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New age control on a mid-shelf grounding event in Eastern Basin, Ross Sea

Amy Noelle Cone
Louisiana State University and Agricultural and Mechanical College

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NEW AGE CONTROL ON A MID-SHELF GROUNDING EVENT IN EASTERN BASIN, ROSS SEA

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 of Science

in

The Department of Geology and Geophysics

by

Amy Noelle Cone
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Acknowledgments

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Abstract

It is widely accepted that the West Antarctic Ice Sheet (WAIS) was grounded at the continental shelf edge in Eastern Ross Sea during the Last Glacial Maximum (LGM), but the precise chronology is debated. Existing post-LGM ice retreat chronologies are considered suspect because nearly all have been developed using radiocarbon dating of acid-insoluble organics (AIO). Foraminifer tests yield more accurate radiocarbon dates than AIO because unlike loose sediment, foram tests are unlikely to be contaminated by allochthonous carbon, but unfortunately forams are sparse in Antarctic marine sediment cores. Here I utilized a new 3-D multibeam survey of a mid-continenetal-shelf grounding zone wedge (GZW) and report four consistent radiocarbon dates of forams from four different depth intervals at two core sites on the foreset of the GZW in Eastern Basin, Ross Sea. The forams dated in this study most likely represent a mixture of in situ forams and forams reworked a short distance. These new radiocarbon dates are inconsistent with dates from Western Ross Sea and suggest that the WAIS began retreat across the Ross Sea Eastern Basin prior to 31,000 $^{14}$C yr BP, more than 10,000 years earlier than previously thought. In the future, if in situ forams can be isolated from foreset sediments within other GZWs, precise dates for grounding event chronologies can be developed, which would ultimately permit us to relate the WAIS retreat to other high-resolution, proxy-based evidence of potential climatic and eustatic forcing.
1. Introduction

Numerous studies have attempted to evaluate the chronology of the West Antarctic Ice Sheet (WAIS) retreat since the Last Glacial Maximum (LGM) (e.g. Conway et al., 1999; Shipp et al., 1999, Licht and Andrews, 2002; Mosola and Anderson, 2006), which occurred about 18 ka according to the relative sea-level reconstruction by Waelbroeck et al. (2002). It is widely accepted that at LGM, the ice sheet was grounded at the Ross Sea continental shelf edge, and subsequently retreated to its present day position in a series of two to four steps (Mosola and Anderson, 2006). Determining the detailed manner and timing of ice retreat across the Ross Sea after LGM will provide perspective into the stability of the current WAIS grounding event. In addition, a detailed chronology is needed to ascertain which phenomena cause WAIS advances, pauses, and retreats. Better constraining retreat mechanisms is especially important today because if the WAIS were to completely collapse, it would cause a rise in global sea level of 5 to 6 m (Conway et al., 1999), which would have devastating effects on coastal cities and the global economy.

1.1 Previous studies

Radiocarbon dates documenting ice retreat since LGM have been obtained in numerous locations around Antarctica. Anderson et al. (2002) provide a complete review of evidence of ice retreat after LGM. In the past, radiocarbon dating of material from terrestrial locations, such as dating of penguin remains, as well as that of marine material, including sediments, foram tests, and shells, has been employed to date Antarctic ice sheet retreat. Dating material from terrestrial locations, while a relatively accurate method, is only a possibility where terrestrial locations are in close proximity to previous ice sheet grounding line positions. In the marine realm, sediments, tests, and shells can be dated from both glacial till and post-glacial deposits. However, the ocean
reservoir effect, which is amplified in the Southern Ocean (Ohkouchi and Eglinton, 2008), as well as carbon contamination may cause inaccuracies in marine radiocarbon dates. In this paper, most dates from previous studies are reported as $^{14}$C yr BP (the dates have not been calibrated to calendar years), except where only calendar years were given in the previous study.

1.1.1 Pine Island Bay, the Antarctic Peninsula, the Windmill Islands, and the Pennell Coast

According to radiocarbon dating of forams in Pine Island Bay (see Figure 1), ice was grounded at the continental shelf edge in that location at LGM, and retreated to a mid-shelf position ~16,000 $^{14}$C yr BP (Lowe and Anderson, 2002). The grounding line reached its present day position ~10,000 $^{14}$C yr BP (Lowe and Anderson, 2002).

On the western margin of the Antarctic Peninsula (see Figure 1), the ice sheet was grounded at the shelf break during LGM (Sugden et al., 2006), and began retreating by 12,430 $^{14}$C yr BP according to radiocarbon dates from foraminifera (Pope and Anderson, 1992). Marguerite Bay was deglaciated by ~9000 $^{14}$C yr BP, according to Bentley et al. (2005), who used radiocarbon dating of penguin remains. Clapperton and Sugden (1982) radiocarbon dated barnacle shells and concluded that George VI Sound was ice-free by 6000 $^{14}$C yr BP. The ice retreat chronology is less constrained for the eastern margin of the Antarctic Peninsula, but Evans et al. (2005) used acid-insoluble organic (AIO) radiocarbon dates to conclude that the ice sheet was grounded at the shelf edge during LGM and Brachfeld et al. (2003) determined that grounded ice had vacated the eastern margin by 10,700 cal yr BP. These data fit with results from James Ross Island (see Figure 1), where radiocarbon dating of mollusks revealed that declaciation occurred shortly before 7400 $^{14}$C yr BP (Hjort et al., 1997).
Figure 1. Map showing the study areas of various previous studies mentioned in this paper concerning ice retreat in Antarctica since the Last Glacial Maximum.
Using radiocarbon dating of terrestrial and lacustrine sediments as well as penguin remains, Goodwin (1993) determined that the Windmill Islands (see Figure 1) off the Wilkes Land coast deglaciated after LGM between 8000 and 5500 $^{14}$C yr BP.

Wellner (2001) used radiocarbon dating of foraminifera within till from the Pennell Coast region (see Figure 1) and determined that ice advanced onto the shelf after 35,000 $^{14}$C yr BP. She also dated forams, bryozoans, algae, and shells from within marine units above till in cores from the Pennell Coast region and concluded that the continental shelf was ice-free by 13,000 $^{14}$C yr BP, and possibly by 15,645 $^{14}$C yr BP.

1.1.2 Weddell Sea and Prydz Bay

Grounded ice is not thought to have occupied the regions of the Weddell Sea and Prydz Bay (see Figure 1) during LGM. In the Weddell Sea, Anderson and Andrews (1999) have interpreted deglaciation to have occurred prior to 26,000 $^{14}$C yr BP, on the basis of radiocarbon dating of forams within ice rafted debris (IRD) deposits. The IRD had to have been deposited when ice did not cover the Weddell Sea, so the presence of material 26,000 $^{14}$C yr old within IRD deposits indicates that the Weddell Sea was ice-free by 26,000 $^{14}$C yr BP. These results are consistent with the results of an earlier study by Elverhoi (1981). In that study, shells and bryozoans within Weddell Sea glacial marine deposits were dated to 21,840 and 28,130 $^{14}$C yr BP, while shells and bryozoans within sediment interpreted to be till were dated to 31,290 and 37,830 $^{14}$C yr BP. This suggests that the transition from glacial to marine sedimentation took place between 28,130 and 31,290 $^{14}$C yr BP, which is consistent with the estimate by Anderson and Andrews (1999).

Domack et al. (1998) used sedimentological analyses to conclude that grounded ice did not occupy Prydz Channel during LGM. Instead, Prydz Channel was covered by an ice shelf.
Thus, continental shelf edge grounding must have taken place prior to 33,600 yr BP, according to foram radiocarbon dates. This means that during LGM, ice in Prydz Bay was not as expansive as it was during previous glaciations. Domack et al. (1998) attribute this to the possibility that duration of a glacial episode may be more influential than the associated sea level change on the growth of the Prydz Bay ice sheet.

1.1.3 Western Ross Sea

Because of the high sedimentation rates and organic rich sediments in the Western Ross Sea, as well as the close proximity of terrestrial settings from which accurate radiocarbon dates can be obtained, a relatively detailed ice retreat chronology has been developed for the Western Ross Sea by previous researchers (e.g., Baroni and Orombelli, 1991; Colhoun et al., 1992; Licht et al., 1996; Conway et al., 1999; Hall and Denton, 2000; Baroni and Hall, 2004; Hall et al., 2004; Emslie et al., 2007; McKay et al., 2008). Shipp et al. (1999) identified a grounding zone wedge (GZW) just north of Coulman Island at approximately ~74°S that presumably represents deposition by the ice sheet during LGM. Domack et al. (1999) provide age control for this GZW using dates from both glacial till and the pelagic drape overlying the till. The till dates as old as 33,000 $^{14}$C yr BP are interpreted as including reworked organic matter. When corrected for old core-top ages, the downcore pelagic drape dates provide a constraint on when open marine sedimentation resumed on the outer shelf. This occurred around 11,000 $^{14}$C yr BP. Therefore, the grounding line in the Western Ross Sea began retreat from its maximum seaward extent by 11,000 $^{14}$C yr BP (Domack et al., 1999). McKay et al. (2008) proposed that the ice sheet retreated in the Western Ross Sea earlier than previous estimates, and that the grounding line passed south of Ross Island ~10,000 $^{14}$C yr BP. However, previous researchers propose that the grounding line passed north of the Drygalski Ice Tongue at 9600 $^{14}$C yr BP (Emslie et al., 2007),
north of Ross Island at 7600 $^{14}$C yr BP (Conway et al., 1999), and the southern Scott Coast ~6600 $^{14}$C yr BP (Hall et al., 2004) (see Figure 2 for locations of landmarks). According to these dates, which were obtained from acid-insoluble organics (AIO) (McKay et al., 2008), penguin remains (Emslie et al., 2007; Hall et al., 2004), and shells (Conway et al., 1999), ice retreated from Western Ross Sea after it retreated from Eastern Ross Sea, which was closer to 20,000 $^{14}$C yr BP (Mosola and Anderson, 2006). The early retreat in Eastern Ross Sea may be due to greater water depths, fewer shallow banks where the ice sheet could have grounded, and a thinner ice sheet in the Ross Sea Eastern Basin (EB) (Mosola and Anderson, 2006).

1.1.4 Ross Sea Eastern Basin

The retreat chronology for Eastern Ross Sea is less well constrained than that for Western Ross Sea. Conway et al. (1999) propose that the grounding line unhinged from a location north of Roosevelt Island (see Figure 2) at about 3200 yr BP based on the bump amplitude profile of Roosevelt Island and model calculations. However, EB grounding line locations proposed by Conway et al. (1999) are based on projections from terrestrial radiocarbon dates along Western Ross Sea as no coherent EB radiocarbon dates were available at that time. Thus, these grounding line locations are not well constrained.

By subsequent geophysical mapping, Mosola and Anderson (2006) identified more precise locations of several EB GZWs. Each GZW represents sediment deposition at the grounding line of the WAIS during a pause in its retreat. The locations of the GZWs define where the WAIS grounding line was located at different times during its retreat, but the age control remains poor due to the scarcity of dateable material within the marine sediments. The dates obtained by Mosola and Anderson (2006) indicate early retreat in EB and thus are seemingly inconsistent with the “swinging gate” retreat chronology for the Ross Sea proposed by
Figure 2. Map of the Ross Sea showing the locations of various landmarks mentioned in this paper (Coulman Island, Franklin Island, Ross Island, Roosevelt Island, the Drygalski Ice Tongue, the Scott Coast, and Marie Byrd Land), as well as the present-day position of the Ross Ice Shelf.
Conway et al. (1999). However, Mosola and Anderson (2006) view their AIO dates as suspect because the AIO may contain older carbon, causing the dates to be older than the sediment deposition episode.

In a review of near-surface seismic stratigraphy, Bart (2004) identified four distinct seismic units in the EB study area (see Figure 3). These units are GZWs. The Purple Unit is stratigraphically the oldest unit, representing deposition at the continental shelf edge, presumably during LGM. The Red, Brown, and Gray Units, respectively, were deposited on top of the Purple Unit during back-steps in WAIS grounding line retreat from the continental shelf edge.

1.2 Excess grounding zone wedge volume

Although ice sheet retreat chronologies for Western Ross Sea as well as those for many other sectors of the Antarctic ice sheet are in agreement with relative sea-level reconstructions using calibrated deep sea core derived oxygen isotopic measurements, such as the one proposed by Waelbroeck et al. (2002), the age control for ice retreat in EB is less well-constrained and has many potential inaccuracies due to the scarcity of dateable material. If the ice sheet in EB retreated synchronously with the ice sheet in Western Ross Sea, then the Purple, Red, Brown, and Gray Units all had to have been deposited within the past 11,000 years, which is how long it took for the grounding line to retreat to its current position after LGM in Western Ross Sea (Domack et al. 1999). However, it looks as if the volume of sediment contained within each of these units is too large to have been deposited in such a short period of time. In fact, using the sediment flux values for the Whillans Ice Stream proposed by Anandakrishnan et al. (2007) and taking into account differences in drainage basin size (see Figure 4), it appears that it may have actually taken closer to 30,000 years to deposit the post-LGM GZWs. Thus, retreat must have begun earlier than 11,000 $^{14}$C yr BP in EB, and a new EB retreat chronology is needed.
Figure 3. (A) Map of Antarctica showing the Ross Sea and the location of Figure 2B. (B) Map of the Ross Sea showing the locations of the four GZWs identified by Bart (2004). The Purple Unit is shown in purple, the Red Unit is shown in Red, the Brown Unit is shown in Brown, and the Gray Unit is shown in Gray. Seismic line M89-27a is highlighted in black. (C) Interpretation of dip profile M89-27a showing in cross-section the four GZWs identified by Bart (2004).
Figure 4. Map of the Ross Sea showing current drainage basins for ice streams draining to the Ross Ice Shelf (from Joughin and Tulaczyk, 2002) along with the LGM drainage basin configuration (from Stuiver et al., 1981). The Whillans Ice Stream drainage basin is a part of the entire drainage basin for the paleo ice stream that constructed the Gray Unit.
1.3 Foram dates from the Eastern Basin

Previous studies (Domack et al., 1999; Licht and Andrews, 2002; Mosola and Anderson, 2006) have obtained radiocarbon dates from the Purple, Red, and Gray Units (see Table 1 and Figure 5). Table 1 summarizes radiocarbon dates obtained in previous studies from the Purple, Red, and Gray Units. Colors in the “Seismic Unit” column correspond to the color of the seismic unit (Purple Unit, Red Unit, Brown Unit, and Gray Unit). Colors in the “Core” column correspond to the core locations in Figure 5. No dates are shown from the Brown Unit because no cores with dated samples have penetrated the Brown Unit. In Table 1, no dates have been corrected for old core-top ages or the ocean reservoir effect.

All EB sediment cores contain the same two basic units (see Figure 6). The top-most unit is a gray-green diatomaceous ooze interpreted to be a pelagic drape representing open marine deposition. Below the draping unit is a gray, poorly-sorted diamicton interpreted to be a subglacial till. The AIO dates from the 2002 study by Licht and Andrews were from till. Mosola and Anderson (2006) warn that dates from till have the potential to be too young due to mixing of the pelagic drape into the till caused by bioturbation or iceberg turbation. In addition, till is, by definition, a mix of sediments, so any carbon retrieved for a radiocarbon date from AIO in till is likely to be from a combination of sources.

Licht and Andrews (2002) were able to obtain sufficient carbonate material (foraminifer tests) for radiocarbon dating in three samples. These samples were from till within a Purple Unit core. According to the seismic stratigraphy of the study area, the Purple Unit is the oldest GZW, followed by the Red, Brown, and Gray Units, respectively. Therefore, dates from Purple Unit samples should be the older than dates from Gray Unit samples. However, the forams dated by Licht and Andrews (2002) yielded a date of 13,770 $^{14}$C yr BP, which contradicts their AIO Gray
<table>
<thead>
<tr>
<th>Seismic Unit</th>
<th>Publication</th>
<th>Core</th>
<th>Depth (cm)</th>
<th>Age (14C yr BP)</th>
<th>Material</th>
<th>Location in core</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gray</td>
<td>Domack et al. (1999)</td>
<td>95-TC16</td>
<td>0-2</td>
<td>4530</td>
<td>AIO</td>
<td>Pelagic drape</td>
</tr>
<tr>
<td>Gray</td>
<td>Mosola and Anderson (2006)</td>
<td>99-TC3</td>
<td>3-5</td>
<td>8959</td>
<td>AIO</td>
<td>Pelagic drape</td>
</tr>
<tr>
<td>Gray</td>
<td>Mosola and Anderson (2006)</td>
<td></td>
<td>10-12</td>
<td>22,600</td>
<td>AIO</td>
<td>Pelagic drape</td>
</tr>
<tr>
<td>Gray</td>
<td>Mosola and Anderson (2006)</td>
<td></td>
<td>30-32</td>
<td>20,520</td>
<td>AIO</td>
<td>Pelagic drape</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>contact with till</td>
</tr>
<tr>
<td>Gray</td>
<td>Licht and Andrews (2002)</td>
<td>95-PC18</td>
<td>10-12</td>
<td>17,760</td>
<td>AIO</td>
<td>Post-glacial</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>sediment</td>
</tr>
<tr>
<td>Gray</td>
<td>Licht and Andrews (2002)</td>
<td></td>
<td>21.5-23.5</td>
<td>27,580</td>
<td>AIO</td>
<td>till</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>sediment</td>
</tr>
<tr>
<td>Red</td>
<td>Licht and Andrews (2002)</td>
<td>94-PC36</td>
<td>6-8</td>
<td>26,955</td>
<td>AIO</td>
<td>till</td>
</tr>
<tr>
<td>----------</td>
<td>--------------------------</td>
<td>-------</td>
<td>--------</td>
<td>---------</td>
<td>--------</td>
<td></td>
</tr>
<tr>
<td>Purple</td>
<td>Licht and Andrews (2002)</td>
<td>95-PC7</td>
<td>2-4</td>
<td>21,980</td>
<td>Benthic forams</td>
<td>till</td>
</tr>
<tr>
<td>Purple</td>
<td>Licht and Andrews (2002)</td>
<td>2-4</td>
<td>22,975</td>
<td>AIO</td>
<td>till</td>
<td></td>
</tr>
<tr>
<td>Purple</td>
<td>Licht and Andrews (2002)</td>
<td>20-22</td>
<td>17,790</td>
<td>Benthic Forams</td>
<td>till</td>
<td></td>
</tr>
<tr>
<td>Purple</td>
<td>Licht and Andrews (2002)</td>
<td>63-66</td>
<td>14,970</td>
<td>Benthic Forams</td>
<td>till</td>
<td></td>
</tr>
<tr>
<td>Purple</td>
<td>Licht and Andrews (2002)</td>
<td>63-66</td>
<td>20,780</td>
<td>AIO</td>
<td>till</td>
<td></td>
</tr>
</tbody>
</table>
Figure 5. Map of Eastern Basin seismic units and core locations with colors corresponding to Table 1.
Figure 6. Diagram illustrating the two units found in most EB cores, as well as the locations of samples taken for dating of AIO from each of the four cores used in this study. From each of the four cores, one sample was taken from the surface and one from just above the contact between diatomaceous mud and diamicton.
Unit date of 20,955 $^{14}$C yr BP. According to Mosola and Anderson (2006), the young Purple Unit date was due to the fact that the Purple Unit core sampled an iceberg turbate, which would contain young forams.

### 1.4 Acid-insoluble organic material dates from Eastern Basin

Most EB dates were obtained from the AIO fraction of the sediment because of the scarcity of carbonate material available for dating. Unfortunately, most AIO radiocarbon dates from the EB are biased due to carbon mixing (Andrews et al., 1999; Demaster et al., 1996; Domack et al., 1999).

Domack et al. (1999) focused on dating the pelagic drape, but they also dated one till sample in EB. The date from till was 22,740 $^{14}$C yr BP and this sample was interpreted to contain reworked organic material. The pelagic drape dates ranged from about 3,000 to 33,000 $^{14}$C yr BP and were interpreted to represent pelagic sedimentation since ice retreated from the area. The surface ages of cores were 3,000 to 4,000 $^{14}$C yr BP, indicating contamination by old carbon.

The dates from the 2006 study by Mosola and Anderson were from the pelagic drape layer. This layer was deposited during a time of slow sedimentation without any mixing by an ice sheet, so AIO dates from this layer may be more accurate than AIO dates from till. However, pelagic drape dates have the potential to be too old due to old carbon contamination from recycled organic material raining out from ice rafted debris (Ohkouchi and Eglinton, 2008) and the release of old organic material from melting ice sheets (Domack et al., 1989). The radiocarbon age of downcore AIO samples has been attempted to be corrected by subtracting the radiocarbon age of a surface AIO sample from the same core (Licht and Andrews, 2002). However, the surface age correction may lose accuracy when a lithologic boundary is crossed (Licht et al., 1998), or when the sediment-water interface is not recovered in the core.
If the youngest till dates represent the oldest possible age of ice sheet advance and dates from just above the contact with till represent the earliest resumption of open marine sedimentation after ice sheet retreat, then one would expect the EB dates from the 2002 study by Licht and Andrews to be older than the EB dates from the 2006 study by Mosola and Anderson. However, Mosola and Anderson (2006) determined the resumption of open marine sedimentation after Gray Unit deposition to have occurred around 30,440 $^{14}$C yr BP, while Licht and Andrews (2002) determined ice sheet advance to have deposited the Gray Unit no earlier than 27,580 $^{14}$C yr BP. Obviously, a revision to the chronology of the Gray grounding event is needed.

### 1.5 This study

In this study, the focus is on the youngest seismically resolvable EB GZW; the Gray Unit. The Gray Unit is analogous to the GZW currently being constructed at the WAIS grounding line. Once an age for the Gray Unit is established, we can begin to determine when and why the Gray grounding event began, how long it lasted, and what eventually caused it to end. Understanding the duration and mechanisms for retreat after the Gray grounding event will allow us to make predictions about the potential timing of retreat of the WAIS from its current position, which is an important consideration today amidst concerns about global warming.

An accurate method of dating GZW$s$ in EB is needed in order to determine an accurate ice retreat chronology. In this study, forams were dated in order to avoid the problems with carbon contamination encountered in AIO dating. The only correction required for foram radiocarbon dates is the ocean reservoir correction which has been determined by Berkman and Forman (1996) to be 1300±100 years for Antarctic marine calcareous fossils. This investigation has attempted to accurately date the Gray Unit by dating deep (200-700cm) samples taken from
the foreset of the Gray GZW. The foreset is the area between the limit of grounded ice and the sediment downlap limit (see Figures 7 and 8). Forams recovered from deep foreset till samples were dated for the following reasons:

1. Dates from till samples within a GZW yield the actual age of the grounding event, rather than the resumption of open marine sedimentation dated when pelagic drape samples are used. Obviously, dating pelagic drape requires that pelagic sedimentation is sufficiently high following retreat with minimal introduction of old carbon and preservation of continuous pelagic sediment since retreat.

2. The foreset is an area that had a high sedimentation rate (Alley et al., 1989), so large intervals of core (required to acquire sufficient numbers of forams) represent short intervals of time.

3. Sampling below 200cm lowers the possibility of sampling an area where the young pelagic drape was mixed into the till by bioturbation.

4. Since no iceberg scours are visible on the foreset, it is an area that was never disturbed by iceberg turbation, which ensures that pelagic drape was never mixed into the till.

For dating the sediment of the Gray Unit, only forams that appeared to be whole were picked in order to isolate the in situ forams, as opposed to those that might have survived reworking, to obtain an accurate radiocarbon date. The assumption is that forams were living on the foreset of the Gray GZW during the time of deposition. Since the Gray GZW is a progradational feature, the forams were constantly being buried by sediment delivered to the GZW by ice (see Figure 8A). In this scenario, any forams that were reworked would have been broken, so by picking whole forams for dating it was assumed that the possibility of obtaining dates from reworked forams was eliminated.
Figure 7. Multi beam image obtained during Ross Sea cruise NBP0802 showing the Gray GZW and the locations of the four cores sampled for dating in this study (PC1, PC2, PC7, and PC10). NBP0803 seismic lines and locations of additional cores from the NBP0802 and NBP0803 cruises are also shown. The foreset of the Gray GZW is the area in between the limit of grounded ice and the sinuous downlap limit of the Gray GZW. The topset is the area south of the foreset on top of the Gray GZW.
Figure 8. (next page) Diagrams showing the in situ and reworked hypotheses, as well as the locations of the Gray Unit foreset and topset in cross-sectional view. (A) Diagram illustrating my in situ hypothesis. 1: During pre-LGM open marine sedimentation (possibly OIS 5e), forams are deposited onto the seafloor in a pelagic drape layer. 2: When the WAIS advances to cover the Ross Sea, the forams from the pelagic drape are destroyed and not preserved. 3: During retreat, the WAIS pauses and deposits the Gray Unit. At this time, forams are living on the foreset of the Gray Unit. 4: As more sediment is deposited onto the foreset, those forams are buried while new forams come to live on the foreset. 5: Today, the Gray GZW contains forams that are in situ, or were living on the foreset during the time of deposition.

(B) Diagram illustrating my reworked hypothesis. 1: During pre-LGM open marine sedimentation (possibly OIS 5e), forams are deposited onto the seafloor in a pelagic drape layer. 2: When the WAIS advances to cover the Ross Sea, these forams are incorporated into the ice. 3-4: During the Gray grounding event, the forams in the ice are deposited into the Gray GZW. 4: Today, the Gray GZW contains forams that are reworked from a pre-LGM pelagic drape layer.
Determining an accurate and reliable age for the Gray Unit will give us information about when the WAIS grounding line was located on the mid-continental shelf. There are two possible outcomes for the age of Gray Unit deposition; it may be younger than LGM or older than LGM. Deposition after LGM would be consistent with ice sheet retreat in other parts of Antarctica as well as retreat in Western Ross Sea. If ice retreat in EB was synchronous with that in Western Ross Sea, the Gray Unit should be younger than 11,000 $^{14}$C yr BP, the time when ice began retreat from the outer continental shelf in Western Ross Sea (Domack et al., 1999). The Gray Unit is located northwest of Franklin Island (see Figure 2), so in order to be consistent with the retreat chronology proposed by Conway et al. (1999), the Gray Unit should be between 11,000 and 7600 $^{14}$C yr BP. Mosola and Anderson (2006) proposed that retreat was earlier in EB than in Western Ross Sea, so in order to be consistent with their interpretation, the Gray Unit must be older than 11,000 $^{14}$C yr BP. However, the Gray Unit must be older than LGM, or, more specifically, older than 30,440 $^{14}$C yr BP in order to be consistent with their oldest date on post-glacial sediment above the Gray Unit till. If the dating method used in this study proves to be accurate, the same method may then be used on other EB GZW to obtain a more detailed retreat chronology.
2. Methods

During a Ross Sea cruise aboard the RV/IB Nathaniel B. Palmer in January-March 2008 (NBP0802), an expanded 3-D multi-beam image of the Gray GZW was obtained (see Figure 7). This GZW represents sediment deposition at the WAIS grounding line during the ice sheet’s third back-step from its shelf-edge position. The foreset of the Gray GZW was identified as the area between the extent of grounded ice and the sediment downlap limit, while the topset was identified as the top of the GZW. Piston cores were taken from both the foreset and topset and these cores were split, sampled, and described at the Antarctic Marine Geology Research Facility in Tallahassee, Florida.

2.1 Till

2.1.1 Samples for dating of forams

From foreset core PC2 (see Figure 7 and Table 2), consecutive 2-cm long, 20 ml samples were taken from two intervals. These intervals are 356-422 cm and 622-682 cm. From foreset core PC7 (see Figure 7 and Table 2), consecutive 2-cm long, 20 ml samples were taken from three intervals. These intervals are 216-274 cm, 346-376 cm, and 376-406 cm. From topset core PC1 (see Figure 7 and Table 2), consecutive 2-cm long, 20 ml samples were taken from the interval between 30 and 90 cm. This interval is within the deforming till layer beneath the ice sheet that provides material for the foreset (Alley et al., 1989; Shipp et al., 1999), so forams from this interval were dated in order to compare their age with the age of foreset forams. The five sampled intervals from PC2, PC7, and PC1 are labeled 1 through 6 as shown in Figure 9. Each sample was processed in a Class 1000 clean room in order to prevent carbon contamination. Each sample was first disaggregated in distilled water for 12 hours and sieved with a
Table 2. Coordinates and water depth for cores sampled in this study

<table>
<thead>
<tr>
<th>Core</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Water depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NBP0802 PC1</td>
<td>76°S 34.6999</td>
<td>177°W 42.0978</td>
<td>571</td>
</tr>
<tr>
<td>NBP0802 PC2</td>
<td>76°S 32.2000</td>
<td>177°W 33.1009</td>
<td>582</td>
</tr>
<tr>
<td>NBP0802 PC7</td>
<td>76°S 24.7311</td>
<td>178°W 7.8276</td>
<td>621</td>
</tr>
<tr>
<td>NBP0902 PC10</td>
<td>76°S 27.5006</td>
<td>178°W 26.0001</td>
<td>604</td>
</tr>
</tbody>
</table>
Figure 9. Diagram showing the three cores from which foram samples were taken for dating. Diagrams are not to scale. PC2 and PC7 are from the Gray GZW foreset while PC1 is from the topset. The locations of intervals dated using forams are shown (Intervals 1-6) in blue.
45-micron sieve using distilled water. After each sieved sample had air-dried, each was poured into a glass container of distilled water and the float was decanted after 5 seconds. One hour later, the excess water was decanted from the float and the float was allowed to air-dry. Forams that appeared to be whole were picked from the float using a 000 brush and distilled water under a microscope and placed in a glass vial. Approximately 10 forams were found in each sample, and approximately 300 forams were picked from each interval. The floating technique was used because of the small size and scarcity of the forams present in the cores. After forams had been picked from all samples within one interval, the forams from all samples within that interval were combined. The combined forams from each interval were sent to the National Ocean Sciences Accelerator Mass Spectrometry Facility (NOSAMS) in Woods Hole, MA for radiocarbon analyses.

Due to time constraints, forams were not picked individually from the floats from the samples within Intervals 2 and 6. Instead, all of the floats from Intervals 2 were combined and all of the floats from within Interval 6 were combined, and these combined floats were sent to NOSAMS for radiocarbon analysis.

2.1.2 Samples for dating of AIO

Two samples for radiocarbon dating of AIO were taken from within Intervals 1, 2 and 3. One sample for radiocarbon dating of AIO was taken from within Intervals 4 and 5. The ages of these samples can be compared with the ages of the forams picked from the same intervals. A portion of each of the AIO samples was spread onto aluminum foil and placed in a 100° C oven to dry for 24 hours. After drying, each sample was placed in a glass vial and sent to NOSAMS for radiocarbon analysis.
2.2 Pelagic drape

Only samples for dating of AIO were taken from the pelagic drape. One 20 ml sample was taken from the surface of PC1, PC2, PC7, and PC10, and one from the pelagic drape within each of the four cores just above the contact with till (see Figure 6). The ages of the samples from above the contact on the foreset can be compared with the ages of the samples above the contact on the topset and with pelagic drape dates from previous studies. The ages of the surface samples can be used to correct the ages of the samples from above the contact. Each of these samples was processed in the same way as the AIO samples from till.

2.3 Samples for scanning electron microscope imaging of forams

The samples from which forams were picked for SEM imaging are PC2 440-442 cm, PC7 254-256 cm, and PC1 60-62 cm. All samples selected and prepared for SEM imaging were processed in the same way as samples processed for radiocarbon dating of forams. Instead of placing the forams in a glass vial, they were placed on a cylindrical aluminum stub, coated with gold, and imaged using the Scanning Electron Microscope at Louisiana State University. Fifteen forams were picked from the PC2 sample, one was picked from the PC7 sample, and two were picked from the PC1 sample.
3. Results

3.1 Till

3.1.1 Foram dates

The dating results are summarized in Tables 3 and 4 and Figures 10 and 11. In Table 3, shaded rows represent dates from forams and floats, while non-shaded rows represent dates from AIO. An assumed value of -20 per mil for the $\delta^{13}C$ of AIO and 0 per mil for that of forams was used for till samples. The foram dates were corrected for the ocean reservoir effect by 1200 years. Foram ages range from 31,500 ± 850 to 32,400 ± 840 $^{14}C$ yr BP. When corrected by 1200 years to account for the Ocean Reservoir Effect, the range becomes 30,300 to 31,200 $^{14}C$ yr BP. The uncorrected age of the float from Interval 2 is 37,200 ± 340 $^{14}C$ yr BP. The uncorrected age of the float from topset Interval 6 is 35,200 ± 190 $^{14}C$ yr BP, younger than the float date from the foreset.

3.1.2 AIO dates

For all intervals where both AIO and float/foram dates were obtained, AIO ages were greater. The two AIO ages from within Interval 1 are 36,800 ± 560 and 40,900 ± 2000. The two AIO ages from within Interval 2 are 43,400 ± 2800 and 42,100 ± 2100. The two AIO ages from within Interval 3 are 38,900 ± 880 and 42,900 ± 1400. The AIO age from within Interval 4 is 39,700 ± 1300 and the AIO age from within Interval 5 is 41,900 ± 1300.

3.2 Pelagic drape

The $\delta^{13}C$ of the pelagic drape AIO was measured by NOSAMS. The AIO surface ages of PC1 and PC10 are 4470 ± 40 and 5690 ± 45 $^{14}C$ yr BP, respectively. The AIO ages of the pelagic drape just above the contact with till within PC1 and PC10 are 6600 ± 55 and 10,800 ± 50 $^{14}C$ yr BP, respectively. The AIO surface ages of PC2 and PC7 are 4550 ± 40 and 5060 ± 35 $^{14}C$ yr BP,
Table 3. Summary of till dating results

<table>
<thead>
<tr>
<th>Lab Number</th>
<th>Core</th>
<th>Depth (cm)</th>
<th>Interval</th>
<th>Material</th>
<th>$\delta^{13}$C</th>
<th>Uncorrected Age ((^{14})C yr BP)</th>
<th>Corrected Age ((^{14})C yr BP)</th>
<th>Recalculated Age ((^{14})C yr BP)*</th>
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<tr>
<td>72191</td>
<td>PC2</td>
<td>375-377</td>
<td>1</td>
<td>AIO</td>
<td>-20</td>
<td>36,800 ± 560</td>
<td>36,756</td>
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<tr>
<td>72192</td>
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<td>396-398</td>
<td>1</td>
<td>AIO</td>
<td>-20</td>
<td>40,900 ± 2000</td>
<td>40,833</td>
<td></td>
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<tr>
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<td>forams</td>
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<td>32,400 ± 840</td>
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</tr>
<tr>
<td>72193</td>
<td>PC2</td>
<td>640-642</td>
<td>2</td>
<td>AIO</td>
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<td>43,400 ± 2800</td>
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<tr>
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<td>662-664</td>
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<td>AIO</td>
<td>-20</td>
<td>42,100 ± 2100</td>
<td>41,943</td>
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</tr>
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<td>PC2</td>
<td>622-682</td>
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<td>AIO</td>
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<td>376-406</td>
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<td>31,500 ± 850</td>
<td>30,300</td>
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<td>35,200 ± 190</td>
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</tbody>
</table>

*These ages have been recalculated using -26 per mil for the value of $\delta^{13}$C, a more likely value than the assumed value of -20 per mil originally used.
<table>
<thead>
<tr>
<th>Lab Number</th>
<th>Core</th>
<th>Depth (cm)</th>
<th>Uncorrected Age ($^{14}$C yr BP)</th>
<th>Material</th>
<th>$\delta^{13}$C</th>
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<td>76653</td>
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<td>AIO</td>
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<td>76654</td>
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<td>18.5-20.5</td>
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<td>AIO</td>
<td>-26.6</td>
</tr>
<tr>
<td>76652</td>
<td>PC2</td>
<td>3-5</td>
<td>4550 ± 40</td>
<td>AIO</td>
<td>-27.45</td>
</tr>
<tr>
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<td>PC2</td>
<td>7-9</td>
<td>12,450 ± 70</td>
<td>AIO</td>
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<tr>
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<td>5060 ± 35</td>
<td>AIO</td>
<td>-27.22</td>
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<tr>
<td>76650</td>
<td>PC7</td>
<td>4-6</td>
<td>6480 ± 50</td>
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</tr>
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<td>PC10</td>
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<td>5690 ± 45</td>
<td>AIO</td>
<td>-26.36</td>
</tr>
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<td>76657</td>
<td>PC10</td>
<td>13-15</td>
<td>10800 ± 50</td>
<td>AIO</td>
<td>-24.98</td>
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</table>
Figure 10. Diagrams illustrating our foram and float dating results for diamicton from foreset cores PC2 and PC7 (Intervals 1-5) and topset core PC1 (Interval 6). The AIO dates from the same intervals are also shown for comparison.
Figure 11. Core diagram summarizing the pelagic drape dating results from the present study. Cores are not drawn to scale.
respectively. The AIO ages of the pelagic drape just above the contact with till within PC2 and PC7 are 12,450 ± 70 and 6480 ± 50 ^14C yr BP, respectively.

3.3 Scanning electron microscope images

A sample of the SEM images acquired for this study is shown in Figure 12. Forams were found on both the foreset and the topset of the Gray Unit. There did not appear to be any difference in degree of breakage or assemblage of forams between the foreset and the topset. The forams could not be identified down to a species level, but the age ranges of the genera of the forams found on both the foreset and the topset extend back to the Paleogene and older. Thus, the age of the forams was not a useful tool in determining the age of the Gray Unit. Of the fifteen forams imaged from the PC2 sample, two of them showed signs of dissolution, one of them had what appeared to be predation holes, six of them showed signs of breakage, one of them had authigenic calcite growth, two of them had signs of breakage and authigenic calcite growth, and three of them appeared to be fresh. The foram from the PC7 sample showed signs of breakage. Of the two forams from the PC1 sample, one showed signs of dissolution and one appeared to be fresh. The breakage on some of the forams was surprising because only forams appearing to be whole were picked. However, the magnification of the microscope used for picking was not great enough to discern small amounts of breakage on some of the forams.
Figure 12. SEM images of some forams from cores used in this study. A-G are from foreset cores while H-I are from a topset core. (A) Foram from PC2 with dissolution holes. (B) Foram from PC2 with predation holes. (C) Foram from PC2 with breakage. (D) Foram from PC2 with authigenic calcite growth. (E) Foram from PC2 with breakage and authigenic calcite growth. (F) Foram from PC2 that appears to be fresh. SEM images of forams from PC2. (G) Foram from PC7 with breakage. (H) Foram from PC1 with signs of dissolution. (I) Foram from PC1 that appears to be fresh.
4. Discussion

4.1 Comparison of my till dates with previous data from Eastern Basin

4.1.1 AIO dates

Till dates from this study are generally older than the dates reported in previous EB studies. As mentioned earlier, Licht and Andrews (2002) dated till from within the Purple, Red, and Gray Units. Their AIO till dates from EB are in the range of 14,000-31,000 $^{14}$C yr BP. The till date from north of the Gray Unit reported by Domack et al. (1999) is 22,740 $^{14}$C yr BP. AIO dates from the present study from till are in the range of 37,000-43,000 $^{14}$C yr BP. Figure 13 shows the relative sea-level reconstruction by Waelbroeck et al. (2002) from calibrated deep sea core derived oxygen isotopic measurements as well as the relative sea-level curve produced by the ICE-5G (VM2) model (Peltier, 2004). The till dates from the present study and the till dates from Licht and Andrews (2002) are posted below the curves. The older age of the dates from the present study is likely due to the fact that dates from this study were taken from much deeper samples than those from Licht and Andrews (2002). Most samples dated by Licht and Andrews (2002) were taken from less than a meter below the seafloor, an area subject to bioturbation. Licht and Andrews (2002) found evidence of bioturbation in an EB core between 30 and 50 cm. Recent carbon from the pelagic drape may have contaminated their samples, causing them to be younger. The same is probably true for the ~23,000 $^{14}$C yr BP date reported by Domack et al. (1999). This date is from a sample 45 cm below the seafloor, an area that could have been subject to mixing by bioturbation.

Figure 14 shows a plot of sample age versus core depth for all of the cores taken from the EB study area (Purple, Red, Brown, and Gray Units). The dates on forams and AIO from till
Figure 13. Distribution of EB radiocarbon dates on till. The relative sea level reconstruction using oxygen isotopes from Waelbroeck et al. (2002) (thick black curve) and the relative sea level curve using the ICE-5G (VM2) model from Peltier (2004) (thin brown curve) are shown. Each symbol represents one radiocarbon date from EB (not associated with a particular sea level). The oldest and youngest till dates from each core are shown. AIO dates are uncorrected for old core-top ages and foram dates are corrected by 1200 years for the ocean reservoir effect.
**Figure 14.** Plot of sample age versus core depth for dated samples from cores taken from the Purple, Red, Brown, and Gray Units. Dates were taken from Licht and Andrews (2002), Mosola and Anderson (2006), and the present study. All dates are uncorrected.
above 1 m of core depth represent a wide range of ages, indicating that dates on till samples from 0-1 m in cores may have been contaminated by young carbon and may not be reliable. However, the dates on forams and AIO from till from 2 m to 7 m represent a small range of ages that is older than the range of ages represented by shallower samples. This indicates that below 2 m, till is homogenized and dates from till samples below 200 m more accurately represent the age of material deposited coevally with the till.

There is evidence for sediment mixing through bioturbation in the float date from the present study from topset Interval 6 (see Figures 9 and 10 for locations of intervals). Without sediment mixing, this date would have been the same as the float date from Interval 2 because Interval 6 is within the deforming till layer that provides material for the foreset (Alley et al., 1989; Shipp et al., 1999). However Interval 6 was dated to be 2000 years younger than Interval 2. This can be explained by recent carbon contaminating Interval 6 during bioturbation because Interval 6 is less than 1 m deep, while Interval 2 is greater than 6 m deep. Thus, it is believed that the oldest AIO till dates from the present study are a more accurate representation of the material deposited by the ice sheet during its retreat than the AIO till dates reported by Licht and Andrews (2002). However, since these dates represent till, they are likely older than the Gray grounding event because the till includes sediments reworked from before the ice sheet advance.

Some EB radiocarbon dates reported by Mosola and Anderson (2006) were from samples taken landward of the Gray Unit. These dates were in the range of ~9000-30,000 \(^{14}\text{C}\) yr BP, and were from AIO within the pelagic drape, with 30,440 \(^{14}\text{C}\) yr BP being the uncorrected age of the sample just above the contact with till. Although it is expected that the pelagic drape is younger than the till, the date from just above the contact with till should only be slightly younger than the till itself, representing the resumption of open marine sedimentation after ice retreated from
the area. The youngest uncorrected AIO date on till from the present study is 36,800 $^{14}$C yr BP, which is 6360 years older than 30,440 $^{14}$C yr BP, the oldest uncorrected AIO date on the pelagic drape from Mosola and Anderson (2006). Although this date is from deep within the till, the age of till near the contact with pelagic drape should be relatively close to the age of downcore till because of the high sedimentation rate for the GZW. This relatively large discrepancy between the youngest AIO till date and the oldest AIO pelagic drape date may be due to contamination by recent carbon through bioturbation, or it may be due to the slow sedimentation rate of the pelagic drape. Even a small interval of pelagic drape represents a large interval of time, so Mosola and Anderson (2006) may have dated an interval of pelagic drape that represented more than 6360 years. In addition, although it may seem logical at first to compare AIO pelagic drape dates with AIO till dates, the pelagic drape lends itself much better to AIO dating than till because autochthonous carbon deposited coevally with sediment in the pelagic drape is unlikely to be diluted by pre-aged carbon, while till is, by definition, a mix of sediments and likely contains a much higher proportion of allochthonous carbon. The dates from AIO till samples in this study are interpreted to largely represent material reworked from before LGM, and not material coeval with the Gray grounding event.

4.1.2 Foram dates

The forams dated by Licht and Andrews (2002) yielded ages in the range of 14,000-21,000 $^{14}$C yr BP, while forams from this study yielded ages in the range of 30,000-31,000 $^{14}$C yr BP (see Figure 13). However, the forams dated by Licht and Andrews (2002) were from the Purple Unit, a unit that must be older than the Gray Unit. Since foram dates from the present study are more consistent than those from the previous study, dates from the present study are interpreted to be more accurate, having been from foreset samples representative of a
homogenized till containing reworked material and no post-glacial material. The Gray Unit foreset is an area undisturbed by iceberg turbation, while Mosola and Anderson (2006) interpreted the area sampled by Licht and Andrews (2002) to be an iceberg turbate.

In the previous section, AIO pelagic drape dates reported by Mosola and Anderson (2006) were compared with AIO till dates obtained in the present study. However, since AIO dates from till are probably not as accurate as foram dates from till, it may be more reasonable to use the youngest foram till date from the present study, which is 30,300 $^{14}\text{C}$ yr BP, instead of the youngest AIO till date, when comparing with the oldest EB AIO pelagic drape date reported by Mosola and Anderson (2006), which is 30,440 $^{14}\text{C}$ yr BP. In this comparison, the difference between ages is only 140 years. Therefore, the foram till dates reported in the present study are interpreted to more accurately represent the age of the Gray grounding event than the AIO till dates.

4.2 Depositional scenarios

As mentioned earlier, the AIO till dates from the present study are interpreted as representing a homogenized till containing a combination of material older than the Gray Unit and material deposited coevally with the Gray Unit. These dates are an inaccurate representation of the age of the Gray grounding event. The foram dates from this study, however, lend themselves to two endmember depositional scenarios, which are shown in Figure 8:

1. The foram dates, like the AIO till dates, are much older than the age of the Gray grounding event, representing forams deposited before LGM.

2. The foram dates are an accurate indicator of the age of the grounding event, representing forams that were alive on the Gray Unit foreset during the time of deposition.
4.2.1 The foram dates pre-date the Gray grounding event

The AIO till dates from this study have been interpreted as containing material reworked from pre-LGM deposits. The dates, which range from about 37,000 to 43,000 $^{14}$C yr BP may in fact represent material older than the range of radiocarbon dating. The forams dated from the same intervals may also be reworked.

These reworked forams would have originated from a pre-LGM pelagic drape layer (see Figure 8B). If all of the dated forams were reworked from this pelagic drape, then the average foram date of about 31,000 $^{14}$C yr BP predates the age of the grounding event. This scenario would be consistent with the findings of previous researchers in Western Ross Sea, who have determined that ice retreat began around 11,000 $^{14}$C yr BP (Domack et al., 1999). In addition, post-LGM ice retreat in the EB after 31,000 $^{14}$C yr BP is consistent with retreat in many other sectors of the Antarctic ice sheet (e.g., Wellner, 2001; Goodwin, 1993; Hjort et al., 1997; Brachfeld et al., 2003; Evans et al., 2005; Clapperton and Sugden, 1982; Bentley et al., 2005; Pope and Anderson, 1992; Sugden et al., 2006; Lowe and Anderson, 2002).

Although interpreting the foram dates from the present study to be too old is consistent with previous studies, it is unlikely that all forams dated in the present study are reworked from a pre-LGM pelagic drape because the last time the EB was completely ice free was probably OIS 5e, which was centered about 120,000 years ago (Mercer, 1978). Radiocarbon dating can only reliably be used to date materials younger than 50,000 years old, and would have yielded infinite ages (no $^{14}$C content) if the forams dated in this study were all from OIS 5e. Moreover, it is difficult to believe that many forams from OIS 5e would have remained to supply the Gray Unit if the WAIS was grounded at the continental shelf edge during LGM. Most of the pelagic drape from OIS 5e and later would presumably have been excavated to supply the Purple, Red, and
Brown GZWs with sediment before the Gray Unit was even constructed. Therefore, it is not believed that the forams dated in the present study were all reworked from a pre-LGM pelagic drape layer.

4.2.2 The foram dates accurately represent the age of the Gray grounding event

In Figure 8A, the foreset forams dated in the present study accurately represent the age of the Gray grounding event because they were in situ, or alive on the Gray Unit foreset during the time of deposition. In this scenario, the average foram age of 31,000 $^{14}$C yr BP accurately dates the Gray grounding event. However, at least some forams within the Gray GZW foreset had to have been reworked because forams were found within the top 90 cm of the topset of the Gray Unit. These forams could not possibly have been in situ because the topset was covered by ice during the time of Gray Unit deposition. Therefore, any forams found on the topset had to have been reworked. The presence of forams on the topset indicates that foram tests can survive at least a small amount of reworking by an ice sheet, so it is likely that at least some of the forams picked from foreset cores in the present study were also reworked. In addition, the deforming till layer that exists at the base of the WAIS (Alley et al., 1989; Shipp et al., 1999) (on the topset) provides material for the foreset, so the assemblage of reworked forams on the topset must also be present on the foreset. Thus, there is low confidence in the interpretation that all forams dated in the present study were alive on the Gray Unit foreset during the time of deposition.

An alternative possibility is that the foreset forams were reworked, but originated from positions just landward and seaward of the foreset, rather than from a pre-LGM pelagic drape as in Figure 8B. This would allow for the presence of forams on the Gray Unit topset. In this case, the average foram age from this study of 31,000 $^{14}$C yr BP still accurately dates the Gray
grounding event because the forams dated were all alive at some point during Gray GZW construction, whether early or late.

4.3 Evidence from scanning electron microscope images

The SEM images of forams from cores used in this study revealed the possibility of three populations of forams present on the Gray Unit foreset. There are forams from both the foreset and topset that appear to be fresh, and that show signs of breakage and dissolution. On the foreset, approximately 50% of the forams were somewhat broken, 13% showed signs of dissolution, 6% showed signs of breakage and dissolution, and 19% appeared to be fresh. The remaining 12% had what appeared to be predation holes or authigenic calcite growth. On the foreset, the fresh-looking forams are interpreted to be in situ (see Figure 15A). Some of these may also have undergone a small amount of reworking that did not cause damage to the foram test. The somewhat broken forams are interpreted to have undergone a small amount of reworking. These forams were alive on the foreset early in Gray GZW construction. The Gray Unit is a progradational feature, so as more sediment was continually deposited by the ice sheet during the Gray grounding event, these forams were buried and ended up landward of the foreset. They were then picked up by the ice sheet and transported back to the foreset (see Figure 15B). The forams showing signs of dissolution, and in some cases breakage as well, are interpreted to have been exposed to corrosive ocean water for a period of time. This would have occurred as they were sitting on the seafloor seaward of the Gray Unit foreset. As more sediment was deposited by the ice, these forams were buried and ended up beneath the ice sheet, landward of the foreset. They then were transported by the ice to the foreset (see Figure 15C).
Figure 15. Diagrams showing three populations of forams on the Gray GZW foreset that each represent the age of the Gray grounding event. A) In situ forams that were living on the foreset during the time of deposition (green circles). B) In situ forams (green circles) and forams reworked from landward of the foreset (yellow circles). C) In situ forams (green circles) and forams reworked from landward of the foreset (yellow circles) and forams reworked from seaward of the foreset (dark blue circles).
4.4 Comparison of my pelagic drape dates with previous data from Eastern Basin

The surface ages from the present study are consistent with the surface ages reported by Domack et al. (1999) and Mosola and Anderson (2006) for EB cores. All surface sample ages are a few thousand years older than expected due to contamination by old carbon (Ohkouchi and Eglinton, 2006; Rosenheim et al., 2008) and/or the lack of recovery of the sediment-water interface in the piston core. However, similar to the strategy of Mosola and Anderson (2006), dates were also retrieved in this study from samples just above the contact with till. These dates are in the range of 6480-12,450 $^{14}$C yr BP, much younger than the date from above the contact with till just landward of the Gray Unit reported by Mosola and Anderson (2006), which was 30,440 $^{14}$C yr BP, the oldest pelagic drape date just north of the Gray Unit reported by Domack et al. (1999) which was 22,170 $^{14}$C yr BP, and the oldest EB middle-shelf date on post-glacial sediment reported by Licht and Andrews (2002), which was 17,760 $^{14}$C yr BP. Figure 16 shows the relative sea-level reconstruction by Waelbroeck et al. (2002) from calibrated deep sea core derived oxygen isotopic measurements as well as the relative sea-level curve produced by the ICE-5G (VM2) model (Peltier, 2004). The AIO pelagic drape dates reported in this study are posted below the curves along with the EB pelagic drape dates reported by Mosola and Anderson (2006). The difference between the present study’s oldest pelagic drape date and the oldest previously reported pelagic drape date of about 18,000 years could potentially be due to old carbon contamination within samples dated to be older. A more likely explanation, however, is that the entire record of pelagic sedimentation was not recorded in the area of the cores from the present study, possibly due to erosion by currents. If Mosola and Anderson’s (2006) pelagic drape dates were contaminated by old carbon, the pelagic drape dates from the present study
Figure 16. Distribution of EB radiocarbon dates on pelagic drape. The relative sea level reconstruction using oxygen isotopes from Waelbroeck et al. (2002) (thick black curve) and the relative sea level curve using the ICE-5G (VM2) model from Peltier (2004) (thin brown curve) are shown. Each symbol represents one radiocarbon date from EB (not associated with a particular sea level), and only the oldest pelagic drape dates from Mosola and Anderson (2006) are shown. The radiocarbon dates shown have not been corrected for the old core-top ages.
would have had the same contamination. Therefore, the AIO pelagic drape dates from the present study are treated as not representative of the entire record of pelagic sedimentation in the area, and the oldest pelagic drape dates reported by Mosola and Anderson (2006) are accepted as representing the latest possible resumption of open marine sedimentation in EB.

4.5 Interpretations and implications

There are a number of possibilities as to why AIO dates from surface or near-surface samples may be too old, including the rain out of old organic material from ice rafted debris (Ohkouchi and Eglinton, 2008), the release of old organic material from melting ice sheets (Domack et al., 1989), slow sedimentation rates, and sediment mixing due to bioturbation or iceberg turbation. AIO dates from this study, however, are from deep till samples (>2 m) and are from an area undisturbed by iceberg turbation. Therefore, it is probable that the reason why AIO dates from this study are older than foram dates from this study is because the ratio of in situ material to reworked material was higher for the forams dated in the present study than for the AIO dated in the present study, due to the fact that forams appearing to be whole were picked for dating. Therefore, at least some forams of the same age as the Gray grounding event were isolated for dating.

In addition, the date retrieved from the float within Interval 2 is about 6000 years older than the dates retrieved from forams within Intervals 1, 3, 4, and 5 (see Figures 9 and 10 for locations of intervals). This also supports the notion that there was a higher proportion of in situ forams in the pure foram samples than in the float sample. The amount of reworked forams in the float sample was probably small, because the percent of forams that were whole (the percent of forams that were picked in the pure foram samples) was high, around 90%. However, there was carbon-containing material within the float that was older than the forams in the pure foram
samples, driving the float date from Interval 2 older than the foram dates from Intervals 1, 3, 4, and 5.

It is interpreted that not only were some forams of the same age as the Gray grounding event isolated for dating, but in fact all forams isolated for dating are the same age as the Gray grounding event. If there are indeed three populations of forams on the Gray GZW foreset which all were alive during the time of Gray Unit construction and date to about 31,000 \(^{14}\text{C}\) yr BP, the Gray grounding event occurred around 31,000 \(^{14}\text{C}\) yr BP. This age for the Gray grounding event is consistent with the AIO pelagic drape dates from landward of the Gray Unit reported by Mosola and Anderson (2006). If the oldest EB date in that study (30,440 \(^{14}\text{C}\) yr BP) is corrected to account for the old AIO core top age of a core within the same paleo-ice stream axis, the date becomes 26,705 \(^{14}\text{C}\) yr BP (Mosola and Anderson, 2006). Therefore, it is concluded that the WAIS deposited the Gray Unit about 31,000 \(^{14}\text{C}\) yr BP and the resumption of open marine sedimentation began around 26,705 \(^{14}\text{C}\) yr BP. This early retreat of the WAIS in EB may have been caused by warm water currents or a precipitation deficit.

In the trough to the east of the Gray Unit, dates from a GZW presumably deposited coevally with the Gray Unit reported by Mosola and Anderson (2006) are as old as 27,330 \(^{14}\text{C}\) yr BP, or 23,626 \(^{14}\text{C}\) yr BP when corrected for the old surface age. A complete or almost complete record of pelagic sedimentation since ice sheet retreat was also recorded in this trough. Seaward of this GZW, the oldest reported pelagic drape date is 28,520 \(^{14}\text{C}\) yr BP, or 23,907 \(^{14}\text{C}\) yr BP when corrected for the old surface age. If the dates from this trough have not been contaminated by old carbon, the complete record of pelagic sedimentation could not have been recorded in this outer-shelf location because the difference in age between the oldest outer-shelf pelagic drape and the oldest middle-shelf pelagic drape is not enough time for the ice to have retreated from
the outer shelf, grounded on the middle shelf, and then retreated from the middle shelf. In the eastern-most trough, the oldest pelagic drape date is 30,620 $^{14}$C yr BP, or 26,030 $^{14}$C yr BP when corrected for the old surface age. This date is consistent with the notion that open marine sedimentation resumed early in EB.

A retreat of the WAIS in the EB before 26,705 $^{14}$C yr BP is consistent with the observation that the volume of sediment within the post LGM GZWs is too large to have been deposited within the past 11,000 years. Calculations taking into account sediment flux estimates from Anandakrishnan et al. (2007), drainage basin size, and GZW volume appear to predict ice sheet retreat to have taken closer to 30,000 years if each of the GZWs in the study area were deposited during the same retreat, which would put deposition of the shelf-edge Purple Unit at closer to 50 ka. However, many more factors need to be included in such calculations in order to be considered valid methods for calculating grounding event duration. It is also possible that the mid-shelf Gray Unit, rather than the shelf-edge Purple Unit, represents LGM deposition. This would allow for a smaller volume of sediment to have been deposited, and therefore a smaller amount of time to have passed, since LGM. This is a hypothesis that remains to be tested since there is no evidence at this time that the GZWs in the study area are from separate advance and retreat episodes.

Since the Gray grounding event is assumed to represent a pause in grounding line migration during WAIS retreat from the continental shelf edge after LGM (Bart, 2004), deposition of the Gray GZW around 31,000 $^{14}$C yr BP is inconsistent with both the relative sea level reconstruction by Waelbroeck et al. (2002), which puts LGM at around 18 ka, and the relative sea level history modeled by Peltier (2004), which puts LGM at around 26 ka. Assuming the foram dates are accurate indicates either that the WAIS retreated more than 10,000 years
prior to the maximum sea level fall and global cooling associated with LGM (i.e., during OIS 3), or that the Antarctic LGM took place more than 10,000 years earlier than commonly accepted.

It is possible that the ice sheet in the Ross Sea retreated out of sync with (before) LGM since the WAIS is a marine-based ice sheet. Marine-based ice has a minimal effect on sea level, so it is possible that the WAIS retreated prior to the global sea level fall of LGM. In addition, grounding line movement does not necessarily correspond to overall ice volume change. In this study, the focus is on WAIS grounding line migration. However, as the grounding line moved landward, the ice may have thickened, so that the total change in ice volume over time was insignificant. This would also explain an early WAIS retreat without affecting LGM ice volume estimates.

Interestingly, an early retreat of the WAIS in the EB would apparently coincide with an early retreat of the ice sheet in the Weddell Sea, which is the Pacific sector of the WAIS. Data from Elverhoi (1981) and Anderson and Andrews (1999) indicate that retreat in the Weddell Sea took place between 28,130 and 31,290 $^{14}$C yr BP. A retreat of the entire WAIS around 30,000 $^{14}$C yr BP is a departure from the commonly accepted view that ice in Antarctica retreated after LGM. Weaver et al. (2003) used modeling to conclude that Antarctic ice was the source of meltwater pulse 1A, about 12,400 $^{14}$C yr BP. However, if the results of the present study are accurate, meltwater from the WAIS should have contributed to a sea level rise about 18,000 years earlier.

In summary, the AIO till dates from the present study are interpreted as representing a homogenized mixture of pre- and post-LGM material, the foram till dates are interpreted as representing three populations of forams the same age as the Gray grounding event, and the AIO pelagic drape dates are interpreted as being younger than the resumption of open marine
sedimentation after Gray GZW deposition. The Gray grounding event occurred around 31,000 14C yr BP and open marine sedimentation resumed around 26,705 14C yr BP, the oldest pelagic drape landward of the Gray Unit reported by Mosola and Anderson (2006).
5. Conclusions

The Gray GZW foreset contains both in situ forams and reworked forams. In this study, in situ forams as well as those that were reworked only a small distance were isolated for dating. The methods used in this investigation have therefore yielded an accurate age for the Gray grounding event. The Gray grounding event occurred around 31,000 $^{14}$C yr BP, and open marine sedimentation resumed around 26,705 $^{14}$C yr BP. This conclusion contradicts the “swinging gate” retreat chronology proposed by Conway et al. (1999), and illustrates that the WAIS may have retreated out of sync with ice sheets in other sectors of Antarctica.

In the future, an accurate WAIS retreat chronology for the EB may be attained if the Purple, Red, and Brown Units can be accurately dated. This may be achieved by isolating and dating the in situ foram population on these GZW foresets. Alternatively, methods such as the programmed temperature pyrolysis method proposed by Rosenheim et al. (2008), or compound specific radiocarbon dating of Ross Sea sediments proposed by Ohkouchi and Eglinton (2008) may be perfected and used.
References


Vita

Amy Noelle Cone was born and raised in Ann Arbor, Michigan. She graduated from Ann Arbor Pioneer High School in June, 2004. After switching majors from art to geology and communication, she received a Bachelor of Arts degree from Smith College in Northampton, Massachusetts, in May of 2008. After graduation from Louisiana State University, she plans to move to Houston, Texas, to work as a geologist for Southwestern Energy. She enjoys photography and playing clarinet in her free time, as well as spending time outside.