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On the duration of West Antarctic Ice Sheet grounding events in Ross Sea during the Quaternary

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A B S T R A C T

A back-stepping succession of three seismically-defined grounding zone wedges (GZWs) in the Glomar Challenger Basin palaeo-ice-stream trough is usually assigned to the short time that elapsed since the West Antarctic Ice Sheet retreat began at 11 ka ^{14}C BP. Recent radiocarbon dates have however suggested an alternate interpretation in which the youngest of these three GZWs, the Gray Unit GZW on the middle shelf, corresponds to deposition during the Last Glacial Maximum (LGM). If so, then the Gray Unit must represent an amalgamation of erosion and deposition spanning a much longer time interval, i.e., the 100 ky interval between the Last Interglacial and the LGM. To test these conflicting interpretations, the Gray Unit sediment volume was mapped from seismic and multibeam data. Two end-member durations were calculated because flux during ice sheet retreat is significantly higher than flux during ice sheet advance. Using the retreat-mode flux, the 1.47 ky grounding event estimate shows that the middle shelf GZW could have been deposited during the post-LGM retreat. However, the 147.34 ky grounding event estimate based on the advance-mode flux also demonstrates that the GZW might reasonably represent an amalgamation of erosion and deposition as grounded ice gradually advanced between MIS5e and MIS2, i.e., from the Last Interglacial to the Last Glacial Maximum. These data thus require that both interpretations of how the near-surface stratigraphy relates to grounding-line translations in the last glacial cycle be considered feasible working hypotheses.

1. Introduction

Much geological and geophysical data support the view that the Antarctic Ice Sheet advanced to the outer shelf during the Last Glacial Maximum (LGM) (e.g., Anderson, 1999; Bentley, 1999; Conway et al., 1999; Shipp et al., 1999; Anderson et al., 2001; Wellner et al., 2006). It is also generally accepted that the retreat from the outer shelf involved a series of pauses followed by liftoff retreats (Conway et al., 1999; Domack et al., 1999; Mosola and Anderson, 2006; Livingstone et al., 2012). Indeed, high-resolution seismic surveys show that a series of subaqueous moraines referred to as grounding zone wedges (GZWs), are found within the axes of some palaeo-ice-stream troughs on the outer shelf. These broad and low-relief GZWs represent till delta deposition at the terminus of an ice stream (Alley et al., 1989). In the eastern Ross Sea, the West Antarctic Ice Sheet (WAIS) may have paused three to four times on the outer and middle shelf in the Glomar Challenger Basin palaeo-ice-stream trough (Mosola and Anderson, 2006) (Figs. 1 and 2). Based on available bathymetric control, the Glomar Challenger Basin palaeo-ice-stream trough extends southward below the Ross Ice Shelf to the mouth of the Whillans Ice Stream (Bentley and Jezek, 1981; Shipp et al., 1999). The resolution of sub-ice-shelf bathymetric data is insufficient to determine whether additional GZWs exist within that part of the Glomar Challenger Basin below the Ross Ice Shelf. In any case, the last episode of retreat led to the establishment of the current grounding line position (Fig. 2). The timing and style of retreat leading to the modern grounding event are poorly constrained. Conway et al. (1999) assumed that grounding line retreat was gradual as opposed to punctuated by liftoff retreat. The modern grounding event is assumed to have begun 1000 years BP (Conway et al., 1999; Anandrakrishnan et al., 2007). If correct, there has presumably been no significant translation of the WAIS grounding line within this timeframe.

This stratigraphic succession of GZWs on the outer and middle shelf is of special interest because it opens the opportunity to precisely define the locations and dates for the onset, duration and termination of multiple grounding events (Anderson, 2007). Such information is needed to evaluate which factors caused the WAIS to advance, pause and retreat thru time.

Unfortunately, a detailed chronology of discrete retreats has proven difficult to establish for the Antarctic outer shelf. Piston,

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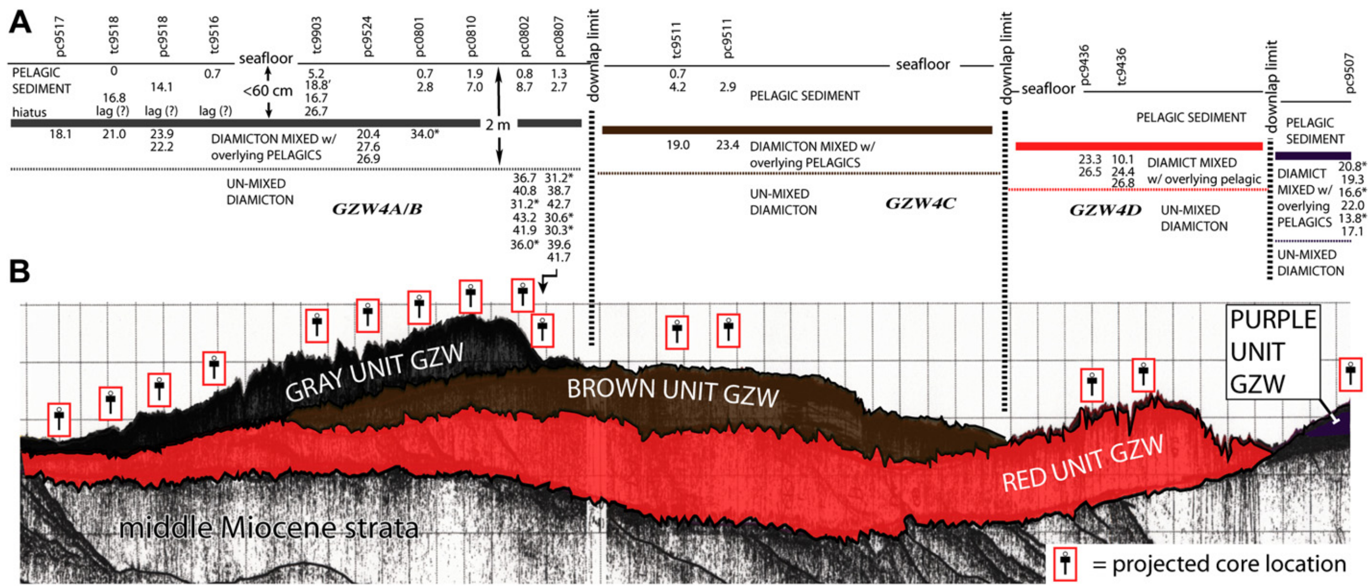

Fig. 1. A) A compilation of radiocarbon dates from piston cores (pc) and trigger cores (tc) in Glomar Challenger Basin from Bart and Cone (2012) projected with respect to grounding zone wedge (GZW) units seen on seismic line 89-27. Those dates marked with an asterisk correspond to radiocarbon dates from foraminifera. All other dates are from acid-insoluble organics. B) Seismic line 89-27 showing a succession of four GZWs (Purple, Red, Brown and Gray Units) in Glomar Challenger Basin of eastern Ross Sea. The middle shelf GZW, the Gray Unit, is usually considered to represent deposition during the third pause of the West Antarctic Ice Sheet as it retreated from the outer shelf. The location of the line is shown in Fig. 2.

Trigger and Kasten cores from the outer shelf generally contain two end-member sediment types associated with retreat of grounded and floating ice. Most cores terminate in pebbly-mud diamict that is usually interpreted to have been deposited as an ice-contact or ice-proximal sediment. The diamict is overlain by diatom ooze that is interpreted to have accumulated as open-marine pelagic sediment since the retreat of grounded and floating ice.[1] Radiocarbon dates from pelagic sediment indicate that open-marine sedimentation has occurred on the western Ross Sea outer shelf since at least 11 ka ^{14}C BP (e.g., NBP95-01 KC37 and KC39 from Domack et al., 1999). These dates are taken to indicate that WAIS retreat began in association with rapid climate warming and sea-level rise during meltwater pulse 1A (Domack et al., 1999). With respect to dating discrete liftoff events, the lack of progress in developing a more detailed radiocarbon chronology is primarily due to a paucity of *in situ* carbonate material in glacial sediment (Andrews et al., 1999). Most radiocarbon dates are from bulk sediment acid-insoluble organics (Domack et al., 1999; Licht and Andrews, 2002) that probably represent a mix of old and contemporaneous carbon sources as indicated by pyrolysis techniques (Rosenheim et al., 2008).

The most recent major synthesis of onshore and offshore data suggested to Conway et al. (1999) that grounded ice had completely vacated the eastern Ross Sea shelf by 7.6 ka ^{14}C BP. These dates represent projections primarily from data in western Ross Sea (e.g., Licht et al., 1996, 1998; Hall and Denton, 2000a,b; Hall et al., 2000). A more recent compilation of marine sedimentologic and radiocarbon data from western Ross Sea suggests that grounded ice vacated the 900-m deep basins surrounding Ross Island by approximately 10.1 ka ^{14}C BP, i.e., WAIS retreat was much earlier and more rapid than inferred by Conway et al. (1999). In the view proposed by Conway et al. (1999), all three post-LGM GZWs on the outer and middle shelf of the Glomar Challenger Basin (Fig. 1) would have been deposited during a short 3.4 ky timeframe, i.e., after 11 ka ^{14}C BP and before 7.6 ka ^{14}C BP. This chronology of WAIS retreat is supported by modeling of ice-penetrating radar reflection data at the Roosevelt Bank ice rise of the Ross Ice Shelf. Modeling of bumps in the ice layering indicates that grounded ice continued its southward retreat pass Roosevelt Island by approximately 3.2 ka ^{14}C BP (Conway et al., 1999).

This interpretation of how the Glomar Challenger Basin GZW stratigraphy relates to post-LGM grounding-line migration is potentially problematic for two reasons. Firstly, the volumes of GZWs may be too large to have been deposited during the short post-LGM timeframe. And secondly, recent radiocarbon dates suggest that the WAIS vacated the middle shelf of eastern Ross Sea much earlier i.e., at ~27.5 ka ^{14}C BP (Bart and Cone, 2012) (Fig. 1). This conclusion is based on a new strategy, which isolated *in situ* forams from foreset strata of the middle shelf GZW. On the basis of their radiocarbon dates, Bart and Cone (2012) proposed an alternate interpretation of how the near-surface stratigraphy of Glomar Challenger Basin relates to Quaternary glacial cycles. Their interpretation is a significant departure from previous ice-sheet reconstructions (e.g., Domack et al., 1999). In the Bart and Cone (2012) view, the middle shelf GZW represents the amalgamation of erosion and deposition during all or part of the last glacial cycle, i.e., ~100 ky from the Last Interglacial (MIS5e) to the LGM (MIS2). Bart (2004) referred to this middle shelf GZW unit as the Gray Unit. Mosola and Anderson (2006) refer to the unit as GZW4B (Fig. 2). If the Gray GZW is assigned to the LGM, i.e., MIS2, then the three older units, the Brown-, Red- and Purple-GZWs (Fig. 1), may correspond to three discrete glacial maxima prior to LGM (i.e., MIS6, MIS8, and MIS10). These two end-member interpretations of how near-surface stratigraphy of Glomar Challenger Basin relates to Quaternary grounding line change are obviously incompatible.

Given the general paucity of datable material, a different strategy was used to evaluate these two interpretations. The objective of this study was to use two end-member sediment flux estimates to evaluate grounding event durations. The first estimate corresponds to flux expected during interglacial retreat. The second estimate corresponds to flux expected during glacial advance. Both fluxes account for the larger drainage area that existed when the WAIS was grounded on the middle shelf. If the GZWs in the Glomar Challenger Basin were deposited following the onset of post-LGM retreat at 11 ka ^{14}C BP, then the cumulative durations of all three

[1] Transitional sediments interpreted to have been deposited in a sub-ice-shelf setting are also present in many core from Ross Sea (Domack et al., 1999).