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West Antarctic ice sheet retreat chronology of two middle-shelf grounding-zone wedges in Eastern Basin, Ross Sea, Antarctica

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WEST ANTARCTIC ICE SHEET RETREAT CHRONOLOGY OF TWO MIDDLE-SHELF GROUNDING-ZONE WEDGES IN EASTERN BASIN, ROSS SEA, ANTARCTICA

A Thesis
Submitted to the Graduate Facility of
Louisiana State University and
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in
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by
Lenora Nicole Copeland
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Table of Contents

Acknowledgements ........................................................................................... ii

Abstract ............................................................................................................. iv

1. Introduction .................................................................................................... 1
   1.1 Study Area ................................................................................................. 1
   1.2 Previous Studies ....................................................................................... 3
   1.3 This Study ................................................................................................ 8

2. Methods .......................................................................................................... 14
   2.1 Foraminifera Study .................................................................................. 14
   2.2 Synthesis of Previous Studies ................................................................ 18

3. Results ........................................................................................................... 21
   3.1 Foraminifera Dates .................................................................................. 21
   3.2 Core Observations of PC 5 and PC 6 ....................................................... 21
   3.3 Synthesis of Terrestrial and Marine Studies .......................................... 22

4. Discussion ...................................................................................................... 40
   4.1 Foraminifera Study .................................................................................. 40
   4.2 Synthesis of Terrestrial and Marine Studies .......................................... 43

5. Conclusions .................................................................................................. 56

References ........................................................................................................ 57

Vita ..................................................................................................................... 61
Abstract

This study isolated a small number of large, *in situ* and reworked foraminifera from diamicts deposited in two grounding zone wedges on the middle continental shelf in Eastern Basin, Ross Sea, Antarctica. All samples were of sufficient weight to yield Holocene dates if the samples were indeed of Holocene age. Of the twelve small samples sent for radiocarbon analysis, the two heaviest were for reworked foraminifera which yielded dates of >22,200 \(^{14}\)C BP and >22,500 \(^{14}\)C BP. None of the other ten samples yielded radiocarbon dates. The lack of Holocene radiocarbon dates for the six *in situ* and four reworked foraminifera samples suggests that West Antarctic Ice Sheet (WAIS) retreated from the middle continental shelf Eastern Basin prior to the Holocene, i.e., much earlier than generally accepted.

A second part of this study involved compiling all previous radiocarbon dates from Eastern Basin as well as chronologic information concerning ice-sheet retreat from the surrounding terrestrial areas. This synthesis of marine and terrestrial data suggests that the WAIS retreated from the middle continental shelf at ~26,000 \(^{14}\)C BP. The WAIS retreat from the middle continental shelf was not associated with coeval deflation of the ice-sheet surface in the far interior reaches of West Antarctica. Instead, WAIS deflation was delayed by >13,000 years. This delay in the onset of deflation suggests that the effects of ice-sheet retreat from the middle shelf slowly propagated to the interior beginning only after the grounding line had retreated far inland. The retreat of the WAIS from the middle continental shelf towards the interior did ultimately cause deflation beginning first at Siple Dome, followed by deflation at Reedy Glacier, Marie Byrd Land, and Discovery Ridge as the grounding line migrated to its present-day position.
1. Introduction

Analyses of geomorphological features and piston-core sediments on the Antarctica continental shelf demonstrate that the Antarctic Ice Sheet (AIS) advanced and retreated in the recent geologic past. It is generally accepted that an ice volume expansion and associated sea-level fall occurred during the Last Glacial Maximum (LGM) around 18,000 years ago (Waelbroeck et al., 2002). Evidence for the LGM expansion in Ross Sea includes mega-scale glacial lineations along sea-floor troughs, irregular erosional features on the inner shelf, drumlins on the middle shelf, and highly-elongated depositional features from molding of sediments on the outer shelf (Shipp et al., 1999). In the subsequent retreat, there were two to four pauses of the AIS until it reached its present-day position (Mosola and Anderson, 2006). These pauses in the Ross Sea are represented by the deposition of grounding zone wedges (GZW). Determining the timing and manner in which the ice retreated since LGM is of interest because it may provide insight concerning the future stability of the West Antarctic Ice Sheet (WAIS).

Age control is needed to determine what phenomena caused the WAIS to advance, pause, and retreat. Obtaining this information is important because oscillations of the WAIS volume affect sea-level elevation. Collapse of the WAIS would cause global sea-level rise of 5 to 6 meters (Conway et al., 1999), which would have devastating consequences for all coastal cities.

1.1 Study Area

Eastern Basin is located in eastern Ross Sea, Antarctica (Figure 1). The Ross Ice Shelf covers an area 526,000 km², roughly the size of France today (Mosola and Anderson, 2006). This region receives drainage from the WAIS via ice streams (Anderson et al., 2002). Currently there are six ice streams that drain the WAIS into Ross Sea (Bart, 2004).
Figure 1. The Ross Sea Embayment at LGM modified from Denton and Hughes (2000). The thick black line represents the extent of the drainage basin and thin black lines represent direction of the ice flow. The LGM grounding line is represented by the thin black line at the base of the ice streams and the light blue line represents the modern grounding line. The red line represents the divide of drainage into the western Ross Sea versus the central and eastern Ross Sea.

These ice streams correspond to six paleo-streams identified from troughs on the outer continental shelf (Bart, 2004). The shelf is covered with mega-scale glacial lineations that are indicative of fast-flowing ice (Wellner et al., 2006). These ice streams erode the underlying strata leaving a wide trough containing streamlined bedforms that were produced under the ice sheet (Cofaigh et al., 2003). The troughs trend south to north. In the troughs, ~30 meter thick GZWts represent deposition at the terminus of grounded ice during a pause in the overall retreat (Anderson, 2007). In Glomar Challenger Basin, GZWts include the Purple, Red, Brown, and Gray Unit (Bart, 2004) (Figure 2). The Purple Unit is the stratigraphically oldest unit and
exhibits the basinward-most extent, so it is assigned to the “LGM”. As ice retreated since LGM, the Red, Brown, and Gray units were successively deposited (Figure 2).

The Ross Sea also receives drainage from the East Antarctic Ice Sheet (EAIS) (Licht, 2005). During the LGM, western Ross Sea received drainage from the EAIS via the Transantarctic Mountains outlet glaciers (Licht, 2005). The central Ross Sea received drainage from both the EAIS and WAIS (Anderson et al., 1984, 2002; Licht et al., 2005) (Figure 2).

1.2 Previous Studies

Previous studies have been conducted in Ross Sea to determine the timing of post-LGM retreat (Domack et al., 1999; Shipp et al., 1999; Licht and Andrews, 2002; Conway et al., 1999). Radiocarbon dates from open-marine muds are used to constrain the timing of the WAIS retreat, i.e., the return to open-marine sedimentation. The majority of radiocarbon dates are from sediment cores in western Ross Sea. Fewer studies have been conducted in the eastern and central portions of the Ross Sea (Licht and Andrews, 2002; Mosola and Anderson, 2006). Terrestrial studies conducted in the Transantarctic Mountains and Marie Byrd Land provides information on the changing elevation of the ice surface (Bockheim et al., 1989; Storey et al., 2010; Baroni et al., 1991; 1994b; Hall et al., 2004; Emslie et al., 2007; Todd et al., 2010; Ackert et al., 2007; Stone et al., 2003). However, these studies are not always located in areas that are not easily related to offshore GZWs. Therefore, in isolation these terrestrial data are of limited utility for constraining the timing of individual grounding events in the marine environment.
Figure 2. (A) Map of the Ross Sea showing the location of the GZW's from Bart (2004) and the location of Figure 2B. (B) Map of the locations of GZW's identified by Bart (2004) along the transect noted in (A). 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. (C) Seismic cross-section from Bart (2004) with the four GZW's highlighted.
1.2.1 Terrestrial Studies

The retreat history of the ice sheet in the terrestrial realm is inferred from ice-core studies (Waddington et al., 2005), modeling (Denton and Hughes, 2002; Parizek et al., 2004), radiocarbon dating of in situ shells along raised beaches (Stuiver et al., 1981), and exposure dating of glacial erratics (Storey et al., 2010; Todd et al., 2010). One current assumption is that the ice sheet had a continent-wide synchronous advance which culminated at the outer continental shelf in eastern and central Ross Sea, and to north of Coulman Island in western Ross Sea (Domack et al., 1999; Conway et al., 1999; Licht et al., 1996; Parizek et al., 2004). Terrestrial dates, specifically radiocarbon dates of mollusks or penguin remains on raised beaches, for western Ross Sea suggest that the WAIS advance to Coulman Island occurred between 27,820 to 12,880 $^{14}$C BP (Conway et al., 1999). These studies suggest ice-sheet retreat was underway in the late to middle Holocene (Conway et al., 1999). Dates from raised beaches along Terra Nova Coast were used to constrain the times at which open-marine conditions returned (Baroni et al., 1991; Stuiver et al., 1981). These data indicate open water existed at the Terra Nova Coast by 7,550 years $^{14}$C BP (Baroni et al., 1991). At Taylor Dome, ice-sheet deflation had occurred by 6,000 years BP (Licht, 2004). A modeling study of ice layering suggests that grounded ice moved southward of Roosevelt Island at 3,200 years BP (Conway et al., 1999) (Figure 3).

1.2.2 Western Ross Sea

In the western Ross Sea, the maximum expansion of the WAIS at the LGM reached approximately 74°S, just north of Coulman Island (Shipp et al., 1999). Radiocarbon dates of acid-insoluble organics (AIO) within diamictons on the continental shelf in the western Ross Sea yielded dates of 34,100-14,100 $^{14}$C BP (Domack et al., 1999).
Figure 3. Map of the Ross Sea and surrounding terrestrial areas modified from Conway (1999) suggesting the timing of ice retreat since the LGM.

The timing of ice advance is constrained from the youngest date in the diamicton; therefore, ice advance occurred by 14,100 $^{14}$C BP (Licht, 2004). Subsequent retreat of the grounding line occurred by 11,000 $^{14}$C BP based on AIO dates from pelagic sediments overlying diamictons (Domack et al., 1999). Grounded ice retreated to Drygalski tongue by 9,900 years BP (Licht and Andrews, 2002) before retreating to Ross Island by 6,600 years BP (Licht et al., 1996).
1.2.3 Central and Eastern Basin Ross Sea

Eastern Basin retreat history is not as well defined as that in the western Ross Sea (Bentley, 1999). The study by Licht and Andrews (2002) suggested that the ice sheet reached its maximum position to the outer continental shelf after 13,800 $^{14}$C BP. This age represents the youngest age from a diamicton in the central Ross Sea based on a strategy similar to that used in western Ross Sea (Domack et al., 1999). In their view, ice advanced over sediment containing in situ foraminifera (Licht and Andrews, 2002). Thus, the foraminiferal age provides a minimum constraint on the time of WAIS advance. The subsequent minimum age of ice retreat was estimated to be at 9,800 $^{14}$C BP based on the oldest date obtained from an ice-proximal glacial marine sediment (Licht and Andrews, 2002).

Conversely, the marine dates from the studies of Mosola and Anderson (2006) and Bart and Cone (in review) suggest an alternative view of pre-LGM deglaciation in Eastern Basin. Mosola and Anderson (2006) reported significantly older radiocarbon dates from acid insoluble organics from glaciomarine sediments above the contact with the underlying diamicton. The uncorrected dates ranged from 30,620 to 18,160 $^{14}$C BP. Mosola and Anderson (2006) concluded that these dates must be considered suspect because these old dates for retreat are in conflict with younger dates for WAIS advance from Licht and Andrews, (2002).

Cone (2010) conducted a study on the stratigraphically youngest GZW in Eastern Basin, the Gray Unit that was defined by Bart (2004). In this study, small juvenile foraminifera were extracted from 50-centimeter core lengths of diamicton (Cone, 2010). Up to 300 foraminifera were isolated and radiocarbon dated (Cone, 2010). The ranges of the dates were 35,000 to 31,000 $^{14}$C BP (Cone, 2010). The small size of the foraminifera made it difficult to distinguish
whole foraminifera from broken foraminifera (Cone, 2010). This visual distinction was used as a first-order estimate as to whether foraminifera were in situ versus reworked (Cone, 2010). In the study by Cone, Scanning Electron Microscope (SEM) images revealed that ~60% of the foraminifera had either little to no physical or chemical damage (Cone, 2010). Using a simple two-part mixing model suggested to Bart and Cone (in review), it was estimated that grounded ice began retreat from the middle shelf at 27,500 $^{14}$C BP (Bart and Cone, in review). This supports the dates from Mosola and Anderson (2006) but is in conflict with the conclusions of others (Conway et al., 1999; Domack et al., 1999, Licht and Andrews, 2002), who favor a Holocene retreat history.

1.3 This Study

1.3.1 Foraminifera Study

This study focused on two seismically resolvable units, the Gray-Unit and the Brown-Unit GZWs, in Eastern Basin, Ross Sea (Figure 2). A goal of this study was to provide an accurate date to determine the timing of the recent ice-sheet retreat and the deposition of the Gray-Unit and Brown-Unit GZWs.

The updated chronology of the retreat history will aid in determining when these two pauses in WAIS retreat occurred and when grounded ice vacated the study area. The correct chronology of ice advance and retreat will assist the study of the current grounding line of the WAIS and aide in evaluating when and why future changes may occur. Radiocarbon dating of foraminifera provides a way to date the GZWs and avoids the multiple sources of error associated with using AIO (Andrews et al., 1999).
Figure 4. Multibeam image obtained during the NBP0802 cruise in the Ross Sea by Bart (2008) showing the Gray GZW and the locations of the 4 cores highlighted in this study (PC 4, JPC 8, PC 5, PC 6).
This study is an attempt to isolate large *in situ* foraminifera to date both the Gray-Unit and Brown-Unit GZWs, thereby avoiding the potential problem of mixing *in situ* and reworked noted by Cone (2010).

The Gray-Unit GZW is expected to be younger than the Brown-Unit GZW as it is stratigraphically above the Brown Unit. With respect to the post-LGM chronology, there are three different hypotheses for the age of the Gray-Unit and Brown-Unit GZWs, that this study will test.

1. The Gray-Unit and Brown-Unit GZWs are significantly younger than the LGM. It is expected that these units are younger than 7,400 $^{14}$C BP, then ice began to retreat from the continental shelf (Conway *et al.*, 1999).

2. The Gray-Unit and Brown-Unit GZWs are the same age as the LGM. Deglaciation of the western Ross Sea began at 11,000 $^{14}$C BP, thus corresponds to MWP-1A (Domack *et al.*, 1999).

3. The Gray-Unit and Brown-Unit GZWs are significantly older than the LGM (Bart and Cone, in review), suggesting deposition of the GZWs during an earlier pre-LGM glacial period. Previous radiocarbon dates from Mosola and Anderson (2006) suggest retreat occurred at ~30,000 $^{14}$C BP (uncorrected).

If the dating method used in this study is capable of resolving this controversy, then it may be used to date the many other GZWs in the Ross Sea and elsewhere in Antarctica.
1.3.2 Synthesis of Previous Studies

The terrestrial and marine data, including radiocarbon dates from raised beaches and Beryllium-10 dating of glacial erratics for the terrestrial realm and radiocarbon dates of acid insoluble organics in the marine realm, for the western Ross Sea support the conventional view of ice advance and retreat of the WAIS after the LGM (Licht, 2005). However, a similar synthesis of terrestrial and marine data has not been conducted for the eastern Ross Sea. The timing and manner of ice-sheet inflation and deflation in the terrestrial areas that surround Eastern Basin are considered in this synthesis. Three different views of inflation and deflation have been made to determine more about the effects of WAIS advance and retreat in Eastern Basin and how that would correlate to the terrestrial locations that drain into Eastern Basin.

A general assumption is that as the WAIS retreats, it has a coeval deflation in the adjacent drainage basin (Todd et al., 2010) (Figure 5). This deflation might be either gradual or “stepped”. In these cases, a succession of stacked moraines in the terrestrial realm would be expected to be associated with Eastern Basin because multiple GZW indicator several discrete pauses in WAIS retreat.

Conversely in a second hypothesis, as the WAIS retreats, the surrounding terrestrial areas experience no change in the interior (Anderson et al., 2004). In this view, the WAIS deflates very late, well after the retreat of grounded ice in marine areas. As retreat continues, deflation in the surrounding terrestrial areas eventually occurs (Figure 6).

In a third hypothesis, the WAIS deflates as the ice-sheet attains its maximum extent of grounded ice and then undergoes maximum inflation during its maximum retreat (Ackert et al., 2007). In the terrestrial realm, a maximum deflation would occur at the glacial maximum followed by inflation in the interglacial maximum (Figure 7).
**Figure 5.** Deflation of the ice sheet as retreat of the ice sheet occurs in a gradual or “stepped” fashion. The Purple GZW represents the stratigraphically oldest unit conventionally thought to be deposited post-LGM. It is followed by the Red-Unit, Brown-Unit, and Gray-Unit GZWs.

**Figure 6.** Late phase deflation only after additional retreat at the margins but not in the interior. Deflation occurs later when ice experiences additional retreat to the interior.

**Figure 7.** Continual inflation of the ice sheet as the ice sheet retreats. The Purple GZW represents the stratigraphically oldest unit conventionally thought to be deposited post-LGM. It is followed by the Red-Unit, Brown-Unit, and Gray-Unit GZWs. The colored lines correlate to the color of the GZW they represent and their inflation through time.
1.3.3 Objectives of Study

In this study, the following three questions will be addressed:

1. Can large *in situ* and reworked foraminifera in the Brown-Unit and Gray-Unit GZWs be isolated?

2. If so, what are the age of the *in situ* and reworked foraminifera in the Brown-Unit and Gray-Unit GZWs?

3. Does a synthesis of marine and terrestrial data from other studies support the view that WAIS retreat began prior to ~26,000 BP (Stage 2) (Peltier *et al.*, 2006) or after ~7,400 BP (Holocene) in Eastern Basin?
2. Methods

2.1 Foraminifera Study

In 2008, a cruise to Ross Sea, Antarctica was taken onboard the Nathanial B. Palmer RVIB. During this cruise, the Gray-Unit GZW was resolved using the hull-mounted multibeam system. This multibeam image was used to determine locations for piston cores. These core locations included the topset, foreset, and taper of the Gray-Unit GZW and the topset of the Brown-Unit GZW. The cores labeled as NBP0802 were sent to the Antarctic Marine Geology Research Facility at Florida State University in Tallahassee, FL where the cores were opened, examined, descriptions were made, and X-rays were taken.

Sampling was done at the Antarctic Marine Geology Research Facility at Florida State University. Sediment samples 2 cm long and 10 cc volume were extracted from the following cores from NBP0802: PC 4, PC 5, PC 6, and JPC 8 (Table 1). All sampling was done with extra precaution to avoid potential contamination of younger carbon from mixing into the sample. The extra precaution included use of clean gloves for each sample and clean spatula’s to extract the samples. At Louisiana State University in Baton Rouge, Louisiana, all processing of core samples was done under a laminar flow hood to avoid contamination. In every step, gloves were worn, and all lab equipment was washed with distilled water to avoid contamination of the samples with modern carbon. Each sample was disaggregated in distilled water for 12 hours. The samples were then completely disaggregated with a magnetic stirring rod and stirring plate. The sediment samples were sieved with a 54-micron mesh using distilled water. The sieved samples were left to air dry. A heavy-liquid separation float was used to isolate the foraminifera from other minerals such as quartz, which was abundant in the samples.
A heavy-liquid separation float was used to isolate the foraminifera from other minerals such as quartz, which was abundant in the samples. Heavy-liquid separation was used as an alternative to Cone’s study (2010), which floated samples with distilled water. Only small juvenile foraminifera with a surface tension greater than water were obtained in Cone’s study.

The new method in this study was an attempt to isolate large foraminifera that did not float in the Cone study (2010). Initially, a heavy-liquid separation of the dried sample was done using a solution of sodium polytungstate and distilled water mixed to a specific gravity of 2.2 (Gibson and Walker, 1967). This solution was poured into a beaker and the dry sediment sample was poured into the solution. The solution was stirred after initial settling had taken place to disaggregate the material and make sure that no foraminifera were carried down with larger, denser grains. The solution and sediment settled for approximately 1 to 2 minutes until separation of heavy and light material was complete. The float was decanted to a filter, washed with distilled water, and left to dry in the laminar flow hood overnight (Wellner, 2001). The heavy sediments were decanted to a separate filter, washed with distilled water, and left to dry overnight. Both the light and heavy samples were stored in labeled vials. In the initial stages of this study, I noted that sodium polytungstate quickly recrystallized and left the sediments and

### Table 1. Location and water depth of the four cores that were used 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 PC 4</td>
<td>-76.48374</td>
<td>-177.533516</td>
<td>596</td>
</tr>
<tr>
<td>NBP0802 JPC 8</td>
<td>-76.416704</td>
<td>-178.333353</td>
<td>639</td>
</tr>
<tr>
<td>NBP0802 PC 5</td>
<td>-76.40011</td>
<td>-177.250278</td>
<td>582</td>
</tr>
<tr>
<td>NBP0802 PC 6</td>
<td>-76.400181</td>
<td>-177.083551</td>
<td>580</td>
</tr>
</tbody>
</table>
foraminifera/sponge spicules/etc clumped into large balls and coated everything in the sample with sodium polytungstate. I determined that lithium polytungstate did not recrystallize as quickly and would not cause the sediment to clump or leave a coating on the sediment (Rick Young, personal communication). A switch was made to lithium polytungstate and the same procedures were followed as stated above.

The dry, isolated floats were picked for foraminifera. The float sample was put in a picking tray and foraminifera were picked using a 000 brush and distilled water under a binocular light microscope. Two different categories of foraminifera from each sample were picked: 1) foraminifera that appeared to be in situ and 2) foraminifera that appeared to be reworked. Foraminifera that appeared to be intact, with no recrystallization, with visible chambers, and a translucent test were considered to be in situ. Foraminifera that appeared broken and recrystallized, with no visible chambers, and an opaque test were considered to be reworked. When possible, these two categories of foraminifera were picked and identified to the genus level.

A key objective of this study was to isolate single, large, in situ foraminifera as the first choice for radiocarbon dating, followed by foraminifera of the same genus, and then foraminifera of a mixed assemblage. Benthic and planktonic foraminifera species were separated. Selected samples of foraminifera were photographed with a mounted Nikon camera on a binocular light microscope to provide an archive image (Figure 8). The foraminifera were weighed on a microbalance (± 0.1 µg).
Figure 8. Examples of common foraminifera species found. Specimens 1-3 (1. *Cibicides* sp., 2. *Fursenkoina* sp., 3. *Epistominella* sp.) are calcareous species that were often found within the diamicton and at depth (Perry, 1999). These species represent excellent foraminifera for the *in situ* dating. The chambers are visible, tests are translucent, and there is dissolution/overgrowth. Specimen 4 (4. *Veleroninoides* sp.) is an example of agglutinated foraminifera often found in samples of pelagic drape (Perry, 1999).

An estimate of the total carbon of the sample was found by dividing the dry weight of the carbonate (the total mass of the foraminifera) by 8.33 (Kathryn Elder of National Ocean Sciences Accelerator Mass Spectrometry Facility, personal communication). This number estimated the maximum amount of carbon in the sample. The different intervals of foraminifera were sent for radiocarbon dating at W.M. Keck Carbon Cycle Accelerator Mass Spectrometry Laboratory (KCCAMS).
2.2 Synthesis of Previous Studies

A synthesis of previous studies from both the western and eastern Ross Sea was conducted by a literature review. This review was conducted by searching through Indexes and Databases, specifically Science Direct, in LSU Libraries system. Selected articles that pertained to the synthesis topic were reviewed. The articles were categorized into different sections including areas for the marine realm in the western and eastern Ross Sea and the terrestrial realm with articles on the following:

- Modeling studies;
- Ice core studies;
- Radiocarbon dating of shells found at raised beaches;
- Radiocarbon dating of penguin remains or penguin guano at raised beaches;
- Radiocarbon dating of algae in proglacial lakes;
- Beryllium-10 dating of glacial erratics found on lateral moraines; and
- Beryllium-10 dating of glacial erratics found on nunataks.

These articles were examined and put into the context of ice advance and retreat. The locations (latitude and longitude) along with the age, the depth interval of the sample, the author who published the date, the type of dating conducted, the sample material, and the interpretation of the sample were entered into an Excel spreadsheet. This spreadsheet was then imported into GeoMapApp (http://www.geomapapp.org) and all the location of the studies were plotted (Figure 9).
Figure 9. All the locations used in this study plotted using GeoMapApp. The thick black line represents the Ross Sea embayment drainage basin (Denton and Hughes 2000). The purple line represents grounded ice at LGM (Denton and Hughes, 2000) and the light blue line represents the modern grounding line (Licht, 2005).

The GZWs from Mosola and Anderson (2006) were posted on the data maps (Figures 12b-18b). Two other maps were generated to show the drainage basin of the Ross Sea Embayment at both the LGM and modern times (Figures 18a, 12a-17a).

The drainage basin of the Ross Sea Embayment (Denton and Hughes, 2000) at the LGM was used to locate the divide between drainage to the western Ross Sea and drainage to the central and eastern Ross Sea. The terrestrial locations in this synthesis were plotted and the LGM ice-flow lines were plotted on one map to determine which terrestrial studies pertained to ice
sheet drainage into Eastern Basin at the LGM. A similar series of maps were generated to highlight the time when a marine area was not covered with grounded ice.

The data from the synthesis study includes data from open-marine sedimentation, the onset of open-marine conditions where raised beaches are present, and an indication of the overall thinning of the ice sheet or outlet glaciers in terrestrial areas, that either exposed previously-ice covered rock or left a morainal-debris band stranded above the deflated ice surface. The maps were generated in 5,000 year increments to determine changes through time in the Ross Sea Embayment. The map synthesis of marine and terrestrial data provides evidence concerning changes in the extent and thickness of grounded ice within the Eastern Basin drainage and receiving basins.
3. Results

3.1 Foraminifera Dates

In all samples that were processed, foraminifera were scarce. Approximately 10 foraminifera per sample were found in the diamictons. Twelve samples, six *in situ* and six reworked were sent for radiocarbon dating at KCCAMS. Eleven of the twelve samples included benthic foraminifera only. Common foraminifera species in the samples included: *Neoconorbina terguemi*, *Globocassidina biora*, *Angulogerina earlandi*, and *Cibicides* sp. The weight range for calcium carbonate in the samples was 0.104 milligrams to 0.441 milligrams, but only the two heaviest samples, both from core PC 6, yielded enough carbon to date (Table 2). Dates of >22,200 $^{14}$C BP and >22,500 $^{14}$C BP were obtained for the crumbled diamicton (see below) and the diamicton stratigraphically below the crumbled diamicton respectively.

3.2 Core Observations of PC 5 and PC 6

The lithology of the piston cores on the topset of the Brown-Unit GZW includes a distinctive crumbled diamicton layer that was not seen in the Gray-Unit GZW. In both PC 5 and PC 6, the top few centimeters consist of pelagic drape, followed by a “crumbly diamicton”, and then a stiff mud rich diamicton as is seen in the sediment cores from the Gray-Unit GZW. The crumbled diamicton contains a less mud-rich matrix and larger, pebble-sized clasts than the underlying muddy diamicton (Figure 10).

It was hoped that JPC 8 on the basinward taper of the Gray-Unit GZW was long enough to penetrate through the Gray Unit and into the topset of the Brown Unit. Evidence of this contact between the Gray Unit and Brown Unit could include a small layer of pelagic drape or a
layer of the crumbled diamicton as seen in PC 5 and PC 6. However, no change in lithology in JPC 8 was seen, suggesting that this 8.3-meter core did not completely penetrate the Gray Unit.

3.3 Synthesis of Terrestrial and Marine Studies

3.3.1 Terrestrial Studies

Figure 11 shows the location of the studies presented below and the ice flow lines at the LGM (Denton and Hughes, 2000). These flow lines demonstrate to which sector of the Ross Sea that grounded ice flowed. From the ice flow lines, it was determined that the studies from Reedy Glacier, Siple Dome, Discovery Ride, Roosevelt Island, and Ford Range all drained into Eastern Basin during the LGM. In the following paragraphs, a review of all information is presented in geographic order in a counter clockwise way starting at North Victoria Land.

In North Victoria Land, there are numerous raised beaches (Figure 11). Raised beaches consist of well-rounded pebbles and boulders (Hall et al., 2004). Beaches require open-marine conditions for at least part of the year (Emslie et al., 2007). The oldest date recorded for a raised beach in Terra Nova Bay (TNB) is 7,505 $^{14}$C BP from in situ pelecypods at Evans Cove. At this time, TNB was ice free and exposed to wave action (Baroni et al., 1991). Another raised beach in this area was dated by Adamussium colbecki, a bivalve, at 7,020 $^{14}$C BP (Stuvier et al., 1981). At Cape Bird, raised beaches were dated to 7,200 $^{14}$C BP, suggesting a similar deglacial time frame as the rest of TNB (Colhoun et al., 1992).

At TNB, older dates of 13,070 $^{14}$C BP and 11,325 $^{14}$C BP on a raised beach at Cape Hickley were determined from penguin guano (Baroni et al., 1994b) (Figure 11).
Table 2. A tabulation of all the core locations, depth intervals, and *in situ* vs. reworked fraction that were sent. The two dates that were received are bolded.

<table>
<thead>
<tr>
<th>Core</th>
<th>Depth, cm</th>
<th>Total Calcium Carbonate Mass, mg</th>
<th><em>In situ</em> or reworked</th>
<th>Radiocarbon date uncorrected</th>
</tr>
</thead>
<tbody>
<tr>
<td>NBP0802 PC 4</td>
<td>193-195</td>
<td>.197</td>
<td><em>In situ</em></td>
<td>-</td>
</tr>
<tr>
<td>NBP0802 PC 4</td>
<td>198-200</td>
<td>.104</td>
<td><em>In situ</em></td>
<td>-</td>
</tr>
<tr>
<td>NBP0802 PC 4</td>
<td>113-223</td>
<td>.166</td>
<td>Reworked</td>
<td>-</td>
</tr>
<tr>
<td>NBP0802 PC 5</td>
<td>130-132</td>
<td>.143</td>
<td><em>In situ</em></td>
<td>-</td>
</tr>
<tr>
<td>NBP0802 PC 5</td>
<td>110-112, 173-175, 210-212, 250-252</td>
<td>.107</td>
<td><em>In situ</em></td>
<td>-</td>
</tr>
<tr>
<td>NBP0802 PC 5</td>
<td>173-175</td>
<td>.178</td>
<td>Reworked</td>
<td>-</td>
</tr>
<tr>
<td>NBP0802 PC 5</td>
<td>110-112, 130-132, 210-212, 250-252</td>
<td>.237</td>
<td>Reworked</td>
<td>-</td>
</tr>
<tr>
<td>NBP0802 PC 6</td>
<td>270-272</td>
<td>.219</td>
<td><em>In situ</em></td>
<td>-</td>
</tr>
<tr>
<td>NBP0802 PC 6</td>
<td>110-112</td>
<td>.275</td>
<td>Reworked</td>
<td>&gt;22,200</td>
</tr>
<tr>
<td>NBP0802 PC 6</td>
<td>200-272</td>
<td>.441</td>
<td>Reworked</td>
<td>&gt;22,500</td>
</tr>
<tr>
<td>NBP0802 JPC 8</td>
<td>185.5-650</td>
<td>.118</td>
<td><em>In situ</em></td>
<td>-</td>
</tr>
<tr>
<td>NBP0802 JPC 8</td>
<td>185.5-650</td>
<td>.163</td>
<td>Reworked</td>
<td>-</td>
</tr>
</tbody>
</table>
Figure 10. Cores photographs with the corresponding X-ray for NBP0802 PC 6.
Figure 11. The Ross Sea Embayment (thick black line) with flow lines during the LGM and the terrestrial locations are labeled. The dark purple line represents the extent of grounded ice at the LGM, the light blue line represents the modern grounding line, and the red line represents the divide of ice flow between the eastern and western portion of the Ross Sea.

These dates suggest that open-marine conditions existed at Terra Nova Bay by 13,000 $^{14}$C BP. This is a 6,000 year difference between these dates and dates from previous work by Baroni (1991) and Stuvier (1981).
A study by Hall (2004) suggested that the old dates from Cape Hickley were a mixture of old and new carbon. Hall (2004) dated stratigraphically higher and older samples of organic remains at a raised beach of Cape Hickley. A radiocarbon date of 7,540 $^{14}$C BP was obtained. This younger data, from a stratigraphically older raised beach, suggests that the previous older dates from Baroni (1994b) probably contained a mixture of old and new carbon.

A study by Emslie (2007) dated the organic remains from abandoned penguin colonies in Cape Hickley and Beaufort Island (BI) (Figure 11). Penguin colonies habitat are restricted to areas in proximity to open-marine conditions (Emslie et al., 2007). Penguin eggshells that predate the LGM at 45,000 to 27,000 $^{14}$C BP years BP were found at both Cape Hickley and Beaufort Island. These dates support conclusions by Licht (1996), who proposed that there was open water in the Ross Sea prior to the LGM. The next evidence of open-marine waters at Ross Island, were dated to 8,000 $^{14}$C BP and are associated with the recolonization of Ross Island by penguins. The hiatus (27,000 – 8,000 $^{14}$C BP) potentially represents a time period that the WAIS advanced and occluded Ross Sea (Emslie et al., 2007).

Hatherton Glacier flows from the EAIS into Darwin Glacier which discharges into the Ross Ice Shelf (Bockheim et al., 1989). Thus, Hatherton Glacier was an important connection between the EAIS and WAIS in the past (Figure 11). Glacial erratics found along morainal deposits near Hatherton Glacier were Beryllium 10 ($^{10}$Be) dated and demonstrated LGM ages from 19,000 to 15,000 years BP for the glacial maximum (Storey et al., 2010). Britannia Drift, which is stratigraphically higher, found ice thickening from 45,000 to 30,000 years BP, suggesting an older interval of glaciation at Hatherton Glacier (Storey et al., 2010).
Another study in Hatherton Glacier radiocarbon dated the blue-green algae that grew in ice-contact lakes (Bockheim et al., 1989). The algae provide the minimum age of the underlying drift. At the outer limit of the glacier, algae were dated to 9,420 years $^{14}$C BP. This suggests that ice had retreated from this location at that time (Bockheim et al., 1989).

Reedy Glacier drains the EAIS into the Ross Sea Embayment via the Mercer Ice Stream (Todd et al., 2010) (Figure 11). Glacial erratics along different locations in Reedy Glacier were $^{10}$Be dated to constrain the inflation and deflation of the glacier as ice presumably advanced and retreated in the Ross Sea during and since the LGM (Todd et al., 2010). The glacial erratics consist of cobbles and boulders that were lodged on slopes of protruding nunataks and appeared to be not weathered and “fresh” as compared to other glacial erratics in the same location (Todd et al., 2010). At Quartz Hills, the maximum ice thickness (i.e., highest morainal debris band) formed between 17,000 to 14,100 years BP (Todd et al., 2010). The thickening was caused by the buttressing of the glacier by an inflated WAIS in Ross Sea (Todd et al., 2010). Thinning of Reedy Glacier was underway by 13,000 years BP as the WAIS thinned and grounded ice retreated to an interior location south of Reedy Glacier (Todd et al., 2010).

In the Ohio Range at Discovery Ridge near the WAIS divide, glacial erratics from nunataks and ridges were $^{10}$Be dated (Ackert et al., 2007). This area had a maximum reported ice thickness value that occurred between 11,500 to 10,000 years BP (Ackert et al., 2007). The timing of maximum ice thickness is interpreted by Ackert (2007) to represent ice-sheet retreat in Ross Sea. According to Ackert (2007), the thickening of ice in the Ohio Range is a response to the increasing accumulation rates as ice retreated. After 10,000 years BP, the ice began thinning (Ackert et al., 2007).
An ice core was obtained at Siple Dome and was reported on in the study by Waddington (2005) (Figure 11). A model incorporating the varying thickness in annual ice layers was used to constrain the timing of the post-LGM thinning of the ice sheet (Waddington et al., 2005). The two best-fit scenarios are that at 16,000 or 8,000 years BP, the ice sheet had begun to thin (Waddington et al., 2005).

On the other side of the Ross Embayment, Marie Byrd Land shows a pattern of steady Holocene deglaciation presumably as the grounded ice in the Ross Sea retreated (Stone et al., 2003). Glacial erratics from the Ford Ranges in western Marie Byrd Land were $^{10}$Be dated (Stone et al., 2003). From 10,400 years BP, a steady deglaciation had occurred (Stone et al., 2003). The older dates of 39,700 to 112,000 years BP for the same locations in the Ford Ranges are thought to be due to prior exposure to cosmic rays (Stone et al., 2003).

A provenance study by Licht (2005) determined that during the LGM interval, the western Ross Sea received drainage from the EAIS through the Transantarctic Mountains. The central Ross Sea acted as a convergence point for ice flow from the EAIS and the WAIS (Licht, 2005). The WAIS ice flow was confined to three troughs in the eastern and central Ross Sea. According to the study by Licht (2005), flow from the Siple Coast ice streams drained into the eastern Ross Sea.

### 3.3.2 Marine Studies

Marine studies, including radiocarbon dating of acid insoluble organics in the central and eastern Ross Sea, suggest contradictory views of WAIS retreat history (Mosola and Anderson, 2006, Bart and Cone, in review). The conventional view is that grounded ice advanced to the continental shelf in the eastern and central Ross Sea after 9,800 $^{14}$C BP (Licht and Andrews,
A study by Bart and Cone (in review) suggests that grounding at a middle shelf GZW in Eastern Basin culminated at 27,500 $^{14}$C BP. Similar dates for glaciomarine units above the diamicton were found in Eastern Basin that suggests grounding of the ice sheet prior to the LGM (Mosola and Anderson, 2006). These dates from the glaciomarine units above the diamicton range from 18,000 $^{14}$C BP to greater than 30,000 $^{14}$C BP and are prior to the LGM (Mosola and Anderson, 2006).

### 3.3.3 Map View of Data

The series of maps (Figures 12-15) illustrate the timing of events occurring during the past 30,000 years BP for both the marine and terrestrial realms in the Ross Sea Embayment. In the maps, the red line represents the ice flow drainage divide at the LGM and the purple line represents the extent of the grounded ice (Denton and Hughes, 2000). The light blue line represents the modern grounding line from Licht (2005). The thick black line represents the outline of the Ross Sea Embayment from Denton and Hughes (2000). In each case, a map specifically of the marine realm with the Mosola and Anderson (2006) GZWs from Eastern Basin and locations of radiocarbon dates are shown. In these maps, the purple line represents the extent of grounded ice at the LGM and the red line represents the ice flow drainage divide at the LGM (Denton and Hughes, 2000).

For greater than 30,000 BP map, open-marine conditions are evidenced by radiocarbon dates from pelagic drape and raised beaches in the terrestrial realm (Figure 12A). These raised beaches include those at Beaufort Island and Cape Hickley (Emslie et al., 2007). There are 3 dates for open-marine sedimentation in the western Ross Sea (Licht et al., 2002; Perry, 1999). There are no open-marine dates for Eastern Basin (Figure 12B).
Figure 12. Interval: 30,000 BP and older. (A) The dark blue dots are radiocarbon dates from the marine realm (Licht et al., 2002; Perry, 1999). The white dots are radiocarbon dates from raised beaches Beaufort Island (BI) and Cape Hickley (CH) (Emslie et al., 2007). The orange line represents the observed divide between where open-marine conditions are known to exist and where grounded ice might have been located. (B) A close up view of the Ross Sea to the modern calving front with the GZWs from Mosola and Anderson (2006). The dark blue dots are radiocarbon dates from the marine realm (Licht et al., 2002; Perry, 1999). The white dots are radiocarbon dates from raised beaches Beaufort Island (BI) and Cape Hickley (CH) (Emslie et al., 2007).
From 30,000 to 25,000 BP, open-marine conditions are evidenced by radiocarbon dates from pelagic drape and raised beaches in the terrestrial realm (Figure 13A). These raised beaches include Beaufort Island and Cape Hickley (Emslie et al., 2007). There are two dates from open-marine sedimentation and one date from the deposition of the Gray Unit GZW (Mosola and Anderson, 2006; Bart and Cone, in review; Licht et al., 2002) (Figure 13B).

From 25,000 to 20,000 BP, open-marine conditions are evidenced by radiocarbon dates from pelagic drape (Figure 14A). There are three open-marine dates in western Ross Sea and three open-marine dates in eastern Ross Sea (Licht et al., 2002; Mosola and Anderson, 2006). In eastern Ross Sea, the radiocarbon dates are located on top of or near GZWs. These GZWs include 5c, south of 5b and 5a, and west of 3b (Mosola and Anderson, 2006) (Figure 14B).

From 20,000 to 15,000 BP, open-marine conditions are evidenced by radiocarbon dates from pelagic drape (Figure 15A). In the terrestrial realm at Reedy Glacier at 17,000 BP there was a change in ice elevation evidenced by $^{10}$Be dating of glacial erratics (Todd et al., 2010). Initial thinning occurred at 16,000 BP at Siple Dome (Waddington et al., 2005). There are two open-marine dates in the western Ross Sea and four marine dates in eastern Ross Sea (Licht et al., 2002; Mosola and Anderson, 2006). In eastern Ross Sea, the radiocarbon dates are from a contact directly above GZWs, specifically 6c, 4a, and 5b (Mosola and Anderson, 2006) (Figure 15B).

From 15,000 to 10,000 BP, open-marine conditions are evidenced by radiocarbon dates from pelagic drape and $^{10}$Be exposure studies in the terrestrial realm (Figure 16A).
Figure 13. Interval: 30,000 to 25,000 BP. (A) The dark blue dots are radiocarbon dates from the marine realm (Mosola et al., 2006; Licht et al., 2002; Bart and Cone, in review). The white dots are radiocarbon dates from raised beaches at Beaufort Island (BI) and Cape Hickley (CH) (Emslie et al., 2007). The orange line represents the divide where there were open-marine conditions and where there might have been grounded ice. (B) A close up view of the Ross Sea to the modern calving front with the GZW’s from Mosola and Anderson (2006). The dark blue dots are radiocarbon dates from the marine realm (Mosola et al., 2006; Licht et al., 2002; Bart and Cone, in review). The white dots are radiocarbon dates from raised beaches at Beaufort Island (BI) and Cape Hickley (CH) (Emslie et al., 2007).
Figure 14. Interval: 25,000 to 20,000 BP. (A) The dark blue dot dots are radiocarbon dates from the marine realm (Mosola et al., 2006; Licht et al., 2002). The orange line represents where there were open-marine conditions and where there might have been grounded ice. (B) A close up view of the Ross Sea to the modern calving front with the GZWs from Mosola and Anderson (2006).
Figure 15. Interval: 20,000 – 15,000 BP. (A) On this map, the dark blue dots are radiocarbon dates from the marine realm (Mosola et al., 2006). The white dot is ice core and modeling study from Siple Dome and represents initial deflation (Waddington et al., 2005). The orange line represents where there were open-marine conditions and where there might have been grounded ice. (B) A close up view of the Ross Sea to the modern calving front with the GZWs from Mosola and Anderson (2006). The dark blue dots are radiocarbon dates from the marine realm (Mosola et al., 2006).
Figure 16. Interval: 15,000 – 10,000 BP. (A) On this map, the dark blue are radiocarbon dates from the marine realm (Domack et al., 1999; Cone, 2010; Mosola et al., 2006; Wellner, 2001). The white dot is an ice core/modeling study at Siple Dome (Parizek et al., 2004). The orange dots are $^{10}$Be dates from terrestrial locations and represent deflation in those locations (Todd et al., 2010; Storey et al., 2010; Stone et al., 2003; Ackert et al., 2007). The orange line represents where there were open-marine conditions and where there might have been grounded ice. (B) A close up view of the Ross Sea to the modern calving front with the GZWs from Mosola and Anderson (2006). The dark blue are radiocarbon dates from the marine realm (Domack et al., 1999; Cone, 2010; Mosola et al., 2006; Wellner, 2001). The white dot is $^{10}$Be dates from Ford Range in Marie Byrd Land (Stone et al., 2003).
These terrestrial studies include Marie Byrd Land (Ford Range), Discovery Ridge (Ohio Range), Reedy Glacier, and Hatherton Glacier (Stone et al., 2003; Ackert et al., 2007; Todd et al., 2010; Storey et al., 2010). Deflation at Marie Byrd Land and Discovery Ridge occurred at 10,000 BP (Stone et al., 2003; Ackert et al., 2007). Deflation at Reedy Glacier occurred at 13,000 BP (Todd et al., 2010). There are just a few marine dates in both eastern and western Ross Sea (Mosola and Anderson, 2006; Bart and Cone, in review; Domack et al., 1999; Wellner, 2001) and GZWs in Eastern Basin are shown (Mosola and Anderson, 2006) (Figure 16B). In the western Ross Sea all dates are north of Ross Island and Terra Nova Bay. In eastern Ross Sea, three dates are present and are near GZW 5a, 5b, and 5c.

From 10,000 to 5,000 BP, open-marine conditions are evidenced by radiocarbon dates from pelagic drape and raised beaches (Figure 17A). The raised beaches include Inexpressible Island and Cape Hickley (Baroni et al., 1991; Hall et al., 2004). Radiocarbon dates from shells along Ross Island and algae at Taylor Valley also give an age between 5,000 and 10,000 years BP (Licht, 2004) (Figure 17A). The marine dates are prevalent in both eastern and western Ross Sea (Mosola and Anderson, 2006; Bart and Cone, in review; Domack et al., 1999; Andrews et al., 1999; Wellner, 2001) and GZWs in Eastern Basin are shown (Mosola and Anderson, 2006) (Figure 17B). No marine dates are found south of Ross Island in this time interval.

From 5,000 to 0 BP, open-marine conditions are evidenced by radiocarbon dates from pelagic drape, raised beaches, and by an ice penetrating radar study (Figure 18A). Radiocarbon dates from raised beaches include Franklin Island and Cape Adare (Colhoun et al., 1992). On Roosevelt Island, a study using ice-penetrating radar was conducted (Conway et al., 1999) (Figure 18B).
Figure 17. Interval: 10,000-5,000 BP. (A) On this map, the dark blue dots are radiocarbon dates from the marine realm (Cone, 2010; Domack et al., 1999; Andrews et al., 1999; Wellner, 2001; Mosola et al., 2006). The yellow dots are radiocarbon dates from raised beaches at Cape Hickley (CH), Cape Bird (CB) and Inexpressible Island (IE) (Baroni et al., 1991; Hall et al., 2004). The white dots are radiocarbon studies that dated mollusk and algae at Taylor Valley (TV) and Ross Island (Licht, 2004). The orange line represents where there were open-marine conditions and where there might have been grounded ice. (B) A close up view of the Ross Sea to the modern calving front with the GZWs from Mosola and Anderson (2006). The dark blue dots are radiocarbon dates from the marine realm (Cone, 2010; Domack et al., 1999; Andrews et al., 1999; Wellner, 2001; Mosola et al., 2006). The yellow dots are radiocarbon dates from raised beaches at Cape Hickley (CH), Cape Bird (CB) and Inexpressible Island (IE) (Baroni et al., 1991; Hall et al., 2004). The white dots are radiocarbon studies dating mollusk and algae at Taylor Valley (TV) and Ross Island (Licht, 2004).
**Figure 18.** Interval: 5,000 to 0 BP. (A) This map shows the modern drainage of the Ross Sea from Licht (2005). The dark blue dots are radiocarbon dates from the marine realm (Cone, 2010; Domack *et al*., 1999; Andrews *et al*., 1999; Wellner, 2001). The yellow dots are radiocarbon dates from raised beaches, Franklin Island (FI) and Cape Adare (CA) (Colhoun *et al*., 1992). The white dot is a modeling study and ice-penetrating radar study at Roosevelt Island (RI) (Conway *et al*., 1999). (B) A close up view of the Ross Sea to the modern calving front with the GZWs from Mosola and Anderson (2006). The dark blue dots are radiocarbon dates from the marine realm (Cone, 2010; Domack *et al*., 1999; Andrews *et al*., 1999; Wellner, 2001). The white dots are radiocarbon dates from raised beaches, Franklin Island (FI) and Cape Adare (CA) (Colhoun *et al*., 1992).
The marine dates are prevalent in both eastern and western Ross Sea (Mosola and Anderson, 2006; Bart and Cone, in review; Domack et al., 1999; Andrews et al., 1999; Wellner, 2001) and the GZWs in Eastern Basin are shown (Mosola and Anderson, 2006) (Figure 18B). The marine dates extended south of Ross Island.
4. Discussion

4.1 Foraminifera Study

One of the objectives of this study was to date in situ single large foraminifera. The one sample that contained a single large foraminifera was 0.197 milligrams; however, it did not yield a radiocarbon age (Table 2). KCCAMS obtained less mass than the mass measured on a microbalance at Louisiana State University. The foraminifera were picked with a brush that was wet at times. The extra water weight could have caused the foraminifera to have a greater mass than their actual mass. Conversely, for other samples containing multiple foraminifera, perhaps all the foraminifera were not extracted out of the glass vials at KCCAMS. During mailing, foraminifera could have been shaken into the lid or statically clung to the sides of the glass vial and may not have been extracted for weighing or $^{14}C$ measurements (personal communication, Dr. Kristine DeLong).

The $^{14}C$ dates from this study are from a reworked fraction and thus do not give any indication of the timing of grounded ice advance for the Gray-Unit or Brown-Unit GZWs. The data only suggests that sometime before 22,200 $^{14}C$ BP open-marine conditions existed south of the Gray-Unit GZW, which is consistent with all models.

If the conventional view of grounded ice advance and retreat is correct (Domack et al., 1999), then these older dates demonstrate that there are reworked foraminifera in the diamicton and all older dates might be considered suspect. However, if these foraminifera are actually in situ and not reworked, then the timing of the Gray and Brown GZWs in Eastern Basin were formed prior to 22,200 $^{14}C$ BP thus pre-dates the LGM. Since the foraminifera are considered
reworked in the two samples that yielded a radiocarbon date and the age is only constrained to be >22,200 $^{14}$C BP, this information cannot be used to support or refute any of the existing retreat models. In the other ten samples, including six samples with foraminifera that were considered \textit{in situ}, no radiocarbon date was obtained. However, from the absence of radiocarbon dates in these samples it can be inferred that the foraminifera were older than the Holocene and potentially upwards of 30,000 $^{14}$C BP (Figure 19). This inference would suggest that the Gray and Brown GZW$s$ are older than the Holocene. If the foraminifera were of Holocene age as expected by the conventional view of WAIS advance and retreat in Eastern Basin then the foraminifera should have yielded radiocarbon dates of 10,000 $^{14}$C BP or younger with the sample size that was provided to KCCAMS (Licht and Andrews, 2002; Conway \textit{et al.}, 1999).

In this study, the heavy-liquid separation helped isolate the large foraminifera that were in the diamicton. Determining the \textit{in situ} versus reworked fraction in each sample was possible with the larger size of foraminifera. However, there was not an abundance of \textit{in situ} foraminifera; therefore not enough mass to generate a radiocarbon date. In a previous study by Perry (1999), the author noted that the diamicton from the western Ross Sea had a low abundance of foraminifera. The author concluded that the entire fraction of foraminifera was reworked. In this study, there is evidence that \textit{in situ} foraminifera were present; however, there were just not enough \textit{in situ} foraminifera in our samples to get an accurate date for the Gray and Brown-Unit GZW$s$.

Current radiocarbon dating by Accelerator Mass Spectrometry (AMS) is only feasible for small-sample sizes. In samples 10 micrograms and below samples older than the Holocene do not contain enough carbon to date (KCCAMS, personal communication). Typical small-sample sizes range from 10 to 100 micrograms of total carbon for dates older than the Holocene.
Figure 19. A graphical representation of the age errors associated with the sample age of carbonates for radiocarbon dating. This graph demonstrates that samples with <.4 mg CaCO$_3$ could have a date up to 30,000 (±3,000 years) $^{14}$C BP (National Ocean Sciences Accelerator Mass Spectrometry Facility).

The samples sent in this study were near the 10-microgram limit and the technology is not currently available to date samples older than the Holocene with less than 10 micrograms of carbon (KCCAMS, personal communication).

Another concern was the absence of smaller juvenile foraminifera that were found in Cone’s (2010) study but absent in the samples of this study. This was likely due to a larger sieve used in this study. Standard sieve mesh size for foraminifera studies is 63 microns. However,
this study used a 54-micron sieve while in Cone’s (2010) study a 45-micron sieve was used. Therefore, the smaller fractions of foraminifera were sieved out in the initial processing of samples.

4.2 Synthesis of Marine and Terrestrial Data

4.2.1 Map View Synthesis

The conventional view of ice advance and retreat in the central and eastern Ross Sea is that the WAIS extended to the continental shelf by LGM and had a subsequent retreat at ~11,000 $^{14}$C BP (Domack et al., 1999; Shipp et al., 1999). This view is contested based on the synthesis of maps generated in this study (Figures 12-18).

At greater than 30,000 BP there is open water in western Ross Sea and no evidence of open-marine or grounded ice conditions in Eastern Basin (Figure 12). It is not possible to say where grounded ice might have occurred in either eastern or western Ross Sea at this time. In the western Ross Sea, open-marine conditions north of Ross Island are evidenced by radiocarbon dates from penguin rookeries at Beaufort Island and Cape Hickley (Emslie et al., 2007). Another study at Hatherton Glacier, suggests inflation at 37,500 $^{10}$Be BP; however, it was noted that the maximum age of inflation could be 45,000 $^{10}$Be BP (Storey et al., 2010). Inflation at Hatherton with a subsequent deflation at 45,000 $^{10}$Be BP corresponds with the Emslie (2007) results. Emslie (2007) concluded that open-marine conditions existed in western Ross Sea north of Ross Island at 45,000 $^{14}$C BP. If Hatherton Glacier was not yet deflated, there is a possibility that Cape Hickley and Beaufort Island would have been covered with ice that would have been present in the western Ross Sea from the inflation of the EAIS.
The Gray-Unit GZW was deposited at 26,500 $^{14}$C BP indicating ice had reached this location by this time (Bart and Cone, in review). Radiocarbon dates from the overlying muds indicate retreat by ~26,500 $^{14}$C BP and a resumption of open-marine sedimentation in Eastern Basin. In western Ross Sea, WAIS had not yet advanced to the middle continental shelf and open-marine conditions are represented by radiocarbon dates from penguin rookeries at Beaufort Island and Cape Hickley until 27,000 $^{14}$C BP (Emslie et al., 2007).

At 25,000 to 20,000 BP, grounded ice was still south of the Gray GZW. There is no indication of interior inflation or deflation at this time. In Marie Byrd Land, this retreat would not have been recorded because there are not rock exposures to date, i.e., even if the ice sheet deflated, no ice-covered rock were exposed (Stone et al., 2003). At Reedy Glacier there are six different deposits that have been identified: Reedy E, Reedy D, Reedy C, Reedy B, Reedy A, and Reedy III (Bromley et al., 2010). Reedy A was deposited sometime between 17,000 and 135,000 BP. This is the only constraint there is on the unit above the Reedy III, the LGM unit (Bromley et al., 2010). At Discovery Ridge, only deposits at the trimline and below were dated to constrain the LGM (Ackert et al., 2007). Deposits above the trimline were considered to be from a time prior to the LGM. In the western Ross Sea, advance of the ice sheet occurred based on the absence of radiocarbon dates from 19,500 to 26,500 $^{14}$C BP (Domack et al., 1999).

At 20,000 to 15,000 BP, Eastern Basin continued to have open-marine conditions as evidenced by radiocarbon dates from pelagic drape (Mosola and Anderson, 2006). The principle of stratigraphic superposition makes it impossible that grounded ice re-occupied Eastern Basin at this time. Western Ross Sea had continual ice advance close to north of Coulman Island (Emslie et al., 2007; Domack et al., 1999; Licht et al., 1996). The change of ice elevation at 16,000 BP
at Siple Dome indicates deglaciation had occurred at this time (Waddington et al., 2005) and was potentially associated with WAIS retreat in Eastern Basin.

At 15,000 to 10,000 BP, Eastern Basin continued to have open-marine conditions as evidenced by radiocarbon dates from pelagic drape (Mosola and Anderson, 2006; Bart and Cone, in review). Discovery Ridge and Marie Byrd Land deflation at 10,000 BP indicate that the grounding line moved south of these locations (Ackert et al., 2007; Stone et al., 2003). The deflation of terrestrial locations that drain into Eastern Basin, Discovery Ridge, Ford Range, and Reedy Glacier must have been associated with additional retreat from a grounding line position below the Ross Ice Shelf. In western Ross Sea, grounded ice culminated at 14,000 $^{14}$C BP north of Coulman Island (Domack et al., 1999). The subsequent retreat began at 11,000 $^{14}$C BP as evidenced by the return to open-marine conditions from radiocarbon dates of pelagic drape (Domack et al., 1999; Licht et al., 1996). Thus, deflation at Hatherton Glacier occurred prior to the onset of retreat from western Ross Sea.

At 10,000 to 5,000 BP, Eastern Basin continued to have open-marine conditions as evidenced by radiocarbon dates from pelagic drape (Mosola and Anderson, 2006; Bart and Cone, in review). In the western Ross Sea, WAIS had retreated to Ross Island by 6,600 $^{14}$C BP (Licht, 2004). This retreat is evidenced by radiocarbon dates from pelagic drape and raised beaches, which require open-marine conditions (Domack et al, 1999; Baroni et al., 1991). However, there is no evidence of pauses during the deflation in the terrestrial locations to match the major depositional episodes associated with the grounding line retreat.

At 5,000 to 0 BP, Eastern Basin continued to have open-marine conditions as evidenced by radiocarbon dates from pelagic drape (Mosola and Anderson, 2006; Bart and Cone, in
review). In eastern Ross Sea, WAIS had retreated to Roosevelt Island by 3,200 BP suggesting grounded ice may have re-advanced and then retreated (Conway et al., 1999). However, the interpretation of retreat at 3,200 BP is built on the assumption that grounded ice existed in Eastern Basin at LGM (Conway et al., 1999). Since this interpretation is not supported by the marine data, the interpretation at Roosevelt Island needs to be revisited.

4.2.2 Inflation and Deflation Histories

The data from the studies reviewed suggests that the WAIS retreat for Eastern Basin at ~26,000 ¹⁴C BP was not coincident with deflation of any of the interior locations surveyed. The earliest deflation occurred at Siple Dome at 16,000 BP, followed by deflation at Reedy Glacier at 13,000 BP and deflation at Marie Byrd Land and Discovery Ridge at 10,000 BP (Waddington et al., 2005; Todd et al., 2010; Stone et al., 2003; Ackert et al., 2007). Thus the deflation of interior locations was delayed by over 13,000 years. From these data, I deduce that deflation of the WAIS was probably confined to the regions near the grounding line whereas more interior locations experienced no change in ice-elevation. Therefore, the proximity of an interior location to the grounding line affects the onset of deflation.

In a recent study of Pine Island Glacier, Payne (2004) found that coeval deflation occurred in this area that receives drainage from the WAIS. As the grounding line retreated, ice thinned over a broad area up to 200 kilometers inland of the grounding line (Payne et al., 2004). In Eastern Basin, a similar coeval deflation is predicted between terrestrial areas and the marine terminus of the grounding line. In this scenario, deflation in the terrestrial areas occurred when the grounding line was within 200 kilometers of the terrestrial locations, similar to what was determined by Payne (2004) at Pine Island Glacier. Differences between the Pine Island and
Ross Sea areas include the lack of a large ice shelf (which occurs in the Ross Sea) and a different bedrock surface (Payne et al., 2004). In a study by Shepherd (2002), it was determined that the current rapid rate of retreat is related to the bedrock, surface slope, and buoyancy of the glacier.

A study at Marie Byrd Land found that deflation from 3,500 BP to the modern time was caused by only 30 kilometers of grounded ice retreat (Stone et al., 2003). Following this line of reasoning, at 10,000 years ago, ~90 kilometers of ice retreat would be needed to explain the observed magnitude of Holocene retreat at Marie Byrd Land. This suggests that a close proximity could be between 90 to 200 kilometers to the marine terminus of the grounding line.

It is inferred that the WAIS retreated from the middle continental shelf to the modern grounding line over a period of 26,000 years. However, this retreat would have been very slow at ~25 meters/year and suggests that perhaps some pauses occurred in the retreat history from the middle continental shelf. The GZWs from these pauses would be located under the broad Ross Ice Shelf.

The inferred configuration of the retreat of the WAIS is shown below at times 26,000; 19,000; 16,000; 13,000 and 10,000 BP (Figures 20-24). Around 26,000 14C BP initial WAIS retreat had occurred from the middle continental shelf in Eastern Basin and open-marine conditions existed to Ross Island in western Ross Sea (Bart and Cone, in review). No change of ice-sheet elevation occurred at any terrestrial locations (Figure 20). At 19,000 BP, continual retreat south of the WAIS occurred in Eastern Basin and potentially reached the calving front of the modern Ross Ice Shelf. Continual advance north of the WAIS occurred in western Ross Sea (Figure 21). At 16,000 BP, continual retreat south of the WAIS occurred. At this time, the grounding line was in close proximity with Siple Dome and initial deflation at Siple Dome.
occurred. In western Ross Sea, continual advance of grounded ice to north of Coulman Island occurred (Figure 22). At 13,000 BP, WAIS retreat continued south in Eastern Basin. Initial retreat in the western Ross Sea occurred. At this time, the grounding line was in close proximity to Reedy Glacier and initial deflation at Reedy Glacier occurred (Figure 23). At 10,000 BP, WAIS retreat occurred near the modern grounding line. The grounding line was in close proximity with Marie Byrd Land and Discovery Ridge and at these locations initial deflation occurred (Figure 24).

4.2.3 Grounding Zone Wedges and the Timing of Retreat in Eastern Basin

Eastern Basin contains multiple GZWs that represent pauses of the WAIS retreat. Each GZW is conventionally viewed as being deposited during a single pause of the WAIS during the post-LGM retreat. If the WAIS paused for a thousand or a few thousand years, then these pauses might also be noted in the terrestrial realm. If the multiple pauses occurred during post-LGM time interval, then there should also be short intervals of inflation and deflation in the terrestrial realm that is evidenced by glacial erratics. However, in the terrestrial realm there is no indication of pauses in the marine retreat for the Purple, Brown, Red, and Gray GZWs that have been identified (Figure 25).

4.2.4 Different Retreat History of Western Ross Sea and Eastern Basin

A greater than 12,000 year difference in the timing of the retreat of Eastern Basin and the western Ross Sea is possible. This timing difference could be the result of the proximity of the western Ross Sea to the Transantarctic Mountains and the difference in retreat between the EAIS and WAIS in the Ross Sea region. Ice streams and the nature of the ice flow beneath the ice sheet could account for major differences and timing in retreat history. A study by Shipp (1999)
suggests that the ice streams are independent and this nature of the ice streams may cause significant differences in deglaciation in the Ross Sea.

**Figure 20.** Grounding line configuration at 26,000 BP is represented by the red dotted line. The thick black line represents the Ross Sea Embayment, the thin black line represents the modern ice shelf, the light blue line represents the modern grounding line, and the purple line represents the “LGM” grounding line (Denton and Hughes, 2000). The green dot is the location of the Gray GZW (Bart and Cone, in review).
Figure 21. Grounding line configuration at 19,000 BP is represented by the red dotted line. The thick black line represents the Ross Sea Embayment, the thin black line represents the modern ice shelf, the light blue line represents the modern grounding line, and the purple line represents the “LGM” grounding line (Denton and Hughes, 2000). The green dot is the location of the Gray GZW (Bart and Cone, in review). The blue dots are the location of open marine conditions from radiocarbon dates on glaciomarine sediments in Eastern Basin (Mosola and Anderson, 2006).
Figure 22. Grounding line configuration at 16,000 BP is represented by the red dotted line. The thick black line represents the Ross Sea Embayment, the thin black line represents the modern ice shelf, the light blue line represents the modern grounding line, and the purple line represents the “LGM” grounding line (Denton and Hughes, 2000). The green dot is the location of the Gray GZW (Bart and Cone, in review). The blue dots are the location of open marine conditions from radiocarbon dates on glaciomarine sediments in Eastern Basin (Mosola and Anderson, 2006). The white dot is the location of Siple Dome (Waddington et al., 2005).
Figure 23. Grounding line configuration at 13,000 BP is represented by the red dotted line. The thick black line represents the Ross Sea Embayment, the thin black line represents the modern ice shelf, the light blue line represents the modern grounding line, and the purple line represents the “LGM” grounding line. The green dot is the location of the Gray GZW (Bart and Cone, in review). The blue dots are the location of open marine conditions from radiocarbon dates on glaciomarine sediments in Eastern Basin (Mosola and Anderson, 2006). The white dot is the location of Siple Dome (Waddington et al., 2005), and the yellow dot is the location of Reedy Glacier (Todd et al., 2010).
Figure 24. Grounding line configuration at 10,000 BP is represented by the red dotted line. The thick black line represents the Ross Sea Embayment, the thin black line represents the modern ice shelf, the light blue line represents the modern grounding line, and the purple line represents the “LGM” grounding line (Denton and Hughes, 2000). The green dot is the location of the Gray GZW (Bart and Cone, in review). The blue dots are the location of open marine conditions from radiocarbon dates on glaciomarine sediments in Eastern Basin (Mosola and Anderson, 2006). The white dot is the location of Siple Dome (Waddington et al., 2005), and the yellow dots are the locations of Marie Byrd Land, Discovery Ridge, and Reedy Glacier (Stone et al., 2003; Ackert et al., 2007; Todd et al., 2010).
This suggests ice flow could have been very different in eastern and western Ross Sea, causing deglaciation to occur at very different times. Other differences include warm water intrusion or a precipitation deficit to Eastern Basin. Eastern Basin is much deeper than western Ross Sea and perhaps warm water intruded, traveled further under the ice shelf causing a quicker decoupling, and allowed for no re-advance of the WAIS in Eastern Basin (Bart and Cone, in review). These differences could all account for the differences in retreat histories of the Ross Sea.
The timing of retreat in Eastern Basin from this study and the relative sea level curve from Peliter (2006) were compared (Figure 26). WAIS advance in Eastern Basin before 26,000 $^{14}$C BP corresponds with a cooling trend and fall in relative sea level. The subsequent retreat after 26,000 $^{14}$C BP correlates to a slight rise in relative sea level. This rise in relative sea level becomes more apparent by 16,000 years BP when initial deflation had begun at Siple Dome and continues to rise with a greater slope after 16,000 years BP, corresponding to deflation of more interior locations that drain into Eastern Basin including Reedy Glacier, Discovery Ridge, and Marie Byrd Land. This data and the study by Peltier suggest that in Eastern Basin, WAIS advance was not an early advance and retreat prior to the LGM, but in sync with the global LGM. This would suggest that in western Ross Sea there was a late phase advance and retreat.

![Figure 26. Revised from Peltier (2006). The red line shows the relative sea level rise and fall from 32,000 years BP. The green dots represent the timing of events mentioned in this study, beginning with initial retreat in Eastern Basin from the middle continental shelf at 26,000 years BP, and then continual retreat noted at 19,000; 16,000; 13,000; and 10,000 years BP.](image)
5. Conclusions

Sufficiently, large foraminifera were not found in Eastern Basin diamictons samples examined. In this study, some of the foraminifera were likely living at the GZW. These in situ foraminifera should reflect an accurate timing of deposition. However, there were insufficient quantities of large foraminifera; therefore, radiocarbon measurements for samples older than the Holocene could not be made on a single or few specimens of foraminifera. The reworked dates reported in this study from the topset of the Brown-Unit suggest that the GZW formed sometime prior to 22,200 $^{14}$C BP.

From the synthesis of marine and terrestrial studies in Eastern Basin, it is suggested that grounded ice did not occlude Eastern Basin at LGM. The WAIS advanced to the middle continental shelf in Eastern Basin at 26,000 $^{14}$C and shortly thereafter retreated. The terrestrial locations that drain into Eastern Basin experienced no change in ice elevation until the Holocene when the WAIS retreat and terrestrial locations equilibrated.

In the future, an accurate WAIS chronology for Eastern Basin may be obtained. This chronology may come about by improvements in the way of isolating in situ foraminifera and advances in AMS technology so that smaller fractions of carbonate can be dated, and/or terrestrial studies in Marie Byrd Land and other areas that drain into Eastern Basin that will help to constrain the retreat history.
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Vita

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