Insights into post-LGM deglaciation at the margins of the Pine Island-Thwaites Palaeo-Ice Stream in the Amundsen Sea Embayment, West Antarctica

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1 Introduction

During recent years interest in the West Antarctic Ice Sheet (WAIS) increased among the geoscientific community because: (1) its bed is located mainly below sea level and drops towards the interior of the Antarctic continent, making the WAIS inherently unstable in a future warming world, (2) extensive thinning and associated grounding-line retreat of the Pine Island and Thwaites glaciers draining into the Amundsen Sea Embayment (ASE) have suggested major changes are underway in the sector, increasing contributions to current sea level rise, (3) a complete collapse of the WAIS in the future would raise global eustatic sea level by 3.4-5 m, while melting of the ASE drainiage basin alone would raise sea level by 1.2-1.5 m. A sea level rise of that magnitude would cause major global socio-economical and ecological problems.

Detailed knowledge of the long-term behaviour of the WAIS in the ASE during the recent geological past (Last Glacial Maximum [LGM] to present) will contribute to a better understanding of current glacier dynamics and help to improve numerical ice-sheet models, which aim to predict future sea-level rise. Previous marine geoscientific studies in the ASE focused on the main palaeo-ice stream troughs to reconstruct the LGM extent of the WAIS on the continental shelf and its subsequent retreat history. However, little is known about elevated marinal areas of the palaeo-ice streams in the ASE, where ice retreat most likely lagged behind that in the troughs.

Here we present results from multibeam swath bathymetry surveys, high-resolution seismic and sedimentological investigations from the former bed in an inter-ice stream area between the Pine Island-Thwaites palaeo-ice stream and a fast-flow tributary emanating from the area now occupied by the Cosgrove Ice Shelf. The data show an unusual assemblage of glacial morphological features including crevasse-squeeze ridges, large-scale hummocks perpendicular to the palaeo-ice flow, associated recessional moraines, and hill-hole pairs. This combination of bedforms has not been described before from the Antarctic shelf and indicates a more complex ice flow behaviour for the eastern ASE than suggested by the pattern of bedforms in the palaeo-ice stream troughs alone. Our data indicate that slow flowing ice masses covered the topographical highs adjacent to the Pine Island-Thwaites palaeo-ice stream (PITPIS) during the LGM. These ice masses most likely stagnated during a phase of general stillstand of the PITPIS. Here we introduce a six-phase formation model based on these interpretations. New radiocarbon ages indicate a pre-Holocene deglaciation of the inter-ice stream ridge between ~11.6 and 16 ka BP. This new information can be used as a reference dataset for interpreting more inter-ice stream areas in future studies, since they are key areas for stabilising ice streams, and form a large part of the ice sheet in general. New insights into ice dynamics here may help improve ice flow models.

2 Methods

The marine geophysical and geological data used in this study were collected on cruise ANT-XXVI/3 of the RV Polarstern in early 2010. The bathymetry data were collected with a hull-mounted Atlas Hydrosweep DS-2 multibeam swath bathymetry system, which emits 59 beams at a frequency of 15.5 kHz. An Atlas PARASOUND sub-bottom profiler, which uses parametric interference between two high frequency primary signals to generate a low frequency secondary signal, was used simultaneously. Sediment cores were recovered with a gravity corer (Kiel type).

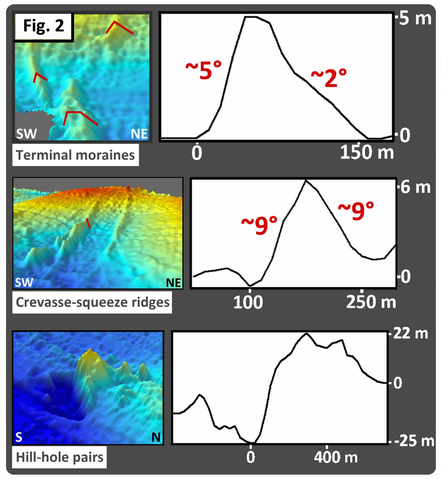
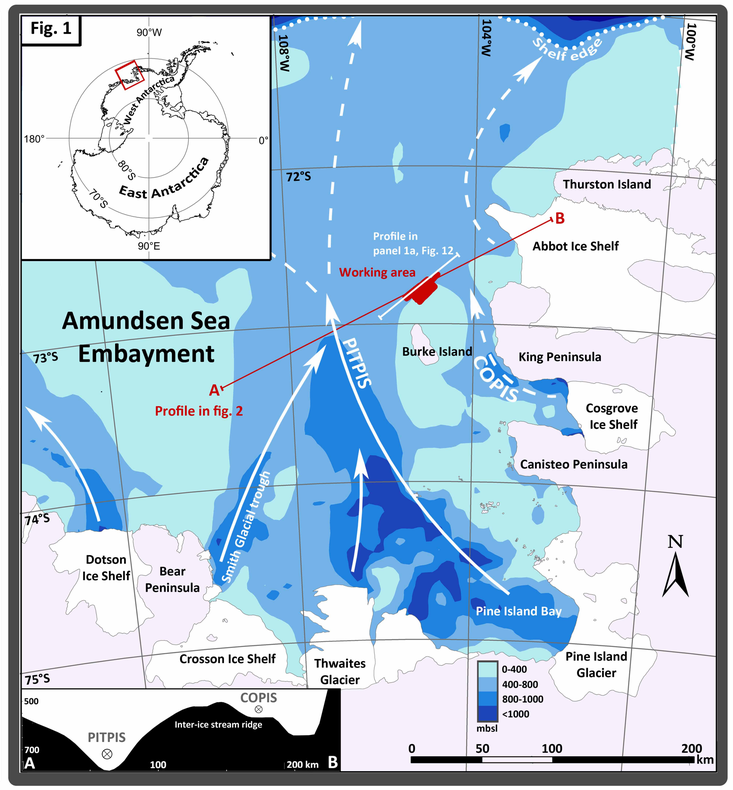
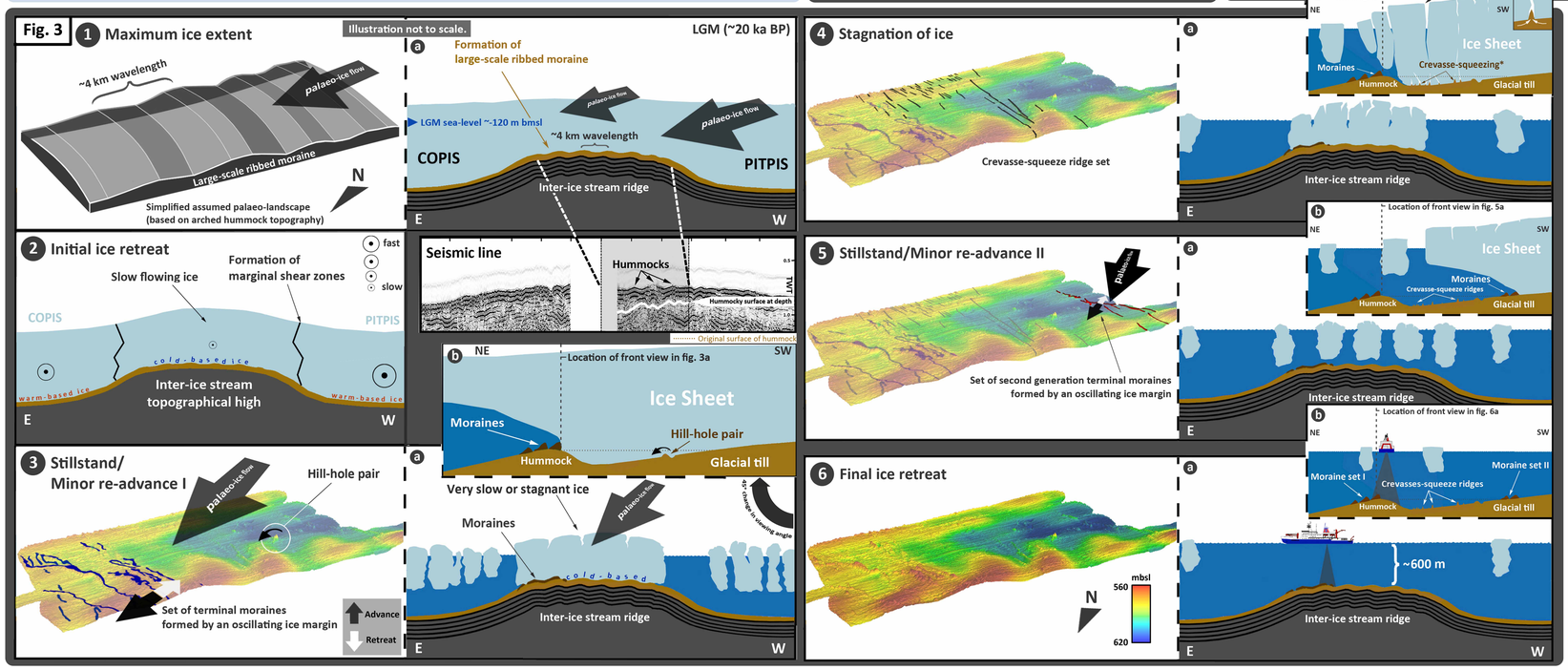


Figure 2. 3D-views and profiles of individual bedforms in the working area: (1) Terminal moraines, (2) Crevasse-squeeze ridges and (3) Hill-hole pairs. For true water depth use color code of figure 3.

Figure 1. Overview map showing the working area (in red) and the general bathymetry of the eastern Amundsen Sea Embayment (Nitsche et al., 2007). The location of the cross-section in panel 1 is indicated by the red line (A-B). The profile of panel 1a in figure 2 is indicated by the continuous white line. White arrows mark the main bathymetric troughs eroded by Pine Island, Thwaites and Smith ice streams. Ice shelves are displayed in white. The shelf edge is indicated by the dotted white line. COPIS - Cosgrove Palaeo-Ice Stream; PITPIS - Pine Island-Thwaites Palaeo-Ice Stream.

Figure 3. (1, 2) Large-scale ribbed moraines indicate an initial slow palaeo-ice flow towards ENE before it began retreating. Seismic investigations indicate a continuation of a hummocky topography with depth, thus showing several generations of large-scale ribbed moraines on top of the inter-ice stream ridge. (3, 5) Terminal moraines in the northeast and southwest of the working area suggest at least two minor ice re-advances or still-stands, respectively. During these phases, slowly flowing ice ripped up subglacial material and deposited it directly downflow resulting in hill-hole pairs (cf. 3D-view in fig. 2), (4) Crevasse-squeeze ridges (cf. 3D-view in fig. 2) in the central part reveal phases of ice stagnation. The inter-ice stream ridge must have been characterized by slow ice flow and stagnation phases over several glacial cycles.





3 Results & interpretation

Large-scale hummocks: wavelength ~4 km; length between 3.2 to 4.5 km; width ~3.3±0.1 km; crest-to-crest distances 4.2±0.1 km; mainly NS-ward strike; crest heights between 20 and 25 m; dipping towards SW; Due to their regular spacing, similar heigths and close spatial relationship we interpret the hummocks as relict moraines formed beneath an ice sheet. Implication: Slow flow on inter-ice stream ridge during LGM.

Hill-hole pairs: Three distinct pairs of hills and holes with similar size and volume in working area; Hill-hole relationship of pair 1: ~25/25 m (Fig. 2, panel 3), pair 2: ~12/12 m, pair 3: ~10/10 m; Ripping up and immediate downstream deposition of material by cold-based grounded ice. Implication: Slow, cold-based ice flow; post-LGM palaeo-ice flow direction NNE.

Asymmetric ridges: Sets of ridges with asymmetric ridge flanks (Figure 2, panel 1); linear to curvilinear with NW-SE and WNW-ESE strike, respectively; steeper flanks face SW-wards, the more gentle ones NE-wards; heights 5-15 m; widths 80-250 m; we interpret them as terminal moraines. Implication: Pushed and deposited by NE-ward facing ice front of minor re-advancing ice.

Symmetric ridges: Highly linear and parallel symmetric ridges; NW-SE strike; heights 4-8 m; widths 60-140 m; Crevasse-squeeze ridges formed by squeezing of basal material into subglacial crevasses. Implication: Stagnation and decay of ice terminus.

4 Conclusions

The bedform assemblage observed on the eastern ASE shelf has not been described before from the Antarctic shelf. Our data show that during the last glacial period the ice on the inter-ice stream ridge between PITPIS and COPIS flowed significantly slower than in the nearby troughs. The dimensions of large-scale ribbed moraines which were formed during the LGM prove the existence of 'mega-scale ribbed moraines' (cf. Dunlop et al., 2008) for the first time and provide crucial insights into the basal regime of the ice sheet between the fast flowing troughs, thus filling a gap in our understanding of subglacial dynamics for the entire palaeo-WAIS. Furthermore, terminal moraines and hill-hole pairs suggest at least two pauses or re-advances of slow cold-based ice, while crevasse-squeeze ridges provide evidence for subsequent stagnation at least once, which most likely coincides with the 600-2000 years of stillstand suggested by Jakobsson et al. (2012). Radiocarbon dates suggest deglaciation between ~11.6 and 16 ka BP. The new landform assemblage mapped on the eastern ASE shelf can be used as a reference dataset for interpreting other inter-ice stream areas of the Antarctic margin in future studies.

References

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