ross Sea region (cf. Conway et al., 1999). We argue that the Coulman High region gives a better estimate of regional-scale retreat within the central Ross Sea, as Darwin and Byrd Glaciers would have been the major outlet glaciers directly feeding the grounded ice sheet passing over the Coulman High sites (Fig. 1), and these were two of the largest catchments feeding into the Ross Sea during the LGM (Licht et al., 2005; Golledge et al., 2013).

Ross Sea in the Broader Context of Antarctic Marine Ice-Sheet Retreat

Geological reconstructions from the Antarctic Peninsula, Amundsen Sea, and Wilkes Land regions all indicate that by 10 ka, grounding lines had retreated to near their modern positions on the inner shelf, and thus retreat of the marine-based LGM Antarctic Ice Sheet must have been initiated prior to the Holocene in these sectors (Bentley et al., 2014). To further examine this in the context of continued retreat into the Holocene in the Ross Sea sector, we ran new, higher-resolution simulations of a previously published model experiment (Golledge et al., 2014). In this new experiment, retreat starts prior to meltwater pulse 1A in the central Ross Sea and in other sectors of West Antarctica, but the lower-viscosity mantle used in this new simulation (see the Data Repository) allows faster glacio-isostatic adjustment and slower retreat. Modeled grounding lines now pass Ross Island in the early Holocene, more closely agreeing with the ^{14}C data presented here than did previous simulations (Golledge et al., 2014). While there still remains a potential data-model mismatch in exact timings, the pattern of retreat is consistent (Fig. 1B). Based on this model output and the strong oceanographic connection between these sectors via the Antarctic Slope Current, which acts to regulate heat incursions onto the continental shelves along the Pacific sector of Antarctica (Smith et al., 2012), we propose that pre-Holocene retreat of the LGM ice sheets was initiated along most of the Pacific Ocean margin of Antarctica, including the Ross Sea (Fig. 1A), due to climatic and oceanographic drivers during the Termination I interval (18–11 ka; Golledge et al., 2014). Modern grounding line positions in the Amundsen and Wilkes Land region were in place by the start of the Holocene (Hillenbrand et al., 2013; Mackintosh et al., 2014; Fig. 1A), yet retreat appears to continue in the Ross Sea, with the first evidence for open water near Ross Island not occurring until 8.6 cal. kyr B.P. Previous studies indicate that continued grounding line recession to the south of Ross Island persisted into the mid-Holocene (Conway et al., 1999; Anderson et al., 2014) despite a period of relative climatic and oceanographic quiescence on the Antarctic Pacific margin (Shevenell et al., 2011). Our glaciological model experiments, which are forced by proxy and model-based changes in ocean heat flux and post-LGM eustatic sea-level rise, match the pattern of retreat inferred from geological data and imply that these differences in the timing of retreat from each of these sectors primarily arose as the result of marine ice-sheet instability on the overdeepened continental shelf of the Ross Sea (Thomas and Bentley, 1978).

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