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On the long duration of Till sheet construction: a reassessment of how quaternary grounding line translations relate to near-surface seismic-stratigraphy of eastern Ross Sea, Antarctica

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ON THE LONG DURATION OF TILL SHEET CONSTRUCTION: A REASSESSMENT OF HOW QUATERNARY GROUNDING LINE TRANSLATIONS RELATE TO NEAR-SURFACE SEISMIC-STRATIGRAPHY OF EASTERN ROSS SEA, ANTARCTICA

A Thesis

Submitted to the Graduate Faculty of Louisiana State University and Agricultural and Mechanical College in the partial fulfillment of the requirements for the degree of Master in Science in The Department of Geology

by
Sydney G. Bowles
B.S., Sewanee: The University of the South, 2010
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Abstract

Previously acquired seismic surveys provide strong evidence that the post-Last Glacial Maximum (LGM) retreat of the West Antarctic Ice Sheet (WAIS) deposited a back-stepping succession of seismically-resolved grounding zone wedges (GZWs) in eastern Ross Sea. However, the chronology of WAIS retreat is debated. The conventional view is that three GZWs (Red, Brown, and Gray Units) were deposited since the LGM. An alternative view, based on recent radiocarbon dates, is that the youngest GZW (the Gray Unit) was deposited during the LGM. If correct, then the older GZWs (Red and Brown Units) were deposited prior to LGM. A recent study (Bart and Owolana, 2012) evaluated these interpretations with respect to the Gray GZW. They concluded that both interpretations are feasible working hypotheses for how the Gray Unit relates to grounding-line translations during the last glacial cycle. They proposed that the volume of the Red and Brown GZWs may be too large to have been deposited in the post-LGM timeframe. However, neither the Red or Brown unit have been mapped in detail. The purpose of this study is to use the framework defined by Bart and Owolana (2012) to evaluate how much time would be required to deposit the Red Unit. Mapping showed that the Red Unit is extensive across eastern Ross Sea and is best described as a till sheet. Isopach mapping shows that the volume of the Red Unit is far less than predicted by Bart and Owolana (2012) and is estimated to be $2.12 \pm 0.06 \times 10^{12} \text{ m}^3$. Using a retreat-mode flux, the Red Unit grounding event duration is calculated to have been $7.5 \pm 1.5 \text{ ky}$. Using the advance-mode flux, the Red Unit grounding event duration is calculated to have been $750.69 \pm 159.70 \text{ ky}$. When combined with the estimated durations for the Gray GZW (Bart and Owolana, 2012) and Brown GZW (Kirst, in prep), both the advance and retreat-mode durations exceed the maximum time of the post-LGM
timeframe. Within this context, the data strongly suggests that the Red Unit represents an amalgamation of erosion and deposition during several glacial-interglacial cycles prior to the LGM.
1. Introduction

1.1 Background

Retreat of the West Antarctic Ice Sheet (WAIS) since the end of the Last Glacial Maximum (LGM) has contributed ~5 meters to the post-LGM eustatic rise. The WAIS has occupied its current position and configuration for 1000 ± 200 years (Anandrakrishnan et al., 2007). Accurately predicting the future dynamics of the WAIS is important because significant translations of the grounding line would cause additional eustatic change. The WAIS currently contains an ice volume equivalent of 5 to 6 meters of sea-level change (Conway et al., 1999, Denton, 1999, Mosola and Anderson, 2006, Bramber et al., 2009). Given the potential for greenhouse warming and the recent history of retreat (Mosola and Anderson, 2006, Bramber et al., 2009), understanding the details of post-LGM retreat is a key factor in predicting the future dynamics of the WAIS (e.g., Hughes, 1973, Anderson, 1999, Conway et al., 1999, Shipp et al., 1999, Mosola and Anderson, 2006, Bramber et al., 2009). The Ross Sea is an important study area for evaluating WAIS retreat history. During LGM, the Ross Sea received ice-volume drainage from roughly 25% of both the East and West Antarctic Ice Sheets (Shipp et al., 1999, Denton et al., 1989). The WAIS in particular is considered to be highly susceptible to retreat because the ice sheet is grounded on land that is mostly below sea level. In addition, several rapidly moving ice streams drain the WAIS, and large areas are bordered by ice shelves. The recent ice-sheet retreat and collapse has been greatest in those areas where ice streams are present (Hughes, 1977, Goldstein, 1993, Mosola and Anderson, 2006).

It is widely accepted that the WAIS advanced significantly during the LGM and has since retreated following the end of the LGM (Anderson, 1999, Bentley, 1999, Conway et al., 1999, Shipp et al., 1999). Since the LGM, the WAIS grounding line in the Ross Sea has retreated by
more than 1200 km from its maximum basinward position in eastern Ross Sea (Conway et al., 1999). The near-surface seismic stratigraphy can be interpreted in two basic ways. In the conventional interpretation, overall retreat from the outer-shelf was characterized by several pauses (Shipp et al., 1999, Bart, 2004, Mosola and Anderson, 2006). The liftoff retreat from the middle shelf created the ice sheet’s current grounding line position (Anandarajeshnan et al., 2007, Bart and Owolana, 2012). During each pause, subaqueous moraines, referred to as grounding zone wedges (GZWs), were deposited at the terminus of the grounded ice sheet (Bart, 2004, Bart and Owolana, 2012). The youngest GZWs are located in the axes of paleo troughs and are visible on seismic data as broad, low relief, sediment wedges (Mosola and Anderson, 2006). GZWs are formed as ice streams drain the ice sheet and deposit till deltas several tens of meters thick and tens of kilometers across at the terminus of the ice stream (Alley et al., 1989) (Figure 1).

Figure 1: Line drawing of seismic interpretations showing the top and base of the Red, Brown, and Gray Unit GZW in Glomar Challenger Basin, Whales Deep Basin, and Little America Basin. A) Profile M89-27; B) Profile NBP08-10; C) Profile NBP08-08; D) Profile NBP08-16; E) Profile NBP08-11; F) Profile PD90-30; G) Profile NBP08-12,13; H) Profile NBP08-01; I) Profile NBP08-15; J) Profile NBP08-17; K) Profile NBP08-03; L) Profile PD90-34; M) Profile PD90-32; N) Profile NBP08-19; O) Profile NBP08-06; P) Profile NBP08-04, Q) Profile PD90-51; R) Profile NBP08-05; S) Profile NBP08-02. The Map location of the profiles is shown on Figure 2.
(Figure 1 continued)
(Figure 1 continued)
High resolution seismic data suggests that several GZWs occupy eastern Ross Sea paleo troughs, specifically the Glomar-Challenger, Whales-Deep, and Little-America basins (Mosola and Anderson, 2006) (Figure 2). These GZWs are located on the outer and middle shelves of these paleo trough basins (Bart, 2004, Mosola and Anderson, 2006, Anderson, 2007). The youngest GZWs in eastern Ross Sea

![Bathymetric map of eastern Ross Sea showing Glomar Challenger Basin, Whales Deep Basin, and Little America Basin, paleo troughs on the shelf. The shaded regions show the map distribution of the three GZWs (Red, Brown, and Gray Units). The bold lines show the location of the seismic lines used in the study. Seismic lines shown in Figure 1 are labeled in red.](image)

Figure 2: Bathymetric map of eastern Ross Sea showing Glomar Challenger Basin, Whales Deep Basin, and Little America Basin, paleo troughs on the shelf. The shaded regions show the map distribution of the three GZWs (Red, Brown, and Gray Units). The bold lines show the location of the seismic lines used in the study. Seismic lines shown in Figure 1 are labeled in red.

appear to be confined to the trough axes but preliminary mapping done in this study suggests that this view needs to be modified. Bart (2004) referred to four near-surface seismic units as the Gray, Brown, Red, and Purple GZWs. The Gray Unit is the youngest and Purple Unit is the
oldest GZW. Understanding the genesis, duration, and termination of these grounding events could lead to a better understanding of the pattern with which the WAIS grounding line migrated and with what duration the WAIS paused during successive grounding events.

1.2 Previous Studies

Several studies have examined the timing of the ice-sheet retreat in Ross Sea. The retreat history is debated (e.g. Licht et al., 1996, Conway et al., 1999, Bart, 2004, Mosola and Anderson, 2006, Bart and Cone, 2012, Bart and Owolana, 2012). Radiocarbon studies have led to neither a consensus concerning the chronology and duration of discrete grounding events that deposited the GZWs nor to a chronology of liftoff retreat events in Ross Sea. This lack of chronologic data is because most of the Antarctic shelf is composed of pre-Holocene glacial till from which it difficult to isolate in situ material from recycled material (Andrews et al., 1999). Not surprisingly, accurately dating when the GZWs were deposited using radiocarbon methods is problematic (Licht and Andrews, 2002). Because of the challenges of isolating in situ material for radiometric dating, there are several conflicting interpretations of when the ice advanced to the shelf edge and when it is that the WAIS retreated to its current position.

The conventional interpretation is that Red, Brown, Gray, and modern GZWs in eastern Ross Sea paleo trough basins were deposited since the end of the LGM. The stratigraphically older Purple GZW presumably was deposited during LGM. In this scenario, the WAIS decoupled from the LGM grounding line position at the shelf edge and began retreating at the onset of meltwater pulse 1A (11 ± 2.2 ka \(^{14}\text{C} \text{BP}\)) in response to global climatic warming and rapid sea level rise (e.g., Licht et al., 1996, Conway et al., 1999, Domack et al., 1999, Shipp et al., 1999). This interpretation is primarily based on Acid Insoluble Organic (AIO) matter
isolated from the oldest open-marine sediments that overlie subglacially deposited diamicton.

Modeling of radar reflection data at Roosevelt Island in the Ross Ice Shelf indicates the grounded ice moved south of Roosevelt Island by \( \sim 3.2 \pm 0.64 \) ka \(^{14}\)C before present (BP) (Conway et al., 1999). If this view is correct, then the Red, Brown, and Gray Units would have been deposited in a 7.8 ky maximum timeframe, i.e., between 11 \( \pm 2.2 \) ka \(^{14}\)C BP. and 3.2 \( \pm 0.64 \) ka \(^{14}\)C BP. The modern grounding event is believed to have begun at 1 \( \pm 0.2 \) ka \(^{14}\)C (Anandakrishnan et al., 2007). [This means the ice sheet retreated the 500 km between Roosevelt Island to the current grounding line within 2.2 ky. This equates to an average retreat rate of 225 m/a.]

The AIO material used to date the lift off retreat events could have been glacially reworked carbon derived from older strata. If so, the pelagic marine sediments from which the AIO was extracted could contain a significant amount of older carbon (Domack et al. 1999, Licht and Andrews, 2002). Conversely, AIO material extracted from ice-contact diamicton could contain Holocene carbon from open-marine sediments that has been reworked into older sediments by bioturbation or iceberg turbation (Mosola and Anderson, 2006, Bart and Cone, 2012). These possibilities are important to consider because many core from which material are sampled for dating where not always chosen ideally located in terms of the former footprint of grounded ice in question or within the context of what if any significant post-depositional disturbances may have affected the core site.

Bart and Cone (2012) used a new method to date the Gray Unit GZW's in the Glomar Challenger Basin paleo trough. Their strategy relied on a regional scale view of the Gray Unit GZW morphology. Cores were obtained on the GZW foreset, i.e., an open marine surface that has not been over-run by grounded ice. Bart and Cone (2012) were able to isolate what they
content are in situ forams that lived on the foreset surface of the GZW during the grounding event. Their radiocarbon dates suggest that the WAIS was grounded on the middle shelf of the Ross Sea around 27.5 ± 5.5 ka $^{14}$C BP. Their dates constrain the last interval for which grounded ice occupied Glomar Challenger Basin. The dates are consistent with the oldest AIO radiocarbon dates of pelagic muds. If correct, their data suggests that the WAIS retreated from the central part of eastern Ross Sea 16 ky earlier than previously thought. As of yet, it is not clear why the WAIS would have retreated early in this sector of eastern Ross Sea. Based on their radiocarbon dates, Bart and Cone (2012) assigned the Gray GZW to the LGM, i.e., MIS2, arguing that it could represent the amalgamation of erosion and deposition during all or part of the last glacial cycle. Following this line of reasoning, the older units (Purple, Red, and Brown Units) would have to be re-assigned to glacial maximum prior to LGM (Bart and Cone, 2012).

A recent study by Bart and Owolana (2012) explored a different strategy to evaluate both the conventional and alternative interpretations of how the near-surface stratigraphy relates to WAIS retreat. They focused on calculating the duration of the Gray GZW within the Glomar Challenger Basin paleo ice stream trough. Bart and Owolana (2012) used two end-member sediment flux estimates to evaluate grounding-event durations corresponding to the conventional and alternate interpretations of how the GZWs formed. Both flux estimates were calculated based on the modern flux for the Whillans Ice Stream (Anandrakrishnan et al., 2007), which occupied the Glomar Challenger Basin during the LGM (Bart and Owolana, 2012). They used a retreat-mode flux to estimate the time it would take to deposit the Gray Unit GZW if it were deposited during the transition from the LGM to the current interglacial. They used a lower advance-mode flux to estimate the time it would take to deposit the Gray Unit GZW if it were deposited during the transition from the last interglacial to the LGM. Using the retreat-mode
flux, they estimated that the Gray Unit grounding event would have lasted $1.47 \pm 0.29$ ky which is consistent with the conventional view that the GZW$s$ were deposited within the post-LGM interval. Using the advance-mode flux, they calculated that the Gray Unit grounding event would have lasted $147.34 \pm 29.47$ ky. This longer duration suggests that the Gray GZW represents an amalgamation of erosion and deposition during an entire cycle of glacial advance from an modern-like interglacial configuration at MIS5e, i.e., ~125 ky BP. Based on these calculations, Bart and Owolana (2012) concluded that both the conventional and alternative views are feasible working hypotheses for the timing of the grounding event for the Gray Unit in Glomar Challenger Basin (Bart and Owolana, 2012).

### 1.3 Objective of Study

Although the examination of the Gray Unit GZW by Bart and Owolana (2012) could not conclusively demonstrate which interpretation is correct, they were able to calculate preliminary duration estimates for the Brown, Red, and Purple Unit grounding events. Using the retreat-mode flux, they estimated that the durations for the Brown, Red, and Purple Units GZW$s$ were 3.9 ky, 37.9 ky, and 16.3 ky, respectively (Bart and Owolana, 2012). If correct, these durations obviously exceed the maximum duration of the post-LGM interval. Hence, their prediction is inconsistent with the conventional view of how near surface GZW units in eastern Ross Sea relate to the LGM and post-LGM timeframe. However, their volume estimates for the Red and Brown GZW units were not based on detailed mapping. Consequently, the Bart and Owolana (2012) estimated grounding event durations need to be investigated further.

The objective of this study was to determine the duration of the Red Unit grounding event to evaluate whether it could have been deposited within the post-LGM timeframe. A
concurrent study evaluated the duration of the Brown Unit GZW (Kirst, in prep.). This study will evaluate the duration of the Red Unit GZW using the framework laid out by the Bart and Owolana (2012). The seismic-based study includes high-resolution seismic surveys to map the extent of the Red Unit GZW across eastern Ross Sea, determining the total volume of the Red Unit GZW, and using the two end-member sediment flux (i.e. advance and retreat-modes) to evaluate the Red Unit grounding event duration.
2. Methods

2.1 Red GZW Volume

This study applied the methods outlined by Bart and Owolana (2012) to the Red Unit. A comprehensive correlation of the top and base of the Red Unit was done using six single-channel seismic surveys (M89, PD90, NBP94, NBP95, NBP03, and NBP08, Figure 2). These seismic grids included over 2000 line kilometers of single-channel data. M89 was acquired with a sparker source. PD and NBP data were acquired with a generator injector airgun source. The top and base of the Red Unit were contoured by hand as time-structure maps in milliseconds below sea level. An isopach map of the Red Unit thickness in milliseconds was generated by hand by subtracting the two-way travel time (TWTT) from the top and base of the Red Unit. The top and base time structure contour maps and isopach map were scanned and saved in JPEG format using a HP Designjet wide format scanner. The resulting JPEG file was then imported into Adobe Illustrator and digitized. The top and base of the Red Unit and isopach thickness in milliseconds were converted to sediment thickness in meters using a sediment velocity of 1750 ± 200 meters/second (m/s) based on data from Cochrane et al. (1995) using Equation 1:

\[ T = \frac{Vt}{2} \]  

where \( T \) is the sediment thickness (in meters), \( V \) is the sediment velocity (in m/s) and \( t \) is the two-way travel time (in seconds).

The Red Unit sediment volume was calculated using the digitized Red Unit isopach map. This is more accurate than the hand gridding approach used by Bart and Owolana (2012). The isopach map has a contour interval of 10 msec and an average thickness was assigned to each
interval. The isopach was exported from Adobe Illustrator as a high resolution JPEG file to Paint.NET (digital photo editing software). Using Paint.NET, the area of each contour interval was calculated in square pixels. The area of a 3000m by 3000m box was also calculated in square pixels. The area of each contour interval was then converted to square meters using this ratio:

\[
\frac{\text{Area box (pixels}^2\text{)}}{\text{Area box (meters}^2\text{)}} = \frac{\text{Area contour interval (pixels}^2\text{)}}{\text{Area contour interval (meters}^2\text{)}}
\]  

(2)

The volume for each contour interval was calculated using the average thickness (in meters) for each interval. The total sediment volume for the Red Unit is the sum of the volumes for each contour interval.

### 2.2 Retreat and Advance Mode Sediment Flux Estimates

Bart and Owolana (2012) used the modern sediment flux at the Whillans Ice Stream to estimate sediment yield and to determine a modified flux to calculate paleo grounding event duration for the Gray Unit GZW on the outer-shelf. These calculations are based on several assumptions. Firstly, sediment yield and flux should be expected to vary during a glacial cycles (Hallet et al., 1996, Elverhoi et al., 1998, Koppes and Montgomery, 2009, Fernandez et al., 2011). Secondly, yield in the interglacial retreat was two orders of magnitude higher than yield in the glacial advance because of the rapid flow of warm ice during the interglacial (Koppes and Montgomery, 2009, Fernandez et al., 2011). Thirdly, paleo sediment yield can be calculated using the modern sediment flux from the Whillans Ice Stream at the Siple Coast. The modern GZW at the Whillans Ice Stream is believed to have been deposited in the last 1000 ±200 years. The modern flux at Whillans Ice Stream is estimated to be 200 ± 18 m³/m/a (Anandrakrishnan et al., 2007). Bart and Owolana (2012) calculated the modern 3D sediment flux (Q_{3D}) to be 5.5 ±
0.5 \times 10^7 \text{ m}^3/\text{a}. Modern 3D sediment flux is defined as the total quantity of sediment that leaves the drainage basin, so passes the grounding line and enters the receiving base per unit of time (Bart and Owolana, 2012). Finally, Bart and Owolana (2012) assumed that all sediment was transferred to the GZW.

Using the modern 3D flux and the modern area of the Whillans Ice Stream drainage basin area (Figure 6), Bart and Owolana (2012) calculated the average sediment yield using Equation 3:

\[
S \left( \frac{\text{m}^3}{\text{m}^2 \text{a}} \right) = \frac{Q_{3D}(\text{m}^3/\text{a})}{\text{Drainage Area (m}^2)}
\]

where \( S \) is yield and \( Q_{3D} \) is 3D sediment flux. While most of the modern drainage area for the Whillans Ice Stream is composed of sedimentary rock, a significant percentage of the drainage area presumably is underlain by Precambrian metamorphic basement rock (Bart and Owolana, 2012), which would produce a lower sediment yield. Bart and Owolana (2012) estimated that metamorphic basement rock produces a yield 30% less than that of sedimentary strata based on data from Schlunegger et al. (2001). Consequently, the yield for metamorphic basement can be calculated using Equation 4:

\[
S_m = 0.7 * S_s
\]

where \( S_m \) is the yield for the drainage basin composed of metamorphic basement rock and \( S_s \) is the yield for the drainage basin underlain by sedimentary rock. Using equations 3 and 4, Bart and Owolana (2012) calculated \( S_s \) to be \( 2.66 \pm 0.24 \times 10^{-4} \text{ m}^3/\text{m}^2/\text{a} \) and \( S_m \) to be \( 1.86 \pm 0.17 \times 10^{-4} \text{ m}^3/\text{m}^2/\text{a} \) (Table 1).
This study will apply the methods described above to the Red Unit based on the assumption that the modern sediment flux at the Whillans Ice Stream can be used to calculate paleo sediment yield for the Red Unit, and therefore, the $S_s$ and $S_m$ sediment yields calculated for the Gray GZW can be directly applied to the Red-GZW drainage basin. However, this study will also account

Table 1: A) Modern drainage basin areas that converge to Glomar Challenger Basin (GCB), Whales Deep Basin (WDB), and Little America Basin (LAB) (see Figure 6). The total drainage area is divided into what rock type underlies the grounded ice for yield estimates with $S=$ sedimentary rock, $M=$metamorphic rock, and $V=$volcanic rock. B. Drainage areas calculated using data from Rignot et al. (2002) and Adobe illustrator and paint.net software with an error of ±0.6%. C. Retreat-mode yields, $S_S$, $S_M$, and $S_V$, (for sedimentary, metamorphic, and volcanic rocks, respectively) and associated retreat-mode flux, $Q_{3DR}$. D) Advance-mode yields and associated advance-mode flux, $Q_{3DA}$. The last row for column B is the total paleo drainage area for the Red GZW. The last row for column C and D is the total flux contributions of all the areas delivering sediment to GCB, WDB, and LAB during the Red grounding event.

<table>
<thead>
<tr>
<th>A. Map region (figure 6)</th>
<th>B. Drainage Area ($m^2$)</th>
<th>C. Retreat-mode yield and flux</th>
<th>D. Advance-mode yield and flux</th>
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</thead>
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<tr>
<td></td>
<td>$S_s$ ($m^3/m^2/a$)</td>
<td>$S_m$ ($m^3/m^2/a$)</td>
<td>$S_v$ ($m^3/m^2/a$)</td>
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<td>A/B_m</td>
<td>8.49±0.05 x 10$^{10}$</td>
<td>1.86±0.17 x 10$^{-4}$</td>
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<tr>
<td>C_s</td>
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<td>2.66±0.24 x 10$^{-4}$</td>
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<tr>
<td>C_m</td>
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<td>1.86±0.17 x 10$^{-4}$</td>
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<tr>
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<tr>
<td>D_v</td>
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<td>1.99±0.18 x 10$^{-4}$</td>
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(Table 1 continued)

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<th>A. Map region (figure 6)</th>
<th>B. Drainage Area (m²)</th>
<th>C. Retreat-mode yield and flux</th>
<th>D. Advance-mode yield and flux</th>
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<tr>
<td></td>
<td>$S_s$ (m³/m²a)</td>
<td>$S_m$ (m³/m²a)</td>
<td>$S_v$ (m³/m²a)</td>
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<td>F_s</td>
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<td>D_v</td>
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<tr>
<td>SUF</td>
<td>2.35±0.01 x 10¹¹</td>
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<td>1.86±0.17 x 10⁻⁴</td>
</tr>
<tr>
<td>Total</td>
<td>1.35±0.01 x 10¹²</td>
<td>-</td>
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</table>

for three new factors: 1) an increase in the paleo drainage basin size to include Whales Deep and Little America Basins, 2) an adjustment in sediment yield for volcanic basement rock in Marie Byrd Land, and 3) an adjustment to the estimated grounding event duration to account for intermittent ice stream stagnation.

1) Preliminary mapping using seismic data acquired in 2008 shows that the Red Unit can be mapped across several ice streams in eastern Ross Sea including Glomar Challenger, Whales Deep, and Little America basins. In other words, the Red Unit is not confined to the paleo
troughs as is the case for the Gray Unit GZW. This situation contrasts with the drainage basin for the Gray GZW, which only includes Glomar Challenger Basin paleo ice stream. The area of the larger paleo drainage basin for all of eastern Ross Sea was calculated using data from Rignot et al. (2011) and paint.net software.

2) The paleo drainage basin for the Red Unit in eastern Ross Sea thus includes parts of Marie Byrd Land, which is composed of mid-Cretaceous plutonic basement rocks including granitoids, basalts, and gabbros (Weaver et al., 1994). Volcanic basement rock produces a yield that is 25% less than that of sedimentary strata (Schlunegger et al., 2001). Therefore, the yield for Marie Byrd Land volcanic rock underlying grounded ice is estimated using Equation 5:

$$S_v = 0.75 * S_s$$

(5)

where $S_v$ is the yield for the drainage basin composed of volcanic rock and $S_s$ is the yield for the drainage basin underlain by sedimentary rock.

3) Very wide ice streams are inherently unstable, and therefore can decelerate or completely stagnate for significant periods of time (Joughin et al., 2002). Stagnation can be caused by a switch from basal melting to basal freezing (Christoffersen and Tulaczyk, 2003). The modern grounding event at the Kamb Ice Stream began ~ 1000 ± 200 years ago (Anandakrishnan et al., 2007) and that the Kamb Ice Stream was stagnant for the last 150 ± 33 years or ~15% of the grounding event duration (Joughin et al., 2002, Christoffersen and Tulaczyk, 2003). However, the modern grounding event duration and ice stream stagnation duration are very difficult to quantify. Because ice streams are unstable, it is probable that the Kamb Ice Stream could have been stagnant over multiple intervals throughout the past 1000 years, i.e., during the modern grounding event. A conservative assumption is that the ice stream
stagnation could have ranged from 15%-30% of the modern grounding event duration with an average stagnation of 22.5 ± 7.5%. The ice stream stagnation time of 150 ± 33 years should be considered an absolute minimum stagnation time. This study assumes that the paleo ice streams that deposited the Red Unit were stagnant for 15% of the grounding event duration. This is the most conservative stagnation estimate. The grounding event duration for the Red Unit was calculated using Equation 6:

\[ d = \frac{V_s}{Q} + \left(\frac{V_s}{Q}\right) \times 0.15 \]  

(6)

where, \( d \) is grounding event duration in years (a), \( V_s \) is sediment volume (m\(^3\)), \( Q \) is the flux (m\(^3\)/a), and .15 is a constant used for ice stream stagnation. The duration was calculated using modern, retreat-mode, and advance-mode fluxes (Table 2).

One aspect that could affect the calculated volume and grounding event duration of the Red Unit is the porosity and water content of the unit. Domack et al. (1999) collected several sediment piston core samples into diamict at the seafloor from the middle and outer shelf throughout the Glomar Challenger Basin. These samples show that the GZW sediment consists of diamicton that is uniform in character, contains clasts, and lacks observable bioturbation structures. In >85% of the cores collected by Domack et al. (1999) in Ross Sea, the average water content of diamicton was 30%, and in all cases, the pore waters were of marine origin. However, deforming basal till at the Whillans Ice Stream has a water content of 45% (Kamb, 2001). Deforming basal till apparently loses 15% water content as it passes the grounding line and is deposited in the GZW.

Even though the Red Unit has a water content of roughly 30%, it does not affect the calculated volume and grounding event duration. This is because the sediment yield, flux, and
volume of the Red Unit calculated in this study account for both the water content and the ~15% water loss of the Red Unit. Firstly, the calculated volume of the Red Unit includes the water within the sediment. Secondly, the calculated sediment yields (Ss, Sm, Sv) for the Red Unit are essentially ‘effective yields’ meaning that they account for the sediment and associated water that gets transferred to the sea bed. The ‘effective yields’ are less than the ‘actual yields’ because the ‘actual yields’ account for the ~15% water loss to the ocean. Because of this, if the ‘effective yields’ calculated in this study are compared to sediment yields calculated in similar studies, they should be roughly 15% smaller. Lastly, the paleo sediment flux calculated in this study should also be considered an ‘effective flux’ because it includes the sediment and water that gets directly transferred to the sea bed. This ‘effective flux’ is roughly 15% less than the ‘actual flux’ which includes water loss to the sea. Because the calculated volume of the Red Unit, the sediment yield, and the sediment flux all include water content within the sediment, the calculated grounding event duration for the Red Unit (equation 6) remains the same.

2.3 Sources of Error

This study tracked the errors that could potentially be associated with the calculated grounding event duration for the Red Unit. The sources of error include the dimensions of the modern GZW (Anandrakrishnan et al., 2007), the modern grounding event duration (Anandrakrishnan et al., 2007), both the modern and paleo sediment flux (Bart and Owolana, 2012), the modern sediment yield (Bart and Owolana, 2012), the sediment velocity (Cochrane et al., 1995), ice stream stagnation duration (Joughin et al., 2002, Christoffersen and Tulaczyk, 2003), the dimensions of the drainage area (Rignot et al., 2011), and, finally, the human error associated with mapping the top and the base of the Red Unit by hand.
Bart and Owolana (2012) assessed the error associated with the dimensions of the modern GZW at the base of the Whillans Ice Stream as calculated by Anandrakrishnan et al. (2007). They did this by using a sensitivity study of the 3D volume of the modern GZW. The average error associated with the dimensions of the modern GZW is ± 9%. Because the modern and paleo sediment flux, and the modern sediment yield used to calculate the Red Unit grounding event duration are based on the dimensions of the modern GZW, the average error associated with the calculated sediment flux and yield is also ± 9% (Bart and Owolana, 2012). The average error associated with the modern grounding event of 1000 years (Anandrakrishnan et al., 2007) is estimated by this study to be ± 20%. The sediment velocity used to convert the top and base of the Red Unit and isopach thickness from milliseconds to meters was 1750 ± 200 meters/ second (m/s) (Cochrane et al., 1995). The error of ± 11.5% was given by Cochrane et al. (1995). The error associated with the ice stream stagnation of 150 years was determined by Joughin et al. (2002) ranged from 15-30%. This study assumed an average error of 22.5%, amounting to 150 ± 33.8 years. There was slight error associated with the calculated dimensions of the drainage area. Rignot et al. (2011) determined that the satellite imagery they used to map the drainage area had an error of ± 300 meters. This study calculated the average error to be ± 0.6%. Finally, there was inherent error in mapping the Red Unit by hand. The error associated with this mapping is estimated to be ± 2%. 
3. Results

3.1 Extent of the Red Unit from Seismic Surveys

The base of the Red Unit corresponds to the Purple Unconformity which represents the culmination of erosion and deposition during the Purple Unit grounding event (Figure 1A). The genetic top of the Red Unit is defined by the Red Unconformity which represents the culmination of erosion and deposition during the Red Unit grounding event (Figure 1A). However, in some areas (such as the Whales Deep and Little America paleo troughs), the top of the Red Unit is defined by erosion that occurred during the subsequent Brown Unit grounding event. In those places, the Brown Unconformity defines the top of the Red Unit (Figure 1F, G, H, J, K, L, M, P).

The line drawing interpretations (Figure 1) show that the Red Unit is a low-relief feature that extends well beyond the limits of Glomar Challenger Basin across Whales-Deep and Little-America basins (Figure 3-5). Unlike the Gray Unit GZW, which is confined to the middle shelf, the Red Unit extends from the outer shelf to roughly 35km north of the calving front (Figure 3-5). The Red Unit GZW has several internal reflectors that dip in a basinward direction or towards the W-NW (Figure 1A, G, H, K, L, S).

Time-structure maps of the top and base of the Red Unit provide an excellent map view of the extent and erosional limits of the Red Unit (Figures 3 and 4). The Red Unit extends approximately 285 ± 14.25km in the N-S direction (from its landward limit to the shelf-edge) and approximately 465 ± 23.25km in the E-W direction (from Glomar-Challenger to Little-America Basin). The Red Unit has several linear erosional limits along the edges of the paleo troughs, particularly, along Whales-Deep Basin. However, the landward erosional limits in the
Glomar-Challenger and Little-America basin are curvilinear. The Red Unit is thick along Hayes and Houtz banks which correspond to the locations at which the Red Unit has its southern most extent.

Figure 3: Time structure map of the top of the Red Unit GZW based on seismic interpretation. The map is in two-way travel time in msecs. The contour interval is 10 msec. The highs are represented by warmer colors while the lows are represented by cooler colors. The solid black line represents the erosional limits of the Red GZW. Glomar Challenger Basin, Whales Deep Basin, and Little America Basin are shown. The Ross Ice Shelf is shown in gray.
Figure 4: Time structure map of the base of the Red Unit GZW based on seismic interpretation. The map is in two-way travel time in msecs. The contour interval is 10 msec. The highs are represented by warmer colors while the lows are represented by cooler colors. The solid black line represents the erosional limits of the Red GZW. Glomar Challenger Basin, Whales Deep Basin, and Little America Basin are shown. The Ross Ice Shelf is shown in gray.
Figure 5: Isopach map of the Red Unit GZW based on seismic interpretation. The map is in two-way travel time in msecs. The contour interval is 10 msec. The Red Unit thickens towards the shelf edge and pinches out along the erosional limits. Progradational foresets dipping towards the NW are represented by arrows. Glomar Challenger Basin, Whales Deep Basin, and Little America Basin are shown. The Ross Ice Shelf is shown in gray.
Figure 6: Modified from Bart and Owolana, 2012. A) Map of Antarctica showing subglacial elevation. The central figure includes the dark yellow shade which shows the modern drainage for the Whillans ice stream as defined from Rignot et al. (2001). The light yellow shade shows the paleo drainage for the Glomar Challenger Basin, Whales Deep Basin, and Little America Basin. The bold lines show Bart and Owolana, 2012 projections of drainage basin divides based on data from Rignot et al. (2010). The brown shade represents bathymetric banks. The grounding line is represented by a dashed-line. B) Ice velocity from Rignot et al. (2010) 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).
3.2 Volume and Grounding Event Durations

An isopach map of the Red Unit illustrates the thickness distribution of the unit across eastern Ross Sea basins and banks (Figure 5). The thickness of the Red Unit ranges from 0 msec (0 m) to 190 ± 3.8 msec (~158 m), with the maximum thickness occurring at the shelf edge. The Red Unit is thick along the banks and thins to 0 m within the troughs. The average thickness of the unit is 66 ± 1.3 m (Figure 5). Using the isopach map, the volume of the Red Unit was calculated to be 2.12 ± 0.06 x 10^{12} m^3 using a velocity of 1750 ± 200 m/s (Table 2). This value represents the minimum sediment volume of the Red Unit because the seismic surveys used in this study do not extend off the shelf (Figure 1). Multichannel seismic data shows that Quaternary strata have appreciable thickness on the slope (Antostrat, 1995), but it is not possible to confidently correlate the top and base of the Red Unit to the lower resolution multichannel seismic data.

The duration of the Red Unit grounding event was estimated using the retreat-mode flux ($Q_{3DR} = 3.24 ± 0.29 \times 10^8$ m$^3$/a), and advance-mode fluxes ($Q_{3DA} = 3.24 ± 0.29 \times 10^6$ m$^3$/a) (Table 2). Using the retreat-mode flux, the duration of the Red Unit grounding event was calculated to have been 7.5 ± 1.5 ky (Table 2, column C). Using the advance-mode flux, the Red Unit grounding event duration was calculated to have been 750.69 ± 159.70 ky (Table 2, column D).
Table 2: 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 3 GZWs. B) GZW volumes as calculated using isopach maps. C) Grounding event duration using retreat-mode flux ($Q_{3DR}$) for GCB, WDB, and LAB. D) Grounding event duration using advance-mode flux ($Q_{3DA}$) for GCB, WDB, and LAB. GCB= Glomar Challenger Basin, WDB= Whales Deep Basin, and LAB= Little America Basin.

<table>
<thead>
<tr>
<th>A. GZW Name</th>
<th>B. GZW Volume (m$^3$)</th>
<th>C. GE duration w/ retreat-mode flux (yr)</th>
<th>D. GE duration w/ advance-mode flux (yr)</th>
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<td>Gray</td>
<td>3.57 ± 0.07 x 10$^{11}$</td>
<td>1,477 ± 312</td>
<td>147,770 ± 31,268</td>
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<tr>
<td>Brown</td>
<td>1.45 ± 0.03 x 10$^{12}$</td>
<td>5,128 ± 1,085</td>
<td>512,886 ± 108,526</td>
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<tr>
<td>Red</td>
<td>2.12 ± 0.06 x 10$^{12}$</td>
<td>7,507 ± 1,588</td>
<td>750,694 ± 158,847</td>
</tr>
<tr>
<td>All GZWs</td>
<td>3.92 ± 0.08 x 10$^{12}$</td>
<td>14,112 ± 2,986</td>
<td>1,390,350 ± 294,198</td>
</tr>
</tbody>
</table>
4. Discussion

4.1 The estimated grounding event durations exceed the maximum time of the post-LGM retreat from the outer shelf

The 750.69 ± 159.70 ky grounding event duration based on the advance-mode flux is obviously too long to fit in the post-LGM time. This duration is significantly shorter than the 2.54 My duration calculated by Bart and Owolana (2012). The smaller duration calculated here is due to the smaller than expected volume of the Red Unit. Nonetheless, this relative long duration for the Red Unit is not surprising given that the advance-mode flux used to calculate grounding event durations is two orders of magnitude smaller than the retreat-mode flux. This long-duration result for the Red Unit grounding event is consistent with the view that the Red Unit represents an amalgamation of erosion and deposition as the WAIS advanced and retreated over the course of multiple glacial cycles (Bart and Owolana, 2012, Bart and Cone, 2012).

Using the retreat mode flux, the Red Unit duration of 7.5 ± 1.5 ky represents 96 ± 19% of the total 7.8 ky post-LGM period. When combined with the calculated retreat-mode durations for the Gray Unit (1.47 ± 0.3 ky) and the Brown Unit (5.1 ± 1.1 ky), the duration for the deposition of all three GZWs is 14.07 ± 3.0 ky which is 180 ± 38% longer than the post-LGM period (Bart and Owolana, 2012, Kirst, in prep).

These calculated durations must also be considered minimum durations. For example, according to Alley et al. (1989), erosion and sediment yield in the drainage basin is highest within the boundaries of ice streams. The sediment yields (Ss, Sm, and Sv) calculated by Bart and Owolana (2012) and by this study, represent the high sediment yield within the ice streams. However, this study applies these high yields to the entire LGM drainage basin when, in fact, they most accurately represent the yields within the modern drainage basin for the Whillans Ice
Stream (Figure 6). The high velocity ice streams represent 17.7% of the modern drainage basin and 2.4% of the LGM drainage basin. Even though the LGM drainage area is roughly 7 times larger than the modern drainage area, the boundaries of the ice streams were not larger during the LGM. Because of this, the sediment flux for the Red Unit and the subsequent grounding event duration for the Red Unit must be considered absolute minimum values.

Given the relatively low resolution of this experimental method and the error associated with the calculated grounding event durations, two conceptual models for the genesis of the near surface stratigraphy were evaluated using the retreat and advance mode fluxes to further investigate these two possibilities of the duration of the Red Unit and of how WAIS grounding line translation relate to the erosion and deposition of the Red Unit. The first conceptual model tests if the three units could have been deposited by subglacial aggradation during pauses in the WAIS grounding line retreat. The second conceptual model tests the amount of time required to complete the grounding-line translations for the three near-surface units in a progradational model.

4.2 Subglacial aggradation is too slow to have produced the observed maximum thickness within the post-LGM time

One possibility of how the Red Unit could have been deposited is by subglacial aggradation during a pause during the overall retreat of the WAIS grounding line. Some conceptual models on the Antarctic continental shelf infer that the continental shelf aggrades only during interglacials and that the slope progrades during glacial periods (Cooper et al., 1989, Larter and Barker, 1989). Recent drill data show that subglacial sediments have appreciable thickness on the Antarctic Peninsula shelf at IODP Site 1097. This demonstrates that aggradation of subglacial deposits does occur on Antarctic shelves. The actual subglacial
processes involved are difficult to confirm because the analogous modern settings are inaccessible (Benn and Evans, 1996). The concept that sediments can be aggraded beneath ice sheets is supported by several studies (Alley et al., 1998, Lawson et al., 1998, Roberts et al., 2002, Evans et al., 1996). Two processes through which the Red Unit could have aggraded are considered.

The first process considered is subglacial melt-out. This process is defined as the slow and passive release of sediment from a debris-rich, stagnant basal ice sheet (Evans et al., 2006, Boulton, 1971, Lawson, 1979a). In this scenario, subglacial till is directly deposited without subsequent transport or deformation (Benn and Evans, 1996, Evans, 2006). Debris-rich basal ice can be widespread throughout glacial systems and, therefore, thick subglacial melt-out till may accumulate by this process (Larson et al., 2006, Evans et al., 2006).

The second process considered is lodgement. This process is defined as sediment deposition by plastering of glacial debris from a sliding ice sheet due to the effects of pressure melting and frictional drag (Evans et al., 2006, Chamberlin, 1895). Lodgement is typically a process associated with the plastering onto a rigid beds but it is possible for clasts to be lodged to soft substrate by the ploughing of the deformable substrate so that it stops the forward momentum of the clasts and gives rise to an aggradational deposit of till (Evans et al., 2006, Boulton, 1982, Clark and Hansel 1989). The thickness of subglacial tills produced by lodgement is difficult to quantify, but studies of modern lodgement tills in Breidamerkurjökull, Iceland indicate that the lodgement process is not capable of producing thick till sequences (Evans et al., 2006, Benn, 2006, Ruszczynska-Szenajch, 2001).
It is unlikely that the Red Unit represents aggradation of subglacial till deposits for several reasons. Firstly, according to Boulton (1996b), subglacial melt-out requires roughly 100 ± 20 m of debris-rich ice to melt to produce a subglacial till sequence 10 ± 2 m thickness. Based on this requirement and the observed maximum thickness of the Red Unit, a 1,580 ± 316 m total thickness of debris-rich basal ice would need to melt to aggrade 158 ± 3 meters thickness of the Red Unit during the 7.5 ± 1.5 ky duration for the retreat-mode grounding event. Within this context, a 3,870 ± 774 m total thickness of debris-rich basal ice would need to melt to deposit all three GZW’s (maximum total of 387 ± 23 m) (Bart and Owolana, 2012, Kirst, in prep, Boulton, 1996b). This thickness of debris-rich ice necessary to deposit the Red Unit is unrealistic when compared to the present-day ice-stream flow rates and thickness of subglacial debris zones (Evans et al., 2006). At the modern grounding line of the Kamb Ice Stream, the basal debris zone has a maximum thickness of 10 ± 2 meters and the average ice-stream velocity is 500 ± 100 m/year (Kamb, 1991). For the maximum dip dimensions of the Red Unit (285 ± 14.25 km), and an average rate of ice-stream flow (500 ± 100 m/year), a maximum of 1 ± 0.2 m of subglacial sediment could be added to the outer shelf every 600 ± 120 years. The maximum thickness of the Red Unit (158 ± 3 m) would thus take 94.8 ± 20.9 ky to aggrade. The total thickness of all three units (387 ± 23 m) would require 232.2 ± 51.1 ky to aggrade. In other words, the inferred rates at which subglacial sediment would aggrade are far slower than is inferred with retreat mode flux calculations.

A retreat-mode grounding event duration of 7.5 ± 1.5 ky for a maximum vertical thickness of 158 ± 3 m for the Red Unit would otherwise suggests that it took 47 ± 9 years to aggrade an 1 ± 0.2 meter thickness of subglacial sediment. This aggradation rate would require that the ice sheet discharge would have to be more than 12x faster than the modern rate to produce the
inferred aggradation rate consistent with the observed maximum thickness of the Red Unit within 7.5 ±1.5 ky time frame. Such a high rate of discharge (6 ± 1 km/year) is unrealistic. Conversely, the subglacial debris zone would have to have been more than 12.5x thicker than the observed 10 ± 2 m thickness to transfer a vertical column of 158 ± 3m to the bed during a 7.5 ±1.5 ky grounding event. Neither the high flux of streaming ice or great thickness of subglacial debris has been observed or modeled.

Secondly, it is unlikely that the Red Unit represents a lodgement till. The thickness of subglacial tills produced by this lodgement process is difficult to quantify, but studies of modern lodgement till indicate that the process is incapable of producing thick till sequences (Evans et al., 2006, Ruszczynska-Szenajch, 2001). In addition, stagnation of the ice streams would tend to freeze sediment to the base of ice, which is a net erosion process.

Thirdly, and perhaps most importantly, there are several internal reflections in the Red Unit that dip in a basinward direction. These stratal surfaces terminate against the underlying Purple Unconformity (Figure 1A, G, H, K, L, S). These internal reflectors are interpreted to be progradational foresets and the termination against the Purple Unconformity is interpreted to be downlap. This stratal arrangement indicates that the grounded WAIS decoupled and retreated after the end of the Purple Unit grounding event. The southern-most foreset stratal surface in the Red Unit requires that WAIS retreated at least 280 ± 14 km (Figure 5). Because progradational foresets are present, the Red Unit could not have been deposited by an aggradational process for those parts of the Red Unit where foresets are present.
4.3 The time required to complete grounding-line translations far exceed the post-LGM time

A fundamental assumption concerning the genesis of GZW Units is that they are progradational features (Bart and Anderson, 1995, Bart, 2003, Anderson et al., 1991, Alley et al., 1989). The internal foresets are present throughout the Red Unit. The most landward foreset surface thus provides a minimum measure of the landward retreat of grounded ice. As the WAIS advanced to the outer-shelf, it eroded the inner continental shelf and streaming ice transported the subglacial debris to the grounding line. At the grounding line, this subglacial debris was subaqueously released to construct low-angle prograding foresets or till deltas. The till deltas advanced basinward through time, but the top and southern limit of the till delta was partially eroded by streaming ice. The advance of grounded ice ended with rapid decoupling retreat, which exposed a subglacially eroded unconformity. During the ensuing interglacial, open-marine sediments aggradationally draped the eroded seafloor unconformity (Bart, 2003).

On the basis of this understanding of how GZWs form with respect to grounding line translations, the amount of time required to complete WAIS grounding line translations for all three (Red, Brown, and Gray) units can be estimated.

If all three GZWs were formed by a progradational delta till model during an overall retreat, then there were significant intervals of time when the ice sheet advanced across the shelf separated by intervals of time when the WAIS retreated inland. For the post-LGM interpretation to be correct, all these grounding line translations would need to have occurred during the post-LGM timeframe.
The stratal constraints on grounding line translations are shown in a conceptual model (Figure 7). The model shows the sequence of WAIS advances and retreats required to deposit the backstepping succession of three separate GZW by the progradational model in the 7.8 ky post-LGM timeframe. The model only considers grounding line translation distance and duration. Prior to the LGM, the Purple GZW (oldest GZW) was deposited as the WAIS advanced from the modern grounding line to the outer shelf. By analogy with the last glacial cycle, WAIS advance occurred over a 100 ± 20 ky period from Marine Oxygen Isotope Stage 5e to Marine Oxygen Isotope Stage 2 (LGM) (Bart, 2004) (Figure 7A). The ice sheet remained at the outer shelf until 11 ± 2.2 ka $^{14}$C BP when WAIS retreat began (Domack et al., 1999). The maximum retreat distance cannot be determined but the southern limit of the Red Unit provides a minimum retreat distance because the entire Red Unit was presumably deposited in a till delta fashion. On this basis of this stratal constraint, the WAIS retreated 320 ± 16 km before re-grounding to begin the Red Unit grounding event (Figure 7B). During the Red Unit grounding event, the isopach map (Figure 5) shows that the WAIS re-advanced to the outer shelf and deposited the Red Unit. This constitutes a minimum 320 ± 16 km grounding line advance after the onset of the overall post-LGM retreat (Figure 7C). Following the culmination of the Red Unit grounding event, the WAIS again retreated. Based on the southern most extent of the Brown Unit, the WAIS retreated at least 285 ± 14 km (Kirst, in prep.) (Figure 7D). The WAIS then re-advanced 285 ± 14 km to the outer shelf to deposit the Brown Unit (Figure 7E). Following the end of the Brown Unit grounding event, the WAIS retreated at least 275 ± 13 km to the landward limit of the Gray Unit (Figure 7F). During the Gray Unit grounding event, the WAIS advanced 185 ± 9 km to a middle shelf position (Figure 7G). Finally, the Gray Unit
grounding event ended and the WAIS retreated 1000 ± 50 km to the modern grounding line (Figure 7H).

This progradational delta till model necessitates that the WAIS grounding line translation would have to include a total of 790 ± 39 km of advance and a total of 1880 ± 94 km of retreat. The retreat of the WAIS can occur rapidly after a decoupling event (Mosola and Anderson, 2006, Bart, 2003, Conway et al., 1999, Domack et al., 1999, Shipp et al., 1999).

Given that penguin rookeries were active on the north side of Ross Island until at least 27 ± 5 ka BP (Emslie et al., 2007) and that the WAIS had advanced to the outer shelf by the start of the LGM (Domack et al., 1999), the grounding line is inferred to have advanced 350 ± 18 km within approximately 8 ± 1.6 ky. This is an average advance rate of 0.0439 ± 0.008 km/yr (Table 3, Column D).

According to this advance rate, the total grounding line advance of 790 ± 40 km requires an advance-duration of 18.02 ± 3.67 ky to complete. The total duration of grounding-line translations for the advance (285 ± 14 km) and retreat (320 ± 16 km) during the Red Unit grounding event is 10.03 ± 2.02 ky (Table 3, Column F). Based on WAIS retreat data presented by Conway et al. (1999) and Domack et al. (1999), the average rate of WAIS retreat was ~8.6 ± 1.15 km/yr (Table 3, Column C). Using this rapid retreat rate, the total grounding line retreat of 1880 ± 94 km requires 16.16 ± 0.84 ky to complete (Table 3, Column C).

Both the grounding line retreat-duration (16.16 ± 0.84 ky) and advance-duration (18.02 ± 3.67 ky) necessary to deposit all three GZWs far exceed the 7.8 ky post-LGM period. The total duration required to complete the grounding line translations for all three post-LGM units (Red, Brown and Gray) would thus have been 34.17 ± 1.78 ky (Table 3, Column E). These durations
Figure 7: Conceptual progradational model showing the sequences of West Antarctic Ice Sheet advances and retreats required to deposit the backstepping succession of 3 separate GZWs (Red, Brown, and Gray Units). A) Prior to the LGM, the Purple GZW (oldest GZW) is deposited as the WAIS advances from the modern grounding line to the outer shelf. This advance occurs over a 100 ky period from Marine Oxygen Isotope Stage 5e to Marine Oxygen Isotope Stage 2. B) The ice sheet remains at the outer shelf until 11 ka $^{14}$C BP when it begins its 319 km retreat to the calving front. C) The WAIS re-advances to the outer shelf and deposits the Red GZW Unit (a 319 km grounding line translation). D) The ice sheet then retreats to at least the landward limit of the Red GZW (285 km). E) The WAIS then advances to the outer shelf deposits the Brown GZW (285km). F) The WAIS retreats to at least the landward limit of the Brown GZW (274 km). G) The ensuing ice sheet advance deposits the Gray GZW on the middle shelf (186 km). H) The WAIS retreats all the way to the modern grounding line (1000 km).
Table 3: Progradational model WAIS grounding line translation distance. A) Grounding line translation modes including advance and retreat modes. B) Grounding line translation distance (km). C) Grounding line translation duration using a retreat rate=8.6 km/yr (from Conway et al., 1999, and Domack et al., 1999). D) Grounding line translation duration using an advance rate=0.0439 km/yr (From Emselie et al., 2007). E) Total grounding line translation duration for the progradational model. F) Grounding line translation duration for the Red GZW Unit.

<table>
<thead>
<tr>
<th>A. Grounding line translation mode</th>
<th>B. Grounding line translation distance (km)</th>
<th>C. Duration (yr) using retreat rate=8.6±1.15 km/yr</th>
<th>D. Duration (yr) using advance rate=0.0439±0.008 km/yr</th>
<th>E. Total duration (yr) for progradational model</th>
<th>F. Duration (yr) for Red GZW Unit</th>
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<tr>
<td>Advance-mode</td>
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<td>18,018±3670</td>
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</tbody>
</table>

also only account for the grounding line translation and, therefore, do not consider any pauses in ice sheet movement. If the Red, Brown, and Gray Units were deposited as three separate events by the progradational model described above, they clearly could not have been deposited in the short post-LGM time.

4.4 The Red Unit could not have been deposited in 7.8 ky post-LGM timeframe

Based on the observations mentioned above, the Red Unit could not have been deposited in the post-LGM interval based on the retreat mode flux. When the retreat-mode grounding event duration for the Red Unit (7.5±1.5 ky) is combined with the retreat-mode durations for the Brown (5.1±1.1 ky) and Gray (1.47±0.3 ky) Units, the total durations surpass the time elapsed since the end of the LGM. If the Red Unit represents a retreat-mode progradational feature, the duration of the grounding line translation (10.03±2.12 ky) alone exceeds the post-LGM time (Table 3, Column F). The Red Unit cannot represent an aggradational feature due to the fact that it contains progradational foresets throughout the unit. Therefore, the Red Unit grounding event
most likely represents a progradational feature that includes an amalgamation of erosion and deposition throughout several glacial cycles prior to the LGM.

4.5 The Red Unit Coin dozer model: vertical stacking of several progradational units rejected for the Red Unit

If the Red Unit represents an amalgamation of erosion and deposition throughout several glacial-interglacial cycles, then the WAIS would have had to advance and retreat several times throughout the Red Unit grounding event. One model that could explain this is vertical stacking of units that were each deposited as till deltas. This conceptual model is summarized by Figure 8. In this scenario, the WAIS advanced to the outer-shelf and deposited a comparatively thin basal sliver of Red Unit after the decoupling retreat following the erosion of the underlying Purple Unconformity (Figure 8A). This basal sliver is analogous to a progradational parasequence in sequence stratigraphic models. The WAIS then retreated to at least the landward limit of the Red Unit (Figure 8B). Retreat was followed by another WAIS advance to the outer-shelf accompanied by deposition of another thin sliver to Red Unit prograding strata (Figure 8C). Multiple advances and retreat over time would have a net aggradation of diamict with the observed thickness and distribution of the Red Unit. The model assumes that decoupling retreat involved negligible sedimentation.

This model is rejected because if the Red Unit were deposited this way, there should be multiple topset reflections within the Red Unit that correspond to subglacial erosion during each advance/retreat cycle. Moreover, where foreset reflections are observed, they extend from the top to the base of the Red Unit. This observation is inconsistent with the model prediction that foresets should occur at multiple stratigraphic levels within the Red Unit.
4.6 The Red Unit Coin-dozer model of horizontal stacking of several progradational units accepted for the Red Unit

An alternative progradational deposition model for the Red Unit is shown in Figure 9. Several glacial-interglacial cycles are shown with each involving grounding line advance and grounding line retreat. At the culmination of each advance, strata is added to the seaward end of the Red Unit. Unlike the vertical stacking model, this horizontal stacking model does not require the presence of topsets and individual sets of foresets within the Red Unit. In Figure 9, the
WAIS advanced to the middle shelf and deposited the oldest part of the preserved Red Unit (Figure 9A) before retreating to at least the landward limit of the Red Unit (Figure 9B). Retreat was followed by a subsequent WAIS re-advance to slightly further onto the middle shelf, depositing a younger part of the Red Unit to that preserved after retreat following in the previous cycle of WAIS advance (Figure 9C). During each advance, the WAIS partially eroded the top of Red Unit. This process of amalgamated erosion and basinward stepping deposition was repeated over several glacial-interglacial cycles until a composite Red Unit was constructed (Figure 9A-G). A key component of the model is that the last major advance removed any evidence of downlap and/or topset development associated with a previous intra-Red Unit WAIS advance and retreat.

This progradational horizontal stacking model predicts that the Red Unit was deposited over several glacial cycles. This coin-dozer model is consistent with the presence of foresets within the Red Unit from top to base (Figure 1A, G, H, K, L, S). But as stated earlier, the grounding line translation associated with the progradational model greatly exceeds the 7.8 ky post-LGM timeframe which means that the Red Unit must have been deposited over several glacial cycles.

4.7 The Red Unit is reassigned to pre-LGM cycles

The data generated in this study strongly suggests that the Red Unit is an amalgamation of erosion and deposition from several glacial-interglacial cycles. The advance-mode duration (750.69 ky) is a maximum duration because each intra-Red Unit advance would have been followed by retreat with the potential to deposit a significant amount of unconsolidated sediment that would easily be eroded and transported to the outer shelf during subsequent intra Red Unit
Figure 9: Conceptual progradational horizontal stacking model demonstrating the sequence of WAIS advances and retreats required to deposit the Red Unit. A) The WAIS advances to the outer-shelf and deposits Red Unit 1. B) The WAIS retreats to at least the landward limit of the Red Unit. C) The WAIS advances to the outer-shelf and deposits Red Unit 2, eroding the top of the Red Unit 1. D) The WAIS retreats to the landward limit of the Red Unit. E) The WAIS advances to the outer-shelf and deposits Red Unit 3, eroding the top of the Red Unit 1 and 2. F) The WAIS retreats to the landward limit of the Red Unit. G) The WAIS advances to the outer-shelf and deposits the Red Unit 4, eroding the top of the Red Unit 1, 2, and 3.
grounding events. On the basis of $\delta^{18}$O data for the Quaternary, it is possible to calculate a grounding event duration for the Red Unit over multiple glacial-interglacial cycles using equation 6. According to Bart and Owolana (2012) the Gray Unit could either be assigned to the post-LGM timeframe (i.e., from MIS2 to MIS1) or could represent a depositional event over the last glacial cycle (i.e., from MIS5e to MIS2). I will evaluate the Red Unit grounding event duration using both scenarios for the Gray Unit deposition presented by Bart and Owolana (2012).

If the Gray Unit was deposited over the last glacial cycle from MIS5e to MIS2, then the Brown Unit grounding event duration is assigned to a 125 ky period between MIS8 to MIS6 (Kirst, 2013). Subsequently, the Red Unit is assigned to a 140 ky period between MIS11 to MIS8 (Figure 10A). All three units (Red, Brown, and Gray) were deposited in roughly less than 400 ky over 4 glacial-interglacial cycles. These durations are shown on a $\delta^{18}$O curve of ice volume over the past 1 million years (via stacked deep-sea core benthic $\delta^{18}$O (Lisiecki and Raymo, 2005) (Figure 10A). If the Gray Unit is assigned to the post-LGM timeframe from MIS2 to MIS1, then the Brown Unit grounding event duration represents a 114 ky period between MIS6 to MIS2. Therefore, the Red Unit is assigned to a 145 ky period between MIS8-9 and MIS6 (Figure 10B). In this scenario, all three units (Red, Brown, and Gray) were deposited in roughly less than 280 ky over roughly 4 glacial-interglacial cycles.

4.8 Red Unit Extent and Volume: Should the Red Unit still be considered a GZW?

The typical assumption of GZW genesis is that they are formed as ice streams that drain the ice sheet and deposit a till delta tens of meters thick at the terminus of the ice stream. This means that GZWs should be confined to the axes of paleo troughs (Alley et al., 1989, Mosola
Figure 10: Simulated total global ice volume over the past 1 million years via stacked deep-sea-core benthic δ¹⁸O. This includes inferred total Antarctic ice volume in a long-term simulation with variations of sub-ice melt and other forcings parameterized mainly from the deep-sea-core δ¹⁸O record. The deep-sea-core benthic δ¹⁸O record and the calculated Gray, Brown, and Red Units deposition durations are juxtaposed against a timeframe of 1 Ma BP. Deep-sea-core benthic δ¹⁸O curve adopted from Lisiecki and Raymo, 2005. A) If the Gray Unit is assigned to the last glacial cycle (i.e., between MIS5e and MIS2), then the Red Unit was deposited over 2 separate 100 ky-glacial cycles between MIS11 and MIS8 in a 140 ky period. B) If the Gray Unit represents a post-LGM deposit, then the Red Unit was deposited over 2 separate 100 ky glacial cycles between MIS8-9 and MIS6 in a 145 ky period.
and Anderson, 2006). The Gray Unit fits this description in that it is confined to the Glomar-Challenger and Whales-Deep paleo troughs (Figure 2) (Bart and Owolana, 2012). However, mapping of the Red Unit revealed that it is not confined to the troughs but extends across the paleo banks (Figure 3-5).

Mapping of the Red Unit indicates that a large part of the Red Unit was eroded during the Brown Unit grounding event. This erosion is especially evident in the troughs where the Brown Unconformity truncates the entire Red Unit (Figure 1). Because the Red Unit is extensively eroded in the troughs (Figures 3, 4, 5), it is inferred that the unit extended across all three basins at the culmination of Red Unit deposition. In other words, erosion at the end of the Brown Unit greatly eroded through the Brown and Red units. There is not clear indication that Red Unit troughs existed at the end of the Red Unit. The major post-depositional erosion of the Red Unit by the Brown Unconformity means that the original volume of the Red Unit was larger by an amount removed at the erosional vacuity of the Whales-Deep and Little-America basins shown on the Isopach Map (Figure 5). The seismic stratigraphy of the outer shelf does not reveal whether ice streams existed at the axes of these locations during the formation of the Red Unit. If the Red Unit had been deposited by several isolated ice streams, the Red Unit would be confined to paleo troughs existing at the end of the Purple Unit grounding event. The isopach and time structure mapping therefore suggests that the Red Unit is a broad line-sourced till delta feature that prograded across Ross Sea as opposed to a point-sourced progradational feature associated with deposition at the mouth of ice streams. Evaluating the implications of these observations for ice sheet discharge and mass balance are beyond the scope of this study but should be investigated in future studies.
5. Conclusions

1. The purpose of this study was to determine if the Red Unit (as defined by Bart, 2004) could have been deposited in the conventional post-LGM timeframe. This study used the framework laid out by Bart and Owolana (2012) to calculate the volume of the Red Unit and the duration of the Red Unit grounding event. The volume of the Red Unit was estimated to be $2.12 \pm 0.06 \times 10^{12} \text{ m}^3$. The advance and retreat mode durations were estimated to be $750 \pm 159$ ky and $7.5 \pm 1.5$ ky, respectively.

2. The advance-mode duration far exceeds the 7.8 ky post-LGM timeframe. The retreat-mode duration nearly fits within the post-LGM timeframe but represents $96 \pm 19\%$ the maximum post-LGM interval. When combined with estimated retreat-mode durations for the Brown ($5.1 \pm 1.1$ ky) and Gray Units ($1.47 \pm 0.3$ ky), the total duration for all three units far exceed the 7.8 ky post-LGM timeframe (Bart and Owolana, 2012, Kirst, in prep.) However, due to the experimental nature of this study, two conceptual depositional models were considered to see if the Red Unit could still potentially be deposited in a post-LGM window. For the progradational model, the grounding-line translations were estimated to be too long (10 ky) for the Red Unit to have been deposited within the post-LGM timeframe. Moreover, the presence of progradational foresets within the Red Unit exclude the aggradational model. On this basis, the possibility that the Red Unit was deposited since the end of the LGM was excluded.

3. The Red Unit must represent an amalgamation of deposition and erosion over several glacial-interglacial cycles. Because of the presence of foresets, this study suggests that the Red Unit was dominantly formed by progradational processes. Two models of progradational deposition over
a long period of time were considered for the Red Unit: 1) a coin-dozer vertical stacking model and 2) a coin-dozer horizontal stacking model. The vertical stacking model predicts that several topsets and individual foresets at multiple stratigraphic levels should be observed within the Red Unit. These stratal patterns were not observed and hence this model was excluded from further consideration. The observed features are more consistent with the horizontal stacking coin-dozer model of deposition.

4. Using the $\delta^{18}$O curve of ice volume (Lisiecki and Raymo, 2005), the Red Unit represents an amalgamation of deposition and erosion over either a 140 ky period from MIS11 - MIS8 or a 145 ky period from MIS8-9 and MIS6. This spans over two 100 ky-glacial cycles.
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Vita

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