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

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ABSTRACT

A back-stepping succession of three seismically-defined grounding zone wedges (GZWs) in the Glomar Challenger Basin palaeo-ice-stream trough are 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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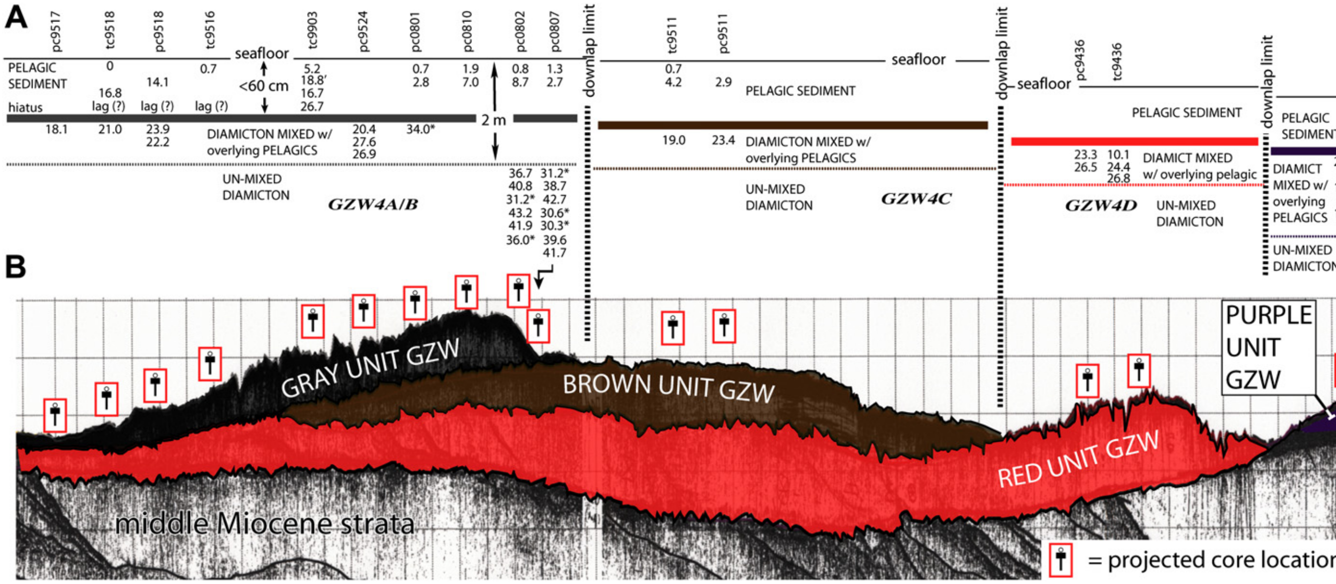


Fig. 1. A) A compilation of radiocarbon dates from piston cores (pc) and trigger cores (tc) in Glomar Challenger Basin from Bart and Cone (2012) projected with respect to grounding zone wedge (GZW) units seen on seismic line 89-27. Those dates marked with an asterisk correspond to radiocarbon dates from 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).

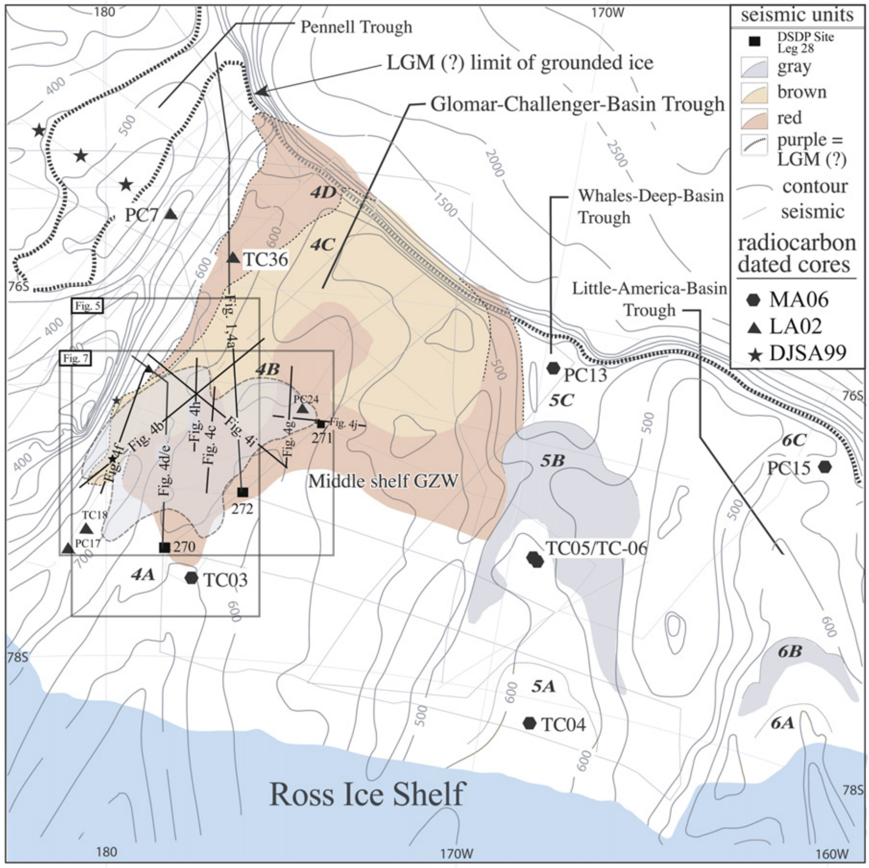


Fig. 2. Bathymetric map of eastern Ross Sea showing Glomar Challenger Basin, a palaeo-ice-stream trough on the shelf. The heavy dashed line shows the extent of grounded ice at the Last Glacial Maximum (LGM) from Shipp et al. (1999). The shaded regions bound by thin dashed lines show the map distribution of three GZWs (Red, Brown and Gray Units). The rectangular grid represents seismic data used in this study. The bold lines show the location of seismic lines shown in Fig. 4. The location of seismic line 89-27 (Fig. 1) is the same as that indicated for Fig. 4A, which shows a line drawing interpretation of the Fig. 1. The boxes show the locations for Figs. 5 and 7.

grounding events, the deposition intervals for the Red, Brown and Gray GZWs, should be less than 3400 years. Conversely, if the three GZWs represent deposition during three discrete glacial maxima (i.e., MIS2, MIS6, and MIS8), then the durations for each GZW should be on the order of 100 ky durations.

The stratigraphy of the Glomar Challenger Basin trough was chosen as the focus of this study for three reasons. Firstly, recent estimates of modern flux for the Whillans Ice Stream (Anandakrishnan et al., 2007) provide the best opportunity to deduce the average erosion rate, i.e., sediment yield, for West and East Antarctica. Secondly, bathymetric data shows the Whillans Ice Stream occupied the Glomar Challenger Basin on the eastern Ross Sea outer shelf during the LGM (Bentley and Jezek, 1981; Shipp et al., 1999). Thirdly, the GZWs assigned to LGM and the post-LGM in Glomar Challenger Basin have been well mapped in previous studies using seismic and multibeam data (Shipp et al., 1999; Bart, 2004; Mosola and Anderson, 2006; Bart and Cone, 2012). Each unit is taken to be a discrete depositional episode, i.e., a grounding event, which constructed a GZW. In particular, our study focused on estimating the grounding event duration for the middle shelf GZW, the Gray Unit from Bart (2004).

2. Modern sediment flux at the Whillans Ice Stream grounding zone wedge and its utility for estimating sediment yield and flux to calculate palaeo grounding event duration

A wide range of yields is reported for glaciated and formerly glaciated margins (Elverhoi et al., 1998; Koppes and Hallet, 2006; Dowdeswell et al., 2010). Erosion rates are lowest for polar glaciers whereas higher rates exist for temperate glaciers. The relatively low latitude glaciers in Alaska have the highest sediment fluxes and yields on record (Hallet et al., 1996; Cowan et al., 2010). The high yields are a consequence of the temperate climate, high precipitation, abundant meltwater and easily eroded bedrock (Cowan et al., 2010). The large range of values indicates that yield depends upon many factors. Previous studies indicate that yield depends on the presence, quantity and location of meltwater, ice flow velocity, ice temperature, subglacial lithology and degree of consolidation, relief, fracture, presence of recently eroded sediment, ice thickness, extent of ice cover, and size of drainage basin (Hallet et al., 1996; Elverhoi et al., 1998). Given this spectrum of factors, it is evident that yield and flux should be expected to change during a glacial cycle. Some data suggest that yield increases during glacials because of an increased intensity of glacierization (Hallet et al., 1996). Other data suggest that yield also increases during glacials due to an increase in ice extent over previously ice-free sectors of the drainage basin. Neither of these axioms should apply to Antarctica because all of the drainage basin is continuously covered by grounded ice through the glacial cycle. Instead, we follow Koppes and Montgomery (2009) who proposed that yield is significantly higher in the interglacial because of rapid flow of warm ice. The accelerated ice flow presumably excavates some of the sediment deposited during the preceding advance of grounded ice (e.g., O Cofaigh et al., 2007, 2008). Likewise, yield should decrease during the colder glacial climate as a result of less meltwater reaching the bed of colder, slower-moving ice. Indeed, cold-

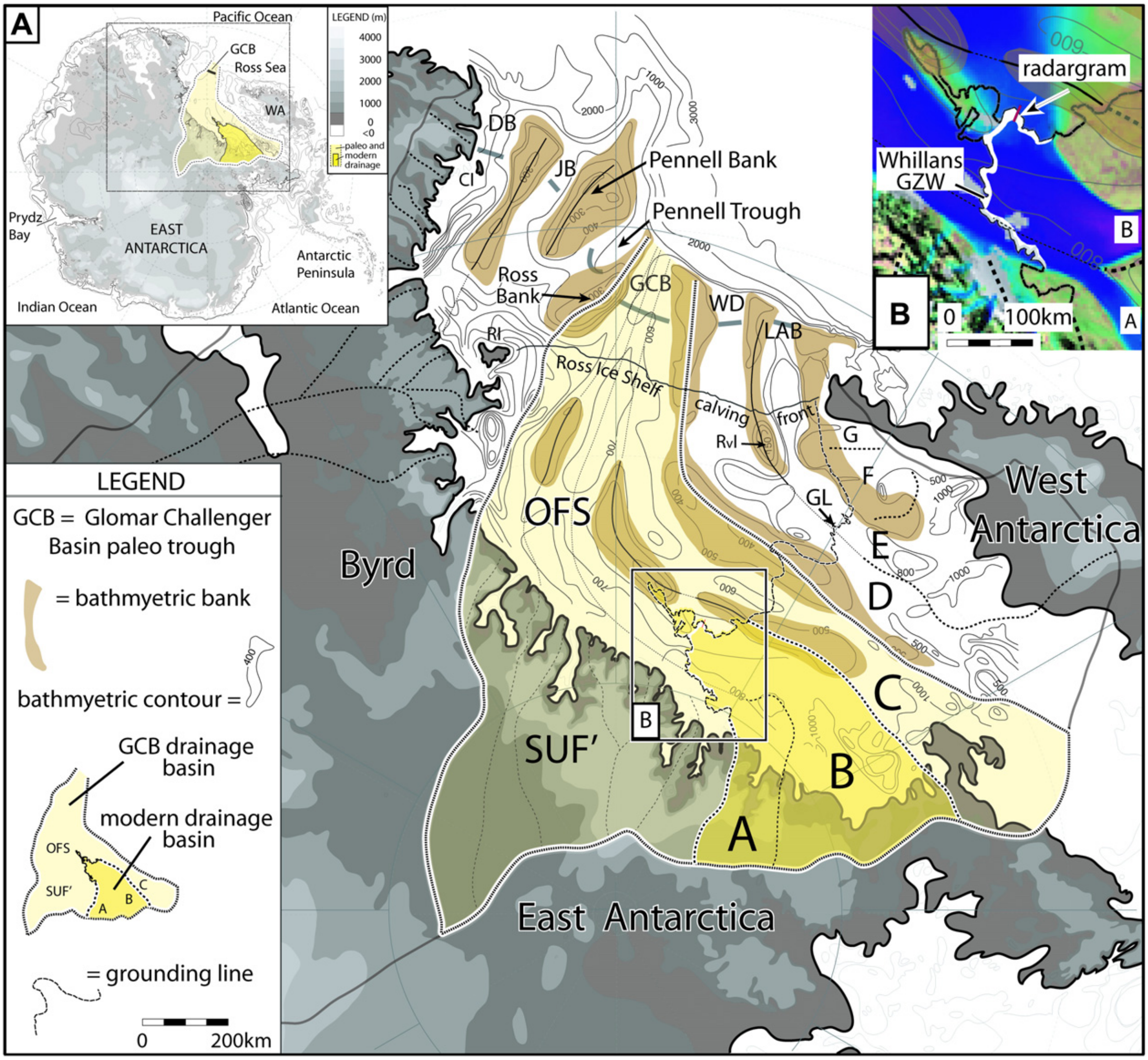


Fig. 3. A) Map of Antarctica showing subglacial elevation. The dark yellow shade shows the modern drainage for ice streams A and B as defined from Rignot et al. (2011). The light yellow shade shows the palaeo-ice sheet drainage for Glomar Challenger Basin when grounded ice existed on the middle continental shelf. The box shows the area enlarged in the central part of the figure. B) Ice velocity from Rignot et al. (2011) shown in color at the mouth of the Whillans and Ice Stream A at the grounding line. The red line shows the location of the radargram obtained by Anandrakrishnan et al. (2007). The white shaded region corresponds to our interpretation of GZW dimensions as inferred from the radargram. The central figure shows the location of data shown in Fig. 3B. The enlargement of the area shown in Fig. 3A shows bathymetric data in Ross Sea from Bentley and Jezek (1981). The bold lines on the continent show our projections of drainage basin divides based on data from Rignot et al. (2011). In the offshore area, the thick gray line in the axes of each palaeo trough represents the approximate location of LGM GZWs as deduced in this study. The shaded onshore and offshore regions correspond to the drainage basin area that existed for the WAIS when grounded ice was located at the middle shelf of Glomar Challenger Basin.

based ice frozen to the bed is expected to produce extremely low yield. Cold ice cover over mountain peaks shields these zones from erosion whereas adjacent fast flowing valley glaciers exhibit much higher erosion (Tomkin and Braun, 2002). According to Koppes and Montgomery (2009), yield in the glacial advance was as much as two orders of magnitude lower than yield during interglacial retreat. In other words, sediment yield should change depending upon whether the WAIS is in the advance-mode or retreat-mode of a grounding-line translation cycle. Fernandez et al. (2011) reached similar conclusions based on their study of Quaternary deposits within Chilean fjords.

Few data based estimates of modern Antarctic yield and flux have been obtained because the erosion and deposition sites of interest are below thick ice cover. The best available estimates of modern flux come from studies of ice streams at Siple Coast. The modern flux at Whillans Ice Stream is estimated to be 200 m^3/m/a (Anandrakrishnan et al., 2007).[2] The estimate is based on a radar image of the actively accumulating modern GZW at the mouth of Whillans Ice Stream (Fig. 3). Therefore, neither the 3D volume nor the duration of the modern grounding event is well constrained. Nonetheless, the modern (2D) flux estimated for Whillans Ice Stream is generally consistent with borehole observations at Upstream B sites (Engelhardt and Kamb, 1997; Kamb, 2001).

Sediment flux estimates for the Kamb Ice Stream (Christoffersen et al., 2010) and for Marguerite Bay (Dowdeswell et al., 2004) are also of the same order of magnitude as that estimated for Whillans Ice Stream. The significantly higher flux estimated for the Pine

[2] Anandrakrishnan et al. (2007) refer to a modern flux on the order of 100 m^3/m/a. We use 200 m^3/m/a because they infer that the total volume of the modern GZW (200,000 m^3) was deposited within 1000 years.

Island Glacier (Joughin et al., 2003; Evans et al., 2006; Graham et al., 2010) may be a consequence of significantly more free flowing meltwater beneath grounded ice for this sector of Antarctica (Lowe and Anderson, 2002, 2003).

The usefulness of modern Whillans Ice Stream flux for our study depends on the veracity of the two following assumptions. Firstly, the Whillans GZW is assumed to have been deposited within the previous 1000 years (Conway et al., 1999; Anandrakrishnan et al., 2007). And secondly, the Whillans GZW is assumed to be a line-source feature. In other words, the cross-sectional area measured by Anandrakrishnan et al. (2007) is representative of the average volume per meter width of the entire grounding line at the mouth of Whillans Ice Stream. As used here, the term 3D sediment flux ($Q_{S(3D)}$) is defined as the total quantity of sediment that leaves the drainage basin to enter the receiving basin per unit of time. Thus, the 3D flux for a drainage basin can be calculated using Equation (1):

$$Q_{3DM}\left(\mathrm{m^3/a}\right) = Q_{2DM}\left(\mathrm{m^3/m/a}\right) \times \text{ice stream width at the grounding line}\left(\mathrm{m}\right) \tag{1}$$

where Q_{3DM} is 3D modern sediment flux and Q_{2DM} is 2D modern sediment flux.

Upstream of the grounding line, the Whillans Ice Stream width is 30 km (Truffer and Echelmeyer, 2003) but in the downstream direction, i.e., closer to the grounding line, the Whillans Ice Stream widens and merges with Ice Stream A (Rignot et al., 2011). At the sinuous grounding line, the width of combined ice-stream flow is 275 km (Fig. 3B). Using Equation (1), we estimate that the modern 3D flux is 5.5×10^7 m^3/a (i.e., 275,000 m $\times$ 200 m^3/m/a) (Table 1). The volume estimates for GZW widths of 250 km and 300 km are also shown in Table 1 for comparison.

Given the modern 3D flux (5.5×10^7 m^3/a) and the modern dimensions of the Whillans and Ice Stream A drainage basin area (235,200 km^2 from Rignot and Thomas, 2002), the average sediment yield, S, can be estimated using Equation (2):

$$S\left(\mathrm{m^3/m^2/a}\right) = Q_{3DM}\left(\mathrm{m^3/a}\right) \Big/ \text{Drainage area}\left(\mathrm{m^2}\right) \tag{2}$$

where S is yield. However, 40% of the modern drainage area for Whillans and Ice Stream A extends to East Antarctica. Metamorphic basement on the East Antarctica sectors of the drainage basin would have liberated a different yield than the sedimentary rock on West Antarctica. Based on data presented by Schlunegger et al. (2001), we infer that the yield from East Antarctica basement may have been 30% less than that for sedimentary strata underlying grounded ice on West Antarctica. Therefore, East Antarctic yield can be related to West Antarctic yield using Equation (3):

$$S_{WA} = 0.7 \times S_{EA} \tag{3}$$

where S_{WA} is yield for West Antarctica and S_{EA} is yield for East Antarctica. Using Equation (3), we re-formulated Equation (2) as shown in Equation (4):

$$Q_{3DM}\left(\mathrm{m^3/a}\right) = \mathrm{Area_{WA}}\left(\mathrm{m^2}\right) \times S_{WA}\left(\mathrm{m^3/m^2/a}\right) + \mathrm{Area_{EA}}\left(\mathrm{m^2}\right) \times S_{EA}\left(\mathrm{m^3/m^2/a}\right) \tag{4}$$

where Area$_{WA}$ is the West Antarctic drainage area and Area$_{EA}$ is the East Antarctica drainage area. Combining Equations (3) and (4) permits us to estimate yield for West and East Antarctica (Table 1).

These inferred yields for West and East Antarctica are lower than yields estimated for modern glacial systems from Alaska, New Zealand, Central Asia, the Swiss Alps, and Greenland (Hallet et al., 1996; Elverhoi et al., 1998; Cowton et al., 2012). This is to be expected given that the Antarctic drainage systems are drier and at colder, higher latitudes. The Whillans' estimates are within the lower range of yield estimates from Svalbard and Norway but higher than yields from Greenland.

The modern estimate of yield for Whillans and Ice Stream A discussed above is specific to the dimensions and geology of the Whillans and Ice Stream A drainage- and receiving-basin dimensions. The modern flux cannot be directly used to calculate the durations of grounding events for GZWs on the outer shelf without first adjusting for differences in the size of the drainage basin area and differences in sub-ice geology for the additional drainage areas (Fig. 3). Another adjustment concerns whether the ice sheet is within retreat- or advance-mode (and thus exhibiting the associated high versus low yield, respectively). In the remainder of this section, we outline how a retreat-mode and advance-mode flux for Glomar Challenger Basin can be generated from the modern estimate of yield and flux at Whillans Ice Stream.

As mentioned earlier, the modern grounding event at Whillans GZW is assumed to have begun only 1000 years BP (Anandrakrishnan et al., 2007). This is generally consistent with syntheses of onshore and offshore data, which suggests a long-term progressive retreat and deflation of the WAIS (Conway et al., 1999; McKay et al., 2008). Thus, in the broader context of grounding-line translations during the last glacial cycle, the rapid ice flow and GZW deposition at the modern grounding line during the past 1000 years can be viewed as being the result of the recent perturbation to WAIS stability and the associated overall retreat of grounded ice. If this line of reasoning is accepted, then the modern estimate of yield probably is a reasonable approximation of retreat-mode yield existing in the earlier (post-LGM) pauses and associated GZW

Table 1
Calculated volume, flux, drainage area and yield for the modern grounding zone wedge (GZW) at mouth of Whillans and A ice streams based on three inferred width dimensions of the GZW at the grounding line. A. Whillans/Ice Stream A GZW and drainage paramaters. B. Values based on a 2D slice view of the GZW volume. C. Values based on a 3D estimate of the GZW volume using three possible cross-section widths of the GZW at the modern line. We assume that the modern GZW has a cross-section width of 275 km at the modern grounding line (shaded area). The drainage area estimate is from Rignot and Thomas (2002). Drainage areas and yield estimates are not applicable (NA) for a 2D slice volume measurement. Q = Flux. In column B, the flux has units of m^3/m/a because it is based on a 1-m wide 2D slice estimate of volume. In column C, the flux has units of m^3/a because it is based on a 3D estimate of GZW volume. S_{WA} = modern yield for West Antarctica. S_{EA} = modern yield for East Antarctica.

A. Whillans/A GZW & drainage parameters	B. Whillans/A GZW 2D slice volume (m^3/m)	C. 3D volume (m^3) estimates for various GZW cross-section widths (m) at the modern Whillans/A grounding line		
		250,000 m	275,000 m	300,000 m
Volume	2×10^5 m^3/m	5×10^{10} m^3	5.5×10^{10} m^3	6×10^{10} m^3
Q	200 m^3/m/a	5×10^7 m^3/a	5.5×10^7 m^3/a	6×10^7 m^3
Drainage area	2.352×10^{11} m^2	2.352×10^{11} m^2	2.352×10^{11} m^2	2.352×10^{11} m^2
S_{WA}	NA	2.417×10^{-4} m^3/m^2/a	2.659×10^{-4} m^3/m^2/a	2.900×10^{-4} m^3/m^2/a
S_{EA}	NA	1.692×10^{-4} m^3/m^2/a	1.862×10^{-4} m^3/m^2/a	2.030×10^{-4} m^3/m^2/a

deposition, i.e., when grounded ice was on the outer and middle continental shelf.

Ice-sheet reconstructions show that the drainage area for Glomar Challenger Basin was significantly larger when the WAIS was grounded on the middle continental shelf (e.g., Denton and Hughes, 2002; Licht et al., 2005). Based on these reconstructions, the drainage area for the Glomar Challenger Basin trough captured drainage from a larger area of West Antarctica and parts of East Antarctica (Fig. 2; Table 2, column B). The Glomar Challenger Basin drainage boundary shown in Fig. 3 followed results from Licht et al. (2005), which indicate that the East Antarctic contribution to Glomar Challenger Basin did not include the Byrd Glacier.

The products of the yield and the larger drainage area (Equation (2)) for the individual West and East Antarctic sectors of the Glomar Challenger Basin drainage basin can be combined to obtain a cumulative flux. The cumulative (retreat-mode) flux for Glomar Challenger Basin drainage area is thus deduced to be 2.424×10^8 m^3/a (Table 2, bottom row column C). Within this scenario, the Glomar Challenger Basin retreat-mode flux (Table 2) is 4.4 times higher than the modern flux (Table 1). The higher flux is solely the consequence of the larger Glomar Challenger Basin drainage area, which is more than 4× the size of the modern drainage basin area for Whillans and Ice Stream A.

As noted earlier, yields were as much as two orders of magnitude lower during glacials (Koppes and Hallet, 2002; Koppes and Montgomery, 2009; Koppes et al., 2010; Fernandez et al., 2011). Given the anomalously high retreat-mode yields for West and East Antarctica (2.659×10^{-4} and 1.862×10^{-4} m^3/m^2/a, respectively) (Table 2 column C) then the cumulative advance-mode yields are estimated to be 2.659×10^{-6} and 1.862×10^{-6} m^3/m^2/a, respectively for West and East Antarctica (Table 2 column D). Applying the same rationale as in the preceding paragraphs to account for the larger drainage areas of East and West Antarctica, the advance-mode flux for Glomar Challenger Basin is estimated to be 2.424×10^6 m^3/a (Table 2). Models predict gradual advance of grounded ice during the buildup to the LGM configuration (Huybrechts, 2002; Pollard and DeConto, 2009). Lower yield during glacial advance is attributed to the slower flow and associated progressive inflation of cold ice containing comparatively less meltwater during the gradual advance of grounded ice (Koppes and Montgomery, 2009; Fernandez et al., 2011). We acknowledge that alternative scenarios may be occurring in West Antarctica which physical models may be able to address.

3. Methods

A detailed assessment of the Gray GZW map extent and sediment volume was completed using a grid of seismic data and a large-area multibeam survey (Fig. 2). The top and base of the Gray Unit was correlated on seismic data from six single-channel seismic surveys, M89, PD90, NBP94, NBP95, NBP03, and NBP08. The available seismic lines included over 2000 line kilometers of single-channel data (Fig. 2). M89 was acquired with a sparker source. PD and NBP data were acquired with a generator injector airgun source. The multibeam survey acquired in NBP08 by Bart was also used to more precisely define the limits of the Gray GZW. The top and base of the GZW were contour mapped. The isopach thickness in (milliseconds) of the Gray GZW was generated by hand posting of the two-way travel time (TWTT) from the top and base of the Gray GZW. The isopach thickness in milliseconds was converted to sediment thickness in meters using a sediment velocity of 1750 m/s (meters/second) based on data from Cochrane et al. (1995).

The Gray Unit sediment volume was calculated by assigning an average thickness for grid boxes approximately 3 km by 3 km dimensions for the entire isopach map. We assumed that all flux was sequestered in the GZW as traction mode. This assumption is consistent with modern observations showing that no significant meltwater plumes exist in the current dry Antarctic polar climate (Anderson, 1999). Given the absence of sediment plumes in the current interglacial, it is improbable that copious meltwater sediment plumes existed during the colder intervals when grounded ice existed on the middle and outer shelf. In the case of the advance-mode model of deposition, we also assumed that 100% of the GZW sediment was recycled as the ice sheet advanced to the middle shelf. This assumption is consistent with the abrupt depositional pinchout of GZWs (Bart and Anderson, 1995, 1996, 1997; Vanneste and Larter, 1995; Graham et al., 2010).

The grounding event duration for the Gray Unit 3D volume was calculated using retreat-mode and advance-mode flux estimates discussed in the preceding section (Table 2 columns C and D). Our calculations of grounding event duration were based on the relationship between GZW volume and flux shown in Equation (5),

$$d = v_s / Q \quad (5)$$

where v_s is sediment volume (m^3), Q is the flux (m^3/a) and d is grounding event duration in years (a).

4. Results

4.1. Extent and thickness of the Gray Unit from seismic and multibeam data

The top of the Gray Unit GZW is defined by the Gray Unconformity, which corresponds to seafloor reflection over much of the survey area, whereas the base of the Gray Unit corresponds to the

Table 2
A. Modern drainage basin areas for West Antarctic and East Antarctic and offshore regions of West Antarctica that converge to Glomar Challenger Basin (see Fig. 3). The total drainage area for ice streams A and B are divided into West Antarctic and East Antarctic sectors for yield estimates. B. Drainage areas from Rignot and Thomas (2002). We estimated the area for the offshore region using Diger software. C) Retreat-mode yields, S, (for West and East Antarctica, WA and EA, respectively) and corresponding retreat-mode flux, Q_{3DR} based on Equations (3) and (4). D) Advance-mode yields, S, and corresponding advance-mode flux, Q_{3DA}. The dimensions of the drainage area for Glomar Challenger Basin (see shaded region on Fig. 3) include parts of West Antarctica and East Antarctica and a large offshore region of West Antarctica. The last row for columns C and D shows the cumulative flux contributions for all West Antarctic and East Antarctic sectors delivering sediment to Glomar Challenger Basin when the WAIS was grounded at the middle shelf. GCB = Glomar Challenger Basin.

A. Map region (see Fig. 3)	B. Drainage area (m^2)	C. GCB Retreat-mode yield (m^3/m^2/a) and flux (m^3/a)			D. GCB advance-mode yield (m^3/m^2/a) and flux (m^3/a)		
		S_{WA}	S_{EA}	Q_{3DR}	S_{WA}	S_{EA}	Q_{3DA}
A/B	2.352×10^{11}	–	–	–	–	–	–
A/B$_{WA}$	1.41×10^{11}	2.659×10^{-4}	–	3.749×10^7	2.659×10^{-6}	–	3.749×10^5
A/B$_{EA}$	9.4×10^{10}	–	1.862×10^{-4}	1.750×10^7	–	1.862×10^{-6}	1.750×10^5
C	1.534×10^{11}	2.659×10^{-4}	–	4.079×10^7	2.659×10^{-6}	–	4.079×10^5
SUF'	2.352×10^{11}	–	1.862×10^{-4}	4.379×10^7	–	1.862×10^{-6}	4.379×10^5
Offshore	3.867×10^{11}	2.659×10^{-4}	–	1.028×10^8	2.659×10^{-6}	–	1.028×10^6
GCB$_{area}$ = 10.105×10^{11}		Retreat-mode flux = 2.424×10^8			Advance-mode flux = 2.424×10^6		

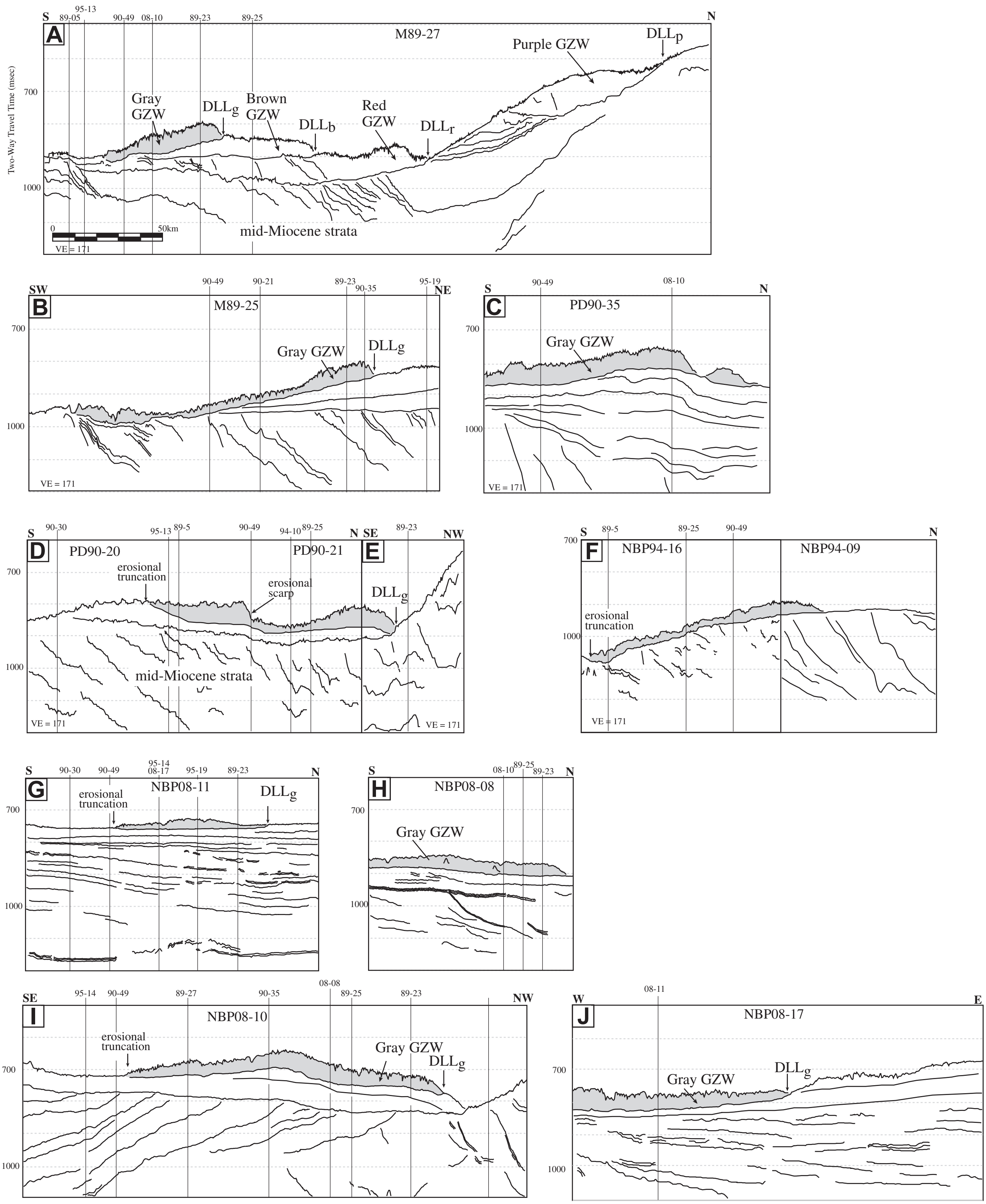


Fig. 4. Line drawing of seismic interpretations showing the top and base of the Gray Unit GZW in Glomar Challenger Basin. A) Profile M89-27; B) Profile M89-25; C) Profile PD90-35; D) Profile PD90-20/21; E) Profile NBP94-16; F) Profile NBP08-11; G) Profile NBP08-10; H) Profile NBP08-8; and I) Profile NBP08-17. The map location of the profiles is shown on Fig. 2.

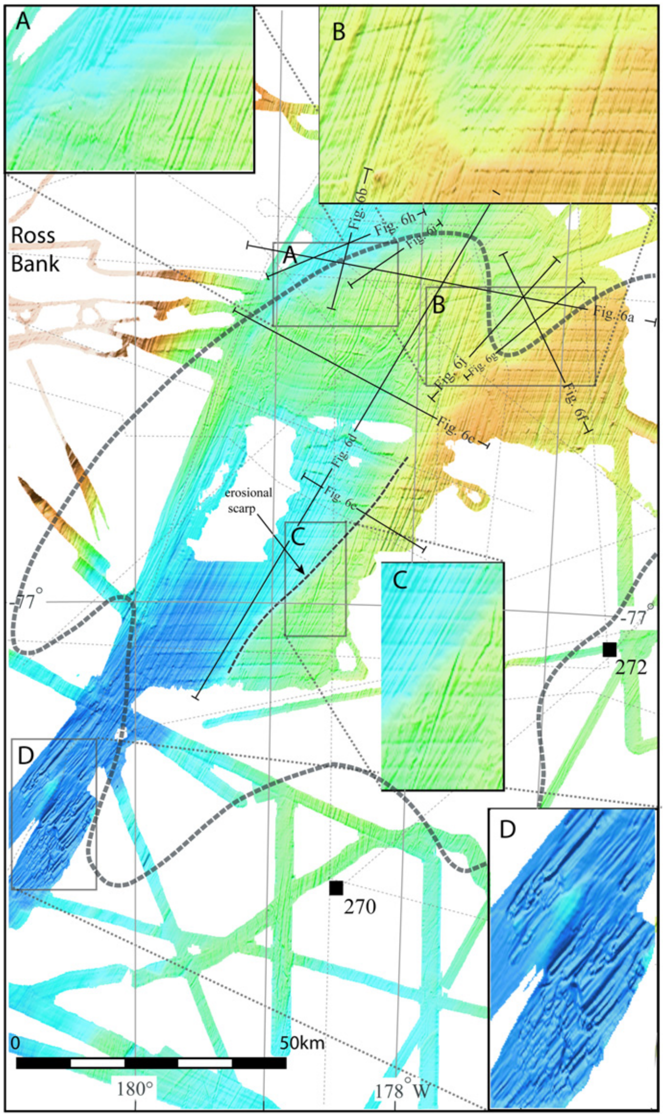


Fig. 5. Multibeam survey acquired by PJ Bart during NBP08-02 and NBP08-03. The survey includes some transects from an earlier multibeam survey collected by JB Anderson during NBP94 (Mosola and Anderson, 2006). The dashed line shows the limit of the Gray GZW. At the basinward end of the Gray GZW limit (toward the top of the image), the dashed line corresponds to the depositional downlap limit and hence approximately represents the limit of grounded ice prior to liftoff retreat. The linear fabric represents mega scale glacial lineations (MSGLs) of at least two generations. The dip-aligned MSGLs north of the Gray Unit downlap limit were generated during the Brown Unit grounding event, whereas the MSGLs southward of the downlap limit were generated during the Gray Unit grounding event. A) Inset showing an enlarged view of the foreset surface on the western lobe of the GZW. B) Inset enlargement showing the obliquity between the two sets of MSGLs. C) Inset enlargement showing an erosional scarp where the ice stream incised deeply into the Gray GZW. D) Inset enlargement showing a zone where basement rock is exposed.

Brown Unconformity (Fig. 4A–I). In many places, the Brown Unconformity corresponds to the top of the Brown GZW (Fig. 4A and C), but in some places the Brown unconformity truncates middle Miocene strata (Chow and Bart, 2003) (Fig. 4B and D).

The line drawing interpretations (Fig. 4) show that the Gray GZW is a low-relief bathymetric feature confined to the middle shelf of the Glomar Challenger Basin between Ross Bank to the west and an un-named bank to the east (Fig. 2). The Gray Unit GZW has few internal reflections but where present, the surfaces dip in a basinward (i.e., seaward) direction and downlap the underlying Brown Unconformity. In a basinward direction, the unit terminates by depositional pinchout (e.g., Fig. 4A and B). In a landward direction, the GZW terminates by erosional truncation at the Gray Unconformity, which corresponds to the seafloor.

The large multibeam survey provides an excellent map view of the Gray GZW downlap limit (Fig. 5). The basinward limit of the Gray Unit has a sinuous trend and shows that the GZW has two lobes, i.e., strictly speaking, the basinward termination of the GZW is not a linear feature. Only part of the eastern lobe is imaged on the multibeam data but its eastern extent is confirmed with seismic data (Figs. 2 and 4I). Well-defined Mega Scale Glacial Lineations (MSGLs) are dip-aligned with the axis of the Glomar Challenger Basin and can be followed to within a few kilometers of the Gray Unit GZW clinoform break (see dashed line on Fig. 5), i.e., the boundary between the foredeepened topset and basinward-dipping foreset (Fig. 6D). The extent of MSGLs thus represents the limit of grounded ice at the end of the Gray Unit grounding event. Given that a parallel set of MSGLs can be traced for more than 50 km indicates that the bathymetry of the GZW topset corresponds to the basal topography of the WAIS prior to liftoff retreat. Conversely, if grounding-line retreat had been gradual, then multiple sets of short MSGLs would have been preserved on the GZW topset. Immediately seaward of the Gray GZW topset, a narrow zone without MSGL dips seaward at a 0.5° (Fig. 5A). The absence of lineations on this surface shows that this seaward dipping surface corresponds to the foreset surface of the GZW that was constructed in open water and was not overrun by grounded ice. Some iceberg-keel marks cross the foreset (Fig. 5B). The pinchout of the Gray GZW occurs less than 5 km northward of the Gray Unit topset boundary. The surface is thus wide enough to piston core (Bart and Cone, 2012).

In addition to the seismic interpretation, we constructed bathymetric cross-section interpretations from the multibeam survey data (Figs. 5 and 6). The multibeam cross sections show our interpretation of the Gray Unit subsurface distribution (Fig. 6). The maximum height of the Gray GZW foreset surface is ~40 m, which thus defines the maximum preserved vertical height of accommodation beneath the grounding zone at the margin of the ice stream (Fig. 6B and D). The Gray Unit GZW buries the MSGL formed on the top of the Brown Unit GZW (Fig. 6A). The orientations of MSGLs on the top of the Brown Unit GZW are noticeably oblique to the orientation of MSGLs on top of the Gray Unit GZW (Fig. 5A and B). The large-area multibeam survey also revealed that some basinward-dipping ramps are actually erosional scarps as opposed to foreset dip surfaces (Figs. 5, 6C and 6E). These erosional surfaces can easily be mis-interpreted as constructional foreset surfaces on 2D seismic data or smaller-scale multibeam surveys.

4.2. Volume and grounding event duration for the gray GZW

An isopach map was constructed from the Gray Unit thickness distribution observed from the interpretation of the seismic data (Fig. 7). The basinward limit of the isopach map is based on the downlap limit interpreted from multibeam data. The landward pinchout is not evident from the multibeam data and thus is solely based on seismic interpretations. The Gray Unit GZW is at least 140 km wide and occupies most of the Glomar Challenger Basin cross-section. The dip-oriented dimensions of the GZW range from 100 to 20 km. The maximum thickness of the wedge is 80 m, but average thickness is 34 m (Fig. 7). The volume of the Gray GZW was estimated to be 3.5716×10^{11} m^3 using a velocity of 1750 m/s (Table 3).

The duration of the Gray Unit grounding event (Table 3) was estimated using the retreat-mode flux (2.424×10^8 m^3/a) and the advance-mode flux (2.424×10^8 m^3/a) (see Table 2). Using the

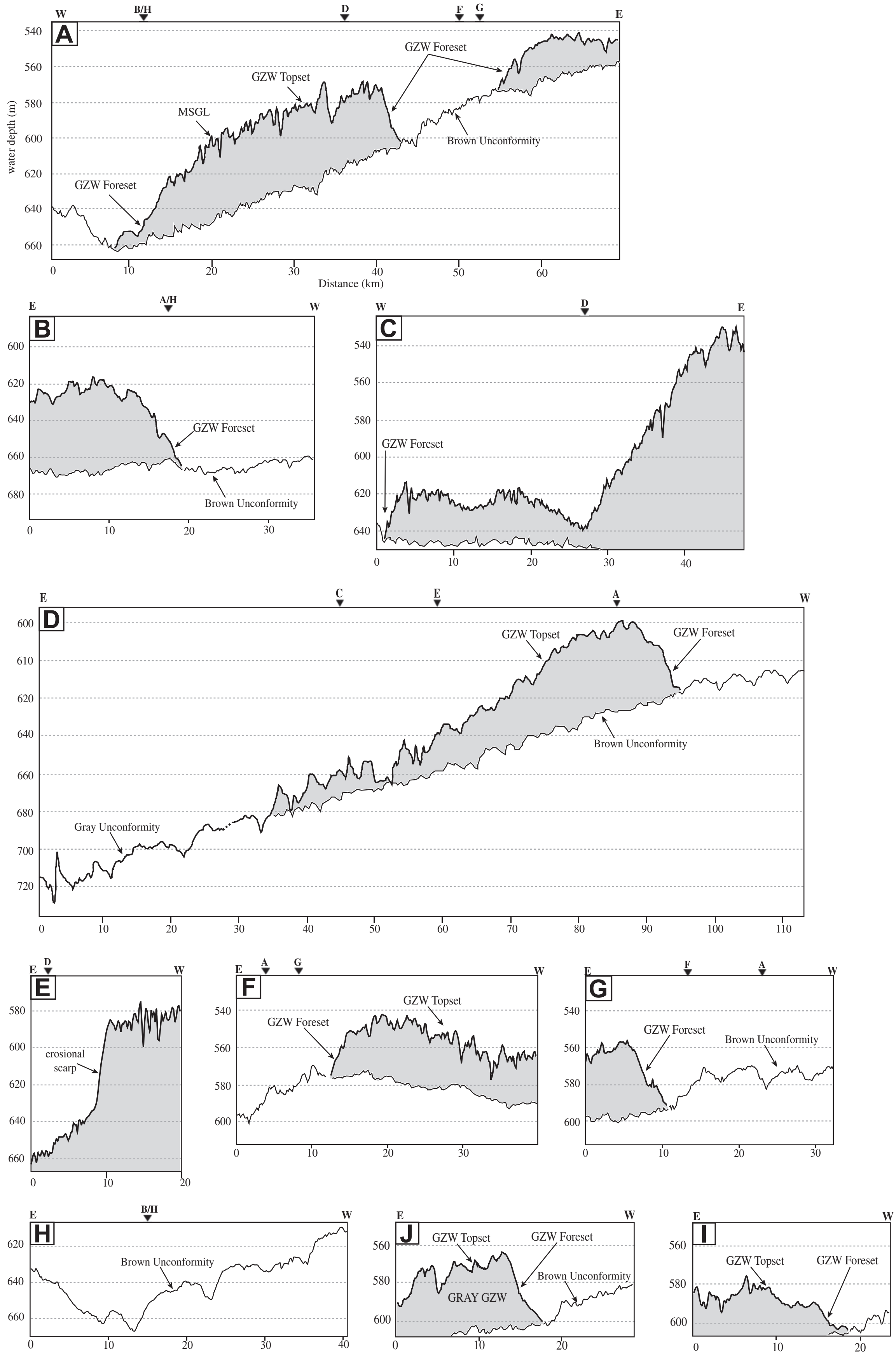


Fig. 6. Cross-section of the multibeam survey generated from MB systems. The Gray shade shows our interpretation of the Gray Unit distribution based on our synthesis of the seismic data interpretation. The locations of the cross-section 6A through 6J are shown on Fig. 5.

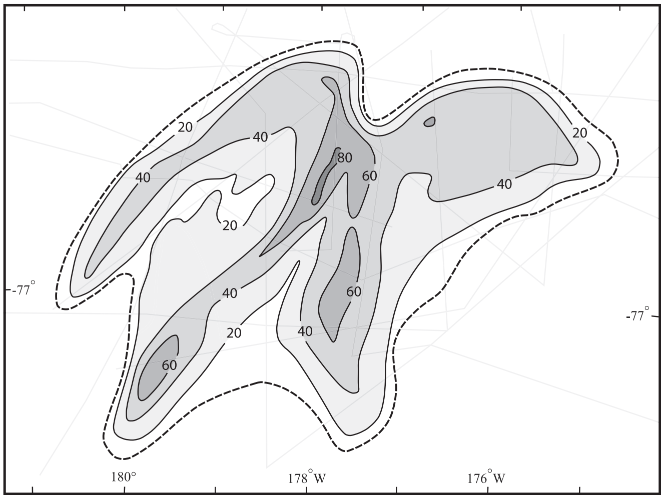


Fig. 7. Isopach map of the Gray Unit GZW based on seismic and multibeam data evaluated in this study. The map extent of the Gray Unit is also shown in Fig. 2. This map extent of the Gray Unit replaces that shown in Bart (2004) and Bart and Cone (2012).

retreat-mode flux, the duration of the Gray Unit grounding event was estimated to have been 1473 years (Table 3, column D). Using the advance-mode flux, the duration of the Gray Unit grounding event is estimated to have been 147,343 years (Table 3, column E). If the modern flux were used, the grounding event duration is estimated to be 6494 years (Table 3, column C).

5. Discussion

5.1. The 3D characterization of the middle shelf Gray Unit grounding zone wedge: implications for the veracity of modern flux estimates from 2D transects

The synthesis of seismic and multibeam interpretations confirms the GZW interpretation of the low-relief feature on the middle shelf sector of Glomar Challenger Basin (Figs. 4–6). These data provide the best documented 3D and 2D views of an Antarctic GZW and provides an ancient analog of the GZWs being constructed at the mouths of modern ice streams hidden below the thick WAIS and Ross Ice Shelf. The preserved MSGLs leave no doubt that the grounding event ended by liftoff retreat. The lack of pervasive iceberg scours shows that the Gray Unit GZW stratigraphy was not significantly disturbed by iceberg turbation (Mosola and Anderson, 2006). The multibeam survey proved useful to precisely delineate the basinward extent of the GZW and to confirm that this termination indeed represents a sharp depositional pinchout limit (Fig. 5C). The absence of channelized features on the foreset surface suggests that bottom-hugging meltwater discharge did not exist during or since the grounding event. The abrupt pinchout shows that the depositional setting did not include a significant quantity of suspended sediment, i.e., sedimentation was confined to a short distance from the grounding line. The isopach map (Fig. 7) and its outline (Fig. 5) replaces the distribution of the Gray GZW originally presented by Bart (2004).

The middle shelf GZW shows significantly different cross-section dimensions (Figs. 4 and 6; Table 4). The variable cross-section areas show that caution should be used when inferring grounding event duration from a single seismic data transect. For example, using the retreat-mode flux, the duration of the Gray GZW grounding event would be 1612 years on seismic line 0811 and 6311 years on seismic line 9020/21 (Table 4). For the eight seismic transects shown in Table 4, the average duration is 3528 ± 2170. The large standard deviation (Table 4) shows that GZW duration estimated from a single-transect 2D analysis could produce significant error. If the thickness distribution of the Gray Unit GZW (Fig. 7) is typical of other Antarctic GZWs, then a large-area multibeam survey and a companion orthogonal seismic grid with approximately 10-km line spacing may be optimal to accurately characterize GZW volume.

The observed variability of the Gray Unit cross-section slice volume also calls into question our assumption that the single radar cross-section from Anandrakrishnan et al. (2007) is sufficient to generate a reasonable 3D volume estimate for the modern GZW at the mouth of the Whillans Ice Stream. More data are obviously needed to properly characterize the dimensions of the modern GZW because our assumptions about the modern system form the basis of our yield and flux estimates for the GZWs constructed by the Glomar Challenger Basin palaeo-ice-stream. Given the lack of other flux data, we proceed with the constraints we derived from Anandrakrishnan et al. (2007).

5.2. Grounding event duration: two working hypotheses as to how the Gray Unit GZW relates to the last glacial cycle

The 1.473 ky grounding event duration based on the retreat-mode flux represents about 43% of the 3.4 ky post-LGM timeframe for the deposition of all three GZWs (Table 3). Given the relatively low resolution of our experimental approach, we conclude that this result is reasonably consistent with the conventional view that the Gray GZW could have been deposited as a recessional moraine within the post-LGM timeframe (Domack et al., 1999).

The 147.343 ky grounding event duration based on the advance-mode flux is 47% longer than the 100 ky duration of the last glacial cycle (Table 3). We conclude that this result is also reasonably consistent with the alternate view that the Gray GZW could represent the amalgamation of erosion and deposition associated with a single gradual advance of WAIS to the middle shelf spanning the majority of the last glacial cycle (Fig. 8, see discussion in Section

Table 3
Grounding event duration for the Gray, Brown and Red grounding zone wedges (GZWs). A) GZW name: individual GZWs are shown for the first four rows and the last row corresponds to data for all 4 GZWs. B) GZW volumes. The volumes for the Brown, Red and Purple Units are estimated from data presented by Bart (2004). C) Grounding event duration using modern flux (Q_{3DM}) at Whillans/A Ice Streams. D) Grounding event duration using the retreat-mode flux (Q_{3DR}) for GCB. E) Grounding event duration using advance-mode flux (Q_{3DA}) for GCB. GCB = Glomar Challenger Basin.

A. GZW name	B. GZW volume (m^3)	C. GE duration w/modern flux (yr)	D. GE duration w/retreat-mode flux (yr)	E. GE duration w/advance-mode flux (yr)
		$Q_{3DM} = 5.5 \times 10^7$ m^3/a	$Q_{3DR} = 2.424 \times 10^8$ m^3/a	$Q_{3DA} = 2.424 \times 10^6$ m^3/a
Gray	3.5716×10^{11}	6494	1473	147,343
Brown	6.25×10^{11}	11,364	2578	257,838
Red	6.08×10^{12}	110,545	25,082	2,508,251
Purple	2.59×10^{12}	47,091	10,685	1,068,482
4 GZWs	18.492×10^{12}	175,494	39,818	3,981,914

Table 4
Grounding event durations of the Gray Unit grounding zone wedge (GZW) from the eight seismic profiles shown in Fig. 4 using 2D modern flux (modern drainage basin), 2D retreat-mode flux (GCB drainage basin) and advance-mode flux (GCB drainage basin). A) Seismic line name. B) Gray Unit slice volume. C) Grounding event duration estimates using 2D modern flux, Q_{3DM}. D) Grounding event duration estimates using the retreat-mode flux, Q_{3DR}. E) Grounding event duration estimates using the advance-mode flux, Q_{3DA}. The last row for columns C–E shows the average and standard deviation for the estimated grounding event durations.

A. Seismic line name (see Fig. 4)	B. Gray GZW volume (m^3/m)	C–E. Estimated grounding event durations (ky)		
		C. From 2D modern flux ($Q_{3DM} = 200$ m^3/m/a)	D. From 2D retreat-mode flux ($Q_{3DR} = 881$ m^3/m/a)	E. From 2D advance-mode flux ($Q_{3DA} = 8.81$ m^3/m/a)
08-11	1.42×10^6	7.1	1612	161,200
94-16	1.44×10^6	7.2	1634	163,400
08-08	1.67×10^6	8.35	1895	189,500
89-25	1.89×10^6	9.45	2145	214,500
89-27	2.30×10^6	11.5	2611	261,100
90-35	5.06×10^6	25.3	5743	574,300
08-10	5.53×10^6	27.7	6277	627,700
90-20/21	5.56×10^6	27.8	6311	631,100
Ave. duration & std. deviation		15.55 ± 9.56	3528 ± 2170	352,850 ± 215,803

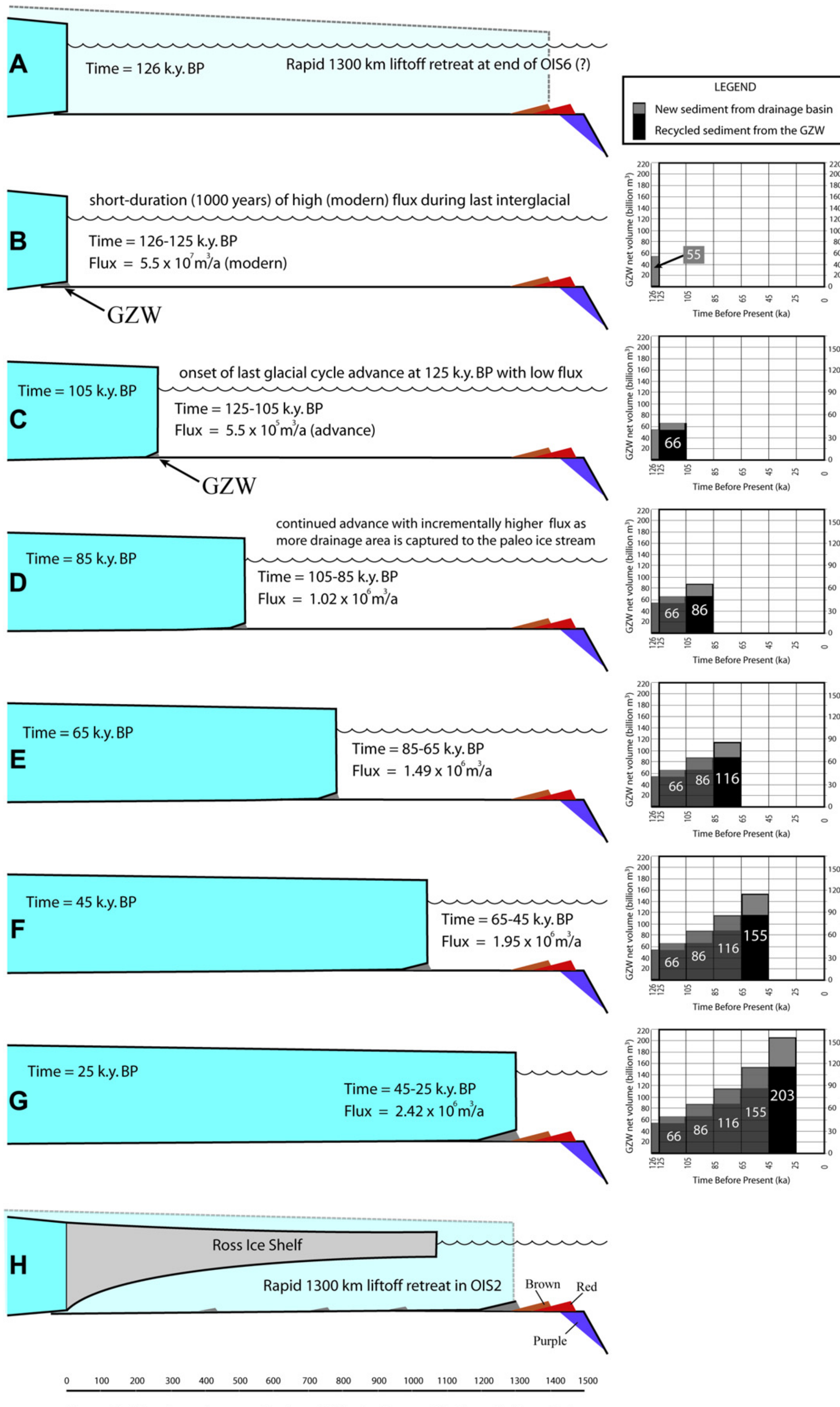
5.4). Given that the fluxes we used are separated by two orders of magnitude, it is not surprising that the grounding event durations are separated by two orders of magnitude. Nonetheless, the data generally show that both interpretations of how the Gray Unit GZW relates to the last glacial cycle (Domack et al., 1999; Bart and Cone, 2012) should both be considered feasible working hypotheses.

The post-LGM retreat interpretation has been widely discussed in previous studies (Conway et al., 1999; Domack et al., 1999; Shipp et al., 1999; Mosola and Anderson, 2006). On the other hand, the possibility that each GZW represents a discrete glacial cycle has not been considered in detail. Since this alternate hypothesis has not yet been evaluated in detail, we focus the remainder of the discussion on the evidence and lines of reason supporting the view that the middle shelf GZW is the product of erosion and deposition during the long-duration phase of WAIS advance in the last glacial cycle.

5.3. Evidence supporting the view that the middle shelf grounding event represents an amalgamation of erosion and deposition during the last glacial cycle

We present six lines of reasoning in support of the view that the Gray Unit GZW in Glomar Challenger Basin represents the amalgamation of erosion and deposition during the last glacial cycle.

1. The middle shelf position of the Gray GZW is generally regarded as being a consequence of WAIS retreat from an outer shelf position since LGM. Early studies generally assumed that the extent of grounded ice during LGM was only limited by the dimensions of the continental shelf. Subsequent detailed studies of western Ross Sea have however shown that grounded ice was more than 200 km from the shelf edge in Drygalski and Joides and Pennell basin palaeo-ice-stream troughs (Licht et al., 1996, 1998; Domack et al., 1999; Shipp et al., 1999; Hall et al., 2000; Hall and Denton, 2000a,b). Thus, a middle shelf position in Glomar Challenger Basin is not unusual with respect to the LGM extent of grounded ice elsewhere in Ross Sea. This pattern of sub-maximum extent of grounded ice at the LGM is also consistent with geologic data from Prydz Bay where grounded ice was confined to the inner shelf (Domack et al., 1998; Passchier et al., 2003). Grounded ice certainly advanced to the shelf edge in many sectors of West and East Antarctica during the LGM (e.g., Heroy and Anderson, 2005; Weber et al., 2011). As pertains to eastern Ross Sea, the ice volume difference for a WAIS grounding line on the eastern Ross Sea outer shelf versus the middle shelf would be relatively small with respect to the global ice volume at LGM. For example, the entire added periphery of Antarctic ice-volume contributed 14 m to the lowering of eustatic sea-level during the LGM (Denton and Hughes, 2002). Moreover, since the WAIS is a marine-based ice sheet, we infer that the differential in the ice volume at the middle shelf versus the outer shelf would not have appreciably affected the Antarctic ice volume contribution to global sea-level lowstand at LGM.
2. Based on the seismic correlations presented by Bart (2004), we conservatively estimate that the Brown and Red Units contain more than 18 times the volume of the Gray Unit (Table 3). The volume of the Purple Unit represents an additional large volume that would take a considerable time to deposit. Using the retreat-mode flux to calculate the grounding event durations for the Gray, Brown and Red GZWs creates a significant problem for the post-LGM interpretation because the three units would collectively take 29,133 years to deposit, i.e., significantly longer than the 3.4 ky post-LGM timeframe. Phases of intermittently higher flux may have well been possible during periods of rapid retreat. However, on the basis of their large volumes, we provisionally infer that the Brown, Red and Purple units each represent amalgamation of erosion and deposition during several glacial cycles. A similar conclusion was reached for some Quaternary GZW units in North Basin Ross Sea (Bart et al., 2011). Numerical modeling of erosion and deposition during successive climate cycles also suggests that GZWs are the products of multiple cycles of ice sheet advance and retreat (Pollard and DeConto, 2007).
3. Early conceptual models proposed that advance and retreat of grounded ice on the Antarctic shelves were primarily driven by sea-level fall and rise, respectively (Denton and Hughes, 1983). In contrasts, recent numerical models suggest that ocean melt played a more important role than sea-level rise is triggering retreat (Pollard and DeConto, 2009; Mackintosh et al., 2011). The degree to which sea-level change and warm-water intrusion were genetically linked is not known (Bart and Iwai, 2012). The onset of major retreat of the WAIS is still generally attributed to rapid and large amplitude sea-level rise associated with meltwater pulse 1A (Domack et al., 1999). In the case of the Glomar Challenger Basin, which has four discrete GZWs (i.e., the Purple, Red, Brown and Gray Units), meltwater pulse 1A presumably triggered liftoff retreat following the deposition of the Purple Unit GZW on the outer-most shelf. However, as of yet, there is no radiocarbon or other chronologic data from Antarctica requiring a genetic link between three additional meltwater pulses (after meltwater pulse 1A) that would have triggered liftoff retreat following deposition of the Red, Brown and Gray GZW. In fact, taken at face value, radiocarbon data


A
Time = 126 k.y. BP
Rapid 1300 km liftoff retreat at end of OIS6 (?)
LEGEND
New sediment from drainage basin
Recycled sediment from the GZW
B
short-duration (1000 years) of high (modern) flux during last interglacial
Time = 126-125 k.y. BP
Flux = 5.5 x 10^7 m^3/a (modern)
GZW
55
C
Time = 105 k.y. BP
onset of last glacial cycle advance at 125 k.y. BP with low flux
Time = 125-105 k.y. BP
Flux = 5.5 x 10^5 m^3/a (advance)
GZW
66
D
Time = 85 k.y. BP
continued advance with incrementally higher flux as more drainage area is captured to the paleo ice stream
Time = 105-85 k.y. BP
Flux = 1.02 x 10^6 m^3/a
66 86
E
Time = 65 k.y. BP
Time = 85-65 k.y. BP
Flux = 1.49 x 10^6 m^3/a
66 86 116
F
Time = 45 k.y. BP
Time = 65-45 k.y. BP
Flux = 1.95 x 10^6 m^3/a
66 86 116 155
G
Time = 25 k.y. BP
Time = 45-25 k.y. BP
Flux = 2.42 x 10^6 m^3/a
66 86 116 155 203
GZW net volume (billion m³)
Flux (million m³/a)
Time Before Present (ka)
H
Ross Ice Shelf
Rapid 1300 km liftoff retreat in OIS2
Brown
Red
Purple
0 100 200 300 400 500 600 700 800 900 1000 1100 1200 1300 1400 1500
Distance (km) from the modern grounding line at Whillans Ice Stream within Glomar Challenger Basin

from Mosola and Anderson (2006) suggest that the WAIS had retreated from the eastern Ross Sea outer and middle shelf during the peak of the LGM.

4. Shipp et al. (1999) was the first to present a major marine mapping synthesis of the LGM age features on a drainage-sector wide scale. Only LGM GZWs (i.e., without any post-LGM GZWs) were noted in Drygalski and Joides Basins palaeo-ice-stream troughs in western Ross Sea. In contrast, the multiple pGZW units (i.e., the Red, Brown and Gray GZWs) noted in eastern Ross Sea palaeo-ice-stream troughs were assigned to an overall post-LGM back-stepping retreat from the LGM grounding event (i.e., the Purple GZW) at the shelf edge (Shipp et al., 1999). Our mapping in Glomar Challenger Basin suggests that the volume of the Purple, Red and Brown GZWs is far greater than the volume of the Gray Unit GZW in Glomar Challenger Basin. Moreover, the volume of the Gray Unit GZW appears to be similar to the volume of GZW units assigned to the LGM in western Ross Sea (e.g., Drygalski, Joides, Pennell and Whales Deep Basin palaeo-ice-stream troughs) (Shipp et al., 1999; Bart et al., 2000; Howatt and Domack, 2003). The scale similarity suggests that the Gray Unit GZW in Glomar Challenger Basin had a genesis and chronology similar to that for GZW units assigned to LGM in western Ross Sea palaeo-ice-stream troughs.
5. In contrast to the volume of GZWs assigned to the LGM, the volumes of GZWs assigned to the post-LGM are typically of much smaller volume. Two post-LGM GZWs reported from the outer shelf sector of the Pine Island palaeo-ice-stream trough (Graham et al., 2010) are significantly smaller in extent and volume than the Gray GZW. Based on data from Graham et al. (2010) and Jakobsson et al. (2011), we estimate that the volume of the largest Pine Island Bay post-LGM GZW is 60 times smaller than the Gray GZW in the Glomar Challenger Basin (6×10^9 m^3 versus 3.5716×10^{11} m^3). The basal dynamics at Pine Island Bay may be distinctly different from those at eastern Ross Sea. In addition, ice drained through a narrow trough out of Pine Island Bay, and encountered bottlenecks on the middle shelf. Therefore, small volume GZWs might be expected in Pine Island Bay.

The best example of small volume post-LGM GZWs comes from a succession of back-stepped ridges on the eastern flank of Pennell Bank and in Pennell Trough (Shipp et al., 1999; Howatt and Domack, 2003). The succession includes several GZWs with dip-oriented dimensions ranging from 4 km to a few hundred meters length and maximum thicknesses ranging from ~30 to 5 m. The smaller GZW dimensions suggest that these units may have each been constructed within an extremely short timeframe, i.e., decades. The succession of the GZWs on Pennell Bank and in Pennell Trough might be due to the net influence of three bathymetric elements in this region, which probably served as pinning points that slowed the overall retreat of the WAIS for this sector of Ross Sea that was elsewhere rapid. For example, grounded ice may have remained in Pennell Trough as ice pinned on the two shallow and broad crests of Pennell Bank to the west and Ross Bank to the east (Fig. 3). In addition, Pennell Trough has a discrete saddle at the middle shelf. Pinning on these three bathymetric features may have permitted the WAIS to briefly pause numerous times as grounded ice vacated Pennell Trough.

6. A major advantage of assigning older ages to the Purple, Red, Brown and Gray Units (Table 3) is that it permits these strata to be related to a longer interval of the Quaternary. Otherwise, the eastern Ross Sea strata currently assigned to the LGM and post-LGM represent the entirety of the post-early Pliocene section as defined by correlation to DSDP Site 272 (Alonso et al., 1992; Bart, 2004). Indeed, the conventional interpretation creates an unusual situation in which the record of the LGM and post-LGM is greatly expanded whereas the remainder of the Quaternary is extremely condensed on the continental shelf. There is no evidence that major bypass of the eastern Ross Sea shelf during the Quaternary in the form of an expanded Quaternary section on the adjacent Ross Sea abyssal plain (ANTOSTRAT, 1995; De Santis et al., 1995, 1999), but this has yet to be confirmed because the deep-water margin of eastern Ross Sea has not been drilled. Drill data from the Antarctic Peninsula and Prydz Bay abyssal plain indicate that sedimentation rates decreased on the seafloor during the Quaternary. On the Antarctic Peninsula, the drop in sedimentation rates suggests that the thin Quaternary section on the shelf was not a consequence of erosion and bypass (Bart and Iwai, 2012).

5.4. Conceptual models of grounding zone wedge evolution in Glomar Challenger Basin

In this section, we present a conceptual model showing one possible view of how the Gray GZW may have evolved with respect to an inferred chronology of the last glacial cycle. We acknowledge that many other possibilities are equally plausible. In this model, the WAIS advanced to the outer shelf during MIS6, eroded the Brown Unconformity and added sediment to the Brown Unit (Fig. 8A). The WAIS subsequently experienced liftoff followed by a large distance (i.e., 1300 km) retreat from the outer shelf to the inner shelf in association with sea-level rise and warming at the end of the glacial (Fig. 8A). Sedimentation during retreat was probably negligible because otherwise, MSGLs that define the top of the Brown Unit would have been buried (e.g., Dowdeswell et al., 2008). At the peak of the MIS5e interglacial, the configuration of the WAIS presumably was similar to that existing today. During MIS5e, δ^{18}O values oscillated by up to 0.17 ppm (Lisiecki and Raymo, 2005). Therefore, the interval of absolute minimum global ice volume was significantly shorter than the approximately 4000-year duration of MIS5e. We arbitrarily placed the WAIS on the inner shelf for 1000 years, between 126 ky and 125 ky BP because δ^{18}O values vary significantly during MIS5e with the smallest δ^{18}O values occurring over a shorter timeframe. During the 1000-year interval (Fig. 8B), a GZW was constructed with the same flux as that existing for Whillans Ice Stream in the modern (Table 1). The histogram for Fig. 8B shows the cumulative sediment volume of the GZW after this 1000 year time interval. In the next stage (Fig. 8C), the WAIS began a gradual advance toward the outer shelf. During all subsequent stages of WAIS advance (Fig. 8C–G), sediment yield was two orders of magnitude lower (with respect to the yield existing in the preceding

Fig. 8. Conceptual model showing how the Gray Unit GZW in the Glomar Challenger Basin palaeo trough relates to West Antarctic Ice Sheet grounding-line translations through the last glacial cycle. A) Major liftoff retreat of the WAIS from the outer shelf at the end of MIS6 and re-establishment of the grounding line 1300 km inland in the continental interior. B) At 125 ky BP, after 1000 years of GZW deposition at a 'modern-like" flux. The histograms show the cumulative volume of the GZW. C) At 105 ky BP, after 20,000 years of erosion and deposition associated with gradual advance of the WAIS. The yield is two orders of magnitude lower than existed during the previous stage (B). The incremental increase in flux reflects the incremental increase in the drainage basin capture area. D thru F) Amalgamated erosion and deposition associated with continued advance of the WAIS at 85 ky, 65 ky and 45 ky BP (respectively). G) At 25 ky BP, WAIS advance culminated on the middle shelf in Glomar Challenger Basin followed by liftoff retreat. H) At present, the WAIS liftoff retreat may have involved several pauses (see small GZWs below the Ross Ice Shelf) before reaching the modern grounding line location 1000 years BP.

stage, Fig. 8B). As a consequence of the lower yield, the advance-mode flux decreased by two orders of magnitude (Fig. 8C). The sediment previously deposited at the GZW between 126–125 ky BP (Fig. 8B) was eroded, transported a short distance basinward, and re-deposited at the new grounding line position as the WAIS gradually advanced (Fig. 8C). Our inference that streaming ice eroded all GZW sediment deposited during the preceding stage (Fig. 8B) is based on the observed southern limit of the Gray Unit (Figs. 4 and 7). The histogram for Fig. 8C shows that the cumulative volume includes the recycled sediment plus sediment contemporaneously eroded from the drainage basin at the lower yield.

Our conceptual model shows realistic distances between the modern grounding line position and the middle shelf position of the Gray GZW. On this basis, we infer that the average rate of WAIS grounding line advance over the duration of the last glacial cycle was 13 m/a (i.e., 1300 km within 100,000 years). As the WAIS advanced, the drainage area captured by the WAIS increased. As a result of the larger drainage area, the flux increased. In the next four stages (Fig. 8D through Fig. 8G), we incrementally increased flux so that the flux at 25 ky BP (Fig. 8G) was equal to the advance-mode flux calculated for the Glomar Challenger Basin (Table 2, column D). By 25 ky BP (Fig. 8G), the WAIS was grounded at the middle shelf sector of Glomar Challenger Basin. The associated cumulative volume (2.03×10^{11} m^3) is considerably less than the observed volume of the Gray GZW (3.5716×10^{11} m^3). The difference may indicate that the Gray Unit is an amalgamation of two glacial cycles or simply that the interglacial (Fig. 8B) was ~2750 years longer than we inferred. Alternately, the average advance-mode yield may not have uniformly lowered by the full two orders of magnitude that we assumed. The WAIS experienced liftoff retreat circa 25 ky BP (Fig. 8H) which generally agrees with radiocarbon dates from Mosola and Anderson (2006) and Bart and Cone (2012). The Ross Ice Shelf formed in association within pinning of grounded ice at Roosevelt Island and Ross Island (Figs. 2 and 3). The WAIS presumably reached the modern grounding line position at 1000 years BP, which suggests that the WAIS may have experienced numerous pauses since the onset of retreat at 25 ky BP. If so, multiple GZWs should exist below the Ross Ice Shelf.

6. Conclusions

1. The grounding event durations calculated in this study demonstrate that the GZWs in Glomar Challenger Basin palaeo-ice-stream trough could have been deposited in association with either post-LGM retreat or in association with multiple glacial cycles. In other words, both hypotheses should be considered feasible working hypotheses.
2. Seismic interpretation and isopach mapping showed that the middle shelf GZW has a variable distribution of thickness. Thus, estimates of grounding event duration based on a 2D analysis of the GZW should be done with caution.
3. Sediment flux values from the modern interglacial grounding line should not be directly used to estimate ground event duration for GZWs on the outer and middle shelf without consideration of at least the three following factors: 1) the larger dimension of the drainage area when grounded ice advances to the middle or outer shelf; 2) the dimensions of the receiving basin; and 3) whether the ice sheet is in advance- or retreat-mode.

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