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When, How, and Why Did the West Antarctic Ice Sheet Retreat in the Ross Sea Since the Last Glacial Maximum Using Foraminiferal And Porewater Geochemistry

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WHEN, HOW, AND WHY DID THE WEST ANTARCTIC ICE SHEET RETREAT IN THE ROSS SEA SINCE THE LAST GLACIAL MAXIMUM USING FORAMINIFERAL AND POREWATER GEOCHEMISTRY

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PREFACE

This dissertation is presented in five chapters with a unifying theme of Antarctic Ice Sheet retreat in the Ross Sea during the late Pleistocene and Holocene. Chapter 1 is a comprehensive introduction. Chapters 2 through 4 are written as cohesive manuscripts that will be submitted to peer reviewed journals. Chapter 5 provides a unifying conclusion for the entire dissertation.

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ABSTRACT

The Antarctic Ice Sheets (AIS) began to retreat from their Last Glacial Maximum (LGM) position sometime after 19,000 years ago. However, the corrosive waters circulating around Antarctica has prevented the recovery of radiocarbon-dateable material, hindering the development of deglacial chronologies. During *Expedition NBP1502B* to the eastern Ross Sea, an unprecedented quantity of fossil foraminifera and bivalves were recovered. Radiocarbon-dated specimens have been used to constrain the timing of West-AIS retreat from Whales Deep basin and Ross Bank. Whales Deep samples show that the WAIS retreated from its LGM position on the continental shelf edge by 14,700 ± 400 calibrated radiocarbon years ago (cal yr BP). Additional ages, seafloor geomorphology and core sedimentology show that the WAIS paused several times before rapidly retreating south of the modern Ross Ice Shelf 11,500 ± 300 cal yr BP. These retreat events are concomitant with Meltwater Pulse -1a and -1b suggesting these two rapid sea-level rise events played a primary role. This finding potentially resolves a point of contention amongst Antarctic scientists.

An additional factor influencing ice sheet retreat includes subglacial meltwater hydrology. Subglacial meltwater generation and drainage may have significantly influenced retreat of Antarctic ice streams in the past and at present. Oxygen isotope ratios ($\delta^{18}O$) from porewater recovered from Whales Deep Basin sediment cores are characteristic of modern Ross Sea waters indicating that fresh meltwater was not preserved in subglacial or glaciomarine sediment. This suggests that subglacial meltwater hydrology did not significantly affect the early stages of WAIS retreat in the Whales Deep Basin.

Ross Bank – a seamount rising to 174 meters below sea level – is covered with a thin layer of pelagic sediment. A box core recovered an abundance of calcareous fossils. Radiocarbon

ages indicate that the Ross Ice Shelf was grounded on Ross Bank until ~600 cal yr BP when it retreated to its present position. This is significant because it suggests that three topographic features acted to buttress the Ross Ice Shelf up until the last few centuries. Since unpinning, there are only two features, Roosevelt Island and Ross Island, that stabilize the modern Ross Ice Shelf calving front.

CHAPTER 1: INTRODUCTION

1.1 Dissertation Introduction

Continental ice sheets began to retreat from their Last Glacial Maximum (LGM) positions between 19,000 to 14,500 years ago (Clark et al., 2009; Carlson and Clark, 2012). Ablation continued through the Holocene causing 125 ± 5 meters of sea-level rise (Carlson and Clark, 2012). However, the timing of retreat of the Laurentide Ice Sheet and Antarctic Ice Sheets is not well constrained. Therefore, determining the relative contributions to global mean sea-level rise for the individual ice sheets is debated. This prohibits an understanding of the local and/or global mechanisms that forced ice sheet retreat.

Understanding the behavior of the West Antarctic Ice Sheet (WAIS) is of particular importance because its subaqueous terminus on the continental shelf makes it susceptible to retreat induced from sea-level rise, warming ocean temperatures and drainage of subglacial lakes (Lowe and Anderson, 2003; Alley et al., 2005; Joughin et al., 2012; Bart and Cone, 2012; Mackintosh et al., 2014; Fogwill et al., 2017). Moreover, the WAIS currently contains 3.3 meters of sea-level equivalent ice volume (Bamber et al., 2009) and is melting at a significant rate (Jenkins et al., 2010; Jacobs et al., 2011; Joughin et al., 2012). Knowing which mechanisms may have caused the WAIS to retreat relies on detailed retreat chronologies. Previous expeditions have not recovered enough *in situ* fossil carbonate to produce reliable deglacial chronologies, in part, due to the corrosive nature of waters that circulate around Antarctica.

Radiocarbon ages from sediment cores are necessary for constraining the age of deglacial sedimentary units and hence produce a retreat model of the Antarctic Ice Sheets. While deglacial chronologies exist, they contain considerable uncertainty due to a number of factors including:

upcore age reversals, ages that are not constrained by core sedimentology, and ages that are derived from glacially reworked sediment that contain an unknown ratio of reworked and *in situ* carbon (Rosenheim et al., 2008; Hillenbrand et al., 2014; Anderson et al., 2014; Subt et al., 2015). To date, these factors have prohibited the establishment of a reliable retreat chronology. Thus, temporally constraining the mechanisms that triggered deglaciation has not been established.

Rising sea-level is cited as a mechanism forcing ice sheet retreat during the Last Glacial Termination (Alley et al., 2005; Mackintosh et al., 2011; Golledge et al., 2014). Rapid sea-level rise (>5 meters) can cause grounded ice to reach its buoyancy limit and decouple from the sea floor initiating retreat (Alley et al., 2007; DeConto and Pollard, 2016). Three distinct intervals of rapid sea-level rise caused by melting continental glaciers occurred since the LGM (Clark et al., 2009). These Meltwater Pulses (MWPs) are defined as 19-kyr MWP, MWP-1a (14.7 kyr BP), and MWP-1b (11.5 kyr BP) (Carlson and Clark, 2012). The 19-kyr MWP is characterized by 5 to 10 meters of sea-level rise (Clark et al., 2004). MWP-1a is characterized by a 16 ± 2 meter sea-level rise occurring in <500 years (Carlson and Clark, 2012; Liu et al., 2015). MWP-1b was originally defined as a rise in sea level by ~15 meters occurring in <500 years (Fairbanks, 1989). Recently, the Barbados sea-level curve has been updated to include 90 additional *Acropora palmate* data-points (U-Th-dated) showing that MWP-1b represented a 14 ± 2 meter sea level rise that occurred over 400 years (Abdul et al., 2016).

In addition to sea-level rise, subglacial lake drainage has also been suggested as a mechanism for ice sheet retreat (Smith et al., 2009; Dowdeswell and Fugelli, 2012; Klages et al., 2014; Halberstadt et al., 2016; Siegfried et al., 2016). Evidence from bathymetric- and satellite-altimeter mapping provide evidence for the drainage of subglacial lakes during the Last Glacial

Termination and from modern ice streams (Stearns et al., 2008; Smith et al., 2009; Greenwood et al., 2012; Siegfried et al., 2016). Subglacial meltwater can be generated by hydrostatic pressure and/or geothermal heat (Alley, 1989; Fisher et al., 2015). This meltwater can act as a lubricant at the base of the ice sheets, accelerating flow (Alley, 1989).

1.2 Background

In the austral summer (January to March) of 2015 the *Nathaniel B Palmer RVIB*, expedition NBP1502B sailed from McMurdo Station to the eastern Ross Sea to perform a large-area bathymetric survey of Whales Deep Basin and collect several sediment cores. One purpose of this expedition was to collect fossil carbonate (e.g. foraminifera, mollusk shells) to radiocarbon date retreat of the WAIS. The capability to directly test a "sea-level induced retreat hypothesis" requires deglacial sedimentary sequences constrained by a suite of radiocarbon dates. During our transit to Whales Deep basin, we sailed over Ross Bank to test the yo-yo seafloor camera. To our surprise, benthos covered the seafloor. A piston core was deployed, however it bounced off the seafloor but a box core (BC01) recovered a 30-cm thick section from the Ross Bank crest (174 meters below sea level). Benthos, including calcareous fossil foraminifera and bivalves, are abundant in BC01. Fourteen radiocarbon dates were produced from a subset of these fossils.

A total of 15 kasten cores (KC) and 6 jumbo piston cores (JPC) were acquired in Whales Deep Basin to recover deglacial sediment from which foraminifera and porewater would be collected and analyzed for their geochemistry. The recovery of foraminifera from ice-proximal glaciomarine sediment provide an unprecedented opportunity to constrain grounding-line and calving-front retreat of the of WAIS retreat – including the break-up of the ice shelf in Whales

Deep Basin. Porewater from these cores was used to test the hypothesis that subglacial meltwater played a major role in WAIS retreat.

1.3 References

Abdul, N.A., Mortlock, R.A., Wright, J.D., and Fairbanks, R.G., 2016, Younger Dryas sea level and meltwater pulse 1B recorded in Barbados reef crest coral Acropora palmata: Paleoceanography, p. 330–344, doi: 10.1002/2015PA002847.

Adkins, J.F., McIntyre, K., and Schrag, D.P., 2002, The salinity, temperature, and delta18O of the glacial deep ocean.: Science (New York, N.Y.), v. 298, no. 5599, p. 1769–73, doi: 10.1126/science.1076252.

Adkins, J.F., and Schrag, D.P., 2003, Reconstructing Last Glacial Maximum bottom water salinities from deep-sea sediment pore fluid profiles: Earth and Planetary Science Letters, v. 216, no. 1–2, p. 109–123, doi: 10.1016/S0012-821X(03)00502-8.

Alley, R.B., 1989, Water-pressure coupling of sliding and bed deformation: I. Water system: Journal of glaciology, v. 35, no. 119, p. 108–118.

Alley, R.B., Anandakrishnan, S., Dupont, T.K., Parizek, B.R., and Pollard, D., 2007, Grounding-Line Stability: , no. March, p. 1838–1841.

Alley, R.B., Clark, P.U., Huybrechts, P., and Joughin, I., 2005, Ice-sheet and sea-level changes.: Science (New York, N.Y.), v. 310, no. 5747, p. 456–460, doi: 10.1126/science.1114613.

Anderson, R.F., Ali, S., Bradtmiller, L.I., Nielsen, S.H.H., Fleisher, M.Q., Anderson, B.E., and Burckle, L.H., 2009, Wind-driven upwelling in the Southern Ocean and the deglacial rise in atmospheric CO2.: Science (New York, N.Y.), v. 323, no. 5920, p. 1443–8, doi: 10.1126/science.1167441.

Anderson, R.F., Chase, Z., Fleisher, M.Q., and Sachs, J., 2002a, The Southern Ocean's biological pump during the Last Glacial Maximum: Deep-Sea Research Part II: Topical Studies in Oceanography, v. 49, no. 9–10, p. 1909–1938, doi: 10.1016/S0967-0645(02)00018-8.

Anderson, J.B., Conway, H., Bart, P.J., Witus, A.E., Greenwood, S.L., McKay, R.M., Hall, B.L., Ackert, R.P., Licht, K., Jakobsson, M., and Stone, J.O., 2014, Ross Sea paleo-ice sheet drainage and deglacial history during and since the LGM: Quaternary Science Reviews, v. 100, p. 31–54, doi: 10.1016/j.quascirev.2013.08.020.

Anderson, J.B., Shipp, S.S., Lowe, A.L., Wellner, J.S., and Mosola, A.B., 2002b, The Antarctic Ice Sheet during the Last Glacial Maximum and its subsequent retreat history: a review: Quaternary Science Reviews, v. 21, no. 1–3, p. 49–70, doi: 10.1016/S0277-3791(01)00083-X.

Arzeno, I.B., Beardsley, R.C., Limeburner, R., and 6, and M.J.M.W.B.O.L.P.S.R.S.C.L.S., 2014, Ocean variability contributing to basalmelt rate near the ice front of Ross Ice Shelf, Antarctica: Journal of Geophysical Research: Oceans, , no. 1, p. 9026–9032, doi: 10.1002/2014JC009792.

Bamber, J., Riva, R., Vermeersen, B., and LeBrocq, A., 2009, Reassessment of the potential sea-level rise from a collapse of the West Antarctic Ice Sheet: Science, v. 0, no. May, p. 1–3.

Bard, E., Hamelin, B., Delanghe-sabatier, D., Science, S., Series, N., Mar, N., Bard, E., Hamelin, B., and Delanghe-sabatier, D., 2010, Deglacial Meltwater Pulse 1B and Younger Dryas Sea Levels Revisited with Boreholes at Tahiti: Science, v. 327, no. 5970, p. 1235–1237.

Bart, P.J., 2004, West-directed flow of the West Antarctic Ice Sheet across Eastern Basin, Ross Sea during the Quaternary: Earth and Planetary Science Letters, v. 228, no. 3–4, p. 425–438, doi: 10.1016/j.epsl.2004.10.014.

Bart, P.J., Anderson, J.B., and Nitsche, F.O., 2017a, Post-LGM grounding-line positions of the Bindschadler Ice Stream in Ross Sea: Journal of Geophysical Research: Earth Surface, v. Submitted.

Bart, P.J., and Cone, A.N., 2012, Early stall of West Antarctic Ice Sheet advance on the eastern Ross Sea middle shelf followed by retreat at 27,50014CyrBP: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 335–336, p. 52–60, doi: 10.1016/j.palaeo.2011.08.007.

Bart, P.J., Krogmeier, B.J., Bart, M.P., and Tulaczyk, S.M., 2017b, The paradox of a two millennia grounding duration of the West Antarctic Ice Sheet in Ross Sea: Scientific reports, v. Submitted.

Bart, P.J., and Owolana, B., 2012, On the duration of West Antarctic Ice Sheet grounding events in Ross Sea during the Quaternary: Quaternary Science Reviews, v. 47, p. 101–115, doi: 10.1016/j.quascirev.2012.04.023.

Batchelor, C.L., and Dowdeswell, J.A., 2015, Ice-sheet grounding-zone wedges (GZWs) on high-latitude continental margins: Marine Geology, v. 363, p. 65–92, doi: 10.1016/j.margeo.2015.02.001.

Bentley, M.J., Ó Cofaigh, C., Anderson, J.B., Conway, H., Davies, B., Graham, A.G.C., Hillenbrand, C.-D., Hodgson, D. a., Jamieson, S.S.R., Larter, R.D., Mackintosh, A., Smith, J. a., Verleyen, E., Ackert, R.P., et al., 2014, A community-based geological reconstruction of Antarctic Ice Sheet deglaciation since the Last Glacial Maximum: Quaternary Science Reviews, v. 100, p. 1–9, doi: 10.1016/j.quascirev.2014.06.025.

Berkman, P.A., Andrews, J.T., Björck, S., Colhoun, E.A., Emslie, S.D., Goodwin, I.D., Hall, B.L., Hart, C.P., Hirakawa, K., Igarashi, A., Ingólfsson, O., López-Martínez, J., Lyons, W.B., Mabin, M.C.G., et al., 1998, Circum-Antarctic coastal environmental shifts during the Late Quaternary reflected by emerged marine deposits: Antarctic Science, v. 10, no. 3, p. 345–362, doi: 10.1017/S0954102098000406.

Berkman, P., and Forman, S., 1996, Pre-bomb radiocarbon and the reservoir correction for calcareous marine species in the Southern Ocean: Geophysical Research Letters, v. 23, no. 4, p. 363–366, doi: 10.1029/96GL00151.

Borstad, C.P., Rignot, E., Mouginot, J., and Schodlok, M.P., 2013, Creep deformation and buttressing capacity of damaged ice shelves: Theory and application to Larsen C ice shelf: Cryosphere, v. 7, no. 6, p. 1931–1947, doi: 10.5194/tc-7-1931-2013.

Carlson, A.E., and Clark, P.U., 2012a, Ice-Sheet Sources of Sea-Level Rise and Freshwater Discharge During the Last Deglaciation: Reviews of Geophysics, v. 50, no. 2011, p. 1–72, doi: doi: 10.1029/2011rg000371.

Carlson, A.E., and Clark, P.U., 2012b, Ice sheet sources of sea level rise and freshwater discharge during the last deglaciation: Reviews of Geophysics, v. 50, no. 4, p. 1–72, doi: 10.1029/2011RG000371.

Chambers, S.R., 1991, 19 . Solute Distributions And Stable Isotope Chemistry Of Interstitial Waters: Proceedings of the Ocean Drilling Program, Scientific Results, v. 119, p. 375–392.

Clark, P.U., Dyke, A.S., Shakun, J.D., Carlson, A.E., Clark, J., Wohlfarth, B., Mitrovica, J.X., Hostetler, S.W., and McCabe, A.M., 2009, The Last Glacial Maximum.: Science (New York, N.Y.), v. 325, no. 5941, p. 710–714, doi: 10.1126/science.1172873.

Conway, H., Hall, B.L., Denton, G.H., Gades, A.M., and Waddington, E.D., 1999, Past and Future Grounding-Line Retreat of the West Antarctic Ice Sheet: Science (New York, N.Y.), v. 280, no. 1999, p. 280–284, doi: 10.1126/science.286.5438.280.

Domack, E.W., Jacobson, E.A., and Anderson, J.B., 1999, Late Pleistocene – Holocene retreat of the West Antarctic Ice-Sheet system in: , no. 10, p. 1517–1536.

Dowdeswell, J. a., and Fugelli, E.M.G., 2012, The seismic architecture and geometry of grounding-zone wedges formed at the marine margins of past ice sheets: Geological Society of America Bulletin, v. 124, no. 11–12, p. 1750–1761, doi: 10.1130/B30628.1.

Dowdeswell, J.A., and Pudsey, C.J., 2004, Thickness and extent of the subglacial till layer beneath an Antarctic paleo – ice stream: , no. 1, p. 13–16, doi: 10.1130/G19864.1.

Fairbanks, R.G., 1989, A 17,000-year glacio-eustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation: Nature, v. 342, no. 6250, p. 637–642, doi: 10.1038/342637a0.

Favier, L., Pattyn, F., Berger, S., and Drews, R., 2016, Dynamic influence of pinning points on marine ice-sheet stability: A numerical study in Dronning Maud Land, East Antarctica: Cryosphere, v. 10, no. 6, p. 2623–2635, doi: 10.5194/tc-10-2623-2016.

Fisher, A.T., Mankoff, K.D., Tulaczyk, S.M., and Tyler, S.W., 2015, High geothermal heat flux measured below the West Antarctic Ice Sheet: , no. July, p. 1–9.

Fogwill, C.J., Phipps, S.J., Turney, C.S.M., and Golledge, N.R., 2015, Sensitivity of the Southern Ocean to enhanced regional Antarctic ice sheet meltwater input: Earth's Future, v. 3, no. 10, p. 317–329, doi: 10.1002/2015EF000306.

Fogwill, C.J., Turney, C.S.M., Golledge, N.R., Etheridge, D.M., Rubino, M., Thornton, D.P., Baker, A., Woodward, J., Winter, K., van Ommen, T.D., Moy, A.D., Curran, M.A.J., Davies, S.M., Weber, M.E., et al., 2017, Antarctic ice sheet discharge driven by atmosphere-ocean feedbacks at the Last Glacial Termination: Scientific Reports, v. 7, no. November 2016, p. 39979, doi: 10.1038/srep39979.

Golledge, N.R., Menviel, L., Carter, L., Fogwill, C.J., England, M.H., Cortese, G., and Levy, R.H., 2014, Antarctic contribution to meltwater pulse 1A from reduced Southern Ocean overturning: Nature Communications, v. 5, no. SEPTEMBER, p. 5107, doi: 10.1038/ncomms6107.

Greenwood, S.L., Gyllencreutz, R., Jakobsson, M., and Anderson, J.B., 2012, Ice-flow switching and East/West Antarctic Ice Sheet roles in glaciation of the western Ross Sea: Bulletin of the Geological Society of America, v. 124, no. 11–12, p. 1736–1749, doi: 10.1130/B30643.1.

Halberstadt, A.R.W., Simkins, L.M., Greenwood, S.L., and Anderson, J.B., 2016, Past ice-sheet behaviour: retreat scenarios and changing controls in the Ross Sea, Antarctica: The Cryosphere, v. 10, no. 3, p. 1003–1020, doi: 10.5194/tc-10-1003-2016.

Hall, B.L., Denton, G.H., Heath, S.L., Jackson, M.S., and Koffman, T.N.B., 2015, Accumulation and marine forcing of ice dynamics in the western Ross Sea during the last deglaciation: Nature Geoscience, v. 8, no. 8, p. 625–628, doi: 10.1038/ngeo2478.

Hall, B.L., Henderson, G.M., Baroni, C., and Kellogg, T.B., 2010, Constant Holocene Southern-Ocean 14C reservoir ages and ice-shelf flow rates: Earth and Planetary Science Letters, v. 296, no. 1–2, p. 115–123, doi: 10.1016/j.epsl.2010.04.054.

Heroy, D.C., and Anderson, J.B., 2007, Radiocarbon constraints on Antarctic Peninsula Ice Sheet retreat following the Last Glacial Maximum (LGM): Quaternary Science Reviews, v. 26, no. 25–28, p. 3286–3297, doi: 10.1016/j.quascirev.2007.07.012.

Hillenbrand, C.D., Bentley, M.J., Stolldorf, T.D., Hein, A.S., Kuhn, G., Graham, A.G.C., Fogwill, C.J., Kristoffersen, Y., Smith, J.A., Anderson, J.B., Larter, R.D., Melles, M., Hodgson, D.A., Mulvaney, R., et al., 2014, Reconstruction of changes in the Weddell Sea sector of the Antarctic Ice Sheet since the Last Glacial Maximum: Quaternary Science Reviews, v. 100, p. 111–136, doi: 10.1016/j.quascirev.2013.07.020.

Hillenbrand, C.D., Smith, J.A., Kuhn, G., Esper, O., Gersonde, R., Larter, R.D., Maher, B., Moreton, S.G., Shimmield, T.M., and Korte, M., 2010, Age assignment of a diatomaceous ooze deposited in the Western Amundsen Sea embayment after the last glacial maximum: Journal of Quaternary Science, v. 25, no. 3, p. 280–295, doi: 10.1002/jqs.1308.

Hindmarsh, R.C.A., 1999, Pore-water signal of marine ice-sheets: Global and Planetary Change, v. 23, no. 1–4, p. 197–211, doi: 10.1016/S0921-8181(99)00057-0.

Horgan, H.J., Walker, R.T., Anandakrishnan, S., and Alley, R.B., 2011, Surface elevation changes at the front of the Ross Ice Shelf: Implications for basal melting: Journal of Geophysical Research: Oceans, v. 116, no. 2, p. 1–12, doi: 10.1029/2010JC006192.

Jacobs, S.S., Fairbanks, R.G., and Horibe, Y., 1985, Origin and Evolution of water masses near the antarctic continental margin (S. S. Jacobs, Ed.): Oceanography of the Antarctic Continental Shelf, v. 43, p. 59–85, doi: 10.1029/AR043.

Jacobs, S.S., Jenkins, A., Giulivi, C.F., and Dutrieux, P., 2011, Stronger ocean circulation and increased melting under Pine Island Glacier ice shelf: Nature Geoscience, v. 4, no. 8, p. 519–523, doi: 10.1038/ngeo1188.

Jakobsson, M., Anderson, J.B., Nitsche, F.O., Gyllencreutz, R., Kirshner, A.E., Kirchner, N., O'Regan, M., Mohammad, R., and Eriksson, B., 2012, Ice sheet retreat dynamics inferred from glacial morphology of the central Pine Island Bay Trough, West Antarctica: Quaternary Science Reviews, v. 38, p. 1–10, doi: 10.1016/j.quascirev.2011.12.017.

Jenkins, A., Dutrieux, P., Jacobs, S.S., McPhail, S.D., Perrett, J.R., Webb, A.T., and White, D., 2010, Observations beneath Pine Island Glacier in West Antarctica and implications for its retreat: Nature Geoscience, v. 3, no. 7, p. 468–472, doi: 10.1038/ngeo890.

Joughin, I., and Alley, R.B., 2011, Stability of the West Antarctic ice sheet in a warming world: Nature Geoscience, v. 4, no. 8, p. 506–513, doi: 10.1038/ngeo1194.

Joughin, I., Alley, R.B., and Holland, D.M., 2012, Ice-sheet response to oceanic forcing: Science, v. 338, no. 6111, p. 1172–6, doi: 10.1126/science.1226481.

Kirshner, A.E., Anderson, J.B., Jakobsson, M., O'Regan, M., Majewski, W., and Nitsche, F.O., 2012, Post-LGM deglaciation in Pine Island Bay, West Antarctica: Quaternary Science Reviews, v. 38, p. 11–26, doi: 10.1016/j.quascirev.2012.01.017.

Klages, J.P., Kuhn, G., Hillenbrand, C.D., Graham, a. G.C., Smith, J. a., Larter, R.D., Gohl, K., and Wacker, L., 2014, Retreat of the West Antarctic Ice Sheet from the western Amundsen Sea shelf at a pre- or early LGM stage: Quaternary Science Reviews, v. 91, p. 1–15, doi: 10.1016/j.quascirev.2014.02.017.

Lambeck, K., Yokoyama, Y., and Purcell, T., 2002, Into and out of the last glacial maximum: Sea-level change during oxygen isotope stages 3 and 2: Quaternary Science Reviews, v. 21, no. 1–3, p. 343–360, doi: 10.1016/S0277-3791(01)00071-3.

Licht, K.J., and Andrews, J.T., 2002, The 14 C record of late-Pleistocene ice advance and retreat in the central Ross Sea, Antarctica: Arctic, Antarctic and Alpine Research, v. 34, no. 3, p. 324–333, doi: 10.2307/1552491.

Liu, J., Milne, G.A., Kopp, R.E., Clark, P.U., and Shennan, I., 2015a, Sea-level constraints on the amplitude and source distribution of Meltwater Pulse 1A: Nature Geoscience, v. 9, no. December, p. 6–12, doi: 10.1038/ngeo2616.

Liu, Y., Moore, J.C., Cheng, X., Gladstone, R.M., Bassis, J.N., Liu, H., Wen, J., and Hui, F., 2015b, Ocean-driven thinning enhances iceberg calving and retreat of Antarctic ice shelves.: Proceedings of the National Academy of Sciences of the United States of America, v. 112, no. 11, p. 3263–8, doi: 10.1073/pnas.1415137112.

Lowe, A.L., and Anderson, J.B., 2003, Evidence for abundant subglacial meltwater beneath the paleo-ice sheet in Pine Island Bay, Antarctica: Journal of Glaciology, v. 49, no. 164, p. 125–138, doi: 10.3189/172756503781830971.

Mackintosh, A., Golledge, N., Domack, E., Dunbar, R., Leventer, A., White, D., Pollard, D., DeConto, R., Fink, D., Zwartz, D., Gore, D., and Lavoie, C., 2011, Retreat of the East Antarctic ice sheet during the last glacial termination: Nature Geoscience, v. 4, no. 3, p. 195–202, doi: 10.1038/ngeo1061.

Mackintosh, A.N., Verleyen, E., Brien, P.E.O., White, D.A., Jones, R.S., Mckay, R., Dunbar, R., Gore, D.B., Fink, D., Post, A.L., Miura, H., Leventer, A., Goodwin, I., Hodgson, D.A., et al., 2014, Retreat history of the East Antarctic Ice Sheet since the Last Glacial Maximum: Quaternary Science Reviews, v. 100, p. 10–30, doi: 10.1016/j.quascirev.2013.07.024.

Majewski, W., and Anderson, J.B., 2009, Holocene foraminiferal assemblages from Firth of Tay, Antarctic Peninsula: Paleoclimate implications: Marine Micropaleontology, v. 73, no. 3–4, p. 135–147, doi: 10.1016/j.marmicro.2009.08.003.

Malone, M.J., Martin, J.B., Scho, J., Ninnemann, U.S., Nu, D., and White, T.S., 2004, The oxygen isotopic composition and temperature of Southern Ocean bottom waters during the last glacial maximum: v. 222, p. 275–283, doi: 10.1016/j.epsl.2004.02.027.

Matsuoka, K., Hindmarsh, R.C.A., Moholdt, G., Bentley, M.J., Pritchard, H.D., Brown, J., Conway, H., Drews, R., Durand, G., Goldberg, D., Hattermann, T., Kingslake, J., Lenaerts, J.T.M., Martín, C., et al., 2015, Antarctic ice rises and rumples: Their properties and significance for ice-sheet dynamics and evolution: Earth-Science Reviews, v. 150, p. 724–745, doi: 10.1016/j.earscirev.2015.09.004.

McGlannan, A.J., Bart, P.J., Chow, J.M., and DeCesare, M., 2017, On the influence of post-LGM ice shelf loss and grounding zone sedimentation on West Antarctic Ice Sheet Stability: Marine Geology, v. Submitted.

McKay, R., Golledge, N.R., Maas, S., Naish, T., Levy, R., Dunbar, G., and Kuhn, G., 2015, Antarctic marine ice-sheet retreat in the Ross Sea during the early Holocene: Geology, v. 44, no. 1, p. 1–4, doi: 10.1130/G37315.1.

Menviel, L., Timmermann, A., Timm, O.E., and Mouchet, A., 2011, Deconstructing the Last Glacial termination: The role of millennial and orbital-scale forcings: Quaternary Science Reviews, v. 30, no. 9–10, p. 1155–1172, doi: 10.1016/j.quascirev.2011.02.005.

Millard, A., 2014, Conventions for Reporting Radiocarbon Determinations: Radiocarbon, v. 56, no. 2, p. 555–559, doi: 10.2458/56.17455.

Miller, M.D., Adkins, J.F., and Hodell, D.A., 2014, Rhizon sampler alteration of deep ocean sediment interstitial water samples, as indicated by chloride concentration and oxygen and hydrogen isotopes: Geochemistry, Geophysics, Geosystems, v. 15, no. 6, p. 2401–2413, doi: 10.1002/2014GC005308.

Mosola, A.B., and Anderson, J.B., 2006, Expansion and rapid retreat of the West Antarctic Ice Sheet in eastern Ross Sea: possible consequence of over-extended ice streams? Quaternary Science Reviews, v. 25, no. 17–18, p. 2177–2196, doi: 10.1016/j.quascirev.2005.12.013.

Nereson, N.A., and Raymond, C.F., 2001, The elevation history of ice streams and the spatial accumulation pattern along the Siple Coast of West Antarctica inferred from ground-based radar data from three inter-ice-stream ridges: Journal of glaciology, v. 47, no. 157, p. 303–313.

Peltier, W.R., and Fairbanks, R.G., 2006, Global glacial ice volume and Last Glacial Maximum duration from an extended Barbados sea level record: Quaternary Science Reviews, v. 25, no. 23–24, p. 3322–3337, doi: 10.1016/j.quascirev.2006.04.010.

Pollard, D., and DeConto, R.M., 2009, Modelling West Antarctic ice sheet growth and collapse through the past five million years.: Nature, v. 458, no. 7236, p. 329–332, doi: 10.1038/nature07809.

Pollard, D., DeConto, R.M., and Nyblade, A. a., 2005, Sensitivity of Cenozoic Antarctic ice sheet variations to geothermal heat flux: Global and Planetary Change, v. 49, no. 1–2, p. 63–74, doi: 10.1016/j.gloplacha.2005.05.003.

Pritchard, H.D., Ligtenberg, S.R.M., Fricker, H. a., Vaughan, D.G., van den Broeke, M.R., and Padman, L., 2012, Antarctic ice-sheet loss driven by basal melting of ice shelves: Nature, v. 484, no. 7395, p. 502–505, doi: 10.1038/nature10968.

Rayne, T.W., and Domack, E.W., 1996, Porewater chemistry of Ross Sea diamictons: A till or not a till: Antarctic Journal of the United States, v. 31, p. 97–98.

Reimer, P.J., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Buck, C.E., Cheng, H., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Haflidason, H., Hajdas, I., et al., 2013, IntCal13 and Marine13 Radiocarbon Age Calibration Curves 0–50,000 Years cal BP: Radiocarbon, v. 55, no. 4, p. 1869–1887, doi: 10.2458/azu_js_rc.55.16947.

Rignot, E., Jacobs, S., Mouginot, J., and Scheuchl, B., 2013, Ice-shelf melting around Antarctica.: Science, v. 341, no. 6143, p. 266–70, doi: 10.1126/science.1235798.

Rignot, E., Mouginot, J., Morlighem, M., Seroussi, H., and Scheuchl, B., 2014, Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith, and Kohler glaciers, West Antarctica, from 1992 to 2011: Geophysical Research Letters, v. 41, no. 10, p. 3502–3509, doi: 10.1002/2014GL060140.

Rosenheim, B.E., Day, M.B., and Hayes, J.M., 2008, Antarctic sediment chronology by programmed-temperature pyrolysis: Methodology and data treatment: , p. 1–16, doi: 10.1029/2007GC001816.

Schrag, D.P., Adkins, J.F., McIntyre, K., Alexander, J.L., Hodell, D. a., Charles, C.D., and McManus, J.F., 2002, The oxygen isotopic composition of seawater during the Last Glacial Maximum: Quaternary Science Reviews, v. 21, no. 1–3, p. 331–342, doi: 10.1016/S0277-3791(01)00110-X.

Schrag, D.P., and DePaolo, D.J., 1993, Determination of δ18O of Seawater in the Deep Ocean during the Last Glacial Maximum: Paleoceanography, v. 8, no. 1, p. 1–6, doi: 10.1029/92pa02796.

Schweizer, M., Bowser, S.S., Korsun, S., and Pawlowski, J., 2012, Emendation of Cibicides Antarcticus (Saidova, 1975) Based on Molecular, Morphological, and ecological Data: The Journal of Foraminiferal Research, v. 42, no. 4, p. 340–344, doi: 10.2113/gsjfr.42.4.340.

Seeberg-elverfeldt, J., and Feseker, T., 2005, OCEANOGRAPHY : METHODS Rhizon sampling of porewaters near the sediment-water interface: , p. 361–371.

Shipp, S., Anderson, J., and Domack, E., 1999, Late Pleistocene-Holocene retreat of the West Antarctic Ice-Sheet system in the Ross Sea: Part 1 - Geophysical results: Bulletin of the Geological Society of America, doi: 10.1130/0016-7606(1999)111<1486.

Siegfried, M.R., Fricker, H.A., Carter, S.P., and Tulaczyk, S., 2016, Episodic ice velocity fluctuations triggered by a subglacial flood in West Antarctica: Geophysical Research Letters, v. 43, no. 6, p. 2640–2648, doi: 10.1002/2016GL067758.

Smith, J. a., Hillenbrand, C.-D., Kuhn, G., Klages, J.P., Graham, A.G.C., Larter, R.D., Ehrmann, W., Moreton, S.G., Wiers, S., and Frederichs, T., 2014, New constraints on the timing of West Antarctic Ice Sheet retreat in the eastern Amundsen Sea since the Last Glacial Maximum: Global and Planetary Change, v. 122, p. 224–237, doi: 10.1016/j.gloplacha.2014.07.015.

Smith, J.A., Hillenbrand, C.-D., Kuhn, G., Larter, R.D., Graham, A.G.C., Ehrmann, W., Moreton, S.G., and Forwick, M., 2011, Deglacial history of the West Antarctic Ice Sheet in the western Amundsen Sea Embayment: Quaternary Science Reviews, v. 30, no. 5–6, p. 488–505, doi: 10.1016/j.quascirev.2010.11.020.

Smith, J. a., Hillenbrand, C.D., Larter, R.D., Graham, A.G.C., and Kuhn, G., 2009, The sediment infill of subglacial meltwater channels on the West Antarctic continental shelf: Quaternary Research, v. 71, no. 2, p. 190–200, doi: 10.1016/j.yqres.2008.11.005.

Stearns, L. a., Smith, B.E., and Hamilton, G.S., 2008, Increased flow speed on a large East Antarctic outlet glacier caused by subglacial floods: Nature Geoscience, v. 1, no. 12, p. 827–831, doi: 10.1038/ngeo356.

Stolldorf, T., Schenke, H., and Anderson, J.B., 2012, LGM ice sheet extent in the Weddell Sea : evidence for diachronous behavior of Antarctic Ice Sheets: Quaternary Science Reviews, v. 48, p. 20–31, doi: 10.1016/j.quascirev.2012.05.017.

Stuiver, M., Reimer, P., and Reimer, R., 2005, CALIB 7.1: [http://calib.qub.ac.uk/calib/],.

Subt, C., Fangman, K.A., Wellner, J.S., and Rosenheim, B.E., 2015, Sediment chronology in Antarctic deglacial sediments: Reconciling organic carbon 14C ages to carbonate 14C ages using Ramped PyrOx: The Holocene, doi: 10.1177/0959683615608688.

WAIS Divide Project Members, 2013, Onset of deglacial warming in West Antarctica driven by local orbital forcing.: Nature, v. 500, no. 7463, p. 440–4, doi: 10.1038/nature12376.

Webb, P.-N.P., and Strong, C.C.P., 2006, Foraminiferal biostratigraphy and palaeoecology in Upper Oligocene–Lower Miocene glacial marine sequences 9, 10, and 11, CRP-2/2A drill hole, Victoria Land Basin, Antarctica: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 231, no. 1–2, p. 71–100, doi: 10.1016/j.palaeo.2005.07.036.

Weber, M.E., Clark, P.U., Kuhn, G., Timmermann, A., Sprenk, D., Gladstone, R., Zhang, X., Lohmann, G., Menviel, L., Chikamoto, M.O., Friedrich, T., and Ohlwein, C., 2014, Millennial-scale variability in Antarctic ice-sheet discharge during the last deglaciation.: Nature, v. 510, no. 7503, p. 134–8, doi: 10.1038/nature13397.

Wycech, J., Clay Kelly, D., and Marcott, S., 2016, Effects of seafloor diagenesis on planktic foraminiferal radiocarbon ages: Geology, v. 44, no. 7, p. 551–554, doi: 10.1130/G37864.1.

Yokoyama, Y., Anderson, J.B., Yamane, M., Simkins, L.M., Miyairi, Y., Yamazaki, T., Koizumi, M., Suga, H., Kusahara, K., Prothro, L., Hasumi, H., Southon, J.R., and Ohkouchi, N., 2016, Widespread collapse of the Ross Ice Shelf during the late Holocene: Proceedings of the National Academy of Sciences, p. 201516908, doi: 10.1073/pnas.1516908113.

CHAPTER 2: MELTWATER PULSE-1A AND -1B TRIGGERED WEST ANTARCTIC ICE SHEET RETREAT IN THE EASTERN ROSS SEA

2.1 Main Text:

During the Last Glacial Maximum (LGM), 24,000 to 19,000 years ago (kyr) (Clark et al., 2009), ice streams were grounded at or near the Antarctic continental shelf edge (Bentley et al., 2014). The Antarctic Ice Sheets (AISs) have since retreated hundreds of kilometers. The associated ice-volume wastage contributed to the ~120 meters of post-LGM global mean sea-level (GMSL) rise (Clark et al., 2009; Carlson and Clark, 2012a; Golledge et al., 2014; Liu et al., 2015a). The majority of GMSL rise was due to melting of northern hemisphere ice sheets (Peltier and Fairbanks, 2006; Pollard and DeConto, 2009; Liu et al., 2015a). The incursion of relatively warm Circumpolar Deep Water onto the Antarctic continental shelf has been suggested as a principal driver of post-LGM WAIS retreat (Pollard and DeConto, 2009; Golledge et al., 2014; Fogwill et al., 2017) with sea-level rise playing a secondary role (Alley et al., 2005; Mackintosh et al., 2011; Golledge et al., 2014). Several studies have combined radiocarbon ages with seafloor geomorphology and sedimentology to support a link between AIS retreat and rapid GMSL rise events, i.e., Meltwater Pulse (MWP) events (Domack et al., 1999; Heroy and Anderson, 2007; Clark et al., 2009; Mackintosh et al., 2011; Smith et al., 2011; Kirshner et al., 2012). Two significant MWPs occurred at 14.5 kyr (MWP-1a), and 11.3 kyr (MWP-1b; Figure 2.1). MWP-1a is characterized by a 11.6 ± 3 meter sea-level rise that occurred in 350 years (Liu et al., 2015a) and MWP-1b is described as a 14 ± 2 meter sea level rise that occurred over 400 years (Bard et al., 2010; Abdul et al., 2016). In contrast, other studies have suggested that AIS deglaciation was unrelated to MWPs (Hillenbrand et al., 2010; Bart and Cone, 2012; Klages et al., 2014; Yokoyama et al., 2016).

Seafloor morphology and core lithology (Bart et al., 2017a; McGlannan et al., 2017) were used to constrain the relative timing of WAIS grounding line and calving front retreat as well as ice shelf collapse in the eastern Ross Sea. Multibeam swath bathymetry and seismic stratigraphic surveys covering the continental shelf edge to the modern calving front of the Ross Ice Shelf (Figure 2.2) in the Whales Deep Basin were obtained during expedition NBP1502B. These data

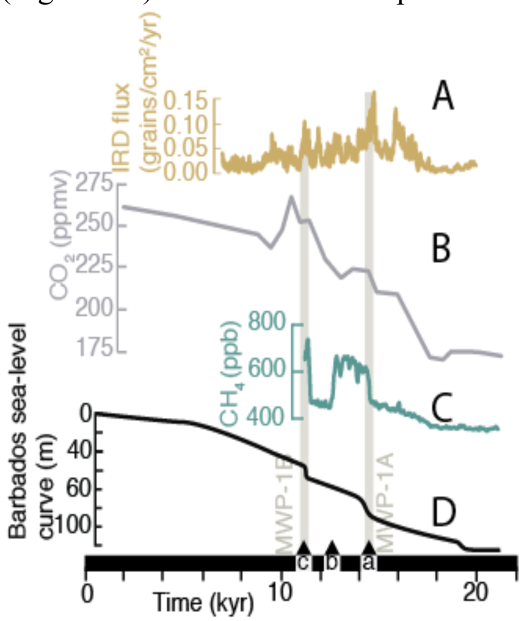

Figure 2.1: Post-LGM deglacial records showing correlation to MWPs. Lower case a, b, and c correlate to the retreat of the initial 40 km retreat of the BIS, break-up of the ice-shelf and 200 km retreat respectively. **(A)** IRD records showing increases in flux during intervals of rising sea level(Weber et al., 2014). Peaks in IRD flux not associated with MWPs suggest deglacial events occurred for reasons other than rapid sea-level rise. **(B)** CO_2 records (average of Siple Dome, Taylor Dome, WAIS divide and Byrd glacier) increase at the end of the LGM ~19 kyr BP and correlate well with increasing sea level. **(C)** methane (CH_4) records from the WAIS Divide core showing drastic increases coinciding with MWPs. Increases in CO_2 and CH_4 suggest warming atmospheric temperatures. **(D)** Barbados sea level curve indicates rapid increases during MWPs.

provided new details showing that grounded ice paused to construct as many as seven grounding zone wedges (GZWs 1–7) after the initiation of WAIS retreat from the shelf edge. GZWs form when the grounding line pauses during retreat. Deposition acts to stabilize ice streams by continually aggrading sediment (Alley et al., 2007; Bart and Cone, 2012).

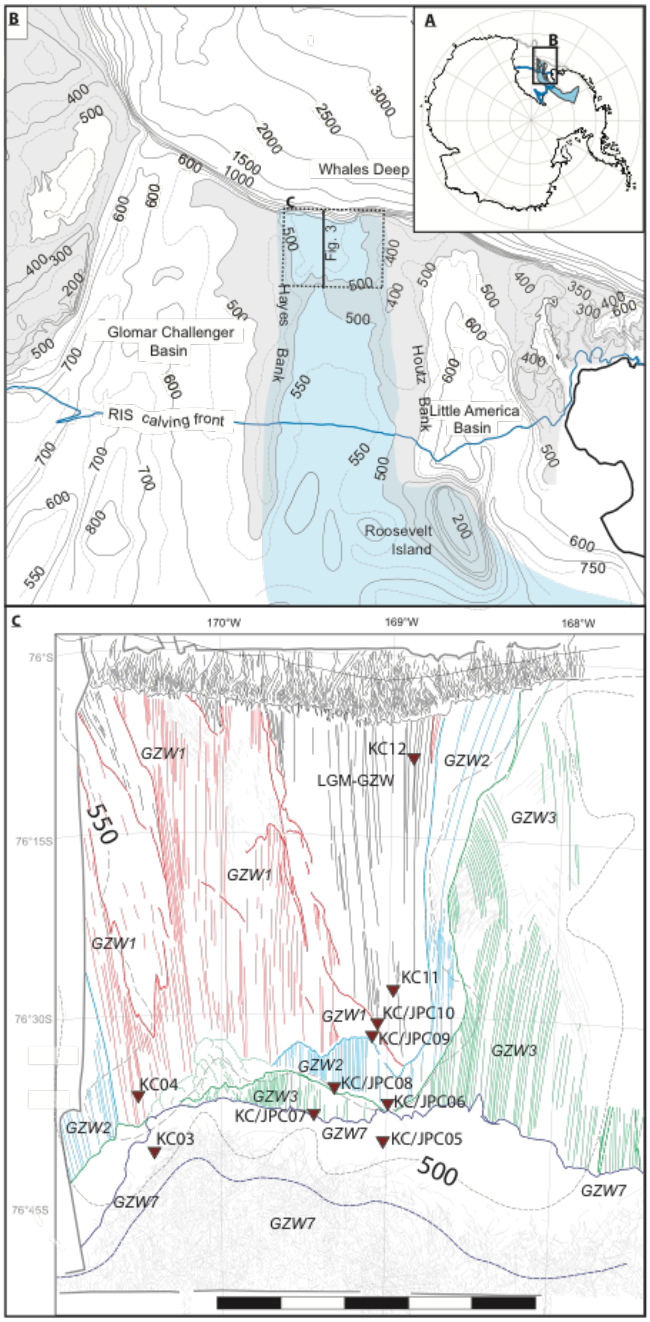

Fig. 2.2: Maps showing the Bindschadler ice stream (BIS) and geomorphic features in the Whales Deep outer and middle shelf, (A) Antarctica, BIS highlighted in blue, **(B)** the eastern Ross Sea centered on Whales Deep. The BIS was confined by the Hayes and Houtz banks (shaded in grey). The modern calving front is traced by a dark blue line. The BIS became pinned at Roosevelt Island 3.2 kyr BP, where it now acts as an ice rise for the modern ice shelf. The dotted black box expands to **(C)** bathymetric map of Whales Deep from the shelf edge to the topset of GZW7. The downlap limit of the GZWs are outlined in red (the extent of GZW1 is uncertain and represented by a dotted line). The bathymetric termination of Hayes (to the left) and Houtz Bank is shown by black lines. Bathymetry collected during NBP1502**.**

A total of 15 kasten cores (KC) and 6 jumbo piston cores (JPC) penetrated the topsets and foresets of four GZWs that are exposed on the Whales Deep Basin outer continental shelf. The core reveal a complete post-LGM deglacial sedimentary sequence (McGlannan et al., 2017). Four primary sediment facies have been identified which correlate to different paleoenvironments as the grounding-line and calving-front positions of the WAIS oscillated during its overall retreat (Figure 2.3). Upcore transitions from GZW diamict to sub-ice-shelf facies correspond to southward migration of the grounding-line past the core locations. A second upcore transition, a change from sub-ice-shelf facies to either an ice-shelf-breakup or directly to open-marine facies, corresponds to the southward migration of the calving front past the core location. The GZW diamict and sub-ice-shelf facies contain an unprecedented amount of *in situ* foraminifera that exhibit pristine preservation. Obtaining foraminiferal radiocarbon dates from

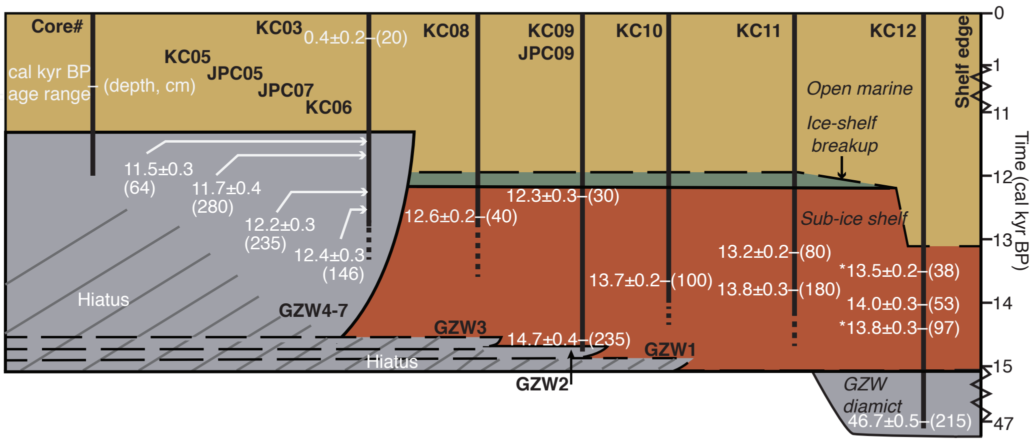

Figure 2.3: Radiocarbon results with respect to core locations, stratigraphy and depth. Horizontal axis (not to scale) shows relative position of sediment cores, vertical scale is geologic time. Dashed lines denote facies changes that are not directly constrained by ^{14}C ages. GZW diamict was deposited directly by grounded ice proximal to the grounding line during pauses in retreat. Grounding-line retreat from the shelf edge and deposition of GZW1 and 2 occurred by 14.7 ± 0.4 cal kyr BP. Deposition of GZW3 though 7 occurred between 14.7 ± 0.4 cal kyr BP and 11.5 ± 0.3 cal kyr BP. Ice-shelf collapse occurred shortly ~12.3 ± 0.3 cal kyr BP based on dates from directly below the ice-shelf breakup unit. The onset of open marine conditions on the middle and inner shelf was established after the end of GZW7, 11.5 ± 0.3 cal kyr BP. Ages are from monospecific species with exception of those labeled *; 13.8 ± 0.3 at 97cm in KC12 is placed with respect to core depth.

near the facies transitions were a primary objective. These specimens provided a unique opportunity to radiocarbon date and constrain retreat of the grounding line, calving front and ice shelf collapse across a transect of the eastern Ross Sea. A deglacial chronology with this level of detail has, to date, not been produced for the WAIS.

The WAIS advanced to the continental shelf edge in Whales Deep Basin (henceforth the paleo-Bindschadler Ice Stream, paleo-BIS) where it remained grounded throughout the LGM (Figure 2.2, 2.4). Based on the oldest date from the lower most sub-ice-shelf sediment, retreat of the paleo-BIS from the continental shelf edge was underway by 14.7 ± 0.4 cal kyr BP [ages are reported as the median value ± the 95% confidence interval (Millard, 2014), (Figure 2.3, Table 2.1)]. Paleo sediment flux estimates for the paleo-BIS (Bart et al., 2017b) suggest the relatively small volumes of GZW1 and 2 represent a short interval, from decades to centuries. Consequently, the initial grounding line retreat from the shelf edge must have occurred within the "±" time range associated with MWP-1a, 14.5 ± 0.2 kyr (Liu et al., 2015a). These interpretations suggest that the abrupt large-amplitude sea-level rise at MWP-1a likely triggered the initial decoupling of grounded ice in Whales Deep Basin from its LGM position.

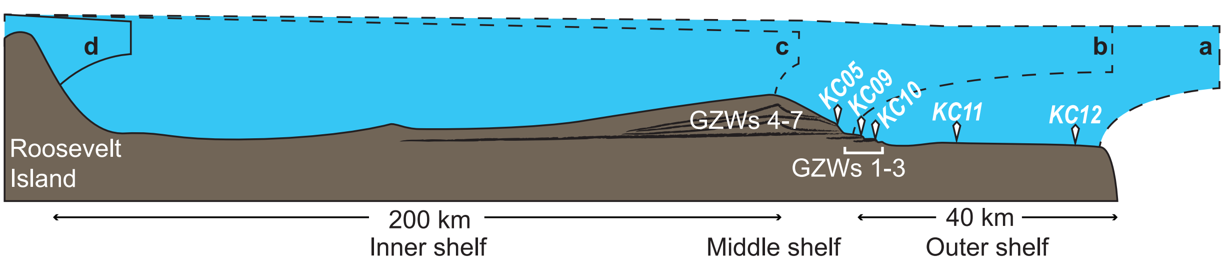

Figure 2.4: Retreat history of the BIS in Whales Deep based on radiocarbon ages, core stratigraphy and seafloor geomorphology. (**a**) Inferred LGM configuration of the BIS. (**b**) The grounding line retreated from its LGM position and paused to construct GZW1 and 2 at 14.7 ± 0.4 cal kyr BP. (**c**) Breakup of the ice shelf occurred ~12.4 ± 0.2 kyr BP. The grounding line retreated to construct GZW 4-7 until 11.5 ± 0.3 cal kyr BP. (**d**) Retreat of the BIS from GZW7 to Roosevelt Island occurred at 11.5 ± 0.3 cal kyr BP, during MWP-1b.

In isolation, this small magnitude ablation of the paleo-BIS would not have made a detectable contribution to GMSL rise during MWP-1a, given that the grounding line backstepped a maximum of 60 km from the continental shelf edge. A correlation between GMSL rise during MWP-1a and WAIS grounding line retreat is in agreement with several previous studies (Clark et al., 2009; Heroy and Anderson, 2007; Smith et al., 2011; Golledge et al., 2014; Weber et al., 2014; Liu et al., 2015b; Fogwill et al., 2017). However, our results – even applied to the entire Ross Embayment – calls into question the magnitude of WAIS contribution to MWP-1a (Golledge et al., 2014; Liu et al., 2015a). It remains plausible that the other sectors of the WAIS contributed to MWP-1a as evidenced in IRD flux (Weber et al., 2014) (Figure 2.1) and suggested by numerical models (Golledge et al., 2014; Liu et al., 2015a).

During the time that the paleo-BIS grounding line shifted inland, a small ice shelf formed over the outer continental shelf (McGlannan et al., 2017). Two radiocarbon dates from two individual cores indicate that ice shelf collapse occurred 12.4 ± 0.2 cal kyr BP (Figure 2.3 and 1.4). These results indicate that ice shelf retreat from the continental shelf edge occurred more than 6,000 years earlier than results from compound specific radiocarbon dating (Yokoyama et al., 2016). The evidence for retreat at ~5,000 years ago was based on a linear interpolation linking the median value of two ^{14}C ages dates from the sub-ice-shelf and open-marine facies, respectively. Conversely, our stratigraphy is based on 15 radiocarbon dates that are consistent with the geomorphology and core sedimentology of 8 core stations. Photographs of the seafloor show that benthic life is abundant in Whales Deep and hence dates from open-marine sediments might reflect significant bioturbation rendering dates from the open-marine sediments difficult to interpret. In contrast, our dates are from sub-ice-shelf and grounding-zone proximal environments, where sedimentation rates would have been higher.

As GMSL continued to rise the grounding line remained stable, with construction of GZWs 4 through 7 continuing until 11.5 ± 0.3 cal kyr BP. After the termination of GZW7, the paleo-BIS retreated >200 km towards a grounding position directly north of Roosevelt Island (Conway et al., 1999) (Figure 2.4). This massive ablation event occurred concomitant with MWP-1b, which is in agreement with sea-level records and computer simulations (Golledge et al., 2014; Abdul et al., 2016). The thickness of the GZW cluster indicates that ice at the grounding line thinned by 140 meters by the termination of GZW7 (Bart et al., 2017a). The combination of ice-stream deflation, the preceding break-up of the ice shelf causing loss of buttressing, and post-LGM sea-level rise affected the relationship between the WAIS and ocean such that the buoyancy limit was exceeded. It is likely that the rate of GMSL rise was the trigger for paleo-BIS retreat events, not necessarily the total magnitude of GMSL. Atmospheric CO_2 reached near pre-industrial levels (250 ppm) and atmospheric methane also reached a peak concentration (Figure 2.1) near the timing of MWP-1b retreat with the associated warming potentially further contributing to ice sheet ablation (Clark et al., 2009; Anderson et al., 2009).

The large-scale loss of ice volume in Whales Deep Basin during MWP-1b leaves open the question as to whether the entire WAIS retreated in other sectors during this event. Taken at face value, the existing radiocarbon chronologies are not consistent with the view of synchronous retreat in Ross Sea. In the Glomar Challenger Basin, immediately to the west of Whales Deep Basin, foraminifera and bulk AIOM dates suggested that the WAIS retreated from the middle shelf at ~26 kyr BP (Bart and Cone, 2012), well prior to MWPs. This may have occurred because of the much greater depth of the Glomar Challenger Basin (Bart and Cone, 2012) (700 m versus 450 m), and if so, the differences in ages would suggest localized deglaciation that were temporally variable from trough to trough. Conversely, given the relatively young chronology for

the Whales Deep Basin (and for the western Ross Sea) the foraminifera dated from Glomar Challenger Basin may have contained a higher-than-expected fraction of reworked or diagenetically altered specimens in which case the radiocarbon ages would have been biased towards older ages (Wycech et al., 2016).

In paleo ice-stream basins of western Ross Sea, radiocarbon results from onshore and offshore areas suggest that the grounding line experienced a long-distance retreat from its LGM position near Coulman Island after 12.8 kyr BP (Hall et al., 2015) but before 11 cal kyr BP (Domack et al., 1999). These data permit the possibility that a long-distance retreat in western Ross Sea may have occurred during MWP-1b. It is important to keep in mind that most other deglacial chronologies are based on radiocarbon dating of bulk acid-insoluble organic matter (AIOM) which has been deemed unreliable in the Ross Sea (Anderson et al., 2014) and hence a one-to-one comparison between our foraminifera-based chronology and to those based on AIOM is not possible.

Irrespective of the regional pattern of retreat, foraminiferal radiocarbon ages from Whales Deep Basin presented here clearly indicate that retreat of the paleo-BIS occurred in two discrete steps that were concomitant with MWP-1a and -1b. During the interval between these events the ice shelf collapsed, yet the paleo-BIS grounding line remained stable. Interestingly, ablation of the paleo-BIS coincided with two intervals of high IRD flux to Scotia Sea (Weber et al., 2014), however, the ice-shelf-breakup event is not recorded. While the source of the IRD in Scotia Sea cores is not known, the record there suggests that site-specific circum-Antarctic ablation events occurred during distinct intervals. Not only does our study provide strong evidence that rapid GMSL during MWPs caused WAIS retreat with at least a small contribution to GMSL rise, it suggests that the retreat histories of individual ice streams in the WAIS system were highly

variable given other retreat chronologies (Bentley et al., 2014; Golledge et al., 2014). Future studies and numerical models incorporating the results presented here may shed light on the dynamics of AIS ice streams in the geologic past and future.

2.2 References

Abdul, N.A., Mortlock, R.A., Wright, J.D., and Fairbanks, R.G., 2016, Younger Dryas sea level and meltwater pulse 1B recorded in Barbados reef crest coral Acropora palmata: Paleoceanography, p. 330–344, doi: 10.1002/2015PA002847.

Adkins, J.F., McIntyre, K., and Schrag, D.P., 2002, The salinity, temperature, and delta18O of the glacial deep ocean.: Science (New York, N.Y.), v. 298, no. 5599, p. 1769–73, doi: 10.1126/science.1076252.

Adkins, J.F., and Schrag, D.P., 2003, Reconstructing Last Glacial Maximum bottom water salinities from deep-sea sediment pore fluid profiles: Earth and Planetary Science Letters, v. 216, no. 1–2, p. 109–123, doi: 10.1016/S0012-821X(03)00502-8.

Alley, R.B., 1989, Water-pressure coupling of sliding and bed deformation: I. Water system: Journal of glaciology, v. 35, no. 119, p. 108–118.

Alley, R.B., Anandakrishnan, S., Dupont, T.K., Parizek, B.R., and Pollard, D., 2007, Grounding-Line Stability: , no. March, p. 1838–1841.

Alley, R.B., Clark, P.U., Huybrechts, P., and Joughin, I., 2005, Ice-sheet and sea-level changes.: Science (New York, N.Y.), v. 310, no. 5747, p. 456–460, doi: 10.1126/science.1114613.

Anderson, R.F., Ali, S., Bradtmiller, L.I., Nielsen, S.H.H., Fleisher, M.Q., Anderson, B.E., and Burckle, L.H., 2009, Wind-driven upwelling in the Southern Ocean and the deglacial rise in atmospheric CO2.: Science (New York, N.Y.), v. 323, no. 5920, p. 1443–8, doi: 10.1126/science.1167441.

Anderson, R.F., Chase, Z., Fleisher, M.Q., and Sachs, J., 2002a, The Southern Ocean's biological pump during the Last Glacial Maximum: Deep-Sea Research Part II: Topical Studies in Oceanography, v. 49, no. 9–10, p. 1909–1938, doi: 10.1016/S0967-0645(02)00018-8.

Anderson, J.B., Conway, H., Bart, P.J., Witus, A.E., Greenwood, S.L., McKay, R.M., Hall, B.L., Ackert, R.P., Licht, K., Jakobsson, M., and Stone, J.O., 2014, Ross Sea paleo-ice sheet drainage and deglacial history during and since the LGM: Quaternary Science Reviews, v. 100, p. 31–54, doi: 10.1016/j.quascirev.2013.08.020.

Anderson, J.B., Shipp, S.S., Lowe, A.L., Wellner, J.S., and Mosola, A.B., 2002b, The Antarctic Ice Sheet during the Last Glacial Maximum and its subsequent retreat history: a review: Quaternary Science Reviews, v. 21, no. 1–3, p. 49–70, doi: 10.1016/S0277-3791(01)00083-X.

Arzeno, I.B., Beardsley, R.C., Limeburner, R., and 6, and M.J.M.W.B.O.L.P.S.R.S.C.L.S., 2014, Ocean variability contributing to basalmelt rate near the ice front of Ross Ice Shelf, Antarctica: Journal of Geophysical Research: Oceans, , no. 1, p. 9026–9032, doi: 10.1002/2014JC009792.

Bamber, J., Riva, R., Vermeersen, B., and LeBrocq, A., 2009, Reassessment of the potential sea-level rise from a collapse of the West Antarctic Ice Sheet: Science, v. 0, no. May, p. 1–3.

Bard, E., Hamelin, B., Delanghe-sabatier, D., Science, S., Series, N., Mar, N., Bard, E., Hamelin, B., and Delanghe-sabatier, D., 2010, Deglacial Meltwater Pulse 1B and Younger Dryas Sea Levels Revisited with Boreholes at Tahiti: Science, v. 327, no. 5970, p. 1235–1237.

Bart, P.J., 2004, West-directed flow of the West Antarctic Ice Sheet across Eastern Basin, Ross Sea during the Quaternary: Earth and Planetary Science Letters, v. 228, no. 3–4, p. 425–438, doi: 10.1016/j.epsl.2004.10.014.

Bart, P.J., Anderson, J.B., and Nitsche, F.O., 2017a, Post-LGM grounding-line positions of the Bindschadler Ice Stream in Ross Sea: Journal of Geophysical Research: Earth Surface, v. Submitted.

Bart, P.J., and Cone, A.N., 2012, Early stall of West Antarctic Ice Sheet advance on the eastern Ross Sea middle shelf followed by retreat at 27,50014CyrBP: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 335–336, p. 52–60, doi: 10.1016/j.palaeo.2011.08.007.

Bart, P.J., Krogmeier, B.J., Bart, M.P., and Tulaczyk, S.M., 2017b, The paradox of a two millennia grounding duration of the West Antarctic Ice Sheet in Ross Sea: Scientific reports, v. Submitted.

Bart, P.J., and Owolana, B., 2012, On the duration of West Antarctic Ice Sheet grounding events in Ross Sea during the Quaternary: Quaternary Science Reviews, v. 47, p. 101–115, doi: 10.1016/j.quascirev.2012.04.023.

Batchelor, C.L., and Dowdeswell, J.A., 2015, Ice-sheet grounding-zone wedges (GZWs) on high-latitude continental margins: Marine Geology, v. 363, p. 65–92, doi: 10.1016/j.margeo.2015.02.001.

Bentley, M.J., Ó Cofaigh, C., Anderson, J.B., Conway, H., Davies, B., Graham, A.G.C., Hillenbrand, C.-D., Hodgson, D. a., Jamieson, S.S.R., Larter, R.D., Mackintosh, A., Smith, J. a., Verleyen, E., Ackert, R.P., et al., 2014, A community-based geological reconstruction

of Antarctic Ice Sheet deglaciation since the Last Glacial Maximum: Quaternary Science Reviews, v. 100, p. 1–9, doi: 10.1016/j.quascirev.2014.06.025.

Berkman, P.A., Andrews, J.T., Björck, S., Colhoun, E.A., Emslie, S.D., Goodwin, I.D., Hall, B.L., Hart, C.P., Hirakawa, K., Igarashi, A., Ingólfsson, O., López-Martínez, J., Lyons, W.B., Mabin, M.C.G., et al., 1998, Circum-Antarctic coastal environmental shifts during the Late Quaternary reflected by emerged marine deposits: Antarctic Science, v. 10, no. 3, p. 345–362, doi: 10.1017/S0954102098000406.

Berkman, P., and Forman, S., 1996, Pre-bomb radiocarbon and the reservoir correction for calcareous marine species in the Southern Ocean: Geophysical Research Letters, v. 23, no. 4, p. 363–366, doi: 10.1029/96GL00151.

Borstad, C.P., Rignot, E., Mouginot, J., and Schodlok, M.P., 2013, Creep deformation and buttressing capacity of damaged ice shelves: Theory and application to Larsen C ice shelf: Cryosphere, v. 7, no. 6, p. 1931–1947, doi: 10.5194/tc-7-1931-2013.

Carlson, A.E., and Clark, P.U., 2012a, Ice-Sheet Sources of Sea-Level Rise and Freshwater Discharge During the Last Deglaciation: Reviews of Geophysics, v. 50, no. 2011, p. 1–72, doi: doi: 10.1029/2011rg000371.

Carlson, A.E., and Clark, P.U., 2012b, Ice sheet sources of sea level rise and freshwater discharge during the last deglaciation: Reviews of Geophysics, v. 50, no. 4, p. 1–72, doi: 10.1029/2011RG000371.

Chambers, S.R., 1991, 19 . SOLUTE DISTRIBUTIONS AND STABLE ISOTOPE CHEMISTRY OF INTERSTITIAL WATERS: Proceedings of the Ocean Drilling Program, Scientific Results, v. 119, p. 375–392.

Clark, P.U., Dyke, A.S., Shakun, J.D., Carlson, A.E., Clark, J., Wohlfarth, B., Mitrovica, J.X., Hostetler, S.W., and McCabe, A.M., 2009, The Last Glacial Maximum.: Science (New York, N.Y.), v. 325, no. 5941, p. 710–714, doi: 10.1126/science.1172873.

Conway, H., Hall, B.L., Denton, G.H., Gades, A.M., and Waddington, E.D., 1999, Past and Future Grounding-Line Retreat of the West Antarctic Ice Sheet: Science (New York, N.Y.), v. 280, no. 1999, p. 280–284, doi: 10.1126/science.286.5438.280.

Domack, E.W., Jacobson, E.A., and Anderson, J.B., 1999, Late Pleistocene – Holocene retreat of the West Antarctic Ice-Sheet system in: , no. 10, p. 1517–1536.

Dowdeswell, J. a., and Fugelli, E.M.G., 2012, The seismic architecture and geometry of grounding-zone wedges formed at the marine margins of past ice sheets: Geological Society of America Bulletin, v. 124, no. 11–12, p. 1750–1761, doi: 10.1130/B30628.1.

Dowdeswell, J.A., and Pudsey, C.J., 2004, Thickness and extent of the subglacial till layer beneath an Antarctic paleo – ice stream: , no. 1, p. 13–16, doi: 10.1130/G19864.1.

Fairbanks, R.G., 1989, A 17,000-year glacio-eustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation: Nature, v. 342, no. 6250, p. 637–642, doi: 10.1038/342637a0.

Favier, L., Pattyn, F., Berger, S., and Drews, R., 2016, Dynamic influence of pinning points on marine ice-sheet stability: A numerical study in Dronning Maud Land, East Antarctica: Cryosphere, v. 10, no. 6, p. 2623–2635, doi: 10.5194/tc-10-2623-2016.

Fisher, A.T., Mankoff, K.D., Tulaczyk, S.M., and Tyler, S.W., 2015, High geothermal heat flux measured below the West Antarctic Ice Sheet: , no. July, p. 1–9.

Fogwill, C.J., Phipps, S.J., Turney, C.S.M., and Golledge, N.R., 2015, Sensitivity of the Southern Ocean to enhanced regional Antarctic ice sheet meltwater input: Earth's Future, v. 3, no. 10, p. 317–329, doi: 10.1002/2015EF000306.

Fogwill, C.J., Turney, C.S.M., Golledge, N.R., Etheridge, D.M., Rubino, M., Thornton, D.P., Baker, A., Woodward, J., Winter, K., van Ommen, T.D., Moy, A.D., Curran, M.A.J., Davies, S.M., Weber, M.E., et al., 2017, Antarctic ice sheet discharge driven by atmosphere-ocean feedbacks at the Last Glacial Termination: Scientific Reports, v. 7, no. November 2016, p. 39979, doi: 10.1038/srep39979.

Golledge, N.R., Menviel, L., Carter, L., Fogwill, C.J., England, M.H., Cortese, G., and Levy, R.H., 2014, Antarctic contribution to meltwater pulse 1A from reduced Southern Ocean overturning: Nature Communications, v. 5, no. SEPTEMBER, p. 5107, doi: 10.1038/ncomms6107.

Greenwood, S.L., Gyllencreutz, R., Jakobsson, M., and Anderson, J.B., 2012, Ice-flow switching and East/West Antarctic Ice Sheet roles in glaciation of the western Ross Sea: Bulletin of the Geological Society of America, v. 124, no. 11–12, p. 1736–1749, doi: 10.1130/B30643.1.

Halberstadt, A.R.W., Simkins, L.M., Greenwood, S.L., and Anderson, J.B., 2016, Past ice-sheet behaviour: retreat scenarios and changing controls in the Ross Sea, Antarctica: The Cryosphere, v. 10, no. 3, p. 1003–1020, doi: 10.5194/tc-10-1003-2016.

Hall, B.L., Denton, G.H., Heath, S.L., Jackson, M.S., and Koffman, T.N.B., 2015, Accumulation and marine forcing of ice dynamics in the western Ross Sea during the last deglaciation: Nature Geoscience, v. 8, no. 8, p. 625–628, doi: 10.1038/ngeo2478.

Hall, B.L., Henderson, G.M., Baroni, C., and Kellogg, T.B., 2010, Constant Holocene Southern-Ocean 14C reservoir ages and ice-shelf flow rates: Earth and Planetary Science Letters, v. 296, no. 1–2, p. 115–123, doi: 10.1016/j.epsl.2010.04.054.

Heroy, D.C., and Anderson, J.B., 2007, Radiocarbon constraints on Antarctic Peninsula Ice Sheet retreat following the Last Glacial Maximum (LGM): Quaternary Science Reviews, v. 26, no. 25–28, p. 3286–3297, doi: 10.1016/j.quascirev.2007.07.012.

Hillenbrand, C.D., Bentley, M.J., Stolldorf, T.D., Hein, A.S., Kuhn, G., Graham, A.G.C., Fogwill, C.J., Kristoffersen, Y., Smith, J.A., Anderson, J.B., Larter, R.D., Melles, M., Hodgson, D.A., Mulvaney, R., et al., 2014, Reconstruction of changes in the Weddell Sea sector of the Antarctic Ice Sheet since the Last Glacial Maximum: Quaternary Science Reviews, v. 100, p. 111–136, doi: 10.1016/j.quascirev.2013.07.020.

Hillenbrand, C.D., Smith, J.A., Kuhn, G., Esper, O., Gersonde, R., Larter, R.D., Maher, B., Moreton, S.G., Shimmield, T.M., and Korte, M., 2010, Age assignment of a diatomaceous ooze deposited in the Western Amundsen Sea embayment after the last glacial maximum: Journal of Quaternary Science, v. 25, no. 3, p. 280–295, doi: 10.1002/jqs.1308.

Hindmarsh, R.C.A., 1999, Pore-water signal of marine ice-sheets: Global and Planetary Change, v. 23, no. 1–4, p. 197–211, doi: 10.1016/S0921-8181(99)00057-0.

Horgan, H.J., Walker, R.T., Anandakrishnan, S., and Alley, R.B., 2011, Surface elevation changes at the front of the Ross Ice Shelf: Implications for basal melting: Journal of Geophysical Research: Oceans, v. 116, no. 2, p. 1–12, doi: 10.1029/2010JC006192.

Jacobs, S.S., Fairbanks, R.G., and Horibe, Y., 1985, Origin and Evolution of water masses near the antarctic continental margin (S. S. Jacobs, Ed.): Oceanography of the Antarctic Continental Shelf, v. 43, p. 59–85, doi: 10.1029/AR043.

Jacobs, S.S., Jenkins, A., Giulivi, C.F., and Dutrieux, P., 2011, Stronger ocean circulation and increased melting under Pine Island Glacier ice shelf: Nature Geoscience, v. 4, no. 8, p. 519–523, doi: 10.1038/ngeo1188.

Jakobsson, M., Anderson, J.B., Nitsche, F.O., Gyllencreutz, R., Kirshner, A.E., Kirchner, N., O’Regan, M., Mohammad, R., and Eriksson, B., 2012, Ice sheet retreat dynamics inferred from glacial morphology of the central Pine Island Bay Trough, West Antarctica: Quaternary Science Reviews, v. 38, p. 1–10, doi: 10.1016/j.quascirev.2011.12.017.

Jenkins, A., Dutrieux, P., Jacobs, S.S., McPhail, S.D., Perrett, J.R., Webb, A.T., and White, D., 2010, Observations beneath Pine Island Glacier in West Antarctica and implications for its retreat: Nature Geoscience, v. 3, no. 7, p. 468–472, doi: 10.1038/ngeo890.

Joughin, I., and Alley, R.B., 2011, Stability of the West Antarctic ice sheet in a warming world: Nature Geoscience, v. 4, no. 8, p. 506–513, doi: 10.1038/ngeo1194.

Joughin, I., Alley, R.B., and Holland, D.M., 2012, Ice-sheet response to oceanic forcing: Science, v. 338, no. 6111, p. 1172–6, doi: 10.1126/science.1226481.

Kirshner, A.E., Anderson, J.B., Jakobsson, M., O’Regan, M., Majewski, W., and Nitsche, F.O., 2012, Post-LGM deglaciation in Pine Island Bay, West Antarctica: Quaternary Science Reviews, v. 38, p. 11–26, doi: 10.1016/j.quascirev.2012.01.017.

Klages, J.P., Kuhn, G., Hillenbrand, C.D., Graham, a. G.C., Smith, J. a., Larter, R.D., Gohl, K., and Wacker, L., 2014, Retreat of the West Antarctic Ice Sheet from the western Amundsen Sea shelf at a pre- or early LGM stage: Quaternary Science Reviews, v. 91, p. 1–15, doi: 10.1016/j.quascirev.2014.02.017.

Lambeck, K., Yokoyama, Y., and Purcell, T., 2002, Into and out of the last glacial maximum: Sea-level change during oxygen isotope stages 3 and 2: Quaternary Science Reviews, v. 21, no. 1–3, p. 343–360, doi: 10.1016/S0277-3791(01)00071-3.

Licht, K.J., and Andrews, J.T., 2002, The 14 C record of late-Pleistocene ice advance and retreat in the central Ross Sea, Antarctica: Arctic, Antarctic and Alpine Research, v. 34, no. 3, p. 324–333, doi: 10.2307/1552491.

Liu, J., Milne, G.A., Kopp, R.E., Clark, P.U., and Shennan, I., 2015a, Sea-level constraints on the amplitude and source distribution of Meltwater Pulse 1A: Nature Geoscience, v. 9, no. December, p. 6–12, doi: 10.1038/ngeo2616.

Liu, Y., Moore, J.C., Cheng, X., Gladstone, R.M., Bassis, J.N., Liu, H., Wen, J., and Hui, F., 2015b, Ocean-driven thinning enhances iceberg calving and retreat of Antarctic ice shelves.: Proceedings of the National Academy of Sciences of the United States of America, v. 112, no. 11, p. 3263–8, doi: 10.1073/pnas.1415137112.

Lowe, A.L., and Anderson, J.B., 2003, Evidence for abundant subglacial meltwater beneath the paleo-ice sheet in Pine Island Bay, Antarctica: Journal of Glaciology, v. 49, no. 164, p. 125–138, doi: 10.3189/172756503781830971.

Mackintosh, A., Golledge, N., Domack, E., Dunbar, R., Leventer, A., White, D., Pollard, D., DeConto, R., Fink, D., Zwartz, D., Gore, D., and Lavoie, C., 2011, Retreat of the East Antarctic ice sheet during the last glacial termination: Nature Geoscience, v. 4, no. 3, p. 195–202, doi: 10.1038/ngeo1061.

Mackintosh, A.N., Verleyen, E., Brien, P.E.O., White, D.A., Jones, R.S., Mckay, R., Dunbar, R., Gore, D.B., Fink, D., Post, A.L., Miura, H., Leventer, A., Goodwin, I., Hodgson, D.A., et al., 2014, Retreat history of the East Antarctic Ice Sheet since the Last Glacial Maximum: Quaternary Science Reviews, v. 100, p. 10–30, doi: 10.1016/j.quascirev.2013.07.024.

Majewski, W., and Anderson, J.B., 2009, Holocene foraminiferal assemblages from Firth of Tay, Antarctic Peninsula: Paleoclimate implications: Marine Micropaleontology, v. 73, no. 3–4, p. 135–147, doi: 10.1016/j.marmicro.2009.08.003.

Malone, M.J., Martin, J.B., Scho, J., Ninnemann, U.S., Nu, D., and White, T.S., 2004, The oxygen isotopic composition and temperature of Southern Ocean bottom waters during the last glacial maximum: v. 222, p. 275–283, doi: 10.1016/j.epsl.2004.02.027.

Matsuoka, K., Hindmarsh, R.C.A., Moholdt, G., Bentley, M.J., Pritchard, H.D., Brown, J., Conway, H., Drews, R., Durand, G., Goldberg, D., Hattermann, T., Kingslake, J., Lenaerts,

J.T.M., Martín, C., et al., 2015, Antarctic ice rises and rumples: Their properties and significance for ice-sheet dynamics and evolution: Earth-Science Reviews, v. 150, p. 724–745, doi: 10.1016/j.earscirev.2015.09.004.

McGlannan, A.J., Bart, P.J., Chow, J.M., and DeCesare, M., 2017, On the influence of post-LGM ice shelf loss and grounding zone sedimentation on West Antarctic Ice Sheet Stability: Marine Geology, v. Submitted.

McKay, R., Golledge, N.R., Maas, S., Naish, T., Levy, R., Dunbar, G., and Kuhn, G., 2015, Antarctic marine ice-sheet retreat in the Ross Sea during the early Holocene: Geology, v. 44, no. 1, p. 1–4, doi: 10.1130/G37315.1.

Menviel, L., Timmermann, A., Timm, O.E., and Mouchet, A., 2011, Deconstructing the Last Glacial termination: The role of millennial and orbital-scale forcings: Quaternary Science Reviews, v. 30, no. 9–10, p. 1155–1172, doi: 10.1016/j.quascirev.2011.02.005.

Millard, A., 2014, Conventions for Reporting Radiocarbon Determinations: Radiocarbon, v. 56, no. 2, p. 555–559, doi: 10.2458/56.17455.

Miller, M.D., Adkins, J.F., and Hodell, D.A., 2014, Rhizon sampler alteration of deep ocean sediment interstitial water samples, as indicated by chloride concentration and oxygen and hydrogen isotopes: Geochemistry, Geophysics, Geosystems, v. 15, no. 6, p. 2401–2413, doi: 10.1002/2014GC005308.

Mosola, A.B., and Anderson, J.B., 2006, Expansion and rapid retreat of the West Antarctic Ice Sheet in eastern Ross Sea: possible consequence of over-extended ice streams? Quaternary Science Reviews, v. 25, no. 17–18, p. 2177–2196, doi: 10.1016/j.quascirev.2005.12.013.

Nereson, N.A., and Raymond, C.F., 2001, The elevation history of ice streams and the spatial accumulation pattern along the Siple Coast of West Antarctica inferred from ground-based radar data from three inter-ice-stream ridges: Journal of glaciology, v. 47, no. 157, p. 303–313.

Peltier, W.R., and Fairbanks, R.G., 2006, Global glacial ice volume and Last Glacial Maximum duration from an extended Barbados sea level record: Quaternary Science Reviews, v. 25, no. 23–24, p. 3322–3337, doi: 10.1016/j.quascirev.2006.04.010.

Pollard, D., and DeConto, R.M., 2009, Modelling West Antarctic ice sheet growth and collapse through the past five million years.: Nature, v. 458, no. 7236, p. 329–332, doi: 10.1038/nature07809.

Pollard, D., DeConto, R.M., and Nyblade, A. a., 2005, Sensitivity of Cenozoic Antarctic ice sheet variations to geothermal heat flux: Global and Planetary Change, v. 49, no. 1–2, p. 63–74, doi: 10.1016/j.gloplacha.2005.05.003.

Pritchard, H.D., Ligtenberg, S.R.M., Fricker, H. a., Vaughan, D.G., van den Broeke, M.R., and Padman, L., 2012, Antarctic ice-sheet loss driven by basal melting of ice shelves: Nature, v. 484, no. 7395, p. 502–505, doi: 10.1038/nature10968.

Rayne, T.W., and Domack, E.W., 1996, Porewater chemistry of Ross Sea diamictons: A till or not a till: Antarctic Journal of the United States, v. 31, p. 97–98.

Reimer, P.J., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Buck, C.E., Cheng, H., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Haflidason, H., Hajdas, I., et al., 2013, IntCal13 and Marine13 Radiocarbon Age Calibration Curves 0–50,000 Years cal BP: Radiocarbon, v. 55, no. 4, p. 1869–1887, doi: 10.2458/azu_js_rc.55.16947.

Rignot, E., Jacobs, S., Mouginot, J., and Scheuchl, B., 2013, Ice-shelf melting around Antarctica.: Science, v. 341, no. 6143, p. 266–70, doi: 10.1126/science.1235798.

Rignot, E., Mouginot, J., Morlighem, M., Seroussi, H., and Scheuchl, B., 2014, Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith, and Kohler glaciers, West Antarctica, from 1992 to 2011: Geophysical Research Letters, v. 41, no. 10, p. 3502–3509, doi: 10.1002/2014GL060140.

Rosenheim, B.E., Day, M.B., and Hayes, J.M., 2008, Antarctic sediment chronology by programmed-temperature pyrolysis: Methodology and data treatment: , p. 1–16, doi: 10.1029/2007GC001816.

Schrag, D.P., Adkins, J.F., McIntyre, K., Alexander, J.L., Hodell, D. a., Charles, C.D., and McManus, J.F., 2002, The oxygen isotopic composition of seawater during the Last Glacial Maximum: Quaternary Science Reviews, v. 21, no. 1–3, p. 331–342, doi: 10.1016/S0277-3791(01)00110-X.

Schrag, D.P., and DePaolo, D.J., 1993, Determination of δ18O of Seawater in the Deep Ocean during the Last Glacial Maximum: Paleoceanography, v. 8, no. 1, p. 1–6, doi: 10.1029/92pa02796.

Schweizer, M., Bowser, S.S., Korsun, S., and Pawlowski, J., 2012, Emendation of Cibicides Antarcticus (Saidova, 1975) Based on Molecular, Morphological, and ecological Data: The Journal of Foraminiferal Research, v. 42, no. 4, p. 340–344, doi: 10.2113/gsjfr.42.4.340.

Seeberg-elverfeldt, J., and Feseker, T., 2005, OCEANOGRAPHY : METHODS Rhizon sampling of porewaters near the sediment-water interface: , p. 361–371.

Shipp, S., Anderson, J., and Domack, E., 1999, Late Pleistocene-Holocene retreat of the West Antarctic Ice-Sheet system in the Ross Sea: Part 1 - Geophysical results: Bulletin of the Geological Society of America, doi: 10.1130/0016-7606(1999)111<1486.

Siegfried, M.R., Fricker, H.A., Carter, S.P., and Tulaczyk, S., 2016, Episodic ice velocity fluctuations triggered by a subglacial flood in West Antarctica: Geophysical Research Letters, v. 43, no. 6, p. 2640–2648, doi: 10.1002/2016GL067758.

Smith, J. a., Hillenbrand, C.-D., Kuhn, G., Klages, J.P., Graham, A.G.C., Larter, R.D., Ehrmann, W., Moreton, S.G., Wiers, S., and Frederichs, T., 2014, New constraints on the timing of West Antarctic Ice Sheet retreat in the eastern Amundsen Sea since the Last Glacial Maximum: Global and Planetary Change, v. 122, p. 224–237, doi: 10.1016/j.gloplacha.2014.07.015.

Smith, J.A., Hillenbrand, C.-D., Kuhn, G., Larter, R.D., Graham, A.G.C., Ehrmann, W., Moreton, S.G., and Forwick, M., 2011, Deglacial history of the West Antarctic Ice Sheet in the western Amundsen Sea Embayment: Quaternary Science Reviews, v. 30, no. 5–6, p. 488–505, doi: 10.1016/j.quascirev.2010.11.020.

Smith, J. a., Hillenbrand, C.D., Larter, R.D., Graham, A.G.C., and Kuhn, G., 2009, The sediment infill of subglacial meltwater channels on the West Antarctic continental shelf: Quaternary Research, v. 71, no. 2, p. 190–200, doi: 10.1016/j.yqres.2008.11.005.

Stearns, L. a., Smith, B.E., and Hamilton, G.S., 2008, Increased flow speed on a large East Antarctic outlet glacier caused by subglacial floods: Nature Geoscience, v. 1, no. 12, p. 827–831, doi: 10.1038/ngeo356.

Stolldorf, T., Schenke, H., and Anderson, J.B., 2012, LGM ice sheet extent in the Weddell Sea : evidence for diachronous behavior of Antarctic Ice Sheets: Quaternary Science Reviews, v. 48, p. 20–31, doi: 10.1016/j.quascirev.2012.05.017.

Stuiver, M., Reimer, P., and Reimer, R., 2005, CALIB 7.1: [http://calib.qub.ac.uk/calib/],.

Subt, C., Fangman, K.A., Wellner, J.S., and Rosenheim, B.E., 2015, Sediment chronology in Antarctic deglacial sediments: Reconciling organic carbon 14C ages to carbonate 14C ages using Ramped PyrOx: The Holocene, doi: 10.1177/0959683615608688.

WAIS Divide Project Members, 2013, Onset of deglacial warming in West Antarctica driven by local orbital forcing.: Nature, v. 500, no. 7463, p. 440–4, doi: 10.1038/nature12376.

Webb, P.-N.P., and Strong, C.C.P., 2006, Foraminiferal biostratigraphy and palaeoecology in Upper Oligocene–Lower Miocene glacial marine sequences 9, 10, and 11, CRP-2/2A drill hole, Victoria Land Basin, Antarctica: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 231, no. 1–2, p. 71–100, doi: 10.1016/j.palaeo.2005.07.036.

Weber, M.E., Clark, P.U., Kuhn, G., Timmermann, A., Sprenk, D., Gladstone, R., Zhang, X., Lohmann, G., Menviel, L., Chikamoto, M.O., Friedrich, T., and Ohlwein, C., 2014, Millennial-scale variability in Antarctic ice-sheet discharge during the last deglaciation.: Nature, v. 510, no. 7503, p. 134–8, doi: 10.1038/nature13397.

Wycech, J., Clay Kelly, D., and Marcott, S., 2016, Effects of seafloor diagenesis on planktic foraminiferal radiocarbon ages: Geology, v. 44, no. 7, p. 551–554, doi: 10.1130/G37864.1.

Yokoyama, Y., Anderson, J.B., Yamane, M., Simkins, L.M., Miyairi, Y., Yamazaki, T., Koizumi, M., Suga, H., Kusahara, K., Prothro, L., Hasumi, H., Southon, J.R., and Ohkouchi, N., 2016, Widespread collapse of the Ross Ice Shelf during the late Holocene: Proceedings of the National Academy of Sciences, p. 201516908, doi: 10.1073/pnas.1516908113.

CHAPTER 3: INVESTIGATING THE POSSIBILITY OF A SUBGLACIAL MELTWATER TRIGGER ON POST-LGM WEST ANTARCTIC ICE SHEET RETREAT USING POREWATER GEOCHEMISTRY

3.1 Introduction

The regional deglacial history of the West Antarctic Ice Sheet (WAIS) is not well constrained (Bentley et al., 2014). Deglacial chronologies range from a pre-Last Glacial Maximum (LGM) retreat (e.g., Bart and Cone, 2012; Stolldorf et al., 2012; Klages et al., 2014) to a post-LGM retreat beginning sometime during the Last Glacial Termination into the Holocene 18,000 to 11,000 years ago (e.g., Domack et al., 1999; Clark et al., 2009; Smith et al., 2014; McKay et al., 2015; DeCesare et al., 2016). These opposing scenarios suggest that deglaciation may have been asynchronous, with discrete mechanisms forcing retreat of individual ice streams (e.g., Pollard and DeConto, 2009). Factors such as incursion of relatively warm Circumpolar Deep Water onto the Antarctic continental shelf (Jenkins et al., 2010; Jacobs et al., 2011; Rignot et al., 2014), global mean sea-level rise (Alley et al., 2007; Golledge et al., 2014), and subglacial lake drainage (Lowe and Anderson, 2003; Stearns et al., 2008; Smith et al., 2009; Greenwood et al., 2012; Siegfried et al., 2016) may all play critical roles in Antarctic ice-stream retreat.

The terminus of the WAIS is primarily grounded below sea level, making it highly susceptible to ablation from increasing ocean temperature, oscillations in relative sea level, and geothermal heat flux (Anderson et al., 2002b; Pollard et al., 2005; Jakobsson et al., 2012; Batchelor and Dowdeswell, 2015). Direct melting by ocean currents is currently occurring in the Amundsen Sea sector of the WAIS and this has been proposed to have also been a mechanism for WAIS retreat in the geologic past (Jenkins et al., 2010; Jacobs et al., 2011; Rignot et al., 2014; Pollard and DeConto, 2009; Menviel et al., 2011; Joughin and Alley, 2011; Golledge et

al., 2014).

Intervals of large magnitude rapid sea-level rise may also act to destabilize the grounding line causing retreat (Alley et al., 2005; Alley et al., 2007). New foraminiferal radiocarbon ages from the Whales Deep Basin, an eastern Ross Sea paleo-ice-stream trough, suggest that rapidly rising global mean sea level triggered the WAIS to retreat in two stages (DeCesare et al., submitted). Backstepping of the WAIS began during Meltwater Pulse-1a at 14,700 ± 400 radiocarbon calibrated years ago (cal yr BP). A subsequent retreat occurred during MWP-1b at 11,500 ± 300 cal yr BP (DeCesare et al., submitted).

Subglacial meltwater discharge can also potentially cause ice stream retreat (Lowe and Anderson, 2003; Stearns et al., 2008; Smith et al., 2009; Greenwood et al., 2012; Siegfried et al., 2016). Subglacial meltwater is incorporated into subglacial till (deformation till) at the ice-sediment interface lubricating the ice stream and causing accelerated flow (Alley, 1989; Rayne and Domack, 1996; Hindmarsh, 1999; Lowe and Anderson, 2003). Evidence of meltwater channels in Antarctic paleo-ice-stream troughs suggests that subglacial meltwater processes have influenced ice stream behavior (Smith et al., 2009; Dowdeswell and Fugelli, 2012; Klages et al., 2014; Halberstadt et al., 2016). Evidence from seafloor geomorphology from multibeam swath bathymetry suggest subglacial meltwater has caused fluctuations in the WAIS at the Whillans and Mercer paleo-ice streams (Siegfried et al., 2016) and ice streams that drain into Pine Island Bay (Lowe and Anderson, 2003).

Meltwater at the grounding line is generated by several processes including drainage of subglacial lakes or melting induced by a warm marine water mass. This fresh meltwater signal could be preserved in grounding-line proximal and sub-ice-shelf sediment (Chambers, 1991; Hindmarsh, 1999). Hence, a freshwater signal could hypothetically be identified by analyzing

porewater geochemistry in deglacial sediment deposits (Rayne and Domack, 1996). Numerical models and direct observation provide evidence that freshwater is retained in glacimarine sediment (Chambers, 1991; Hindmarsh, 1999). Due to the high clay content of glacial sediment, it could act as an impermeable barrier to diffusion of freshwater after infiltration by the ice stream (Chambers, 1991; Hindmarsh, 1999). Using a simple idealized model for deglaciation including Antarctic continental shelf parameters, subglacial meltwater would be preserved in sediment for an entire interglacial period (Hindmarsh, 1999). Furthermore, the relatively more saline waters of the LGM interval have been identified in the geochemical signature of sedimentary pore waters (Schrag and DePaolo, 1993; Adkins et al., 2002; Schrag et al., 2002; Adkins and Schrag, 2003).

If subglacial lake drainage influenced WAIS retreat, a freshwater signal should be preserved in sediment that was deposited subglacially (Rayne and Domack, 1996; Hindmarsh, 1999). In addition, it may be possible that meltwater is retained in grounding zone proximal sediment because subglacial water can be incorporated into deformation till which is deposited at the grounding line of retreating ice streams (Dowdeswell and Pudsey, 2004). Analyzing the oxygen and hydrogen isotope content ($\delta^{18}O$ and δD, respectively) of interstitial waters from sediment cores would reveal the extent that freshwater was incorporated into post-LGM sediment. Glacial ice is composed of freshwater that is highly depleted in ^{18}O with $\delta^{18}O$ values of the WAIS ranging from -30 to -50‰ (WAIS Divide Project Members, 2013). In contrast the average $\delta^{18}O$ value of ocean water is ~0‰. Furthermore, hydrogen isotopes, deuterium (δD), of Antarctic bottom waters are approximately -4‰ while meteoric water analyzed in Antarctic proximal environments are approximately -30‰ (Chambers, 1991). Mixing of marine and fresh waters should yield a value somewhere in between these end-members. Porewater samples from

the Shona Ridge suggests that the chemistry of seawater, particularly oxygen isotopes of seawater ($\delta^{18}O_{sw}$), can be preserved in sediment >20,000 years old (Schrag and DePaolo, 1993; Adkins et al., 2002; Schrag et al., 2002). The $\delta^{18}O_{sw}$ during the LGM was enriched by ~1‰ compared to average modern $\delta^{18}O_{sw}$ (Adkins et al., 2002; Malone et al., 2004).

3.2 Background

During the austral summer of 2015, the *RVIB Nathanial B Palmer* Expedition *NBP1502B* completed a large area bathymetric and seismic survey of the Whales Deep paleo-ice stream-trough in the eastern Ross Sea (Bart et al., submitted). This provided new detail showing that grounded ice paused on the outer shelf to construct seven grounding zone wedges (GZWs 1–7 from oldest to youngest). GZWs are subaqueous terminal moraines constructed when the grounding line had a stable position during the overall retreat of grounded ice (Dowdeswell and Fugelli, 2012; Bart and Cone, 2012; Bart and Owolana, 2012). A total of 15 kasten cores (KC) and 6 jumbo piston cores (JPC) penetrated the topset and foreset of the four exposed GZWs (GZW1–3 and GZW7, Figure 3.1). Four sediment facies were identified which can be directly related to the translation of the grounding-line and calving-front positions on a regional scale (McGlannan et al., submitted). Grounding-zone-proximal diamict, the lower-most sedimentary unit, was deposited directly by basal ice proximal to the grounding line during pauses in the retreat. This GZW diamict is overlain by a grey-brown granulated sub-ice-shelf facies with weak laminations in all cores, with the exception to those cores located on the GZW7 foreset. An "ice-shelf breakup" unit lies above the sub-ice shelf deposits in cores taken from GZW1, 2 and 3; and on the outer shelf site KC11. An open marine surface unit has been accumulating on the outer continental shelf in the time since ice-free or seasonal sea-ice conditions were established. The

diamict on the foreset of GZW7 is directly overlain by an open marine unit (McGlannan et al., submitted). This stratal relationship indicates that the ice shelf broke up prior to the end of GZW7 time.

Key stratigraphic levels that constrain the relative time of grounding-line and calving-front retreat were identified in sediment cores (McGlannan et al., submitted). The transition from GZW diamict to sub-ice-shelf (or open marine facies) correspond to southward migration of the grounding-line past the core location. A second upcore transition, the change from sub-ice-shelf facies to ice shelf breakup (or open marine) facies, corresponds to the southward migration of the calving front past the core location. Sediment directly above and below these facies transitions was the primary target for acquiring porewater using Rhizon extractors (see Methods). Chemical analysis of these samples has been used to test if a meltwater signal can be detected in (sub)glacial and deglacial sediment.

3.3 Methods

Porewater was extracted from sediment contained in KCs using Rhizon samplers for geochemical analysis. These microfilter extractors were used instead of the traditional methods involving sediment extraction, squeezing and centrifugation because they are non-destructive and do not significantly alter the chemical composition of the porewater (Rhizosphere Research Products; Seeberg-elverfeldt and Feseker, 2005; Miller et al., 2014). Rhizons have been utilized to successfully extract porewater from deep-sea marine sediment samples for chemical analysis (Schrum et al., 2011; Dickens et al., 2007).

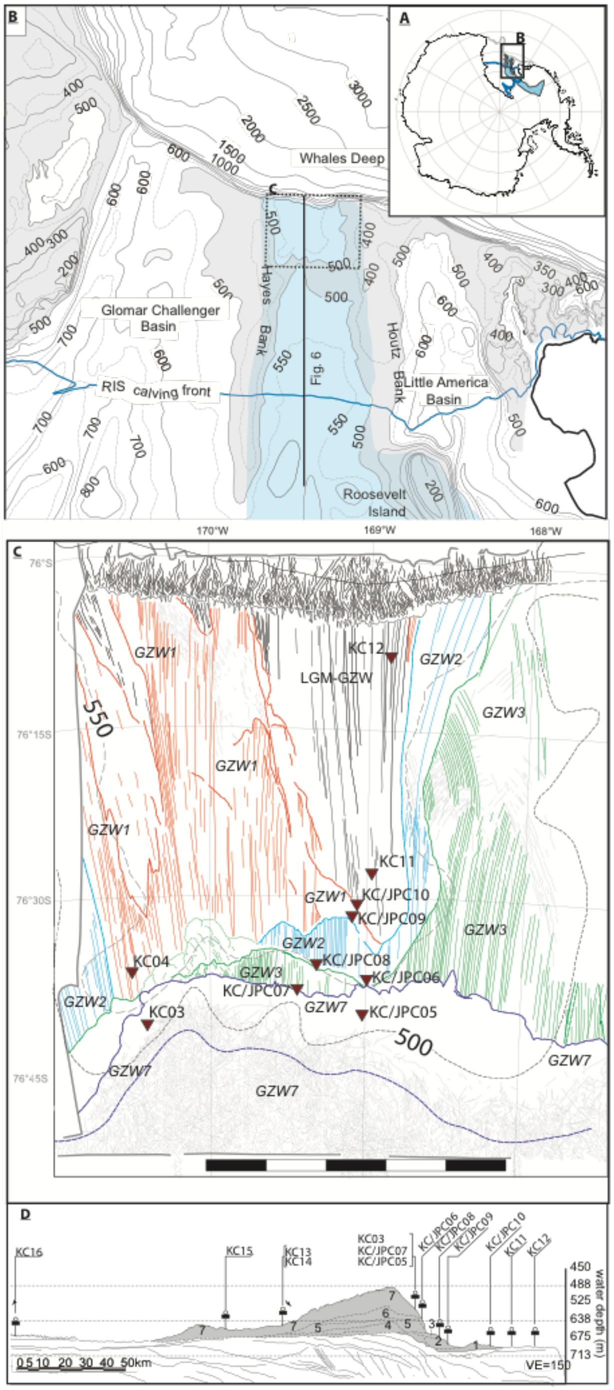

Figure 3.1: **(A)** Outline of Antarctica, the blue shaded area is the LGM configuration of the Bindschadler ice stream, the black box is panel **(B)** bathymetric map of the eastern Ross Sea. The dark blue line outlines the extent of the modern calving front. The black dashed box shows the area represented by **(C)**. The black line shows the seismic transect shown in **(D)** and in Figure 3.5. Panel **(C)** is a line drawing overlay of the multibeam image (map view) collected during Expedition NBP1502B. Each color represents the area of discrete GZWs 1,2,3 and 7. Cores locations are labeled. Panel **(D)** shows the extent of the seismic survey. Figures slightly modified from McGlannan et al., (submitted); Bart et al., (submitted).

Porewater extraction was performed during expedition *NBP1502B* onboard the *Nathaniel B. Palmer RVIB* as soon as possible after KCs were opened to minimize the potential of mixing the marine water with porewater. The Rhizons were inserted into the sediment as close to the middle of the core as possible (at least 2 cm from the edge of the KC). This precaution was taken to maximize the volume of porewater extracted and avoid zones that may have been subjected to shearing by the coring process. Rhizons (CSS 19.21.23F, 0.1µm filter) were then attached to a luer lock three-way stopcock and 10 mL syringes. After insertion, the plunger was pulled to create a vacuum. Once water was flowing, the three-way stopcock was rotated to eject any headspace and the extraction was continued to allow water to flow into the syringe.

Porewater samples were extracted from four sediment facies: 1) open marine sediment; 2) ice shelf break up sediment; 3) sub-ice shelf sediment; and 4) GZW diamict. In the absence of easily discernable facies transitions, Rhizons were evenly spaced downcore. At the end of extraction, the stopcock was rotated to cut off flow from the Rhizon and the syringe was removed. Syringes were detached when at least 4 mL of porewater was extracted. Ideally, 9 mL of porewater was extracted.

Water was then decanted into 4 mL high-density polyethylene vials until a meniscus formed at the mouth of the vial. A cap was than screwed on and the vial was wrapped with parafilm and electrical tape and labeled. This procedure was performed to prevent evaporation, which would compromise the $\delta^{18}O$ signal. Samples were stored in a 4ºC refrigerator onboard the *Nathaniel B. Palmer RVIB*. From the dock, the samples were then shipped in a 4°C refrigerated container to Louisiana State University and subsequently stored at 4ºC. Additional porewater samples were extracted from JPCs, using the methods outlined above, in July 2015 at the Antarctic Marine Geology Research Facility (AMGRF) in Tallahassee, Florida.

Isotopic composition of the porewater ($\delta^{18}O$ and δD) was completed at UC Berkeley by Dr. Wenbo Yang at the Laboratory for Environmental and Sedimentary Isotope Geochemistry. $\delta^{18}O$ was analyzed by continuous flow (CF) using a Thermo Gas Bench II interfaced to a Thermo Delta Plus XL mass spectrometer. The method is described in detail in the Thermo GAS Bench II operating manual, ThermoQuest, Oct 1999. In brief, ~100 µL of water (depending on sample volume) for both standards and samples were pipetted into 10 mL glass vials and quickly sealed to prevent evaporation. The vials were then purged with 0.2% CO_2 in helium and allowed to equilibrate at room temperature for ≥ 48 hours. The $\delta^{18}O$ in the CO_2 was then analyzed. Long-term external precision is ± 0.12‰. Deuterium (δD) in water was analyzed in dual inlet (DI) using a hot chromium reactor unit (H/Device™) interfaced with a Thermo Delta Plus XL mass spectrometer. Multiple standards were run with every batch and corrected for differential drift of standards with different isotope ratios. Long-term external precision of δD is ± 0.80‰.

Two tests were performed to determine if Rhizons can be used to extract porewater to detect the $\delta^{18}O$ signature indicative of a subglacial meltwater influence on WAIS retreat. The first test involved analyzing the $\delta^{18}O$ of porewater contained in sediment samples that were once in the subglacial setting and comparing them to porewater from sediment that was deposited in the sub-aqueous environment. If these results are similar, this would suggest no meltwater was contained in the glacial sediment. A second test was used to determine if the pore waters retained the LGM signal independent of a meltwater influence. Results were then used to determine if retreat of the WAIS was influenced by meltwater generation and/or discharge at the grounding line.

3.4 Results

Porewater samples from Whales Deep Basin sediments range from core depths of 390 to 2 cm. The estimated age range of these sediments is 35,500 to 1,600 thousand years ago (calibrated radiocarbon age – cal kyr BP), respectively. Porewater samples were taken from each of the four sedimentary unit types. Extraction of the minimum volume of porewater (4 mL) took less than an hour for the open marine and ice shelf breakup facies; between 1 and 6 hours for the sub-ice shelf sediment; and between 6 and 12 hours for the GZW diamict. In instances where <4 mL were extracted after 5 to 6 hours, the Rhizon position and angle was slightly changed. This did not affect the chemical results. For some of the GZW diamict extractions that took longer than 6 to 8 hours, sediment was removed from the core and enveloped in plastic cling-wrap to prevent loss of interstitial waters and interaction with the atmosphere. This technique was used because of the lack of available room to store uncut KCs on the *Nathanial B. Palmer RVIB (NBP)*. Chemical results from this technique did not deviate from *in situ* extractions.

Porewater was extracted during two occasions. One set was extracted during Expedition NBP1502B and one set after cores were shipped to the Antarctic Marine Geology Research Facility (AMGRF) where they are archived. Porewater extracted during the expedition yielded essentially homogenous $\delta^{18}O$ values ranging from -0.96 to -0.24‰; σ =0.13. Excluding maximum and minimum values, results are within ± 0.24‰ of each other, with an average of -0.45‰, σ =0.07 (Appendix Table A.2, Figure 3.2). δD range from -2.0 to -7.3‰ with an average of -4.5‰, σ-1.5.

Post-cruise $\delta^{18}O$ results range from 3.65 to -1.68‰, σ=1.98. These samples, from JPC10, KC09 through KC06, are taken from the GZW diamict (Table A.2). These post-cruise $\delta^{18}O_{pw}$ can be further subdivided into values that bin close to the onboard $\delta^{18}O_{pw}$ and those that drastically

deviate. Five $\delta^{18}O_{pw}$ range from -1.21 to -1.68‰, which plot close to the NBP $\delta^{18}O_{pw}$ (Figure 3.2). Four additional offshore $\delta^{18}O_{pw}$ values deviate significantly, and range from 1.22 to 3.65‰ (Table A.2). Due to these deviations and uncertainties in how the $\delta^{18}O_{pw}$ was affected by storage and transportation, we will only refer to the onboard *NBP1502B* results, unless stated otherwise. Post-cruise δD range from -6.1 to -11.5‰, with an average value of -8.5‰, σ=1.6.

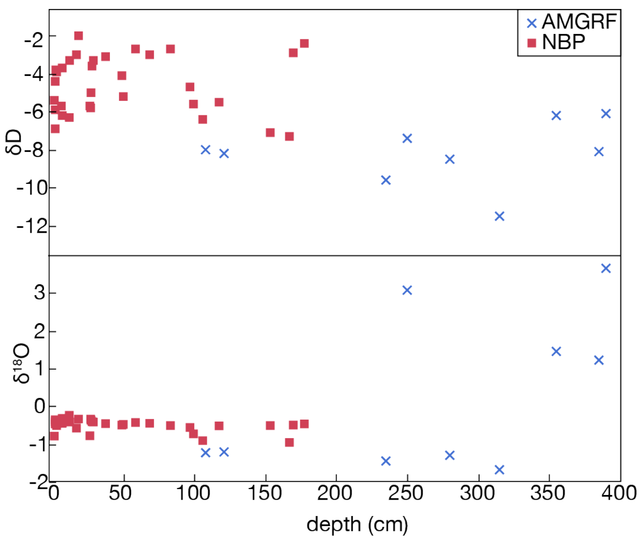

Figure 3.2: Comparison of hydrogen isotopes (δD) and $\delta^{18}O$ between sampling locations. Samples taken during Expedition NBP1502(red squares) show a narrow correlation while samples taken post-cruise at AMGRF (blue x) show a large spread suggesting they are compromised.

Isotope values are not correlated to the sediment facies, i.e., data arranged on quantile plots are statistically similar regardless of facies (Figure 3.3 and 3.4). The GZW diamict can be separated in two depositional environments, the topset of the GZW and the foreset of the GZW. Values from the NBP $\delta^{18}O_{pw}$ samples from the topset and foreset samples do not deviate significant from each other. There is only a slight trend in age (i.e., depth) versus isotopes (Figure 3.5). The lowest $\delta^{18}O_{pw}$ values, -0.73 and -0.96‰, from the sub-ice shelf sediment in KC09 at 99.5 and 167 cm (13.09 and 13.89 cal kyr BP, respectively) do not correlate with age,

facies, or retreat events. Both older and younger samples are relatively more enriched in $\delta^{18}O_{pw}$. The highest $\delta^{18}O_{pw}$ (-0.24‰) is from the open marine unit in KC07 at 12 cm.

3.5 Discussion

Three primary mechanisms have been suggested as triggers for West Antarctic Ice Sheet retreat during the Last Glacial Termination – two of which would have generated significant volumes of freshwater either subglacially or at the grounding line. The first scenario involves drainage of subglacial lakes and/or production of substantial volumes of subglacial meltwater lubrication of basal ice discharging from the interior of the WAIS to the grounding line. This would produce meltwater laden sediment, which would have been deposited at the topset of the GZWs in Whales Deep Basin. If voluminous meltwater discharge was associated with WAIS retreat, $\delta^{18}O_{pw}$ from the subglacial diamict should reflect water depleted in ^{18}O. Of the four samples from the GZW diamict, only two are from the GZW topset. Samples located on the topset of the LGM-GZW (KC12) and the topset of GZW7 (KC14) show $\delta^{18}O_{pw}$ values closely representative of modern Ross Sea water -0.47 and -0.91‰, respectively (Jacobs et al., 1985). These values do not reflect WAIS $\delta^{18}O$ values, which are -30 to 50‰. Even if we consider the $\delta^{18}O_{pw}$ from AMGRF, the lowest value is -1.68‰. The δD values suggest that meltwater was not

transferred from the WAIS to be incorporated into underlying glaciogenic sediment.

In another scenario, warm Circumpolar Deepwater (CDW) flowing from the Southern Ocean onto the Ross Embayment could have acted to melt the ice shelf at the grounding line. This would have produced voluminous meltwater at the sediment-ice-ocean interface in a sub-ice-shelf cavity where sediment is expelled from the grounding line. The sediment generated in this zone comprises the GZW foreset and the proximal sub-ice shelf facies. However, there is no indication of a freshwater signal in the $\delta^{18}O_{pw}$ results from the GZW topset or foreset, which

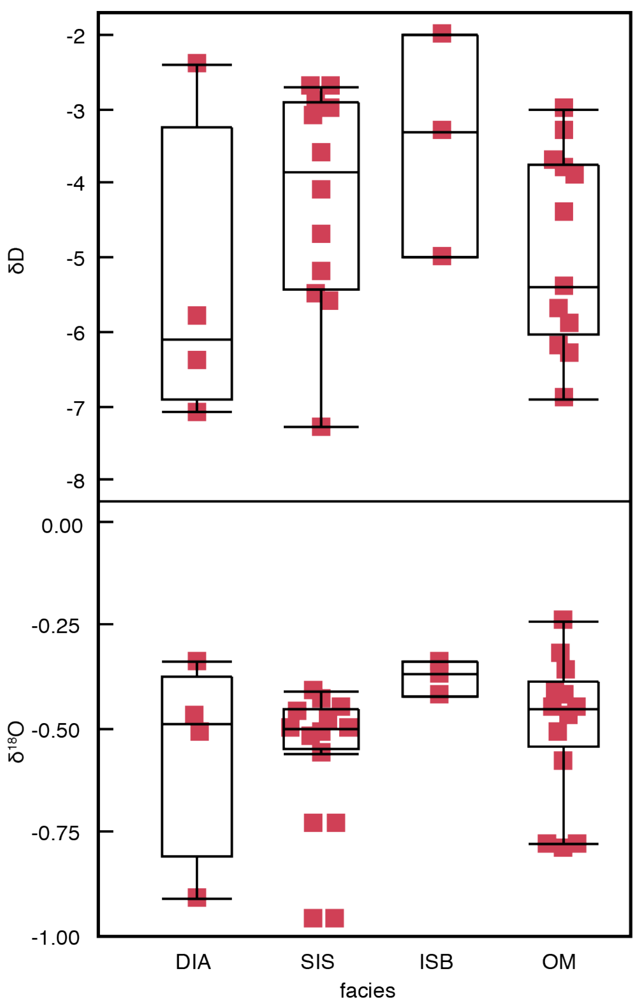

Figure 3.3: Quantile box plot of hydrogen isotopes (δ D) and $\delta^{18}O$ from onboard samples separated by sedimentary facies. Data plot all within a tight group. DIA=diamict, ISB= ice shelf breakup, OM= open marine, SIS= sub- ice shelf.

would have resulted in highly depleted $\delta^{18}O_{pw}$ values. Furthermore, the $\delta^{18}O$ of CDW in the Ross Sea is -0.07‰ (Jacobs et al., 1985). This signal is not reflected in the $\delta^{18}O_{pw}$ values from the sediment cores recovered in Whales Deep. This leaves a third scenario that does not involve a significant meltwater component.

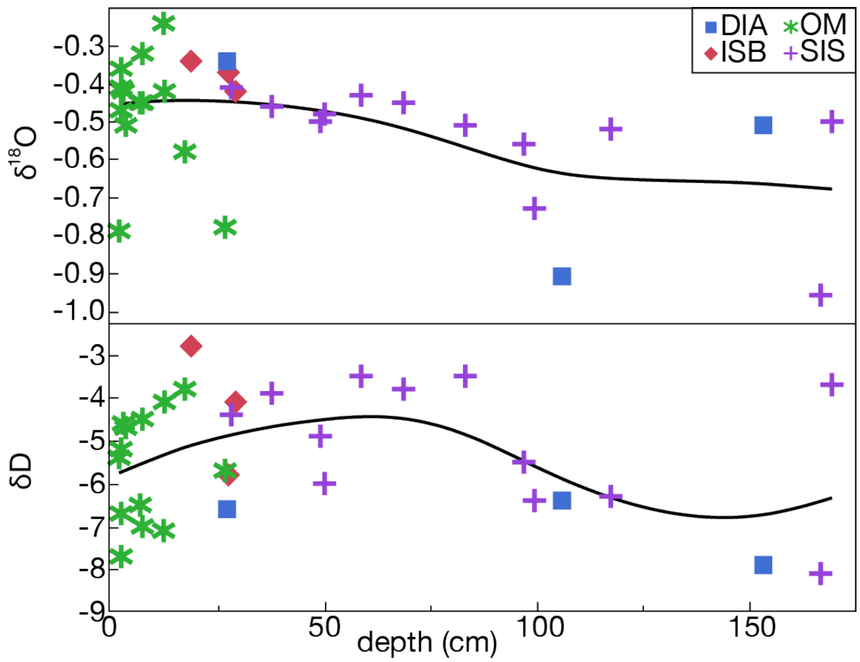

Figure 3.4: $\delta^{18}O$ and δ D vs depth with data plotted from each facies. The trend line shows a slight correlation between depth and geochemical values.

Rising sea-level has been proposed as a trigger for WAIS retreat in the geologic past (Alley et al., 2005; Clark et al., 2009; Mackintosh et al., 2011; Golledge et al., 2014). Since the end of the LGM sea level has risen 125 ± 5 meters (Carlson and Clark, 2012b; Clark et al., 2009). During the Last Glacial Termination, two rapid intervals of sea-level rise occurred, Meltwater Pulse-1a (MWP-1a) at 14,500 years ago (Fairbanks, 1989; Liu et al., 2015a) and MWP1-b at 11,300 years ago (Fairbanks, 1989; Bard et al., 2010; Abdul et al., 2016). New foraminiferal radiocarbon ages suggest that MWP-1a forced the WAIS to retreat ~50 km from the Whales Deep continental shelf edge (to deposit the GZW 1–7 cluster, Figure 3.1 and 3.5). Subsequently, the WAIS retreated 200 km from GZW7 to a position south of the modern calving

front during MWP-1b (DeCesare et al., submitted). The lack of freshwater signal in sedimentary porewater suggest that rising sea level was the primary cause for this early phase of WAIS retreat (DeCesare et al., submitted).

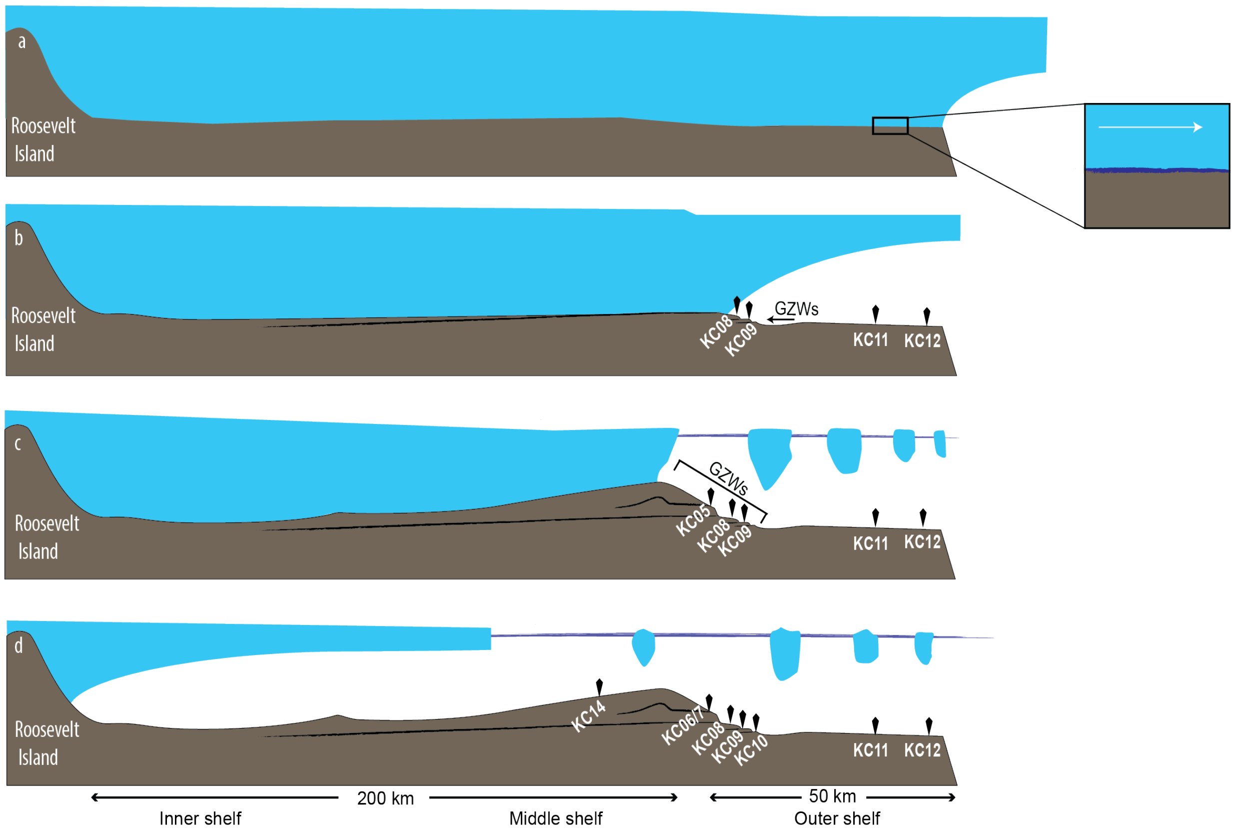

Figure 3.5: Retreat model of the WAIS. **a)** LGM extent of the WAIS, inset shows sediment-ice interface. The arrow depicts the continuous flow of glacial ice over a thin layer of meltwater. **b)** Grounding-line retreat during MWP-1a. Core locations are shown by black diamonds. KC12 and KC11 are from the outer shelf. KC09 and KC08 (as well as JPC09 and JPC08) are located on GZW1 and 2 respectively. **c)** Construction of GZW7 and exposure of the outer shelf due to ice-shelf collapse. Cores KC05, KC06 and KC07 (with corresponding JPCs) are located on the foreset of GZW7. **d)** Retreat of the WAIS during MWP-1b. Core KC14 is on the topset of GZW7.

An alternative interpretation suggests that the original $\delta^{18}O$ signature of meltwater was not preserved in post-LGM glacial sediment either by dewatering or isotope diffusion since decoupling of grounded ice over the last 14,500 or 11,000 years (outer shelf or middle shelf). To test this possibility, we compare our $\delta^{18}O_{pw}$ to modern and LGM $\delta^{18}O_{sw}$ content of Ross Sea

waters. Modern $\delta^{18}O_{sw}$ values for the eastern Ross Sea range from -0.71 to -0.07‰ for sub ice-shelf waters and CDW respectively (Jacobs et al., 1985). These values closely agree with our $\delta^{18}O_{pw}$ which are offset by ~0.2‰ to more negative values (-0.96 to -0.24‰). During the LGM, $\delta^{18}O_{sw}$ had a higher global average of 1.0 ± 0.1‰ relative to today, with the Southern Ocean enriched by 1.1‰ (Schrag et al., 2002; Malone et al., 2004). However, the $\delta^{18}O_{pw}$ data from the Ross Sea cores are mostly from the Last Glacial Termination, 18 to 14.5 kyr BP, with the exception of one pre-LGM data point from 35 cal kyr BP. Corrected estimates suggest that sea level was at a similar elevation (~100 meters below present) at 35 kyr and 14.5 kyr time slices (Lambeck et al., 2002; Clark et al., 2009). This may explain why $\delta^{18}O_{pw}$ values are similar between pre- and post-LGM $\delta^{18}O_{pw}$ (oxygen isotopes record an ice volume/sea level component). Unfortunately, no onboard samples were collected from the LGM (26.5 to 18 kyr BP; Clark et al., 2009). A gradual shift of $\delta^{18}O_{pw}$ from heavier to lighter values may be expected from the time interval 16 to 1.6 kyr BP, however, porewater-sediment systems are not known to preserve records of $\delta^{18}O_{sw}$ history of the ocean except for the large $\delta^{18}O_{sw}$ shifts associated with the glacial/deglacial events (Schrag and DePaolo, 1993; Schrag et al., 2002).

Seafloor morphology from Whales Deep Basin does not exhibit evidence of subglacial meltwater systems (Bart et al., submitted). The slope gullies first observed by Mosola and Anderson (2006) were originally interpreted to have been created by sediment laden subglacial meltwater release from the grounding line at the continental shelf edge. These features have been reinterpreted as sediment gravity flows according to new high resolution multibeam swath bathymetry acquired during expedition *NBP1502B* (Bart et al., submitted). Conversely, multibeam images of some western Ross Sea paleo-ice-stream troughs show evidence of subglacial meltwater systems (Greenwood et al., 2012; Halberstadt et al., 2016). This suggests

that WAIS retreat from those paleo-ice stream troughs may have been at least partly triggered by meltwater generation.

3.6 Conclusions

Rhizon extractors were used to effectively recover porewater from glacial and deglacial sediment contained in cores from the Whales Deep paleo-ice stream trough in the eastern Ross Sea. Results from $\delta^{18}O$ and δD suggest that freshwater was not present in either subglacial or glacial proximal diamict. We infer that sea-level rise was the primary cause for WAIS retreat from the outer continental shelf during the early part of the deglaciation. This interpretation agrees well with seafloor morphology, which does not indicate the existence of either subglacial or proglacial meltwater processes. Understanding the role that subglacial meltwater played in ice sheet retreat during the Last Glacial Termination is essential for determining how it may affect retreat of the modern Antarctic Ice Sheets as is occurring in the Ross Embayment and in Pine Island Bay today, and may continue into the future. It may be the meltwater generation and discharge was less important during the early deglaciation but has become more important in the latter deglacial and current interglacial. Future studies should focus on obtaining porewater samples from paleo-ice stream troughs that have morphologic evidence of subglacial meltwater drainage such as in McMurdo Sound (Greenwood et al., 2012), Pennell and JOIDES Trough (Halberstadt et al., 2016).

3.7 References

Abdul, N.A., Mortlock, R.A., Wright, J.D., and Fairbanks, R.G., 2016, Younger Dryas sea level and meltwater pulse 1B recorded in Barbados reef crest coral Acropora palmata: Paleoceanography, p. 330–344, doi: 10.1002/2015PA002847.

Adkins, J.F., McIntyre, K., and Schrag, D.P., 2002, The salinity, temperature, and delta18O of the glacial deep ocean.: Science (New York, N.Y.), v. 298, no. 5599, p. 1769–73, doi: 10.1126/science.1076252.

Adkins, J.F., and Schrag, D.P., 2003, Reconstructing Last Glacial Maximum bottom water salinities from deep-sea sediment pore fluid profiles: Earth and Planetary Science Letters, v. 216, no. 1–2, p. 109–123, doi: 10.1016/S0012-821X(03)00502-8.

Alley, R.B., 1989, Water-pressure coupling of sliding and bed deformation: I. Water system: Journal of glaciology, v. 35, no. 119, p. 108–118.

Alley, R.B., Anandakrishnan, S., Dupont, T.K., Parizek, B.R., and Pollard, D., 2007, Grounding-Line Stability: , no. March, p. 1838–1841.

Alley, R.B., Clark, P.U., Huybrechts, P., and Joughin, I., 2005, Ice-sheet and sea-level changes.: Science (New York, N.Y.), v. 310, no. 5747, p. 456–460, doi: 10.1126/science.1114613.

Anderson, R.F., Ali, S., Bradtmiller, L.I., Nielsen, S.H.H., Fleisher, M.Q., Anderson, B.E., and Burckle, L.H., 2009, Wind-driven upwelling in the Southern Ocean and the deglacial rise in atmospheric CO2.: Science (New York, N.Y.), v. 323, no. 5920, p. 1443–8, doi: 10.1126/science.1167441.

Anderson, R.F., Chase, Z., Fleisher, M.Q., and Sachs, J., 2002a, The Southern Ocean's biological pump during the Last Glacial Maximum: Deep-Sea Research Part II: Topical Studies in Oceanography, v. 49, no. 9–10, p. 1909–1938, doi: 10.1016/S0967-0645(02)00018-8.

Anderson, J.B., Conway, H., Bart, P.J., Witus, A.E., Greenwood, S.L., McKay, R.M., Hall, B.L., Ackert, R.P., Licht, K., Jakobsson, M., and Stone, J.O., 2014, Ross Sea paleo-ice sheet drainage and deglacial history during and since the LGM: Quaternary Science Reviews, v. 100, p. 31–54, doi: 10.1016/j.quascirev.2013.08.020.

Anderson, J.B., Shipp, S.S., Lowe, A.L., Wellner, J.S., and Mosola, A.B., 2002b, The Antarctic Ice Sheet during the Last Glacial Maximum and its subsequent retreat history: a review: Quaternary Science Reviews, v. 21, no. 1–3, p. 49–70, doi: 10.1016/S0277-3791(01)00083-X.

Arzeno, I.B., Beardsley, R.C., Limeburner, R., and 6, and M.J.M.W.B.O.L.P.S.R.S.C.L.S., 2014, Ocean variability contributing to basalmelt rate near the ice front of Ross Ice Shelf, Antarctica: Journal of Geophysical Research: Oceans, , no. 1, p. 9026–9032, doi: 10.1002/2014JC009792.

Bamber, J., Riva, R., Vermeersen, B., and LeBrocq, A., 2009, Reassessment of the potential sea-level rise from a collapse of the West Antarctic Ice Sheet: Science, v. 0, no. May, p. 1–3.

Bard, E., Hamelin, B., Delanghe-sabatier, D., Science, S., Series, N., Mar, N., Bard, E., Hamelin, B., and Delanghe-sabatier, D., 2010, Deglacial Meltwater Pulse 1B and Younger Dryas Sea Levels Revisited with Boreholes at Tahiti: Science, v. 327, no. 5970, p. 1235–1237.

Bart, P.J., 2004, West-directed flow of the West Antarctic Ice Sheet across Eastern Basin, Ross Sea during the Quaternary: Earth and Planetary Science Letters, v. 228, no. 3–4, p. 425–438, doi: 10.1016/j.epsl.2004.10.014.

Bart, P.J., Anderson, J.B., and Nitsche, F.O., 2017a, Post-LGM grounding-line positions of the Bindschadler Ice Stream in Ross Sea: Journal of Geophysical Research: Earth Surface, v. Submitted.

Bart, P.J., and Cone, A.N., 2012, Early stall of West Antarctic Ice Sheet advance on the eastern Ross Sea middle shelf followed by retreat at 27,50014CyrBP: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 335–336, p. 52–60, doi: 10.1016/j.palaeo.2011.08.007.

Bart, P.J., Krogmeier, B.J., Bart, M.P., and Tulaczyk, S.M., 2017b, The paradox of a two millennia grounding duration of the West Antarctic Ice Sheet in Ross Sea: Scientific reports, v. Submitted.

Bart, P.J., and Owolana, B., 2012, On the duration of West Antarctic Ice Sheet grounding events in Ross Sea during the Quaternary: Quaternary Science Reviews, v. 47, p. 101–115, doi: 10.1016/j.quascirev.2012.04.023.

Batchelor, C.L., and Dowdeswell, J.A., 2015, Ice-sheet grounding-zone wedges (GZWs) on high-latitude continental margins: Marine Geology, v. 363, p. 65–92, doi: 10.1016/j.margeo.2015.02.001.

Bentley, M.J., Ó Cofaigh, C., Anderson, J.B., Conway, H., Davies, B., Graham, A.G.C., Hillenbrand, C.-D., Hodgson, D. a., Jamieson, S.S.R., Larter, R.D., Mackintosh, A., Smith, J. a., Verleyen, E., Ackert, R.P., et al., 2014, A community-based geological reconstruction of Antarctic Ice Sheet deglaciation since the Last Glacial Maximum: Quaternary Science Reviews, v. 100, p. 1–9, doi: 10.1016/j.quascirev.2014.06.025.

Berkman, P.A., Andrews, J.T., Björck, S., Colhoun, E.A., Emslie, S.D., Goodwin, I.D., Hall, B.L., Hart, C.P., Hirakawa, K., Igarashi, A., Ingólfsson, O., López-Martínez, J., Lyons, W.B., Mabin, M.C.G., et al., 1998, Circum-Antarctic coastal environmental shifts during the Late Quaternary reflected by emerged marine deposits: Antarctic Science, v. 10, no. 3, p. 345–362, doi: 10.1017/S0954102098000406.

Berkman, P., and Forman, S., 1996, Pre-bomb radiocarbon and the reservoir correction for calcareous marine species in the Southern Ocean: Geophysical Research Letters, v. 23, no. 4, p. 363–366, doi: 10.1029/96GL00151.

Borstad, C.P., Rignot, E., Mouginot, J., and Schodlok, M.P., 2013, Creep deformation and buttressing capacity of damaged ice shelves: Theory and application to Larsen C ice shelf: Cryosphere, v. 7, no. 6, p. 1931–1947, doi: 10.5194/tc-7-1931-2013.

Carlson, A.E., and Clark, P.U., 2012a, Ice-Sheet Sources of Sea-Level Rise and Freshwater Discharge During the Last Deglaciation: Reviews of Geophysics, v. 50, no. 2011, p. 1–72, doi: doi: 10.1029/2011rg000371.

Carlson, A.E., and Clark, P.U., 2012b, Ice sheet sources of sea level rise and freshwater discharge during the last deglaciation: Reviews of Geophysics, v. 50, no. 4, p. 1–72, doi: 10.1029/2011RG000371.

Chambers, S.R., 1991, 19 . SOLUTE DISTRIBUTIONS AND STABLE ISOTOPE CHEMISTRY OF INTERSTITIAL WATERS: Proceedings of the Ocean Drilling Program, Scientific Results, v. 119, p. 375–392.

Clark, P.U., Dyke, A.S., Shakun, J.D., Carlson, A.E., Clark, J., Wohlfarth, B., Mitrovica, J.X., Hostetler, S.W., and McCabe, A.M., 2009, The Last Glacial Maximum.: Science (New York, N.Y.), v. 325, no. 5941, p. 710–714, doi: 10.1126/science.1172873.

Conway, H., Hall, B.L., Denton, G.H., Gades, A.M., and Waddington, E.D., 1999, Past and Future Grounding-Line Retreat of the West Antarctic Ice Sheet: Science (New York, N.Y.), v. 280, no. 1999, p. 280–284, doi: 10.1126/science.286.5438.280.

Domack, E.W., Jacobson, E.A., and Anderson, J.B., 1999, Late Pleistocene – Holocene retreat of the West Antarctic Ice-Sheet system in: , no. 10, p. 1517–1536.

Dowdeswell, J. a., and Fugelli, E.M.G., 2012, The seismic architecture and geometry of grounding-zone wedges formed at the marine margins of past ice sheets: Geological Society of America Bulletin, v. 124, no. 11–12, p. 1750–1761, doi: 10.1130/B30628.1.

Dowdeswell, J.A., and Pudsey, C.J., 2004, Thickness and extent of the subglacial till layer beneath an Antarctic paleo – ice stream: , no. 1, p. 13–16, doi: 10.1130/G19864.1.

Fairbanks, R.G., 1989, A 17,000-year glacio-eustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation: Nature, v. 342, no. 6250, p. 637–642, doi: 10.1038/342637a0.

Favier, L., Pattyn, F., Berger, S., and Drews, R., 2016, Dynamic influence of pinning points on marine ice-sheet stability: A numerical study in Dronning Maud Land, East Antarctica: Cryosphere, v. 10, no. 6, p. 2623–2635, doi: 10.5194/tc-10-2623-2016.

Fisher, A.T., Mankoff, K.D., Tulaczyk, S.M., and Tyler, S.W., 2015, High geothermal heat flux measured below the West Antarctic Ice Sheet: , no. July, p. 1–9.

Fogwill, C.J., Phipps, S.J., Turney, C.S.M., and Golledge, N.R., 2015, Sensitivity of the Southern Ocean to enhanced regional Antarctic ice sheet meltwater input: Earth's Future, v. 3, no. 10, p. 317–329, doi: 10.1002/2015EF000306.

Fogwill, C.J., Turney, C.S.M., Golledge, N.R., Etheridge, D.M., Rubino, M., Thornton, D.P., Baker, A., Woodward, J., Winter, K., van Ommen, T.D., Moy, A.D., Curran, M.A.J., Davies, S.M., Weber, M.E., et al., 2017, Antarctic ice sheet discharge driven by atmosphere-ocean feedbacks at the Last Glacial Termination: Scientific Reports, v. 7, no. November 2016, p. 39979, doi: 10.1038/srep39979.

Golledge, N.R., Menviel, L., Carter, L., Fogwill, C.J., England, M.H., Cortese, G., and Levy, R.H., 2014, Antarctic contribution to meltwater pulse 1A from reduced Southern Ocean overturning: Nature Communications, v. 5, no. SEPTEMBER, p. 5107, doi: 10.1038/ncomms6107.

Greenwood, S.L., Gyllencreutz, R., Jakobsson, M., and Anderson, J.B., 2012, Ice-flow switching and East/West Antarctic Ice Sheet roles in glaciation of the western Ross Sea: Bulletin of the Geological Society of America, v. 124, no. 11–12, p. 1736–1749, doi: 10.1130/B30643.1.

Halberstadt, A.R.W., Simkins, L.M., Greenwood, S.L., and Anderson, J.B., 2016, Past ice-sheet behaviour: retreat scenarios and changing controls in the Ross Sea, Antarctica: The Cryosphere, v. 10, no. 3, p. 1003–1020, doi: 10.5194/tc-10-1003-2016.

Hall, B.L., Denton, G.H., Heath, S.L., Jackson, M.S., and Koffman, T.N.B., 2015, Accumulation and marine forcing of ice dynamics in the western Ross Sea during the last deglaciation: Nature Geoscience, v. 8, no. 8, p. 625–628, doi: 10.1038/ngeo2478.

Hall, B.L., Henderson, G.M., Baroni, C., and Kellogg, T.B., 2010, Constant Holocene Southern-Ocean 14C reservoir ages and ice-shelf flow rates: Earth and Planetary Science Letters, v. 296, no. 1–2, p. 115–123, doi: 10.1016/j.epsl.2010.04.054.

Heroy, D.C., and Anderson, J.B., 2007, Radiocarbon constraints on Antarctic Peninsula Ice Sheet retreat following the Last Glacial Maximum (LGM): Quaternary Science Reviews, v. 26, no. 25–28, p. 3286–3297, doi: 10.1016/j.quascirev.2007.07.012.

Hillenbrand, C.D., Bentley, M.J., Stolldorf, T.D., Hein, A.S., Kuhn, G., Graham, A.G.C., Fogwill, C.J., Kristoffersen, Y., Smith, J.A., Anderson, J.B., Larter, R.D., Melles, M., Hodgson, D.A., Mulvaney, R., et al., 2014, Reconstruction of changes in the Weddell Sea sector of the Antarctic Ice Sheet since the Last Glacial Maximum: Quaternary Science Reviews, v. 100, p. 111–136, doi: 10.1016/j.quascirev.2013.07.020.

Hillenbrand, C.D., Smith, J.A., Kuhn, G., Esper, O., Gersonde, R., Larter, R.D., Maher, B., Moreton, S.G., Shimmield, T.M., and Korte, M., 2010, Age assignment of a diatomaceous ooze deposited in the Western Amundsen Sea embayment after the last glacial maximum: Journal of Quaternary Science, v. 25, no. 3, p. 280–295, doi: 10.1002/jqs.1308.

Hindmarsh, R.C.A., 1999, Pore-water signal of marine ice-sheets: Global and Planetary Change, v. 23, no. 1–4, p. 197–211, doi: 10.1016/S0921-8181(99)00057-0.

Horgan, H.J., Walker, R.T., Anandakrishnan, S., and Alley, R.B., 2011, Surface elevation changes at the front of the Ross Ice Shelf: Implications for basal melting: Journal of Geophysical Research: Oceans, v. 116, no. 2, p. 1–12, doi: 10.1029/2010JC006192.

Jacobs, S.S., Fairbanks, R.G., and Horibe, Y., 1985, Origin and Evolution of water masses near the antarctic continental margin (S. S. Jacobs, Ed.): Oceanography of the Antarctic Continental Shelf, v. 43, p. 59–85, doi: 10.1029/AR043.

Jacobs, S.S., Jenkins, A., Giulivi, C.F., and Dutrieux, P., 2011, Stronger ocean circulation and increased melting under Pine Island Glacier ice shelf: Nature Geoscience, v. 4, no. 8, p. 519–523, doi: 10.1038/ngeo1188.

Jakobsson, M., Anderson, J.B., Nitsche, F.O., Gyllencreutz, R., Kirshner, A.E., Kirchner, N., O'Regan, M., Mohammad, R., and Eriksson, B., 2012, Ice sheet retreat dynamics inferred from glacial morphology of the central Pine Island Bay Trough, West Antarctica: Quaternary Science Reviews, v. 38, p. 1–10, doi: 10.1016/j.quascirev.2011.12.017.

Jenkins, A., Dutrieux, P., Jacobs, S.S., McPhail, S.D., Perrett, J.R., Webb, A.T., and White, D., 2010, Observations beneath Pine Island Glacier in West Antarctica and implications for its retreat: Nature Geoscience, v. 3, no. 7, p. 468–472, doi: 10.1038/ngeo890.

Joughin, I., and Alley, R.B., 2011, Stability of the West Antarctic ice sheet in a warming world: Nature Geoscience, v. 4, no. 8, p. 506–513, doi: 10.1038/ngeo1194.

Joughin, I., Alley, R.B., and Holland, D.M., 2012, Ice-sheet response to oceanic forcing: Science, v. 338, no. 6111, p. 1172–6, doi: 10.1126/science.1226481.

Kirshner, A.E., Anderson, J.B., Jakobsson, M., O'Regan, M., Majewski, W., and Nitsche, F.O., 2012, Post-LGM deglaciation in Pine Island Bay, West Antarctica: Quaternary Science Reviews, v. 38, p. 11–26, doi: 10.1016/j.quascirev.2012.01.017.

Klages, J.P., Kuhn, G., Hillenbrand, C.D., Graham, a. G.C., Smith, J. a., Larter, R.D., Gohl, K., and Wacker, L., 2014, Retreat of the West Antarctic Ice Sheet from the western Amundsen Sea shelf at a pre- or early LGM stage: Quaternary Science Reviews, v. 91, p. 1–15, doi: 10.1016/j.quascirev.2014.02.017.

Lambeck, K., Yokoyama, Y., and Purcell, T., 2002, Into and out of the last glacial maximum: Sea-level change during oxygen isotope stages 3 and 2: Quaternary Science Reviews, v. 21, no. 1–3, p. 343–360, doi: 10.1016/S0277-3791(01)00071-3.

Licht, K.J., and Andrews, J.T., 2002, The 14 C record of late-Pleistocene ice advance and retreat in the central Ross Sea, Antarctica: Arctic, Antarctic and Alpine Research, v. 34, no. 3, p. 324–333, doi: 10.2307/1552491.

Liu, J., Milne, G.A., Kopp, R.E., Clark, P.U., and Shennan, I., 2015a, Sea-level constraints on the amplitude and source distribution of Meltwater Pulse 1A: Nature Geoscience, v. 9, no. December, p. 6–12, doi: 10.1038/ngeo2616.

Liu, Y., Moore, J.C., Cheng, X., Gladstone, R.M., Bassis, J.N., Liu, H., Wen, J., and Hui, F., 2015b, Ocean-driven thinning enhances iceberg calving and retreat of Antarctic ice shelves.: Proceedings of the National Academy of Sciences of the United States of America, v. 112, no. 11, p. 3263–8, doi: 10.1073/pnas.1415137112.

Lowe, A.L., and Anderson, J.B., 2003, Evidence for abundant subglacial meltwater beneath the paleo-ice sheet in Pine Island Bay, Antarctica: Journal of Glaciology, v. 49, no. 164, p. 125–138, doi: 10.3189/172756503781830971.

Mackintosh, A., Golledge, N., Domack, E., Dunbar, R., Leventer, A., White, D., Pollard, D., DeConto, R., Fink, D., Zwartz, D., Gore, D., and Lavoie, C., 2011, Retreat of the East Antarctic ice sheet during the last glacial termination: Nature Geoscience, v. 4, no. 3, p. 195–202, doi: 10.1038/ngeo1061.

Mackintosh, A.N., Verleyen, E., Brien, P.E.O., White, D.A., Jones, R.S., Mckay, R., Dunbar, R., Gore, D.B., Fink, D., Post, A.L., Miura, H., Leventer, A., Goodwin, I., Hodgson, D.A., et al., 2014, Retreat history of the East Antarctic Ice Sheet since the Last Glacial Maximum: Quaternary Science Reviews, v. 100, p. 10–30, doi: 10.1016/j.quascirev.2013.07.024.

Majewski, W., and Anderson, J.B., 2009, Holocene foraminiferal assemblages from Firth of Tay, Antarctic Peninsula: Paleoclimate implications: Marine Micropaleontology, v. 73, no. 3–4, p. 135–147, doi: 10.1016/j.marmicro.2009.08.003.

Malone, M.J., Martin, J.B., Scho, J., Ninnemann, U.S., Nu, D., and White, T.S., 2004, The oxygen isotopic composition and temperature of Southern Ocean bottom waters during the last glacial maximum: v. 222, p. 275–283, doi: 10.1016/j.epsl.2004.02.027.

Matsuoka, K., Hindmarsh, R.C.A., Moholdt, G., Bentley, M.J., Pritchard, H.D., Brown, J., Conway, H., Drews, R., Durand, G., Goldberg, D., Hattermann, T., Kingslake, J., Lenaerts, J.T.M., Martín, C., et al., 2015, Antarctic ice rises and rumples: Their properties and significance for ice-sheet dynamics and evolution: Earth-Science Reviews, v. 150, p. 724–745, doi: 10.1016/j.earscirev.2015.09.004.

McGlannan, A.J., Bart, P.J., Chow, J.M., and DeCesare, M., 2017, On the influence of post-LGM ice shelf loss and grounding zone sedimentation on West Antarctic Ice Sheet Stability: Marine Geology, v. Submitted.

McKay, R., Golledge, N.R., Maas, S., Naish, T., Levy, R., Dunbar, G., and Kuhn, G., 2015, Antarctic marine ice-sheet retreat in the Ross Sea during the early Holocene: Geology, v. 44, no. 1, p. 1–4, doi: 10.1130/G37315.1.

Menviel, L., Timmermann, A., Timm, O.E., and Mouchet, A., 2011, Deconstructing the Last Glacial termination: The role of millennial and orbital-scale forcings: Quaternary Science Reviews, v. 30, no. 9–10, p. 1155–1172, doi: 10.1016/j.quascirev.2011.02.005.

Millard, A., 2014, Conventions for Reporting Radiocarbon Determinations: Radiocarbon, v. 56, no. 2, p. 555–559, doi: 10.2458/56.17455.

Miller, M.D., Adkins, J.F., and Hodell, D.A., 2014, Rhizon sampler alteration of deep ocean sediment interstitial water samples, as indicated by chloride concentration and oxygen and hydrogen isotopes: Geochemistry, Geophysics, Geosystems, v. 15, no. 6, p. 2401–2413, doi: 10.1002/2014GC005308.

Mosola, A.B., and Anderson, J.B., 2006, Expansion and rapid retreat of the West Antarctic Ice Sheet in eastern Ross Sea: possible consequence of over-extended ice streams? Quaternary Science Reviews, v. 25, no. 17–18, p. 2177–2196, doi: 10.1016/j.quascirev.2005.12.013.

Nereson, N.A., and Raymond, C.F., 2001, The elevation history of ice streams and the spatial accumulation pattern along the Siple Coast of West Antarctica inferred from ground-based radar data from three inter-ice-stream ridges: Journal of glaciology, v. 47, no. 157, p. 303–313.

Peltier, W.R., and Fairbanks, R.G., 2006, Global glacial ice volume and Last Glacial Maximum duration from an extended Barbados sea level record: Quaternary Science Reviews, v. 25, no. 23–24, p. 3322–3337, doi: 10.1016/j.quascirev.2006.04.010.

Pollard, D., and DeConto, R.M., 2009, Modelling West Antarctic ice sheet growth and collapse through the past five million years.: Nature, v. 458, no. 7236, p. 329–332, doi: 10.1038/nature07809.

Pollard, D., DeConto, R.M., and Nyblade, A. a., 2005, Sensitivity of Cenozoic Antarctic ice sheet variations to geothermal heat flux: Global and Planetary Change, v. 49, no. 1–2, p. 63–74, doi: 10.1016/j.gloplacha.2005.05.003.

Pritchard, H.D., Ligtenberg, S.R.M., Fricker, H. a., Vaughan, D.G., van den Broeke, M.R., and Padman, L., 2012, Antarctic ice-sheet loss driven by basal melting of ice shelves: Nature, v. 484, no. 7395, p. 502–505, doi: 10.1038/nature10968.

Rayne, T.W., and Domack, E.W., 1996, Porewater chemistry of Ross Sea diamictons: A till or not a till: Antarctic Journal of the United States, v. 31, p. 97–98.

Reimer, P.J., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Buck, C.E., Cheng, H., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Haflidason, H., Hajdas, I., et al., 2013, IntCal13 and Marine13 Radiocarbon Age Calibration Curves 0–50,000 Years cal BP: Radiocarbon, v. 55, no. 4, p. 1869–1887, doi: 10.2458/azu_js_rc.55.16947.

Rignot, E., Jacobs, S., Mouginot, J., and Scheuchl, B., 2013, Ice-shelf melting around Antarctica.: Science, v. 341, no. 6143, p. 266–70, doi: 10.1126/science.1235798.

Rignot, E., Mouginot, J., Morlighem, M., Seroussi, H., and Scheuchl, B., 2014, Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith, and Kohler glaciers, West Antarctica, from 1992 to 2011: Geophysical Research Letters, v. 41, no. 10, p. 3502–3509, doi: 10.1002/2014GL060140.

Rosenheim, B.E., Day, M.B., and Hayes, J.M., 2008, Antarctic sediment chronology by programmed-temperature pyrolysis: Methodology and data treatment: , p. 1–16, doi: 10.1029/2007GC001816.

Schrag, D.P., Adkins, J.F., McIntyre, K., Alexander, J.L., Hodell, D. a., Charles, C.D., and McManus, J.F., 2002, The oxygen isotopic composition of seawater during the Last Glacial Maximum: Quaternary Science Reviews, v. 21, no. 1–3, p. 331–342, doi: 10.1016/S0277-3791(01)00110-X.

Schrag, D.P., and DePaolo, D.J., 1993, Determination of δ18O of Seawater in the Deep Ocean during the Last Glacial Maximum: Paleoceanography, v. 8, no. 1, p. 1–6, doi: 10.1029/92pa02796.

Schweizer, M., Bowser, S.S., Korsun, S., and Pawlowski, J., 2012, Emendation of Cibicides Antarcticus (Saidova, 1975) Based on Molecular, Morphological, and ecological Data: The Journal of Foraminiferal Research, v. 42, no. 4, p. 340–344, doi: 10.2113/gsjfr.42.4.340.

Seeberg-elverfeldt, J., and Feseker, T., 2005, OCEANOGRAPHY : METHODS Rhizon sampling of porewaters near the sediment-water interface: , p. 361–371.

Shipp, S., Anderson, J., and Domack, E., 1999, Late Pleistocene-Holocene retreat of the West Antarctic Ice-Sheet system in the Ross Sea: Part 1 - Geophysical results: Bulletin of the Geological Society of America, doi: 10.1130/0016-7606(1999)111<1486.

Siegfried, M.R., Fricker, H.A., Carter, S.P., and Tulaczyk, S., 2016, Episodic ice velocity fluctuations triggered by a subglacial flood in West Antarctica: Geophysical Research Letters, v. 43, no. 6, p. 2640–2648, doi: 10.1002/2016GL067758.

Smith, J. a., Hillenbrand, C.-D., Kuhn, G., Klages, J.P., Graham, A.G.C., Larter, R.D., Ehrmann, W., Moreton, S.G., Wiers, S., and Frederichs, T., 2014, New constraints on the timing of West Antarctic Ice Sheet retreat in the eastern Amundsen Sea since the Last Glacial Maximum: Global and Planetary Change, v. 122, p. 224–237, doi: 10.1016/j.gloplacha.2014.07.015.

Smith, J.A., Hillenbrand, C.-D., Kuhn, G., Larter, R.D., Graham, A.G.C., Ehrmann, W., Moreton, S.G., and Forwick, M., 2011, Deglacial history of the West Antarctic Ice Sheet in the western Amundsen Sea Embayment: Quaternary Science Reviews, v. 30, no. 5–6, p. 488–505, doi: 10.1016/j.quascirev.2010.11.020.

Smith, J. a., Hillenbrand, C.D., Larter, R.D., Graham, A.G.C., and Kuhn, G., 2009, The sediment infill of subglacial meltwater channels on the West Antarctic continental shelf: Quaternary Research, v. 71, no. 2, p. 190–200, doi: 10.1016/j.yqres.2008.11.005.

Stearns, L. a., Smith, B.E., and Hamilton, G.S., 2008, Increased flow speed on a large East Antarctic outlet glacier caused by subglacial floods: Nature Geoscience, v. 1, no. 12, p. 827–831, doi: 10.1038/ngeo356.

Stolldorf, T., Schenke, H., and Anderson, J.B., 2012, LGM ice sheet extent in the Weddell Sea : evidence for diachronous behavior of Antarctic Ice Sheets: Quaternary Science Reviews, v. 48, p. 20–31, doi: 10.1016/j.quascirev.2012.05.017.

Stuiver, M., Reimer, P., and Reimer, R., 2005, CALIB 7.1: [http://calib.qub.ac.uk/calib/],.

Subt, C., Fangman, K.A., Wellner, J.S., and Rosenheim, B.E., 2015, Sediment chronology in Antarctic deglacial sediments: Reconciling organic carbon 14C ages to carbonate 14C ages using Ramped PyrOx: The Holocene, doi: 10.1177/0959683615608688.

WAIS Divide Project Members, 2013, Onset of deglacial warming in West Antarctica driven by local orbital forcing.: Nature, v. 500, no. 7463, p. 440–4, doi: 10.1038/nature12376.

Webb, P.-N.P., and Strong, C.C.P., 2006, Foraminiferal biostratigraphy and palaeoecology in Upper Oligocene–Lower Miocene glacial marine sequences 9, 10, and 11, CRP-2/2A drill hole, Victoria Land Basin, Antarctica: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 231, no. 1–2, p. 71–100, doi: 10.1016/j.palaeo.2005.07.036.

Weber, M.E., Clark, P.U., Kuhn, G., Timmermann, A., Sprenk, D., Gladstone, R., Zhang, X., Lohmann, G., Menviel, L., Chikamoto, M.O., Friedrich, T., and Ohlwein, C., 2014, Millennial-scale variability in Antarctic ice-sheet discharge during the last deglaciation.: Nature, v. 510, no. 7503, p. 134–8, doi: 10.1038/nature13397.

Wycech, J., Clay Kelly, D., and Marcott, S., 2016, Effects of seafloor diagenesis on planktic foraminiferal radiocarbon ages: Geology, v. 44, no. 7, p. 551–554, doi: 10.1130/G37864.1.

Yokoyama, Y., Anderson, J.B., Yamane, M., Simkins, L.M., Miyairi, Y., Yamazaki, T., Koizumi, M., Suga, H., Kusahara, K., Prothro, L., Hasumi, H., Southon, J.R., and Ohkouchi, N., 2016, Widespread collapse of the Ross Ice Shelf during the late Holocene: Proceedings of the National Academy of Sciences, p. 201516908, doi: 10.1073/pnas.1516908113.

CHAPTER 4: A MODERN-DAY UNPINNING OF THE ROSS ICE SHELF FROM ROSS BANK: ONE DOWN, TWO TO GO

4.1 Introduction

Ice rises and rumples are formed when ice shelves ground on marine banks that terminate a few hundred meters below sea level (hundreds of meters above the surrounding deeper continental shelf). These features are pinning points that act to stabilize ice shelves by creating zones of lateral friction, providing back stress to advancing ice (Matsuoka et al., 2015). Today, there are several ice rises and additional pinning points around Antarctica. The Ross Ice Shelf – the largest ice shelf in the world – extends into the Ross Embayment, where pinning points include Crary Ice Rise, Conway Ice Ridge, Engelhardt Ice Ridge, Siple Dome, Steershead Ice Rise, Shabtie Ice Ridge, Roosevelt Island and Ross Island. The calving front of the Ross Ice Shelf is buttressed by only Roosevelt Island and Ross Island.

During the Last Glacial Maximum (LGM), 24,000 to 19,000 years ago (kyr BP) large areas of the West- and East Antarctic Ice Sheets (WAIS/EAIS) flowed into the Pacific sector of Ross Embayment and grounded at, or close to the continental shelf edge (Anderson et al., 2014). Grounded ice would have overridden all banks located on the Ross Sea outer continental shelf (Figure 4.1) (Shipp et al., 1999). Ice shelves were probably non-existent and/or significantly smaller during the LGM. As grounding lines retreated, ice shelves would have formed with floating ice anchored to the topographic highs on the outer continental shelf (Shipp et al, 1999; Domack et al., 1999; Bart et al., 2016). When ice shelves were grounded on these outer shelf banks, paleo-ice rises would have formed and these would have partly reduced ice sheet discharge (Shipp et al., 1999; Clark et al., 2009; Anderson et al., 2014; McKay et al., 2015;

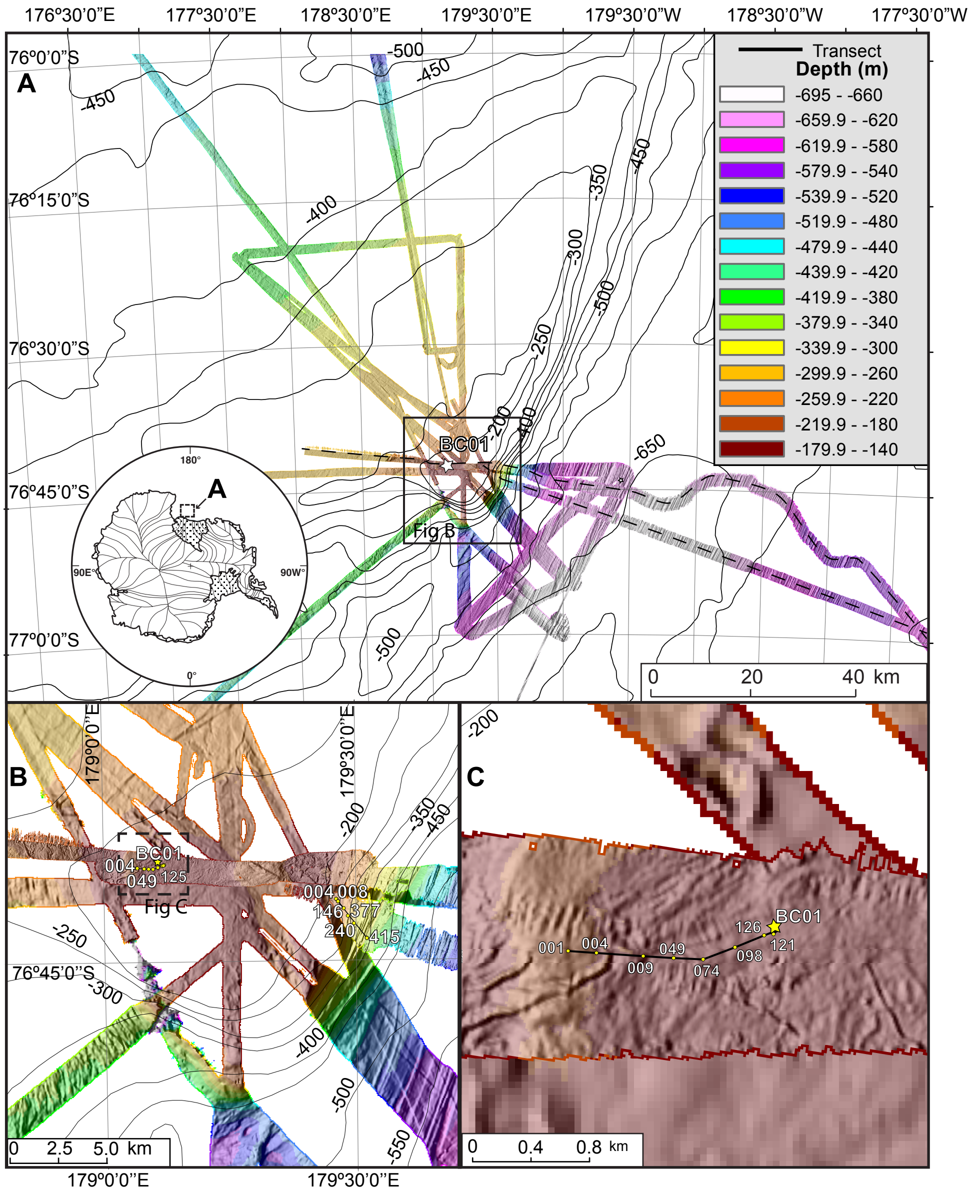

Figure 4.1: Map showing Ross Bank bathymetry, locations of core photos and location of BC01. (inset) Antarctica, showing the location Ross Bank (dashed box). A Ross Bank bathymetric map showing several transects including that of NBP1502 (dashed line). B Locations of yo-yo camera photos on the crest (Figure 4.3A) and flank (Figure 4.3 B–D) of Ross Bank (Figure A.4). C Close-up of NBP1502 swath bathymetry showing the paucity of iceberg scouring, location of BC01 and yo-yo camera photos.

Halberstadt et al., 2016). The timing of the grounding-line and calving-front retreat from these pinning points is not well established. Retreat from the outer continental shelf began in either the late Pleistocene or early Holocene (Domack et al., 1999; Licht and Andrews, 2002; Bart and

Cone, 2012). Further inland, the onset of marine sedimentation around Ross Island in western Ross sea has been constrained to ~8.6 kyr BP using foraminiferal radiocarbon dates (McKay et al., 2015). In eastern Ross Sea, the West Antarctic Ice Sheet (WAIS) grounding line retreated from Roosevelt Island and Siple Dome much later, around 3 kyr BP (Conway et al., 1999; Nereson and Raymond, 2001). Today, the calving front of the Ross Ice Shelf is pinned at Ross Island and Roosevelt Island (Greenwood et al., 2012; Matsuoka et al., 2015). Bathymetry data shows that the crest of Ross Bank rises to above 200 meters below sea level (mbsl). Roosevelt Island has a similar elevation (Conway et al., 1999). These observations strongly suggest that Ross Bank must have acted as a significant pinning point before the calving front moved an additional 100 km to the south, to its modern position.

Understanding the susceptibility of the Ross Ice Shelf to further retreat is essential for assessing its stability. This is important as the WAIS contains ~3.3 meters of sea-level equivalent ice volume and is currently undergoing deglaciation (Bamber et al., 2009; Jenkins et al., 2010; Jacobs et al., 2011). Ice dynamic models suggest that ocean warming may lead to massive deglaciation causing melting and retreat of the WAIS in the Ross Sea (Pritchard et al., 2012; Fogwill et al., 2015). During USAP Expedition *NBP1502B* aboard the *RVIB Nathaniel B Palmer* during the austral summer of 2015, we collected more than 100 photographs and video of the seafloor at the crest and steep flanks of Ross Bank. These new images show that abundant benthic life inhabits Ross Bank. Here we show fourteen radiocarbon ages from both well- and poorly-preserved fossil carbonate collected from box-core sediment draping Ross Bank. The dates cluster in a narrow, nearly modern range. This constrains the minimum time for which the Ross Ice Shelf has decoupled from Ross Bank.

4.2 Background

During tests of a yo-yo camera and video system at Ross Bank, we were surprised to observe abundant benthos inhabiting a 1 km-long transect (Figure 4.2). Based on the abundance of benthos, we hypothesize that the oldest fossil carbonate in these sediments reflects the earliest time at which the Ross Ice Shelf unpinned from the crest of Ross Bank. To test this hypothesis,

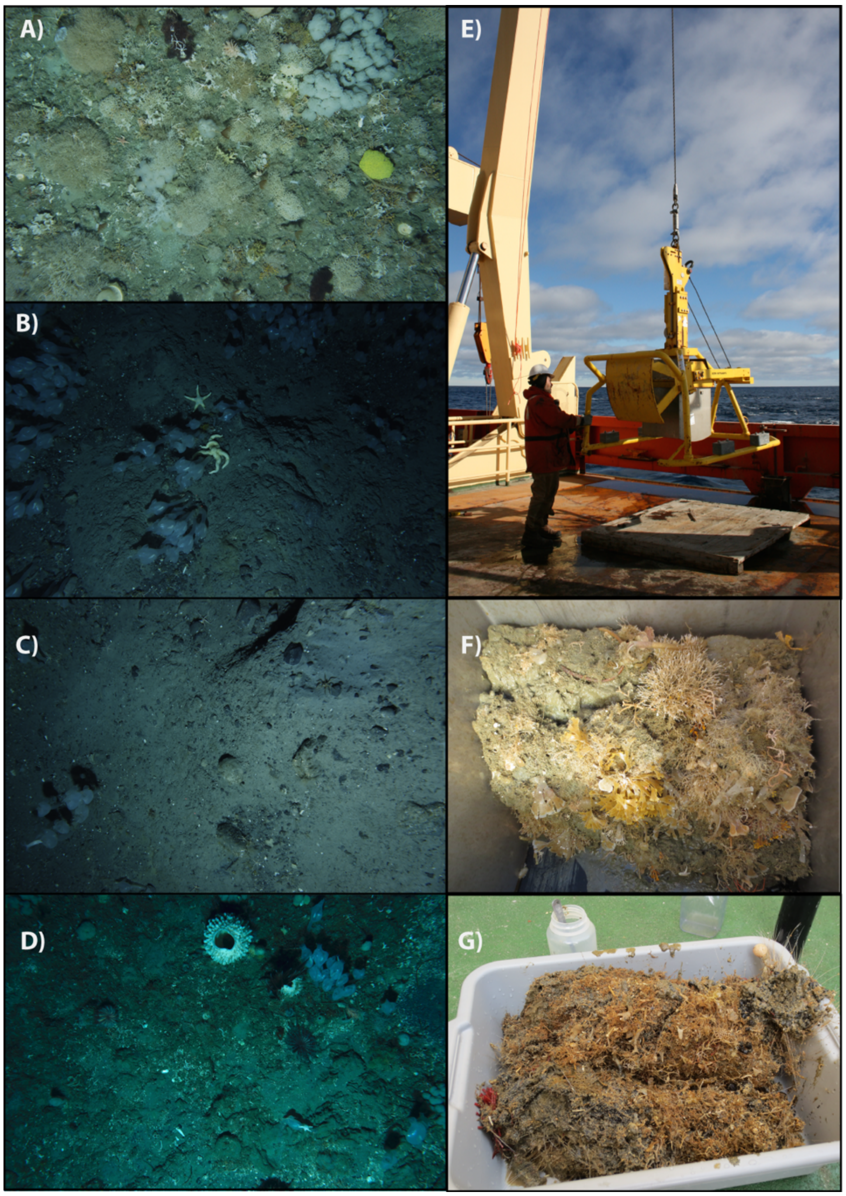

Figure 4.2: Yo-yo camera photographs of Ross Bank crest. **A)** site of BC01 at 174 (180?) mbsl, **B–D)** rock outcrops suggesting that only a thin sediment deposit on the crest of Ross Bank. **E)** Retrieved BC01 core, **F)** BC01 sediment, **G)** top sample of BC01.

we attempted to obtain sediment from the crest of Ross Bank using two different coring techniques. A piston core failed to recover any sediment, indicating that sediment cover is thin over the lithified middle Miocene strata that are known to outcrop on the flanks of the bank (Bart, 2004). A large box core (BC01) recovered ~30 cm sediment at a water depth of 174 mbsl (Figure 4.1). Calcareous fossils including corals, bivalves, gastropods and foraminifera are abundant in the box core.

4.3 Methods

Sediment from BC01 was collected and separated into three layers: the top, middle and bottom. These ~10 cm thick parcels of sediment were then placed into 1-gallon zip lock freezer bags and cold-archived at 4°C onboard the *RVIB Nathaniel B Palmer*. Sediment was washed through 150 and 63 µm sieves to remove sponge spicules and the fine sediment fraction. Sediment was then dry-sieved to isolate calcareous fossil shells. The sieved sediment was observed under a binocular light-microscope and specimens were picked using a fine artist brush dampened with DI water. Abundant specimens of bivalves were obtained from >800 µm size fraction and foraminifera were collected from >425 µm size fraction.

A total of fourteen samples were sent to the Woods Hole Oceanographic Institute to be analyzed for radiocarbon ages on the National Ocean Sciences Accelerator Mass Spectrometer (NOSAMS). Five monospecific benthic foraminifera samples (*E. glabra* or *C. antarcticus;* Table 4.1) were taken from the top layer and of these, two samples exhibited poor-preservation (Appendix figure A.3). Two bivalve specimens were taken from the top layer, one of which was poorly preserved. Five additional benthic foraminifera samples were taken from the bottom layer. Two of these specimens were poorly preserved whereas the other three were well

preserved. Two bivalve specimens were taken from the bottom layer as well, one of which was poorly preserved. Poorly preserved samples were analyzed in an attempt to date the oldest material present on the bank and to investigate whether these samples might include specimens reworked from the older Miocene strata underlying the bank as indicated from seismic correlations to DSPD Leg 28 drill sites in Glomar Challenger Basin (Hayes and Frakes, 1975). Foraminifera were collected until each sample mass exceeded 5 mg of carbonate and then sonicated in DI water before shipment to NOSAMS. A fraction of bivalve shell halves were used as samples for radiocarbon dating.

Table 4.1: Uncalibrated and calibrated radiocarbon ages from BC01 samples. Poorly preserved samples are labeled and highlighted in red. 14C ages are uncalibrated. Calibrated ages are presented using three marine reservoir ages: ΔR=900 is from the general Southern Ocean (Berkman and Forman, 1996), ΔR=821 is from Roosevelt Island (Berkman and Forman, 1996), and ΔR=791 is from McMurdo Sound (Hall et al., 2010).

				Reservoir effects					
				Southern Ocean		Roosevelt Island		McMurdo	
Sediment sample	carbonate type	preservation state	uncorrected 14C age	age range ΔR=900	median age ΔR=900	age range ΔR=821	median ΔR=821	age range ΔR=791	median ΔR=791
Top	Foraminifera		1200						
Top	Foraminifera		1230						
Top	Foraminifera		1270			0 - 229	88	0 - 334	143
Top	Foraminifera	poor	1340			0 - 259	146	0 - 401	186
Top	Foraminifera	poor	1340			1 - 259	147	0 - 401	187
Top	Bivalve		1110						
Top	Bivalve	poor	1310			0 - 244	118	0 - 379	166
Bottom	Foraminifera		1280			0 - 232	94	0 - 337	148
Bottom	Foraminifera		1310			0 - 244	118	0 - 379	166
Bottom	Foraminifera		1320			0 - 249	127	0 - 387	173
Bottom	Foraminifera	poor	1500	40 - 416	229	222 - 467	333	61 - 536	342
Bottom	Foraminifera	poor	1550	57 - 478	289	267 - 482	372	131 - 608	384
Bottom	Bivalve	poor	1230						
Bottom	Bivalve		1250					0 - 318	132

Radiocarbon ages were calibrated to calendar years before present (cal kyr BP) using MARINE13 calibration curve in CALIB 7.1 (Stuiver et al., 2005; Reimer et al., 2013). Three marine reservoir values were selected among the values established for the Southern Ocean. The first is the general marine reservoir effect for the Southern Ocean used in paleoceanographic

research of the Antarctic proximal Southern Ocean. The two other values are established from marine invertebrates from the Ross Sea. Each of these three marine reservoir effects were used to calibrate all fourteen radiocarbon samples presented here yielding three suites of age ranges. The largest marine reservoir effect was established for Antarctic marine carbonates in the regional Southern Ocean represented by 1,300±100 years (differing by 900 years from the global average reservoir age of 400 years; ΔR=900: delta R is the difference between local and the global reservoir effect) (Berkman and Forman, 1996; Anderson et al., 2002b). A second is derived from pre-bomb mollusk shells from the eastern Ross Sea near Roosevelt Island at 490 m depth (Latitude, -164.3300; Longitude, -78.5000) with a reservoir age of 1,122 ±62 (ΔR= 821 years; Berkman and Forman, 1996). A third correction is derived from solitary corals near McMurdo Sound/McMurdo Ice shelf which is most proximal to the Ross Bank and yielded a reservoir age of 1,144 ±120 years (ΔR= 791 years; Hall et al., 2010). These data were selected among numerous published calibrations because they are specifically from calcareous invertebrates in the Ross Sea. A compilation of radiocarbon dates from a variety of biological sources show significant variability suggesting a biological control (Berkman et al., 1998). Other reservoir age values were excluded because they are from the greater Southern Ocean and/or penguin and seal bones (Berkman et al., 1998). All radiocarbon dates presented here are reported as an age range, which represents the 95% confidence interval in 'cal yr BP' notation (Millard, 2014) (Table 4.1).

4.4 Results:

4.4.1 Benthic foraminifera and bivalves on Ross Bank

The most abundant benthic foraminifera species were *Ehrenbergina glabra* and *Cibicides antarcticus* (also known as *C. refulgens* or *C. lobatulus* but is now considered genetically

distinct; Schweizer et al., 2012). The upper-most layer is comprised of pelagic ooze with abundant coral, sponge spicules, foraminifera, bivalves and gastropods (Appendix Figure A.3). The middle and bottom sedimentary layers did not contain abundant corals and contained a higher abundance of less well-preserved foraminifera. In particular, foraminifera tests exhibit some sediment infill and an oxidative veneer (brown-orange coloration to the shell). The middle and bottom layers are essentially indistinguishable in regard to sedimentology and fossil content. Therefore, specimens from only the top and bottom sediment layers were picked for foraminifera and bivalves for radiocarbon dating.

4.4.2 Radiocarbon dates from Ross Bank

Uncorrected radiocarbon ages range from 1,110 to 1,550 radiocarbon years (^{14}C yrs; Table 4.1). From the top layer, foraminiferal radiocarbon ages range from 1,200 to 1,340 ^{14}C yrs averaging 1,276 ^{14}C yrs, $\sigma = 56.8$ whereas the two radiocarbon ages from bivalve shells are 1,110 and 1,310 ^{14}C yrs. Foraminiferal ages from the bottom layer range from 1,280 to 1,550 ^{14}C yrs, averaging 1,392 ^{14}C yrs, $\sigma = 110.5$. The two bivalve ages from the bottom layer are 1,230 and 1,250 ^{14}C yrs.

Using the general Southern Ocean reservoir age of 1,300 ±100 years, only two of the radiocarbon ages could be calibrated because their uncorrected ages are younger – removing the reservoir age would yield negative values (Berkman and Forman, 1996). The two calibrated ages are from the two poorly preserved foraminifera samples from the bottom layer sediment (Table 4.1). The 1,500 ^{14}C yr sample yielded a calibrated age range age of 40 to 416 cal yr BP with a median age of 229 cal yr BP. The 1,550 ^{14}C yr sample yielded a calibrated age range age of 57 to 478 cal yr BP with a median age of 289 cal yr BP.

Local reservoir age calibrations from Roosevelt Island and McMurdo Sound yielded a slightly broader suite of calibrated ages of the Ross Bank samples (Table 4.1). This is because the marine reservoir effect for Roosevelt Island (ΔR= 821 ± 62 years) and McMurdo Sound samples (ΔR= 791 ± 121 years) are less than the general Southern Ocean calibration (ΔR= 900 ± 100 years). The Roosevelt Island calibration yielded a total age range of 0 to 480 cal yr BP. Using the McMurdo Sound/Ice shelf correction, calibrated age ranges span 0 to 610 cal yr BP. Values of 0 in these instances represent ages relative to 1950.

4.5 Discussion: Modern unpinning of the Ross Ice Shelf from the crest of Ross Bank

The calibrated radiocarbon dates from Ross Bank carbonates suggest that foraminifera and bivalves were living in sediment that accumulated since 600 years ago (the oldest and age of the 95% confidence interval respectively; Table 4.1). The calibrated ages of the most poorly preserved samples from the bottom sediment are taken to represent the oldest interval of open-water environmental conditions at the site (Figure 4.2). The radiocarbon ages suggest that these foraminifera and bivalves inhabited sediment that was deposited very recently with respect to the Last Glacial Termination. Radiocarbon ages for modern carbonate that calcified during or after the 1950s could be contaminated by excess ^{14}C released into the atmosphere during extensive nuclear bomb testing. If these organisms had calcified in post-1950s Southern Ocean waters, then their ^{14}C values would have been driven towards relatively younger ages (Berkman et al., 1998). Post-bomb carbonate from invertebrate samples from the Antarctic Southern Ocean yielded uncalibrated ages of 901 ± 227 ^{14}C years (Berkman et al., 1998). This would make the 1,300-year correction inappropriate for any sample in our study that formed post-bomb. However, the average of the uncalibrated radiocarbon ages from Ross Bank is 1,260 ± 109 ^{14}C

years, which is very close to the published pre-bomb uncalibrated ^{14}C ages (1,122 and 1,144 yeas) from Antarctic-proximal carbonate samples suggesting that the Ross Bank samples were alive pre-1950 (Berkman and Forman, 1996; Berkman et al., 1998; Hall et al., 2010).

If the poorly preserved specimens were reworked from significantly older sediments by bioturbation and/or iceberg turbation, then their ages would likely significantly diverge from the well-preserved ages. This is not the case. The ages from foraminifera samples were derived from multiple tests and they are similar to the bivalve ages which were derived from single shells. The bivalve ages suggest that (at the location of BC01) Ross Bank was not significantly affected by reworking during the time interval represented by the box cored sediment. Instead, the age ranges indicate that the box cored sediment column is characterized by a relatively young homogenous sediment profile.

The homogeneity of the sediment and the fact that our attempt to piston core was not successful in recovering sediment (it bounced off underlying lithified sediment likely after blowing away the thin draped Holocene sediments) suggests that BC01 obtained nearly the entire thickness of sediment draping this part of Ross Bank. In addition, photo and video from the Ross Bank crest show rock outcrops, suggesting that only a thin veneer of sediment covers the area (Figure A.3). Furthermore, the absence of any dense network of ice berg furrows (Figure 4.1) suggests that this site has not been exposed to ice berg scouring for long and hence, the sediment recovered from BC01 has probably not been significantly disturbed since its deposition. Deeper seafloor banks on the outer continental shelf that were exposed early during the deglaciation are pervasively furrowed (e.g., Bart et al., submitted).

The large area of Ross Bank indicates that the Ross Ice Shelf acted as a central pinning point with Roosevelt Island serving as the eastern pinning point and Ross Island as the western.

The recent unpinning of the Ross Ice Shelf from Ross Bank decreased the number of pinning points by one sometime within the last 600 years. Evidence for this scenario is provided by sedimentology, radiocarbon ages, and seismic and photographic images. At present, the calving front is ~100 km south of Ross Bank. A reconstruction of the calving front to the north of Ross Bank opens the possibility that Franklin and Beauford Islands may have also acted as pinning points up until recently. These results have important implications for the future of the Ross Ice Shelf, Antarctic Ice Sheet stability and global sea-level rise.

It is not known why the ice shelf unpinned from Ross Bank but ice shelf thickness at the calving front must have since changed. Given the time of unpinning, sea-level rise could not have been a contributing factor. The Ross Ice Shelf currently reaches a depth of ~220 mbsl near its calving line which is ~50 k from Ross Bank (Arzeno et al., 2014). When the Ross Ice Shelf was last grounded on the crest of Ross Bank (i.e., prior to unpinning) it would have been thinner by at least 50 metes (given its 170 meters depth below sea level). This suggests the ice shelf may have decoupled by melting ablation or calving and its thickness below sea level has since increased by ~50 meters. Thinning at the ice shelf edge may have been associated with upstream stagnation. In all possible scenarios, once decoupled from Ross Bank, upstream ice shelf flow should have accelerated. Thickening may have been a result of accelerated ice shelf flow more quickly transporting thicker inland ice to the calving front. Conversely, the loss of buttress may have caused thinning by accelerated flow. The transition to unbuttressed ice-shelf flow may have caused thinning due to an increased contact patch open to the Ross Sea, as well as through the loss of backstress provided by ice-rises, weakening the sheet (Horgan et al., 2011; Borstad et al., 2013). Modeling of other Antarctic ice shelves predicts ice-stream acceleration at the grounding line and calving front retreat on the order of hundreds of meters per year upon initial ice-shelf

decoupling event (Favier et al., 2016). Conversely, sub-ice shelf freeze on and/or surface accumulation may have played a role in thickening the ice shelf at the calving front since unpinning at Ross Bank (Figure 4.3). Measurements show that the modern (2003-2009) Ross Ice Shelf is thickening at the calving front near Ross Bank from surface accumulation at the rate of ~0.03 ± 0.03 m/year (Pritchard et al., 2012) with overall thickening at the calving front (Liu et al., 2015b) of > 1 m/year (Rignot et al., 2013). Net accumulation rates of 0.08 m/year over the

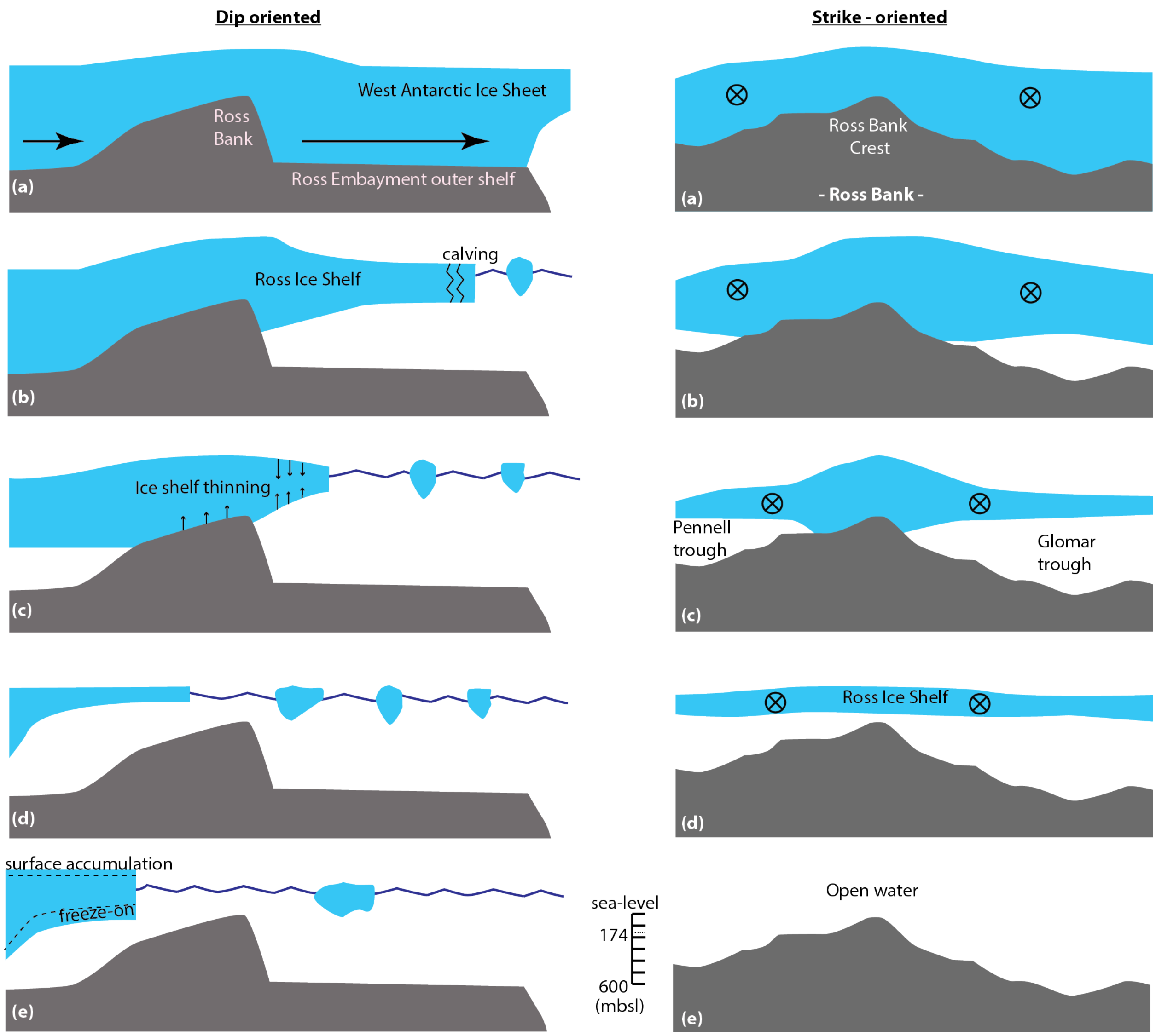

Figure 4.3: WAIS retreat model with a profile view on the left and cross-section view on the right. **a)** WAIS configuration during the Last Glacial Maximum, **b** and **c)** grounding line retreat during the Last Glacial Termination forms the Ross Ice Shelf and an ice rise forms on Ross Bank, **d)** the ice shelf decoupled from Ross Bank 200 ± 200 cal yr BP, **e)** the ice shelf thickens by sub ice shelf freeze-on and surface accumulation.

last 600 years would equate to the sufficient mass needed to reach modern ice shelf thickness at the calving front. If we use the mean of the two oldest radiocarbon ages, 324 cal yr BP, net accumulation rate would need to be at least 0.14 m/year which is also a plausible scenario.

4.6 Conclusions

The rapid retreat of Thwaites and Pine Island Glacier occurred in part because their ice shelves became unpinned from local marine banks (Jenkins et al., 2010; Rignot et al., 2014). The driving mechanism for the thinning and decoupling of the WAIS in this region is the warming of water under the ice sheet and grounding line retreat. Today, the Ross Ice Shelf is also undergoing melting (Horgan et al., 2011; Pritchard et al., 2012; Rignot et al., 2013) and this may have played a key role in unpinning at Ross Bank. Higher water temperatures and increasing melt rate are problematic for the future of the Ross Ice Shelf and Ross Sea sector of the WAIS. If the Amundsen Sea sector of the WAIS has passed its threshold for stability, collapse there could introduce massive volumes of freshwater into the surface ocean causing a drastic decrease in Antarctic Bottom Water production (Joughin and Alley, 2011). This reduction of bottom water production would enhance ocean stratification and promote warm water intrusion onto the Antarctic continental shelf, potentially producing warming in the Ross Sea by 0.5 to >1ºC (Fogwill et al., 2015). Warming of this magnitude could cause a significant shift to widespread melting which would further thin the Ross Ice Shelf and possibly trigger unpinning from Roosevelt Island and the other pinning points on the interior parts of the Ross Ice Shelf.

4.7 References

Abdul, N.A., Mortlock, R.A., Wright, J.D., and Fairbanks, R.G., 2016, Younger Dryas sea level and meltwater pulse 1B recorded in Barbados reef crest coral Acropora palmata: Paleoceanography, p. 330–344, doi: 10.1002/2015PA002847.

Adkins, J.F., McIntyre, K., and Schrag, D.P., 2002, The salinity, temperature, and delta18O of the glacial deep ocean.: Science (New York, N.Y.), v. 298, no. 5599, p. 1769–73, doi: 10.1126/science.1076252.

Adkins, J.F., and Schrag, D.P., 2003, Reconstructing Last Glacial Maximum bottom water salinities from deep-sea sediment pore fluid profiles: Earth and Planetary Science Letters, v. 216, no. 1–2, p. 109–123, doi: 10.1016/S0012-821X(03)00502-8.

Alley, R.B., 1989, Water-pressure coupling of sliding and bed deformation: I. Water system: Journal of glaciology, v. 35, no. 119, p. 108–118.

Alley, R.B., Anandakrishnan, S., Dupont, T.K., Parizek, B.R., and Pollard, D., 2007, Grounding-Line Stability: , no. March, p. 1838–1841.

Alley, R.B., Clark, P.U., Huybrechts, P., and Joughin, I., 2005, Ice-sheet and sea-level changes.: Science (New York, N.Y.), v. 310, no. 5747, p. 456–460, doi: 10.1126/science.1114613.

Anderson, R.F., Ali, S., Bradtmiller, L.I., Nielsen, S.H.H., Fleisher, M.Q., Anderson, B.E., and Burckle, L.H., 2009, Wind-driven upwelling in the Southern Ocean and the deglacial rise in atmospheric CO2.: Science (New York, N.Y.), v. 323, no. 5920, p. 1443–8, doi: 10.1126/science.1167441.

Anderson, R.F., Chase, Z., Fleisher, M.Q., and Sachs, J., 2002a, The Southern Ocean's biological pump during the Last Glacial Maximum: Deep-Sea Research Part II: Topical Studies in Oceanography, v. 49, no. 9–10, p. 1909–1938, doi: 10.1016/S0967-0645(02)00018-8.

Anderson, J.B., Conway, H., Bart, P.J., Witus, A.E., Greenwood, S.L., McKay, R.M., Hall, B.L., Ackert, R.P., Licht, K., Jakobsson, M., and Stone, J.O., 2014, Ross Sea paleo-ice sheet drainage and deglacial history during and since the LGM: Quaternary Science Reviews, v. 100, p. 31–54, doi: 10.1016/j.quascirev.2013.08.020.

Anderson, J.B., Shipp, S.S., Lowe, A.L., Wellner, J.S., and Mosola, A.B., 2002b, The Antarctic Ice Sheet during the Last Glacial Maximum and its subsequent retreat history: a review: Quaternary Science Reviews, v. 21, no. 1–3, p. 49–70, doi: 10.1016/S0277-3791(01)00083-X.

Arzeno, I.B., Beardsley, R.C., Limeburner, R., and 6, and M.J.M.W.B.O.L.P.S.R.S.C.L.S., 2014, Ocean variability contributing to basalmelt rate near the ice front of Ross Ice Shelf,

Antarctica: Journal of Geophysical Research: Oceans, , no. 1, p. 9026–9032, doi: 10.1002/2014JC009792.

Bamber, J., Riva, R., Vermeersen, B., and LeBrocq, A., 2009, Reassessment of the potential sea-level rise from a collapse of the West Antarctic Ice Sheet: Science, v. 0, no. May, p. 1–3.

Bard, E., Hamelin, B., Delanghe-sabatier, D., Science, S., Series, N., Mar, N., Bard, E., Hamelin, B., and Delanghe-sabatier, D., 2010, Deglacial Meltwater Pulse 1B and Younger Dryas Sea Levels Revisited with Boreholes at Tahiti: Science, v. 327, no. 5970, p. 1235–1237.

Bart, P.J., 2004, West-directed flow of the West Antarctic Ice Sheet across Eastern Basin, Ross Sea during the Quaternary: Earth and Planetary Science Letters, v. 228, no. 3–4, p. 425–438, doi: 10.1016/j.epsl.2004.10.014.

Bart, P.J., Anderson, J.B., and Nitsche, F.O., 2017a, Post-LGM grounding-line positions of the Bindschadler Ice Stream in Ross Sea: Journal of Geophysical Research: Earth Surface, v. Submitted.

Bart, P.J., and Cone, A.N., 2012, Early stall of West Antarctic Ice Sheet advance on the eastern Ross Sea middle shelf followed by retreat at 27,50014CyrBP: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 335–336, p. 52–60, doi: 10.1016/j.palaeo.2011.08.007.

Bart, P.J., Krogmeier, B.J., Bart, M.P., and Tulaczyk, S.M., 2017b, The paradox of a two millennia grounding duration of the West Antarctic Ice Sheet in Ross Sea: Scientific reports, v. Submitted.

Bart, P.J., and Owolana, B., 2012, On the duration of West Antarctic Ice Sheet grounding events in Ross Sea during the Quaternary: Quaternary Science Reviews, v. 47, p. 101–115, doi: 10.1016/j.quascirev.2012.04.023.

Batchelor, C.L., and Dowdeswell, J.A., 2015, Ice-sheet grounding-zone wedges (GZWs) on high-latitude continental margins: Marine Geology, v. 363, p. 65–92, doi: 10.1016/j.margeo.2015.02.001.

Bentley, M.J., Ó Cofaigh, C., Anderson, J.B., Conway, H., Davies, B., Graham, A.G.C., Hillenbrand, C.-D., Hodgson, D. a., Jamieson, S.S.R., Larter, R.D., Mackintosh, A., Smith, J. a., Verleyen, E., Ackert, R.P., et al., 2014, A community-based geological reconstruction of Antarctic Ice Sheet deglaciation since the Last Glacial Maximum: Quaternary Science Reviews, v. 100, p. 1–9, doi: 10.1016/j.quascirev.2014.06.025.

Berkman, P.A., Andrews, J.T., Björck, S., Colhoun, E.A., Emslie, S.D., Goodwin, I.D., Hall, B.L., Hart, C.P., Hirakawa, K., Igarashi, A., Ingólfsson, O., López-Martínez, J., Lyons, W.B., Mabin, M.C.G., et al., 1998, Circum-Antarctic coastal environmental shifts during the Late Quaternary reflected by emerged marine deposits: Antarctic Science, v. 10, no. 3, p. 345–362, doi: 10.1017/S0954102098000406.

Berkman, P., and Forman, S., 1996, Pre-bomb radiocarbon and the reservoir correction for calcareous marine species in the Southern Ocean: Geophysical Research Letters, v. 23, no. 4, p. 363–366, doi: 10.1029/96GL00151.

Borstad, C.P., Rignot, E., Mouginot, J., and Schodlok, M.P., 2013, Creep deformation and buttressing capacity of damaged ice shelves: Theory and application to Larsen C ice shelf: Cryosphere, v. 7, no. 6, p. 1931–1947, doi: 10.5194/tc-7-1931-2013.

Carlson, A.E., and Clark, P.U., 2012a, Ice-Sheet Sources of Sea-Level Rise and Freshwater Discharge During the Last Deglaciation: Reviews of Geophysics, v. 50, no. 2011, p. 1–72, doi: doi: 10.1029/2011rg000371.

Carlson, A.E., and Clark, P.U., 2012b, Ice sheet sources of sea level rise and freshwater discharge during the last deglaciation: Reviews of Geophysics, v. 50, no. 4, p. 1–72, doi: 10.1029/2011RG000371.

Chambers, S.R., 1991, 19 . SOLUTE DISTRIBUTIONS AND STABLE ISOTOPE CHEMISTRY OF INTERSTITIAL WATERS: Proceedings of the Ocean Drilling Program, Scientific Results, v. 119, p. 375–392.

Clark, P.U., Dyke, A.S., Shakun, J.D., Carlson, A.E., Clark, J., Wohlfarth, B., Mitrovica, J.X., Hostetler, S.W., and McCabe, A.M., 2009, The Last Glacial Maximum.: Science (New York, N.Y.), v. 325, no. 5941, p. 710–714, doi: 10.1126/science.1172873.

Conway, H., Hall, B.L., Denton, G.H., Gades, A.M., and Waddington, E.D., 1999, Past and Future Grounding-Line Retreat of the West Antarctic Ice Sheet: Science (New York, N.Y.), v. 280, no. 1999, p. 280–284, doi: 10.1126/science.286.5438.280.

Domack, E.W., Jacobson, E.A., and Anderson, J.B., 1999, Late Pleistocene – Holocene retreat of the West Antarctic Ice-Sheet system in: , no. 10, p. 1517–1536.

Dowdeswell, J. a., and Fugelli, E.M.G., 2012, The seismic architecture and geometry of grounding-zone wedges formed at the marine margins of past ice sheets: Geological Society of America Bulletin, v. 124, no. 11–12, p. 1750–1761, doi: 10.1130/B30628.1.

Dowdeswell, J.A., and Pudsey, C.J., 2004, Thickness and extent of the subglacial till layer beneath an Antarctic paleo – ice stream: , no. 1, p. 13–16, doi: 10.1130/G19864.1.

Fairbanks, R.G., 1989, A 17,000-year glacio-eustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation: Nature, v. 342, no. 6250, p. 637–642, doi: 10.1038/342637a0.

Favier, L., Pattyn, F., Berger, S., and Drews, R., 2016, Dynamic influence of pinning points on marine ice-sheet stability: A numerical study in Dronning Maud Land, East Antarctica: Cryosphere, v. 10, no. 6, p. 2623–2635, doi: 10.5194/tc-10-2623-2016.

Fisher, A.T., Mankoff, K.D., Tulaczyk, S.M., and Tyler, S.W., 2015, High geothermal heat flux measured below the West Antarctic Ice Sheet: , no. July, p. 1–9.

Fogwill, C.J., Phipps, S.J., Turney, C.S.M., and Golledge, N.R., 2015, Sensitivity of the Southern Ocean to enhanced regional Antarctic ice sheet meltwater input: Earth's Future, v. 3, no. 10, p. 317–329, doi: 10.1002/2015EF000306.

Fogwill, C.J., Turney, C.S.M., Golledge, N.R., Etheridge, D.M., Rubino, M., Thornton, D.P., Baker, A., Woodward, J., Winter, K., van Ommen, T.D., Moy, A.D., Curran, M.A.J., Davies, S.M., Weber, M.E., et al., 2017, Antarctic ice sheet discharge driven by atmosphere-ocean feedbacks at the Last Glacial Termination: Scientific Reports, v. 7, no. November 2016, p. 39979, doi: 10.1038/srep39979.

Golledge, N.R., Menviel, L., Carter, L., Fogwill, C.J., England, M.H., Cortese, G., and Levy, R.H., 2014, Antarctic contribution to meltwater pulse 1A from reduced Southern Ocean overturning: Nature Communications, v. 5, no. SEPTEMBER, p. 5107, doi: 10.1038/ncomms6107.

Greenwood, S.L., Gyllencreutz, R., Jakobsson, M., and Anderson, J.B., 2012, Ice-flow switching and East/West Antarctic Ice Sheet roles in glaciation of the western Ross Sea: Bulletin of the Geological Society of America, v. 124, no. 11–12, p. 1736–1749, doi: 10.1130/B30643.1.

Halberstadt, A.R.W., Simkins, L.M., Greenwood, S.L., and Anderson, J.B., 2016, Past ice-sheet behaviour: retreat scenarios and changing controls in the Ross Sea, Antarctica: The Cryosphere, v. 10, no. 3, p. 1003–1020, doi: 10.5194/tc-10-1003-2016.

Hall, B.L., Denton, G.H., Heath, S.L., Jackson, M.S., and Koffman, T.N.B., 2015, Accumulation and marine forcing of ice dynamics in the western Ross Sea during the last deglaciation: Nature Geoscience, v. 8, no. 8, p. 625–628, doi: 10.1038/ngeo2478.

Hall, B.L., Henderson, G.M., Baroni, C., and Kellogg, T.B., 2010, Constant Holocene Southern-Ocean 14C reservoir ages and ice-shelf flow rates: Earth and Planetary Science Letters, v. 296, no. 1–2, p. 115–123, doi: 10.1016/j.epsl.2010.04.054.

Heroy, D.C., and Anderson, J.B., 2007, Radiocarbon constraints on Antarctic Peninsula Ice Sheet retreat following the Last Glacial Maximum (LGM): Quaternary Science Reviews, v. 26, no. 25–28, p. 3286–3297, doi: 10.1016/j.quascirev.2007.07.012.

Hillenbrand, C.D., Bentley, M.J., Stolldorf, T.D., Hein, A.S., Kuhn, G., Graham, A.G.C., Fogwill, C.J., Kristoffersen, Y., Smith, J.A., Anderson, J.B., Larter, R.D., Melles, M., Hodgson, D.A., Mulvaney, R., et al., 2014, Reconstruction of changes in the Weddell Sea sector of the Antarctic Ice Sheet since the Last Glacial Maximum: Quaternary Science Reviews, v. 100, p. 111–136, doi: 10.1016/j.quascirev.2013.07.020.

Hillenbrand, C.D., Smith, J.A., Kuhn, G., Esper, O., Gersonde, R., Larter, R.D., Maher, B., Moreton, S.G., Shimmield, T.M., and Korte, M., 2010, Age assignment of a diatomaceous ooze deposited in the Western Amundsen Sea embayment after the last glacial maximum: Journal of Quaternary Science, v. 25, no. 3, p. 280–295, doi: 10.1002/jqs.1308.

Hindmarsh, R.C.A., 1999, Pore-water signal of marine ice-sheets: Global and Planetary Change, v. 23, no. 1–4, p. 197–211, doi: 10.1016/S0921-8181(99)00057-0.

Horgan, H.J., Walker, R.T., Anandakrishnan, S., and Alley, R.B., 2011, Surface elevation changes at the front of the Ross Ice Shelf: Implications for basal melting: Journal of Geophysical Research: Oceans, v. 116, no. 2, p. 1–12, doi: 10.1029/2010JC006192.

Jacobs, S.S., Fairbanks, R.G., and Horibe, Y., 1985, Origin and Evolution of water masses near the antarctic continental margin (S. S. Jacobs, Ed.): Oceanography of the Antarctic Continental Shelf, v. 43, p. 59–85, doi: 10.1029/AR043.

Jacobs, S.S., Jenkins, A., Giulivi, C.F., and Dutrieux, P., 2011, Stronger ocean circulation and increased melting under Pine Island Glacier ice shelf: Nature Geoscience, v. 4, no. 8, p. 519–523, doi: 10.1038/ngeo1188.

Jakobsson, M., Anderson, J.B., Nitsche, F.O., Gyllencreutz, R., Kirshner, A.E., Kirchner, N., O'Regan, M., Mohammad, R., and Eriksson, B., 2012, Ice sheet retreat dynamics inferred from glacial morphology of the central Pine Island Bay Trough, West Antarctica: Quaternary Science Reviews, v. 38, p. 1–10, doi: 10.1016/j.quascirev.2011.12.017.

Jenkins, A., Dutrieux, P., Jacobs, S.S., McPhail, S.D., Perrett, J.R., Webb, A.T., and White, D., 2010, Observations beneath Pine Island Glacier in West Antarctica and implications for its retreat: Nature Geoscience, v. 3, no. 7, p. 468–472, doi: 10.1038/ngeo890.

Joughin, I., and Alley, R.B., 2011, Stability of the West Antarctic ice sheet in a warming world: Nature Geoscience, v. 4, no. 8, p. 506–513, doi: 10.1038/ngeo1194.

Joughin, I., Alley, R.B., and Holland, D.M., 2012, Ice-sheet response to oceanic forcing: Science, v. 338, no. 6111, p. 1172–6, doi: 10.1126/science.1226481.

Kirshner, A.E., Anderson, J.B., Jakobsson, M., O'Regan, M., Majewski, W., and Nitsche, F.O., 2012, Post-LGM deglaciation in Pine Island Bay, West Antarctica: Quaternary Science Reviews, v. 38, p. 11–26, doi: 10.1016/j.quascirev.2012.01.017.

Klages, J.P., Kuhn, G., Hillenbrand, C.D., Graham, a. G.C., Smith, J. a., Larter, R.D., Gohl, K., and Wacker, L., 2014, Retreat of the West Antarctic Ice Sheet from the western Amundsen Sea shelf at a pre- or early LGM stage: Quaternary Science Reviews, v. 91, p. 1–15, doi: 10.1016/j.quascirev.2014.02.017.

Lambeck, K., Yokoyama, Y., and Purcell, T., 2002, Into and out of the last glacial maximum: Sea-level change during oxygen isotope stages 3 and 2: Quaternary Science Reviews, v. 21, no. 1–3, p. 343–360, doi: 10.1016/S0277-3791(01)00071-3.

Licht, K.J., and Andrews, J.T., 2002, The 14 C record of late-Pleistocene ice advance and retreat in the central Ross Sea, Antarctica: Arctic, Antarctic and Alpine Research, v. 34, no. 3, p. 324–333, doi: 10.2307/1552491.

Liu, J., Milne, G.A., Kopp, R.E., Clark, P.U., and Shennan, I., 2015a, Sea-level constraints on the amplitude and source distribution of Meltwater Pulse 1A: Nature Geoscience, v. 9, no. December, p. 6–12, doi: 10.1038/ngeo2616.

Liu, Y., Moore, J.C., Cheng, X., Gladstone, R.M., Bassis, J.N., Liu, H., Wen, J., and Hui, F., 2015b, Ocean-driven thinning enhances iceberg calving and retreat of Antarctic ice shelves.: Proceedings of the National Academy of Sciences of the United States of America, v. 112, no. 11, p. 3263–8, doi: 10.1073/pnas.1415137112.

Lowe, A.L., and Anderson, J.B., 2003, Evidence for abundant subglacial meltwater beneath the paleo-ice sheet in Pine Island Bay, Antarctica: Journal of Glaciology, v. 49, no. 164, p. 125–138, doi: 10.3189/172756503781830971.

Mackintosh, A., Golledge, N., Domack, E., Dunbar, R., Leventer, A., White, D., Pollard, D., DeConto, R., Fink, D., Zwartz, D., Gore, D., and Lavoie, C., 2011, Retreat of the East Antarctic ice sheet during the last glacial termination: Nature Geoscience, v. 4, no. 3, p. 195–202, doi: 10.1038/ngeo1061.

Mackintosh, A.N., Verleyen, E., Brien, P.E.O., White, D.A., Jones, R.S., Mckay, R., Dunbar, R., Gore, D.B., Fink, D., Post, A.L., Miura, H., Leventer, A., Goodwin, I., Hodgson, D.A., et al., 2014, Retreat history of the East Antarctic Ice Sheet since the Last Glacial Maximum: Quaternary Science Reviews, v. 100, p. 10–30, doi: 10.1016/j.quascirev.2013.07.024.

Majewski, W., and Anderson, J.B., 2009, Holocene foraminiferal assemblages from Firth of Tay, Antarctic Peninsula: Paleoclimate implications: Marine Micropaleontology, v. 73, no. 3–4, p. 135–147, doi: 10.1016/j.marmicro.2009.08.003.

Malone, M.J., Martin, J.B., Scho, J., Ninnemann, U.S., Nu, D., and White, T.S., 2004, The oxygen isotopic composition and temperature of Southern Ocean bottom waters during the last glacial maximum: v. 222, p. 275–283, doi: 10.1016/j.epsl.2004.02.027.

Matsuoka, K., Hindmarsh, R.C.A., Moholdt, G., Bentley, M.J., Pritchard, H.D., Brown, J., Conway, H., Drews, R., Durand, G., Goldberg, D., Hattermann, T., Kingslake, J., Lenaerts, J.T.M., Martín, C., et al., 2015, Antarctic ice rises and rumples: Their properties and significance for ice-sheet dynamics and evolution: Earth-Science Reviews, v. 150, p. 724–745, doi: 10.1016/j.earscirev.2015.09.004.

McGlannan, A.J., Bart, P.J., Chow, J.M., and DeCesare, M., 2017, On the influence of post-LGM ice shelf loss and grounding zone sedimentation on West Antarctic Ice Sheet Stability: Marine Geology, v. Submitted.

McKay, R., Golledge, N.R., Maas, S., Naish, T., Levy, R., Dunbar, G., and Kuhn, G., 2015, Antarctic marine ice-sheet retreat in the Ross Sea during the early Holocene: Geology, v. 44, no. 1, p. 1–4, doi: 10.1130/G37315.1.

Menviel, L., Timmermann, A., Timm, O.E., and Mouchet, A., 2011, Deconstructing the Last Glacial termination: The role of millennial and orbital-scale forcings: Quaternary Science Reviews, v. 30, no. 9–10, p. 1155–1172, doi: 10.1016/j.quascirev.2011.02.005.

Millard, A., 2014, Conventions for Reporting Radiocarbon Determinations: Radiocarbon, v. 56, no. 2, p. 555–559, doi: 10.2458/56.17455.

Miller, M.D., Adkins, J.F., and Hodell, D.A., 2014, Rhizon sampler alteration of deep ocean sediment interstitial water samples, as indicated by chloride concentration and oxygen and hydrogen isotopes: Geochemistry, Geophysics, Geosystems, v. 15, no. 6, p. 2401–2413, doi: 10.1002/2014GC005308.

Mosola, A.B., and Anderson, J.B., 2006, Expansion and rapid retreat of the West Antarctic Ice Sheet in eastern Ross Sea: possible consequence of over-extended ice streams? Quaternary Science Reviews, v. 25, no. 17–18, p. 2177–2196, doi: 10.1016/j.quascirev.2005.12.013.

Nereson, N.A., and Raymond, C.F., 2001, The elevation history of ice streams and the spatial accumulation pattern along the Siple Coast of West Antarctica inferred from ground-based radar data from three inter-ice-stream ridges: Journal of glaciology, v. 47, no. 157, p. 303–313.

Peltier, W.R., and Fairbanks, R.G., 2006, Global glacial ice volume and Last Glacial Maximum duration from an extended Barbados sea level record: Quaternary Science Reviews, v. 25, no. 23–24, p. 3322–3337, doi: 10.1016/j.quascirev.2006.04.010.

Pollard, D., and DeConto, R.M., 2009, Modelling West Antarctic ice sheet growth and collapse through the past five million years.: Nature, v. 458, no. 7236, p. 329–332, doi: 10.1038/nature07809.

Pollard, D., DeConto, R.M., and Nyblade, A. a., 2005, Sensitivity of Cenozoic Antarctic ice sheet variations to geothermal heat flux: Global and Planetary Change, v. 49, no. 1–2, p. 63–74, doi: 10.1016/j.gloplacha.2005.05.003.

Pritchard, H.D., Ligtenberg, S.R.M., Fricker, H. a., Vaughan, D.G., van den Broeke, M.R., and Padman, L., 2012, Antarctic ice-sheet loss driven by basal melting of ice shelves: Nature, v. 484, no. 7395, p. 502–505, doi: 10.1038/nature10968.

Rayne, T.W., and Domack, E.W., 1996, Porewater chemistry of Ross Sea diamictons: A till or not a till: Antarctic Journal of the United States, v. 31, p. 97–98.

Reimer, P.J., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Buck, C.E., Cheng, H., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Haflidason, H., Hajdas, I., et al., 2013, IntCal13 and Marine13 Radiocarbon Age Calibration Curves 0–50,000 Years cal BP: Radiocarbon, v. 55, no. 4, p. 1869–1887, doi: 10.2458/azu_js_rc.55.16947.

Rignot, E., Jacobs, S., Mouginot, J., and Scheuchl, B., 2013, Ice-shelf melting around Antarctica.: Science, v. 341, no. 6143, p. 266–70, doi: 10.1126/science.1235798.

Rignot, E., Mouginot, J., Morlighem, M., Seroussi, H., and Scheuchl, B., 2014, Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith, and Kohler glaciers, West Antarctica, from 1992 to 2011: Geophysical Research Letters, v. 41, no. 10, p. 3502–3509, doi: 10.1002/2014GL060140.

Rosenheim, B.E., Day, M.B., and Hayes, J.M., 2008, Antarctic sediment chronology by programmed-temperature pyrolysis: Methodology and data treatment: , p. 1–16, doi: 10.1029/2007GC001816.

Schrag, D.P., Adkins, J.F., McIntyre, K., Alexander, J.L., Hodell, D. a., Charles, C.D., and McManus, J.F., 2002, The oxygen isotopic composition of seawater during the Last Glacial Maximum: Quaternary Science Reviews, v. 21, no. 1–3, p. 331–342, doi: 10.1016/S0277-3791(01)00110-X.

Schrag, D.P., and DePaolo, D.J., 1993, Determination of δ18O of Seawater in the Deep Ocean during the Last Glacial Maximum: Paleoceanography, v. 8, no. 1, p. 1–6, doi: 10.1029/92pa02796.

Schweizer, M., Bowser, S.S., Korsun, S., and Pawlowski, J., 2012, Emendation of Cibicides Antarcticus (Saidova, 1975) Based on Molecular, Morphological, and ecological Data: The Journal of Foraminiferal Research, v. 42, no. 4, p. 340–344, doi: 10.2113/gsjfr.42.4.340.

Seeberg-elverfeldt, J., and Feseker, T., 2005, OCEANOGRAPHY : METHODS Rhizon sampling of porewaters near the sediment-water interface: , p. 361–371.

Shipp, S., Anderson, J., and Domack, E., 1999, Late Pleistocene-Holocene retreat of the West Antarctic Ice-Sheet system in the Ross Sea: Part 1 - Geophysical results: Bulletin of the Geological Society of America, doi: 10.1130/0016-7606(1999)111<1486.

Siegfried, M.R., Fricker, H.A., Carter, S.P., and Tulaczyk, S., 2016, Episodic ice velocity fluctuations triggered by a subglacial flood in West Antarctica: Geophysical Research Letters, v. 43, no. 6, p. 2640–2648, doi: 10.1002/2016GL067758.

Smith, J. a., Hillenbrand, C.-D., Kuhn, G., Klages, J.P., Graham, A.G.C., Larter, R.D., Ehrmann, W., Moreton, S.G., Wiers, S., and Frederichs, T., 2014, New constraints on the timing of West Antarctic Ice Sheet retreat in the eastern Amundsen Sea since the Last Glacial Maximum: Global and Planetary Change, v. 122, p. 224–237, doi: 10.1016/j.gloplacha.2014.07.015.

Smith, J.A., Hillenbrand, C.-D., Kuhn, G., Larter, R.D., Graham, A.G.C., Ehrmann, W., Moreton, S.G., and Forwick, M., 2011, Deglacial history of the West Antarctic Ice Sheet in the western Amundsen Sea Embayment: Quaternary Science Reviews, v. 30, no. 5–6, p. 488–505, doi: 10.1016/j.quascirev.2010.11.020.

Smith, J. a., Hillenbrand, C.D., Larter, R.D., Graham, A.G.C., and Kuhn, G., 2009, The sediment infill of subglacial meltwater channels on the West Antarctic continental shelf: Quaternary Research, v. 71, no. 2, p. 190–200, doi: 10.1016/j.yqres.2008.11.005.

Stearns, L. a., Smith, B.E., and Hamilton, G.S., 2008, Increased flow speed on a large East Antarctic outlet glacier caused by subglacial floods: Nature Geoscience, v. 1, no. 12, p. 827–831, doi: 10.1038/ngeo356.

Stolldorf, T., Schenke, H., and Anderson, J.B., 2012, LGM ice sheet extent in the Weddell Sea : evidence for diachronous behavior of Antarctic Ice Sheets: Quaternary Science Reviews, v. 48, p. 20–31, doi: 10.1016/j.quascirev.2012.05.017.

Stuiver, M., Reimer, P., and Reimer, R., 2005, CALIB 7.1: [http://calib.qub.ac.uk/calib/],.

Subt, C., Fangman, K.A., Wellner, J.S., and Rosenheim, B.E., 2015, Sediment chronology in Antarctic deglacial sediments: Reconciling organic carbon 14C ages to carbonate 14C ages using Ramped PyrOx: The Holocene, doi: 10.1177/0959683615608688.

WAIS Divide Project Members, 2013, Onset of deglacial warming in West Antarctica driven by local orbital forcing.: Nature, v. 500, no. 7463, p. 440–4, doi: 10.1038/nature12376.

Webb, P.-N.P., and Strong, C.C.P., 2006, Foraminiferal biostratigraphy and palaeoecology in Upper Oligocene–Lower Miocene glacial marine sequences 9, 10, and 11, CRP-2/2A drill hole, Victoria Land Basin, Antarctica: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 231, no. 1–2, p. 71–100, doi: 10.1016/j.palaeo.2005.07.036.

Weber, M.E., Clark, P.U., Kuhn, G., Timmermann, A., Sprenk, D., Gladstone, R., Zhang, X., Lohmann, G., Menviel, L., Chikamoto, M.O., Friedrich, T., and Ohlwein, C., 2014, Millennial-scale variability in Antarctic ice-sheet discharge during the last deglaciation.: Nature, v. 510, no. 7503, p. 134–8, doi: 10.1038/nature13397.

Wycech, J., Clay Kelly, D., and Marcott, S., 2016, Effects of seafloor diagenesis on planktic foraminiferal radiocarbon ages: Geology, v. 44, no. 7, p. 551–554, doi: 10.1130/G37864.1.

Yokoyama, Y., Anderson, J.B., Yamane, M., Simkins, L.M., Miyairi, Y., Yamazaki, T., Koizumi, M., Suga, H., Kusahara, K., Prothro, L., Hasumi, H., Southon, J.R., and Ohkouchi, N., 2016, Widespread collapse of the Ross Ice Shelf during the late Holocene: Proceedings of the National Academy of Sciences, p. 201516908, doi: 10.1073/pnas.1516908113.

CHAPTER 5: CONCLUSIONS

Fossil carbonate recovered from the eastern Ross Sea has provided a unique opportunity to constrain the timing of WAIS retreat from the Whales Deep Basin and from the crest of Ross Bank. The deglacial chronology established from Whales Deep sediment cores strongly suggests that intervals of rapid sea-level rise triggered WAIS retreat. The timing of ice sheet retreat in the western Ross Sea, while loosely constrained, fit the conceptual model of major WAIS deglaciation during MWP-1b, ~11,500 years ago. However, retreat from the central Ross Sea remains enigmatic. This implies that the WAIS could have contributed to global mean sea-level rise of during MWP-1a and -1b but the magnitude of contribution would have been relatively minor. This conceptual model should be used to develop ice-dynamic computer simulations to determine the magnitude of sea-level equivalent ice volume released during these MWP events.

Oxygen and hydrogen isotope values of sedimentary porewaters from Whales Deep sediment cores do not provide evidence that subglacial and/or ice shelf meltwater generation played a significant role in WAIS deglaciation in eastern Ross Sea. Oxygen isotopes reflect modern Ross Sea values which are an order of magnitude more enriched than glacial meltwater. Deuterium values also suggest a purely marine signal from the paleo subglacial sediment. Additional samples from the diamict would have provided more data from the topset of the GZW. In future studies, methods for extracting porewater should be refined to concentrate on recovering more samples from the lowermost sections of sediment cores that contain GZW diamict. Future studies should also include analysis of cores recovered from paleo ice stream troughs where paleo-subglacial lake drainage has been previously identified by multibeam surveys to test this methodology. Sediment and radiocarbon ages from Ross Bank provided constraints on Ross Ice Shelf retreat. Results suggest that floating ice had decoupled from this

pinning point within the last few centuries.

The research presented here reinforce and refine methods for future investigations that plan to recover fossil carbonate from the Antarctic continental shelf for geochemical analysis and radiocarbon dating. By focusing on obtaining sediment cores from the GZW system and the outer continental shelf, as well as the crests of undisturbed seamounts, calcareous fossils have a higher chance of being recovered. Additionally, producing a detailed sedimentology allowed the retreat of the grounding line, calving front and breakup of the ice shelf to be constrained. Methods for obtaining porewater geochemistry from deglacial sediment has been demonstrated to work using non-destructive Rhizon extractors, as opposed to compressing extracted sediment to obtain porewater. Care must be taken to extract the porewater as soon as possible after core have been obtained. Extracting water after shipping cores will result in spurious geochemical data possibly due to mixing with the atmosphere and/or the effects of evaporation.

As CO_2 levels continue to rise causing ocean and atmospheric warming, polar regions are expected to experience more increasing melt rates and volumes. The interpretation presented here can be used to enhance climate, ocean circulation, and ice dynamic models to more accurately predict the behavior of the Antarctic Ice Sheets in the future. Interpretations produced from these models has the potential to influence politicians, policy-makers and the public by emphasizing the effect of ice sheet melt on coastal cities, energy bills, and a changing ecosystem.

APPENDIX: SUPPLEMENTAL MATERIAL

A.1 Supplementary Materials for Chapter 1

A.1.1 Methods

The data developed in this study were collected during expedition *NBP1502B* in the austral summer of 2015. Key stratigraphic levels that constrain the relative time of grounding-line and calving front retreat were identified in sediment cores (McGlannan et al., submitted). Our methodology focused on isolating *in situ* foraminifera from the sediment directly above the transition from 1) GZW diamict to sub-ice shelf (or open marine) sediment and 2) sub-ice shelf to ice-shelf-breakup (or open marine). In instances where foraminifera were not abundant enough for ^{14}C analysis, the closest interval above the facies contact was used.

A.1.1.2 Foraminifera analyses

Sediment samples (150 cm^3 volume) were collected from all kasten cores (KC) by the shipboard party at intervals of 5 to 10 cm for foraminifera analyses directly after core description. Care was taken to not include abrupt facies transitions in a single sample. The jumbo piston cores (JPCs) were cut and sampled using a pair of 50 cm^3 sediment plugs in July 2015 at the Antarctic Marine Geology Research Facility (AMGRF) in Tallahassee, Florida. Sediment samples were collected every 10-cm using 2 cm thick core intervals. Samples directly below and above each facies transition were processed using the methods outlined below, however this did not always yield enough carbonate for radiocarbon analysis. In these instances, preliminary foraminiferal abundances were used as a reference for sample selection.

Sediment was washed through a 63 μm sieve to remove silt and clay fractions and dried at ~50º C. Sediment was then dry-sieved using 149, 250 and 425 μm fractions before collecting

foraminifera. Tests were picked under a binocular light microscope and placed into microslides for archiving. Each specimen was identified to the species level. Only unbroken tests that did not exhibit any signs of oxidation or secondary calcite were isolated using a binocular light microscope. A minimum of 0.6 mg of calcite was measured for radiocarbon analysis.

Foraminifera were sent to the University of South Florida College of Marine Sciences to be converted to CO_2, along with modern and ^{14}C-free carbonate reference materials, by reaction with phosphoric acid (H_3PO_4). Glass ampoules of CO_2 gas were sent to Woods Hole Oceanographic Institute to be analyzed for ^{14}C on the National Ocean Sciences Accelerator Mass Spectrometer (NOSAMS). One sample of *G. boria* was split randomly (i.e., not by test appearance as all tests were pristine) into two equal masses and replicate ages were within 50 ^{14}C yr of one another. These data were calibrated to calendar year BP using MARINE13 calibration curve in CALIB 7.1 (Stuiver et al., 2005; Reimer et al., 2013) with a marine reservoir effect of 1,300 ± 100 yr (differing by 900yr from the global average reservoir age of 400 yr) established for Antarctic marine carbonates (Table 4.1) (Berkman et al., 1998; Anderson et al., 2002a). All foraminiferal radiocarbon ages are reported as the median age ± the age range, which represents the 95% confidence interval in 'cal kyr BP' notation. This is with respect to the conventions outlined in Millard (2014).

A.1.2 Results

Benthic and/or planktonic foraminifera were found in all cores, however, they differed between and throughout each core with respect to abundance and species composition. In general, the upper parts of the cores down to 10–20 cm contained agglutinated foraminifera. Abundances and diversities decreased with depth. Agglutinated foraminifera were dominated by

Miliammina arenacea associated with *Paratrochammina*, *Reophax*, *Spiroplectammina*, *Labrospira* and other agglutinated forms. At most locations, calcareous foraminifera were present. Cores KC14, KC15, and KC16 were almost barren of calcareous foraminifera.

Table A.1 Radiocarbon ages from Whales Deep foraminifera in order of cores and sample depth. Sample number from NOSAMS. * denotes samples that are mixed benthic species. ^{14}C yr BP are uncalibrated ages. Calibrated yr BP is the median age results from Calib 7.1 software. ± age range is the 95% confidence interval.

Sample #	Core ID	Interval (cm)	Lithology	Species	14C yr BP	Age Err ±	Fm error	δ13C	Calibrated yr BP	± age range	range -	range +
*OS-126095	KC12	38-42	sub ice shelf	mixed benthic	12,950	65	0.001700	-0.11	13,504	221	13,283	13,742
OS-122390	KC12	53-58	sub ice shelf	*T. earlandi*	13,405	120	0.002833	-0.58	13,990	256	13,734	14,246
*OS-126094	KC12	97-102	sub ice shelf	mixed benthic	13,200	75	0.001800	0.09	13,763	252	13,511	14,015
OS-122389	KC12	215-220	GZW diamict	*G. biora*	44,837	4,200	0.002265	-0.29	46,651	512	46,139	47,163
OS-122357	KC11	80-85A	sub ice shelf	*G. biora*	12,597	70	0.001808	-0.1	13,177	223	12,954	13,400
OS-122358	KC11	80-85B	sub ice shelf	*G. biora*	12,644	70	0.001809	-0.11	13,221	217	13,004	13,438
OS-122363	KC11	180-185	sub ice shelf	*G. biora*	13,201	80	0.001920	-0.56	13,765	252	13,513	14,017
OS-122364	KC10	100-105	sub ice shelf	*G. biora*	13,162	80	0.001915	0.36	13,720	245	13,475	13,965
OS-122394	KC09	30-35	sub ice shelf	*T. earlandi*	11,702	150	0.004432	-0.56	12,268	319	11,949	12,587
OS-122368	JPC09	235-237	sub ice shelf	*G. biora*	13,797	85	0.001925	0.31	14,683	449	14,234	15,132
OS-122391	KC08	40-45	sub ice shelf	*T. earlandi*	12,010	110	0.003136	-0.51	12,630	202	12,428	12,832
OS-122388	JPC07	235-237	GZW diamict	*G. biora*	11,664	85	0.002532	0.54	12,214	346	11,868	12,560
OS-122360	KC06	146-148	GZW diamict	*G. biora*	11,818	75	0.002115	0.04	12,421	281	12,140	12,702
OS-122385	KC05	64-69	GZW diamict	*G. biora*	11,268	90	0.002725	0.65	11,472	341	11,131	11,813
OS-122359	JPC05	280-282	GZW diamict	*G. biora*	11,432	70	0.002116	0.73	11,740	416	11,325	12,156
OS-122383	KC03	20-25	open marine	*N. pachyderma*	1,618	35	0.003302	0.68	357	197	160	554

Total foraminiferal abundances in the lower portions of the cores are strongly dominated by calcareous foraminifera. Abundances varied from barren to only a few specimens per sample up to tens of specimens per gram of dry sediment (Figure A.1). Taxonomic composition, although limited to less than 25 species in total, was variable. The calcareous assemblage was always dominated by *Globocassidulina* and/or *Trifarina*, accompanied by *Cibicides*, *Ehrenbergina*, *Astrononion*, *Epistominella*, and other benthic genus, in addition to the planktonic *Neogloboquadrina pachyderma* sinistral. The latter was persistent practically throughout, but its

proportion as compared to benthic forms shown by the p/b ratio, expressed as proportion of planktonic tests to planktonic and benthic altogether, was also variable, reaching almost 0.5 (Figure A.1) in the more offshore sites (KC11 and KC12).

Preservation of calcareous foraminifera was variable but mostly ranged from fair to good. Some broken or etched tests were encountered but well-preserved, complete, transparent tests

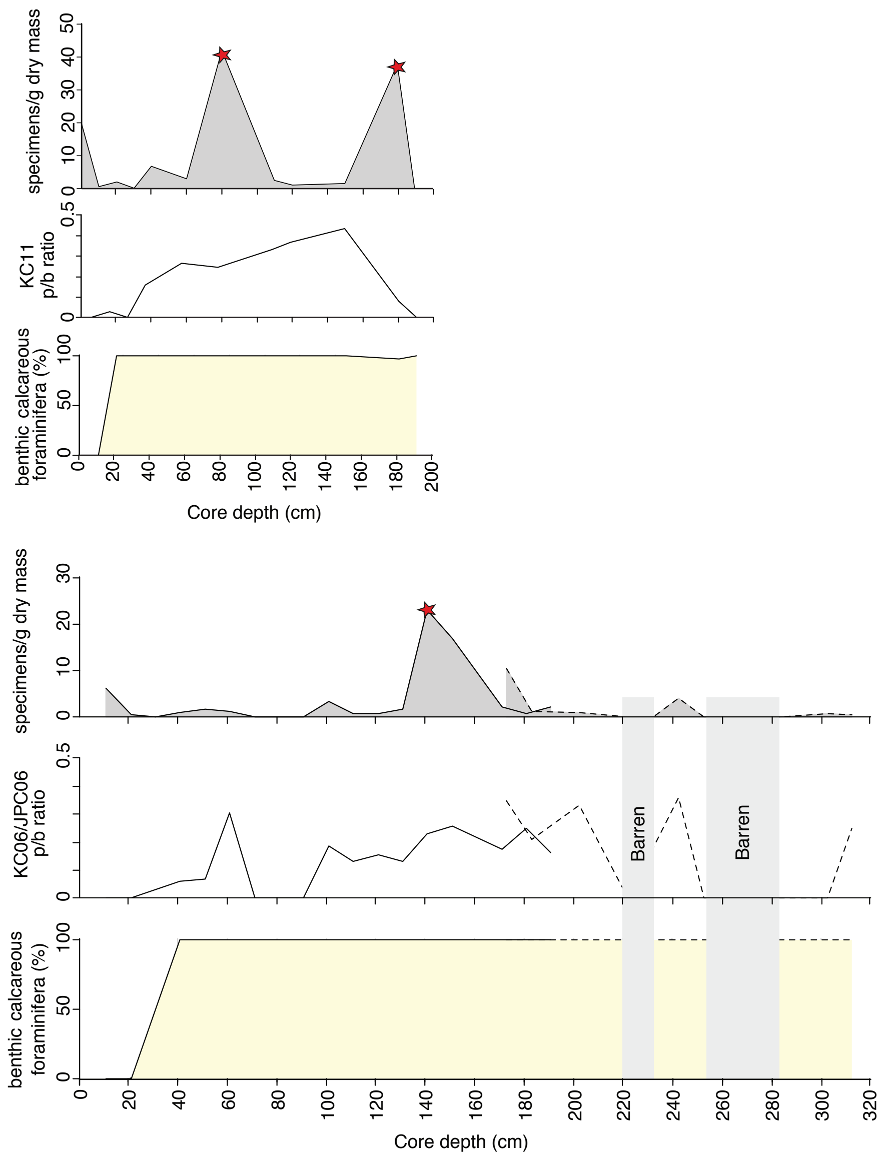

Figure A.1 General foraminiferal parameters from NBP1502B cores KC06 and JPC06 (dotted line) as well as core KC11. Red stars mark stratigraphic position of three foraminiferal samples used for radiocarbon dating.

with no sediment infill were dominant in the most fossiliferous intervals. Some examples of pristine preservation with intact fragile spines, no signs of wall dissolution, and no secondary filling of very fine pores are shown on Figure A.2. These pristine spinose morphotypes were found in abundance.

A.1.2.1 Calcareous foraminifera used for radiocarbon dating

Bart et al. (2016) showed that calcareous foraminifera from grounding zone wedges (GZWs) can be used for radiocarbon dating of marine diamicts from the eastern Ross Sea, however, they must be selected with considerable care. Foraminifera used for this study came from intervals that showed the most abundant calcareous foraminifera (e.g. Figure A.1). Where possible, we used monospecific samples comprised of *G. biora* and *T. earlandi* (and in one instance *N. pachyderma*) that were the most numerous and fairly-massive. The good to pristine

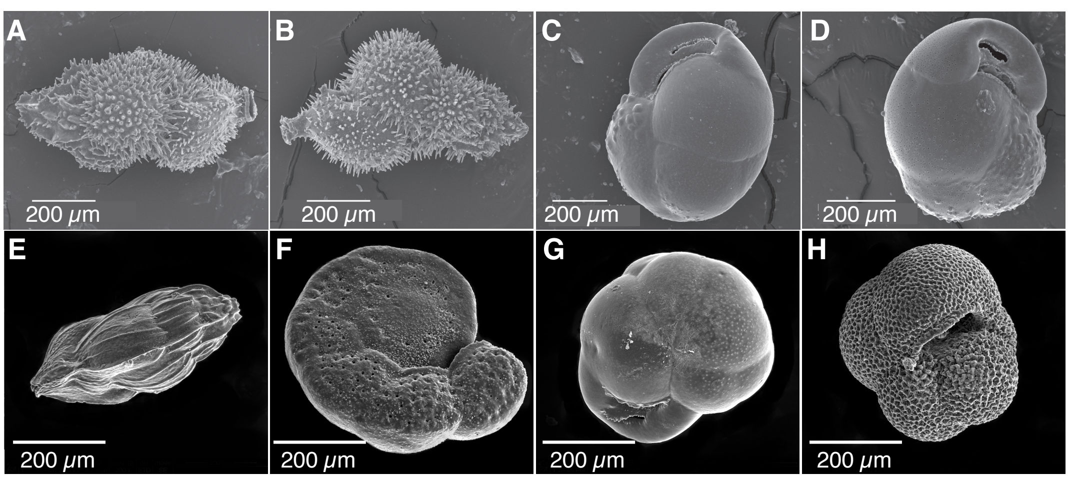

Figure A.2
Examples of pristine preservation among calcareous foraminifera from cores recovered during expedition NBP1502B. **(A)** *T. earlandi* from KC05 at 80 cm. **(B)** *T. earlandi* from KC05 at 140 cm. **(C)** *G. biora* from KC09 80 cm. **(D)** *G. biora* from KC10 100 cm. **(E)** *T. earlandi* from KC12 at 53 cm. **(F)** *Cibicides spp.* from KC11 at 20 cm. **(G)** *G. biora* from KC11 at 80 cm. **(H)** *N. pachyderma* from KC03 at 20 cm.

preservation of these foraminifera, along with lack of clearly reworked specimens, that could be identified either by different coloration, sediment filling (Majewski and Anderson, 2009) and/or unusual taxonomy (Webb and Strong, 2006) indicates that practically all specimens could be considered as being *in situ*. Specimens showing signs of etching, found especially among *Cibicides* or at some intervals with less abundant calcareous foraminifera, although most likely also being *in situ*, were not used for radiocarbon analysis.

To better constrain the sub-ice shelf sediment in KC12, two samples that were comprised of mixed benthic species *G. biora* and *T. earlandi* were radiocarbon dated. These ages are 13.5 ± 0.2 cal kyr BP at 38 cm depth and 13.8 ± 0.3 cal kyr BP at 97 cm depth. These data essentially overlap with the monospecific age 14.0 ± 0.3 at 53 cm and therefore represent viable radiocarbon ages.

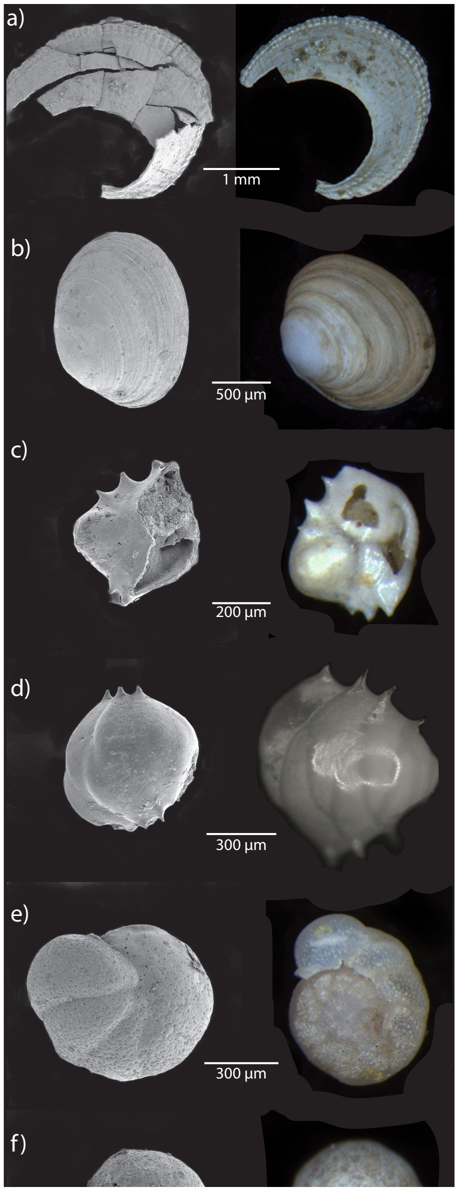

Figure A.3: SEM and light micrographs. **a)** poorly preserved bivalve shell, **b)** well preserved bivalve shell, **c)** poorly preserved *Ehrenbergina glabra*, **d)** well preserved *E. glabra*, **e)** well preserved *Cibicides Antarcticus*, **f)** poory preserved *C. Antarcticus.*

A.2 Supplementary Materials for Chapter 3

Appendix Table A.2: $\delta^{18}O$ (and δD) ordered by core, age and depth and facies. Orange data show the samples that were analyzed post-cruise (at AMGRF). Age are calibrated radiocarbon dates. KC14 ages are younger than 11.5±0.3 cal kyr BP because they are from sediment deposited after WAIS retreated from GZW7 (Figure 3.5 c to d). Facies designations: OM–open marine, ISB–ice-shelf breakup, SIS–sub-ice shelf, DIA–diamict.

Core	Age (cal kyr BP)	depth (cm)	Facies	∂18O (±0.12)	∂D (±0.8)
KC12	5.95	17	OM	-0.58	-3.0
	13.53	59	SIS	-0.43	-2.7
	13.81	83	SIS	-0.51	-2.7
	35.52	178	DIA	-0.47	-2.4
KC11	3.91	3	OM	-0.42	-3.8
	12.50	19	ISB	-0.34	-2.0
	12.62	38	SIS	-0.46	-3.1
	12.88	69	SIS	-0.45	-3.0
	13.70	170	SIS	-0.50	-2.9
KC10	1.76	3	OM	-0.51	-3.9
	6.93	12	OM	-0.42	-3.3
	12.50	29	ISB	-0.42	-3.3
	12.80	49	SIS	-0.50	-4.1
	13.61	97	SIS	-0.56	-4.7
JPC10	18.84	390	DIA	3.65	-6.1
KC09	1.70	2	OM	-0.47	-4.4
	5.94	7	OM	-0.45	-3.7
	12.50	28	SIS	-0.41	-3.6
	13.09	100	SIS	-0.73	-5.6
	13.89	167	SIS	-0.96	-7.3
JPC09	14.87	250	DIA	3.07	-7.4
KC08	1.55	2	OM	-0.41	-5.9
	5.04	7	OM	-0.45	-5.7
	12.50	27	ISB	-0.37	-5.0
	12.93	50	SIS	-0.48	-5.2
	15.93	118	SIS	-0.52	-5.5
JPC08	26.47	355	DIA	1.45	-6.2
KC07	3.54	2	OM	-0.36	-6.9
	11.50	7	OM	-0.32	-6.2
	11.52	12	OM	-0.24	-6.3
	11.56	27	DIA	-0.34	-5.8
	11.96	154	DIA	-0.51	-7.1
JPC07	12.21	235	DIA	-1.45	-9.6
	12.35	280	DIA	-1.30	-8.5
	12.67	385	DIA	1.22	-8.1
KC06	12.12	108	DIA	-1.23	-8.0
	12.22	121	DIA	-1.21	-8.2
JPC06	13.63	315	DIA	-1.68	-11.5
KC14	< 11.5	2	OM	-0.79	-5.4
		27	OM	-0.78	-5.7
		106	DIA	-0.91	-6.4

A.2 Supplementary Materials for Chapter 4

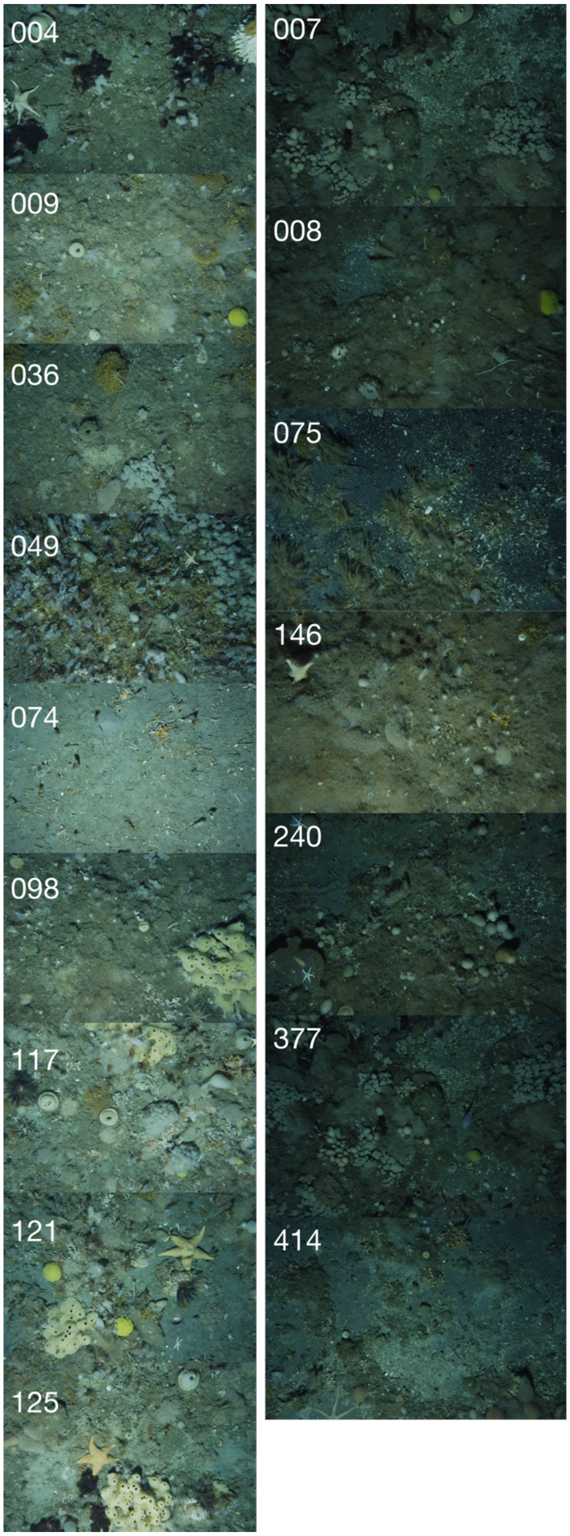

Figure A.4: Yo-yo camera photos from Figure1B transect. Left column (004 to 125) from the crest of Ross Bank. Right column (007 to 414) from the flank of Ross Bank.

Table A.2: Radiocarbon ages listed by NOSAMS. F modern is fraction modern carbon. Err is error.

Accession #	F Modern	Fm Err	Age Err	d13C	d13C Source	d14C	Age
OS-126520	0.8614	0.0022	20	0.59	Measured	-145.36	1,200
OS-126521	0.8541	0.0017	15	0.58	Measured	-152.61	1,270
OS-126522	0.8580	0.0021	20	0.56	Measured	-148.75	1,230
OS-126523	0.8460	0.0018	15	0.82	Measured	-160.62	1,340
OS-126524	0.8464	0.0019	20	0.82	Measured	-160.18	1,340
OS-126525	0.8707	0.0017	15	0.61	Measured	-136.1	1,110
OS-126526	0.8499	0.0019	20	0.76	Measured	-156.72	1,310
OS-126527	0.8527	0.0023	20	0.73	Measured	-153.97	1,280
OS-126528	0.8497	0.0021	20	0.47	Measured	-156.96	1,310
OS-126529	0.8489	0.0019	20	0.51	Measured	-157.74	1,320
OS-126530	0.8294	0.0019	20	0.82	Measured	-177.12	1,500
OS-126531	0.8242	0.0021	20	0.87	Measured	-182.29	1,550
OS-126621	0.8563	0.0018	15	0.17	Measured	-150.38	1,250
OS-126622	0.8584	0.0021	20	0.89	Measured	-148.3	1,230

VITA

Matthew DeCesare, born in Queens, New York, worked at a local library, as a musician, and a welder before pursuing a career in academia in 2006. After receiving his Associates degree from Suffolk County Community College and Bachelor's degree at Stony Brook University, he began to research Antarctic paleoclimate at CUNY Queens College. While researching his Master's project he cultivated a healthy obsession with foraminifera and geochemical paleo-proxies. He decided to follow this passion and was accepted as a PhD student at LSU which led to his participation on an Antarctic expedition NBP1502 to the Ross Sea, a highlight of his academic career – and his life.