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Past ice stream and ice sheet changes on the continental shelf off the Sabrina Coast, East Antarctica

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ABSTRACT

Our understanding of the response of the Antarctic ice sheet to climate and ocean changes requires the improvement of current ice-atmosphere-ocean models and the accurate determination of boundary conditions such as ice thickness and extent at key time intervals, so that satellite gravity observations and isostatic models can be adjusted. However, large portions of the Antarctic margin remain understudied or lack suitable data. One key area where data are lacking, is the Sabrina Coast portion of the East Antarctic Ice Sheet (EAIS) margin where the Totten Glacier, which has the largest ice discharge in East Antarctica, is accelerating, thinning and loosing mass at high rates. In this work, we present the results of the first geological and geophysical marine survey to the continental shelf offshore of the Dalton Ice Tongue and Moscow University ice shelf, east of the Totten Glacier. The data presented include multibeam swath bathymetry and multichannel seismic, focusing on the sea floor morphology and sedimentary section above a regional angular unconformity separating pre- and post-Miocene glacial strata. Sea floor scouring and iceberg keel marks on the outer shelf, associated with gullies on the upper slope indicate that ice expanded in the past and grounded ~5 km from the shelf edge at ~450–500 mbsl, extending ~155 km north of the current Moscow University Ice Shelf. A nearly 1000 m deep area in the inner-middle shelf, oriented NW with paleo-ice flow direction indicated by mega scale glacial lineations (MSGL) and drumlins, is interpreted as a cross shelf glacial trough. A series of geomorphic associations on the north-eastern side of the glacial trough includes glacial lobes, grounding zone wedges (GZW), glacial lineations and transverse ridges, which indicates slower ice, grounding line stabilization and collapse. These geomorphic associations are organized in 4 four sets representing different past ice-flow configurations reflecting changes in ice flow direction, grounding line position, location of fast and slow ice areas, and retreat pattern. Some of the geomorphic features identified are compatible with the presence of an organized subglacial drainage, and others are with rapid grounding line collapse. A well-preserved series of GZWs occurring at different water depths implies they were formed during different glacial stages or cycles. The inferred diminishing ice thickness for consecutives GZWs indicates that the margin of the Antarctic ice sheet evolved to a less extensive coverage of the continental shelf through successive glacial stages or cycles.
The identification of different ice flow configurations, evidence of subglacial water and past ice margin collapse indicates a dynamic ice sheet margin with varying glacial conditions and retreat modes. We observe that some of the described morphological associations are similar to those found in the Amundsen sea sector of the West Antarctic Ice Sheet (WAIS) where they are associated with ice sheet and ice stream collapse. Although further studies are needed to assess the precise timing and rates of the glacial processes involved, we conclude that there is enough evidence to support the hypothesis that the EAIS margin can behave as dynamically as the WAIS margin, especially during glacial retreat and icesheet margin collapse.

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1. Introduction

The East Antarctic Ice Sheet (EAIS) contains ~53 m of sea level equivalent ice volume, ~19 m of which is grounded below sea level and thus susceptible to mass loss processes related to ice-ocean interactions such as termini and basal-ice melting, calving, and sea level rise, which can result in ice sheet instability and grounding line retreat (Lythe et al., 2001; Golledge et al., 2015; Fretwell et al., 2012; DeConto

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and Pollard, 2016). Despite its potential to influence global sea level, the exact magnitude, rate, and timing of the EAIS response to past and current atmospheric and oceanic changes remain uncertain (Gulick et al., 2017). In particular, the sign and trend of the EAIS mass balance is still a matter of debate owing to the difficulty of estimating the net mass change in the continental interior, the feedbacks between ice flow and ice-bed conditions and the complex ice flow dynamics and mass loss processes at the margin of the ice sheet (e.g., Hanna et al., 2013; Ivins et al., 2013; Zwally et al., 2015; Lenaerts et al., 2016). Some estimates indicate that ocean-heat driven basal melt under ice shelves and cavities of the EIAS accounts for almost half of the current mass loss rate, the rest corresponding mostly to calving (e.g., Rignot et al., 2013; Rintoul et al., 2016). However, recent observations (Lenaerts et al., 2016) and analysis of the last decade of aerial photographs and satellite data (Kingslake et al., 2017) indicate that the margin of the EAIS is also sensitive to rising atmospheric temperatures, which could lead to widespread ice shelf instability and breakup. The eventual breakup of ice shelves in the EAIS could subsequently lead to an increase in ice flux to the termini as observed after the breakup of Larsen A and B ice shelves (Rott et al., 2002; Rignot et al., 2004; Scambos et al., 2004), which would add to the current rates of ice mass loss and sea level rise.

Improvement of integrated ice sheet and climate models requires the accurate determination of boundary conditions such as ice thickness and extent at key time intervals so that satellite gravity observations and isostatic models can be adjusted (Hanna et al., 2013; Mackintosh et al., 2014). One such time interval is the termination of the last glacial cycle when global temperatures and sea level rose rapidly while the Antarctic Ice Sheet retreated from the continental shelf (RAISED, 2014). However, two major challenges to overcome are that large portions of the Antarctic margin remain understudied or lack suitable data (e.g., Mackintosh et al., 2014). One key area where data are lacking is the Sabrina Coast portion of the EAIS margin (Mackintosh et al., 2014) where the Totten Glacier, which has the largest ice discharge in East Antarctica, is accelerating and thinning (Li et al., 2016).

The stability and likelihood of collapse of the Antarctic Ice Sheet glaciers strongly depends on the ice-bed coupling near the grounding line, which controls the thickness and floatability of the ice sheet margin (Pingree et al., 2011). In the few areas that have been studied along the East Antarctic margin, the inner shelf is characterized by a deep rugged sea floor, believed to be mostly bedrock, which transitions to a smoother and shallower sedimentary substrate, forming a landward-sloping continental shelf (Leventer et al., 2006; Beaman et al., 2011; Mackintosh et al., 2011; O'Brien et al., 2016). This configuration of the continental shelf implies that during glacial times, the margin of the EAIS would have flowed on a bed of changing downstream conditions, including decreasing rugosity, basal drag, and depth. This sea floor configuration is observed in other regions of the Antarctic margin, such as in the continental shelf areas of the Western Antarctic Ice Sheet (WAIS) (e.g., Evans et al., 2006; Jakobsson et al., 2011) and the Antarctic Peninsula Ice Sheet (APIS) (e.g., Wellner et al., 2006; Lavoie et al., 2015); however, currently data are insufficient to estimate its prevalence for the EAIS.

Subglacial water may play a critical role dictating basal boundary conditions during advances onto and/or retreats from the continental shelf (Lowe and Anderson, 2003; Graham et al., 2009; Smith et al., 2009; Nitsche et al., 2013; Witus et al., 2014). Geophysical surveys of interior and coastal Antarctica reveal complex subglacial hydrologic systems in some East Antarctic locations (Wingham et al., 2006; Young et al., 2011; Wright et al., 2012; Aitken et al., 2014, 2016). However, direct evidence linking past and present subglacial hydrologic changes and ice dynamics is sparse (Stearns et al., 2008; Young et al., 2011; Siegfried et al., 2016). Whether or not subglacial water might play a role influencing ice dynamics in East Antarctic marginal environments is still unknown, but the general concern about the stability of the Antarctic ice sheet under current conditions of a changing climate and ocean requires that this possibility be investigated.

Here we present the results of the first geological and geophysical marine survey (NBP1402) to the inner and middle continental shelf offshore of the Dalton Ice Tongue and Moscow University ice shelf, east of the Totten Glacier (Fig. 1). The data presented include multibeam swath bathymetry and multichannel seismic, focusing on the sea floor morphology and sedimentary section above a regional angular unconformity separating a sequence of dipping strata that include preglacial through late Miocene stratified rocks with internal erosional features consistent with bed erosion under polythermal-glacial conditions and late Miocene to recent strata with internal seismic architecture consistent with polar-glacial conditions; the description and interpretation of the seismic section below this unconformity are presented in Gulick et al. (2017). This area is of special interest since the Totten Glacier is experiencing the largest ice mass loss rate in East Antarctica today (Chen et al., 2009; Rignot et al., 2009; Pritchard et al., 2012), and the area is seaward of the large Aurora Subglacial Basin where a complex subglacial hydrological system has been identified, including numerous subglacial lakes (Siegert et al., 2005; Young et al., 2011; Wright et al., 2012; Aitken et al., 2016). We describe a complex of seafloor features on the continental shelf that provide evidence that the sea floor was modified in the past by glacial processes, although this region is presently free of grounded glacial ice. In addition, these features indicate that in the past, different ice flow configurations and variable ice dynamics characterized the evolution of the paleomargin of the EAIS in our study area. Specifically, we discuss evidence of glacial erosion and deposition, of periods of fast ice flow and grounding line stabilization, of subglacial water, and of ice stream and ice sheet collapse. Our interpretations build upon the knowledge of similar geomorphic features described elsewhere in Antarctica and other glaciated regions and provide the first evidence of dynamic changes occurring in the margin of this sector of the EAIS.

2. Methods

Bathymetry and seismic data were collected as part of the 2014 RVIB Nathaniel B. Palmer (NBP) marine geology and geophysics cruise NBP1402 in the Dalton Ice Tongue polynya, just east of the Totten Glacier terminus and north of the Moscow University Ice Shelf (MUIS; Fig. 1). Swath mapping was conducted using the RV/IB N.B. Palmer's hull-mounted Simrad EM120 multibeam sonar system, which consists of 120 beams that use a 12 kHz source. Post-cruise, data were processed using Caris and Fledermaus software. Artifacts and bad pings were edited and gridded three-dimensional bathymetry data sets produced for geomorphological analysis. Gridded bathymetry data were imported into ArcMap 10.2.2 to map geomorphological features and to calculate magnitude of slopes, slope direction, and bathymetric profiles. Subsets of bathymetry data were stacked for statistical analyses using a Matlab code written by the authors to analyze gridded bathymetry data and to produce descriptive statistics and profiles. The interpretation of sea floor features was done by comparison with similar features described elsewhere in Antarctica and with the identification of associations of features, cross and cut relationships, and the simple assumption that deeper glacial features correspond to thicker ice conditions, which is expected for marginal areas of marine ice sheets. Multichannel seismic (MCS) data were acquired with dual generator–injector (GI) air guns and a 100 m-long gel-filled streamer (75 m active) with 24 channels with a spacing of 3.125 m. The true positioning of the guns and the streamer was obtained by correcting the ship GPS data with their relative position in respect to the receiver antenna and by a simple geometry model for the streamer using a proprietary Matlab code. The MCS data processing included prestack bandpass filtering and spherical divergence correction, deconvolution of the resulting signal to isolate the earth response (predictive, effective source wavelet and/or Hilbert transform deconvolution), trace balancing, normal moveout correction, stacking and dip moveout, and migration in the frequency-wavenumber domain. The final processed sections were visualized and studied

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