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Interglacial Expansion of Alpine Glaciers in Garwood Valley, Antarctica

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INTERGLACIAL EXPANSION OF ALPINE GLACIERS IN GARWOOD VALLEY, ANTARCTICA

by

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ABSTRACT

It is important to understand the response of the Antarctic Ice Sheet (AIS) to ongoing global atmospheric and oceanic warming to anticipate future sea-level change. There are several contrasting views in this regard. Harig and Simons (2015) concur with the IPCC (2013) conclusion that, in recent decades, outflow across the peripheral grounding lines of the ice sheet has exceeded increased accumulation on the interior surface of the ice sheet. In contrast, Zwally et al. (2015) suggest that recent surface accumulation in the interior East and West Antarctica has outpaced peripheral losses. They further suggest that this recent positive imbalance adds to a long-term ice-sheet thickening in interior Antarctica that began at the end of the last ice age when the increase of atmospheric temperature caused a doubling of surface accumulation that has persisted through the Holocene.

An independent glacial geologic history can provide a long-term perspective on the issue of Antarctic ice response to Holocene interglacial warming. As a contribution to this history, my study aims to develop a robust chronology of the Joyce and Garwood land-terminating alpine glaciers in Garwood Valley in the McMurdo sector of the Transantarctic Mountains. The goal is to determine whether these glaciers have expanded during the Holocene and, if so, when and why. Existing data suggest that alpine glaciers in southern Victoria Land fluctuate in concert with nearby land-terminating East Antarctic outlet glaciers, making them a useful proxy for ice-sheet behavior. Such alpine glaciers are isolated from direct marine forcing and therefore are ideal to observe Holocene behavior that may result from changes in accumulation. Here, I present a chronology of the Joyce and Garwood glacial systems from ^{14}C dates of lacustrine algae

samples within moraines and ^{10}Be surface-exposure ages of boulder erratics on moraines. The results indicate glacier expansion since 2820 years BP and do not exclude the possibility that this expansion is ongoing.

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CHAPTER ONE

INTRODUCTION

1.1 The Problem

The Antarctic Ice sheet (AIS) is the largest ice mass on Earth and thus plays a major role in global climate. Aside from its impacts on planetary albedo and atmospheric circulation, the ice sheet effects changes in global sea level that are of societal importance. An estimated ~58 m of sea-level equivalent is currently contained in the largely terrestrial East Antarctic Ice Sheet (EAIS) and another ~3.3 m in the marine-based West Antarctic Ice Sheet (WAIS) (Bamber et al., 2009; Fretwell et al., 2013). Understanding the mechanisms that govern the past behavior of the AIS affords background for anticipating future sea-level change. Thus, knowledge of ice-sheet behavior under past warm climates will enable better-informed predictions of ice-sheet response to ongoing anthropogenic forcing.

In a time of global atmospheric and oceanic warming, it has become important to understand the past responses of the AIS to elevated temperatures. WAIS is generally thought to be susceptible to rapid collapse, because it is primarily grounded below sea level. Moreover, the subglacial topography is such that the bed slopes downward toward the center of the ice sheet (Hughes, 1973). Buttressing ice shelves that protect the WAIS are in danger of shrinkage because of melting by the warming Southern Ocean. In fact, several significant sections of ice shelves on the Antarctic Peninsula have begun to degrade (Scambos et al., 2004; Cook & Vaughan, 2010; Rignot et al., 2014). Mercer (1978) predicted that degradation on a wider scale could lead to the demise of the WAIS, which potentially could open a gateway that would render the EAIS vulnerable to significant recession (Hughes, 2009).

Conflicting reports have led to opposing hypotheses on current ice-sheet behavior. A study from Harig and Simons (2015) validates the IPCC report (2013) that the outflow of ice mass at the grounding lines is exceeding the accumulation rate at the interior, thus contributing to sea-level rise and undermining the stability of the ice sheet. In contrast, Zwally et al. (2015) suggest that accumulation at the interior is outpacing the loss, with thickening of the ice sheet as a result of warming temperatures and increased precipitation.

During the last glacial maximum (LGM) grounded ice fed from both the EAIS and the WAIS filled the Ross Embayment. Studies of moraines alongside EAIS outlet glaciers that fed this grounding show that the timing of the local LGM position became younger with increasing distance from the coast, with some glaciers reaching their maximum at the edge of the EAIS only at 4-8 years BP (Todd et al. 2010). Hall et al. (2015) suggested that this was due to accumulation overwhelming the marine downdraw effect, which was propagating up glacier from the retreat of marine portions. This leads to the hypothesis that land-based portions of the ice sheet, such as certain outlet glaciers in the Dry Valleys and the interior ice sheet, may be affected primarily by accumulation changes driven by temperature. When the climate warms, Antarctic air masses have an increased capacity to hold water vapor, which then leads to an increase in precipitation on the ice sheet (Simpson, 1934). Under such circumstances, interior portions of the EAIS may have thickened throughout the Holocene and may continue to do so in the face of future warming.

One way to determine the Holocene behavior of land-terminating ice is to examine moraines of independent alpine glaciers, which appear to behave in a fashion similar to the land-terminating outlet glaciers (Stuiver et al., 1981). The geometry of moraines in Taylor Valley shows that alpine glaciers expanded and merged with an enlarged Taylor Glacier, an outlet of the EAIS, during the last interglacial period (Denton et al., 1989; Higgins et al., 2000). Both Taylor Glacier and adjacent Rhone and Hughes alpine glaciers were smaller than at present during the last glacial maximum, as indicated by the age of preserved lacustrine deltas in front of the present-day glaciers (Stuiver et al., 1981).

1.2 Goals and Objectives

The goals of this study are to understand better the history of the EAIS by studying the behavior and relationship of local alpine glaciers that are experiencing the same climate as the ice sheet and that have previously shown coeval behavior with that of EAIS outlets. In doing this we hope to address whether or not land-terminating glaciers advance during times of warm climate and high accumulation, such as the Holocene. Or do they advance in concert with the marine, Ross Sea ice during the global LGM and retreat in the Holocene? To test this my study aims to develop a robust chronology of two land-terminating alpine glaciers in Garwood Valley to determine the timing and cause of their most recent advance. The valley is isolated from oceanic influences and therefore an ideal place to observe glacier behavior as a result of climate.

1.3. Background

Understanding the changes in behavior and extent over long-term climate cycles, such as throughout the Plio-Pleistocene, is necessary for our assessment of how the EAIS will be impacted by future climate and ocean changes. The Ross Embayment is an area of substantial change during the last glacial-interglacial cycle. The grounding line in the embayment advanced by as much as 1000 km, and the catchment area expanded by approximately 30% during the LGM relative to present (Greenwood et al., 2018). In the Ross Embayment, EAIS outlet glaciers flowing through the Transantarctic Mountains and ice streams draining the WAIS coalesced to create an expanded ice sheet that extended close to the continental shelf edge of the Ross Sea (Denton and Hughes, 2000; Anderson et al., 2014). Chronologies based on marine sediments suggest deglaciation of the western Ross Embayment about 13,000 years BP with a further retreat to Ross Island by 7800 years BP and near Beardmore Glacier by ~7000 years BP (Conway et al., 1999; Anderson et al., 2014; Spector et al., 2017).

Local glaciers may have behaved differently from the Ross Sea ice. Geomorphological evidence from cross-cutting relationships at Walcott Glacier suggests that its fluctuations may have been out of phase with that of the Ross Sea ice. However, numerical chronologies of local glacier behavior are nearly non-existent. My goal is to examine two of these local glaciers in detail and provide a chronology of their most recent advance.

The field area selected for this study is the western basin of Garwood Valley located in the largely ice-free Dry Valleys region of the Transantarctic Mountains in southern Victoria Land (Fig. 1). The valley is ~2.5 km long and 1.2 km wide and constrained by two cold-based glaciers, Garwood in the east and Joyce in the west.

Meltwater from Joyce Glacier forms a large delta complex that supplies Lake Colleen near the center of the valley. Both glaciers are land terminating. Previous chronologic work in the valley consists of one cosmogenic nuclide study of seven samples taken from moraines along the western and southern margin of Garwood Glacier and three samples taken from degraded terraces outboard of the recent moraines at Joyce Glacier (Joy et al., 2017). The significant findings reported by Joy's group placed the timing of advance of Garwood and Joyce Glacier between 26,000 and 51,000 years BP.

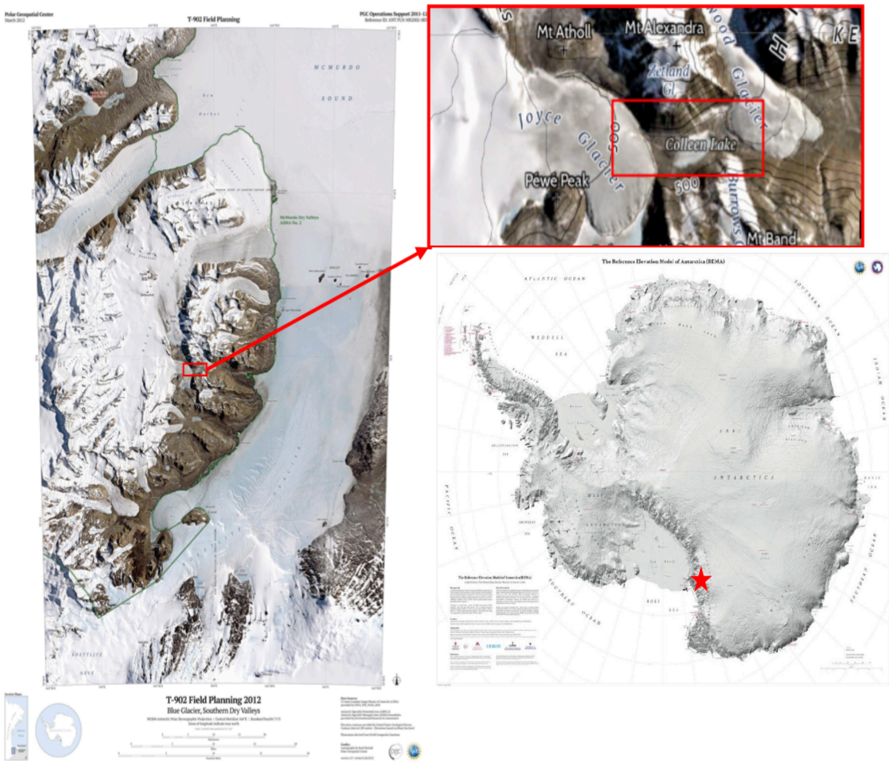

Figure 1. Location of field area in reference to the Antarctic continent

Garwood Valley is separated into eastern and western basins by Garwood Glacier. The western basin is the subject of this study and is outlined in red. The maps are provided by the Polar Geospatial Center. Valley is approximately 2,380 m long and 855 m wide.

CHAPTER TWO

METHODS

2.1 Mapping

Prior to the field season, I examined landforms on World View half-meter resolution satellite images obtained from the Polar Geospatial Center. Once I arrived in Antarctica, the landforms identified from imagery were examined in detail by traversing them in the field and examining natural sections in stream cuts. GPS coordinates, morphology, composition, cross-cutting relationships, and degree of erosion and weathering were recorded for each landform of significance. I created a georeferenced glacial geomorphological map using ArcGIS.

2.2 Sample Collection

I collected samples of *in situ* subfossil algae from moraines for radiocarbon dating. Algae samples were found either in natural exposures or by digging into sediments using small metal spades. At each site, I noted the geographic location, elevation, and depth of each sample. The geographic position was determined using a handheld GPS, which was compared to a base station, whose elevation was known precisely (sub-meter) by differential GPS. Photos of each sample site were taken for later reference. After collection, the algae were air-dried, separated from sand using tweezers, and sealed in plastic vials. Samples were shipped to the University of Maine where they were kept at 4^{o}C until analysis.

I collected samples for beryllium cosmogenic isotope dating from large, stable boulders embedded in moraine crests or perched on other boulders. Boulders that were at risk of having been disturbed because of steep slopes and fluvial channels, or that appeared older than surrounding rocks, were not selected. Rocks that were exfoliated, pitted, disintegrated, fractured or otherwise strongly altered also were avoided. I preferred samples that had glacial polish, as that indicates minimal material loss at the surface.

The geographic location and elevation of each sample was recorded using a handheld GPS and compared against a static base station, whose elevation was known precisely (sub-meter) by differential GPS. I also recorded elevations using a Kestrel barometric altimeter, set at least twice a day at the base station. A handheld clinometer was used to assess the topographic shielding. Photographs of each sample were taken prior to sampling for later reference of geomorphic context.

I extracted samples using hammers and chisels. The depth of a sample was kept to a maximum of 4 cm, if possible, to obtain the most accurate beryllium ratios. Rock surfaces in excess of 4 cm or that had other unwanted portions, such as edges, were marked at the time of collection with a pen and trimmed with a saw upon arrival at the lab.

2.3 Radiocarbon Dating

Algae samples were re-examined in the laboratory, and any remaining sediment was removed. Samples were sent to the National Ocean Sciences Accelerator Mass Spectrometry (NOSAMS) laboratory at Woods Hole Oceanographic Institution for accelerator analysis. Radiocarbon samples were subjected to acid-base-acid pretreatment, and resulting ages were corrected for $\delta^{13}C$ values. The ages were then calibrated to calendar years within 1-sigma error using version 7.1 of the CALIB radiocarbon calibration program and the INTCAL13 curve (Reimer et al., 2013). Ages presented in the text are the midpoints of the calibrated ranges. Ages were not corrected for a lake reservoir effect, because none was anticipated. The algae are thought to have lived in a shallow pond with an open moat, which should have been well aerated (Doran et al., 1999; Hendy and Hall, 2006).

2.4. ^{10}Be Exposure Dating

Rocks at the earth's surface are exposed to high-energy particles generated in outer space, referred to as cosmic rays. These particles bombard rock surfaces and cause spallation reactions in the oxygen and silicon atoms that constitute quartz (SiO_2), resulting in the formation of the cosmogenic radionuclide ^{10}Be in a reaction that occurs at a known rate (Gosse and Phillips, 2001). Thus, by measuring the concentration of ^{10}Be, one can calculate the age of exposure to cosmic rays. Boulders that are deposited by a glacier are assumed to begin their accumulation of ^{10}Be at the time of deposition. Intense erosion associated with glacial transport is thought to remove any nuclides from prior episodes of exposure. However, this doesn't always happen in the Antarctic, because the glaciers are cold-based and non-erosive. Thus, some rocks have inherited ^{10}Be from previous periods of exposure and, as a result, the concentration of ^{10}Be in the rock leads to an overestimate of the age of the last glacial event. Such rocks with prior exposure commonly can be identified in the field by their degree of weathering but generally are more apparent after data collection, where results may appear as anomalously old outliers in the data set.

2.5 Laboratory Processing

Beryllium-10 samples were processed at the University of Maine Cosmogenic Isotope Laboratory. The process began by describing and measuring the thickness of each sample with calipers. The sample was then crushed and sieved to ensure that the grain size was between 250-500 mm. The desired grain fraction was then washed with water to remove dust and then boiled in 10% HCl to remove weathering products. The samples were then subject to froth floatation with lauryl amine and essential oil to remove feldspar and other non-quartz minerals. The remaining sample was placed in a 2% HF:2% HNO_3 acid solution and then placed in an ultrasonic hot water bath for multiple days. This was done to dissolve any other minerals in the sample aside from quartz. The purity of each sample was checked via ICP-OES and if deemed clean enough (<100 ppm each of Al, Ca, Fe, and Ti) proceeded to the clean laboratory. Impure samples repeated the acid etching process.

Samples that passed the ICP-OES test had their beryllium extracted in the University of Maine Cosmogenic Isotope Laboratory following their established protocol which is posted at: https://umaine.edu/earthclimate/research/glacial-geology-and-geochronology-research-group/cosmogenicisotope/. Samples were weighed, spiked with low-level ^{9}Be carrier, and dissolved in concentrated HF acid. Upon dissolution, the acid was evaporated, and the samples were taken back up in 6M HCl. After a series of dry downs and additions of HCl to remove fluorides, the samples were loaded onto columns to remove iron. This was followed by sulfate conversion and processing of the samples through additional resin columns to remove titanium. Samples were evaporated, taken back up in 1% nitric acid, and $Be(OH)_2$ was precipitated by ammonium hydroxide additions. Samples were combusted to form BeO, mixed with niobium, and packed into targets. Beryllium targets were sent to the Center for Accelerator Mass Spectrometry at Lawrence Livermore National Laboratory in Livermore, CA.

2.6 ^{10}Be Age Calculations

For each sample, I calculated the cosmogenic exposure-age using the CRONUS-Earth online exposure-age calculator with the "New Zealand" production rate (Putnam et al., 2010). The New Zealand rate was chosen due to it being the closest calibration site to Garwood Valley.

CHAPTER THREE

RESULTS

3.1 Overview of Surficial Geology and Geomorphology

Several prominent ice-cored moraines flank Joyce and Garwood glaciers. Weathered drift occurs in patches distal to these moraines. This drift is partially overlain by aeolian, alluvial and fluvial deposits. An expansive outwash plain with several active and inactive channels is visible in front of Joyce Glacier. Multiple alluvial fans originating in the surrounding mountains occur on the valley floor.

Figure 2. Panoramic View of Garwood Valley

The photograph was taken looking south towards Mt. Steep. Garwood Glacier is visible to the east beyond Lake Colleen. Pre-LGM ground moraine with surface boulders is visible in the foreground. The photograph was taken on January 17th, 2018.

3.2 Joyce Glacier

A prominent belt of discontinuous and largely ice-cored moraines occurs alongside the terminus of Joyce Glacier. These large moraines display 2-10 m of relief and extend as much as ~0.35 km from the glacier. Additional, smaller moraines occur outboard of the large main ridges and trend obliquely both to the large moraines and to the present-day glacier margin. Active meltwater channels divide the moraines into separate ridges, cutting sections that expose the internal sediments and structures. The moraine crests are sharp and are marked with rare granitoid and metagranite boulders. For the most part, the moraines are constructed from largely horizontal to slightly dipping layers of sorted fine sediment that contain abundant ancient algal mats. In the core of the moraines, these sediments are faulted and folded.

Weathered drift occurs on the north side of the valley approximately 175 m beyond the margin of Joyce Glacier. This drift forms a small discontinuous terrace that extends along the north valley wall with less relief on the uphill flank than on the valley side. The surface of the terrace exhibits scattered metagranite boulders and cobbles.

Figure 3. Photograph of the Joyce moraines and the terminal ice cliff of Joyce Glacier.

This image faces west across aeolian deposits and towards the moraines and terminus of Joyce Glacier. Joyce ice cliffs are approximately 10-15 m high and display several debris bands. The photograph was taken on January 17, 2018.

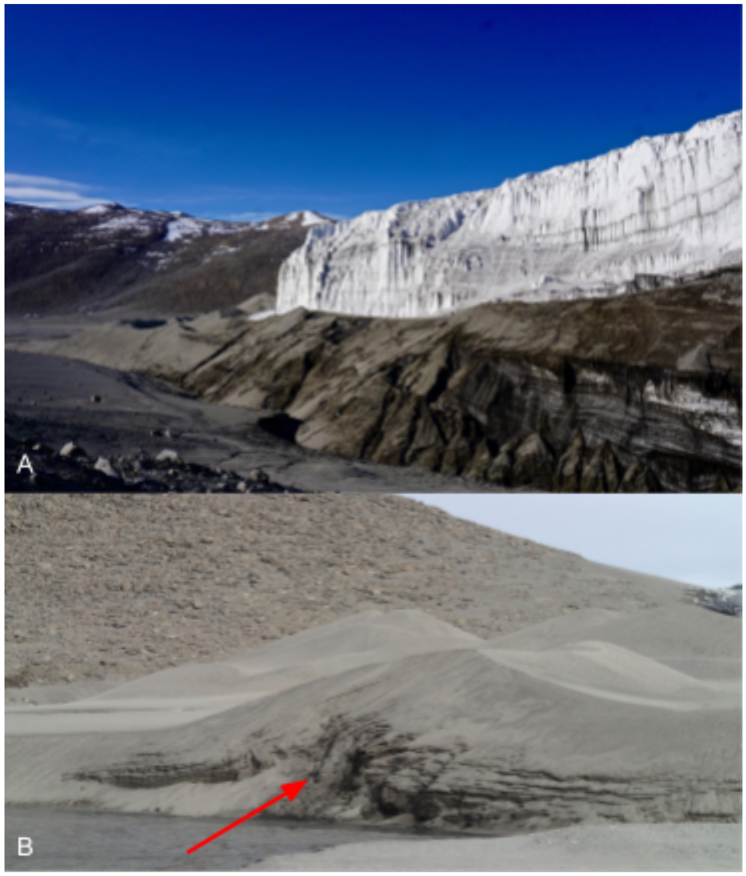

Figure 4. Photograph of Joyce moraines

A. This image shows the terminal moraines at Joyce Glacier. Vantage is toward the northeast, showing the ice-cored moraines. The terminal ice cliffs of Joyce Glacier are approximately 10-15 m in relief.

B. Image shows faulting and folding (red arrow) of previously deposited lacustrine sediments that now make up the Joyce moraines.

3.3 Garwood Glacier

Several moraine ridges exist alongside the western terminus of Garwood Glacier. Three of these steep-sided ridges exhibit 2-6 m in relief and are separated by 1-3 m. Together, the moraines extend ~0.25 km from the present-day glacier margin. In some places, it appears that the glacier currently is overriding the innermost moraine ridge. The moraines are formed of fine-grained sand and cobble- and boulder-sized clasts comprised primarily of granitoids. Algae occur in thick mats that crop out in dipping beds of silica rich sand in one moraine segment. An extensive, bouldery drift sheet occurs on the valley floor for more than 175 m outboard of the moraines.

3.4 Alluvial Deposits

Numerous alluvial fans descend the valley walls towards the valley floor and crosscut older deposits. An outwash plain comprised of silicic sand and gravel extends along the valley floor between Joyce Glacier and Lake Colleen.

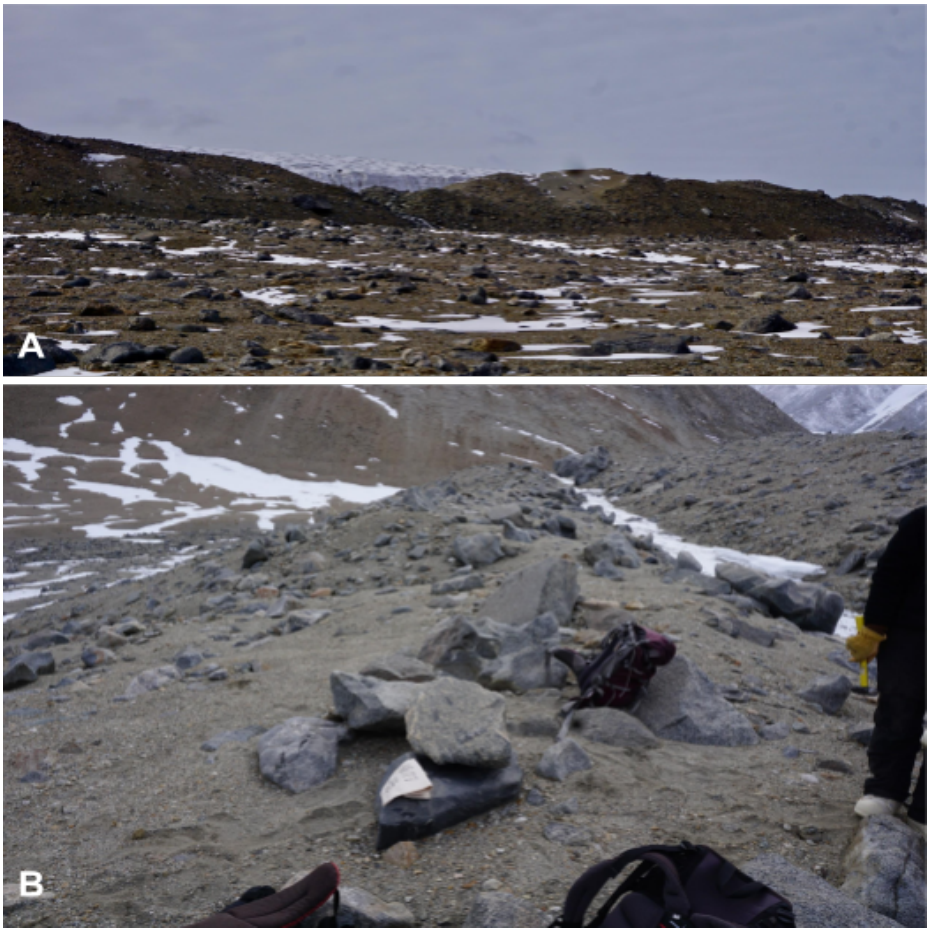

Figure 5. The Garwood moraines

This image has vantage looking east across the older Garwood drift toward the moraines alongside Garwood Glacier. It appears that the glacier is overriding these moraines in some sectors.

This view of the outer Garwood moraine crest was taken with vantage to the north looking along the crest line. The moraine has medium-sized boulders on the surface. Both photographs were taken on January 28th, 2017.

3.5 Radiocarbon chronology

Radiocarbon dates (Table 3.1; Fig. 6; Fig. 7) provide maximum-limiting age constraints on the time of moraine formation. I collected samples of ancient algae from varying depths in prominent moraines. Some samples were collected near the crest, whereas others were as much as 8 m below the crest in section. Twelve samples of *in situ* algae from the Joyce moraines yielded calibrated ages that range from ~2820 to 6230 years BP. Two samples collected from the same moraine gave ages of 2820 and 5350 years BP in proper stratigraphic order. A single sample was collected from the Garwood moraines and dated to 11,280 years BP. Two samples were collected adjacent to Lake Colleen about 2 m above present lake level and may be from a remnant of a higher-elevation delta that has been largely eroded.

3.6 Exposure sample chronology

I measured ^{10}Be concentrations in quartz isolated from three metagranite boulders from the surface of moraines alongside Garwood Glacier and from two samples of similar composition from Joyce moraines. Nuclide concentrations are summarized in Table 3.2, and ages are presented in Table 3.3 and Figure 3.2. The two ages from Joyce moraines are 527,380 ± 4180 and 491,610 ± 4030 years BP. Ages from the Garwood moraines are 8790 ± 170, 55,080 ± 740, and 129,050 ± 1180 years BP. Interpretation of potential reasons for the age differences between radiocarbon and exposure samples is provided in Chapter 4.

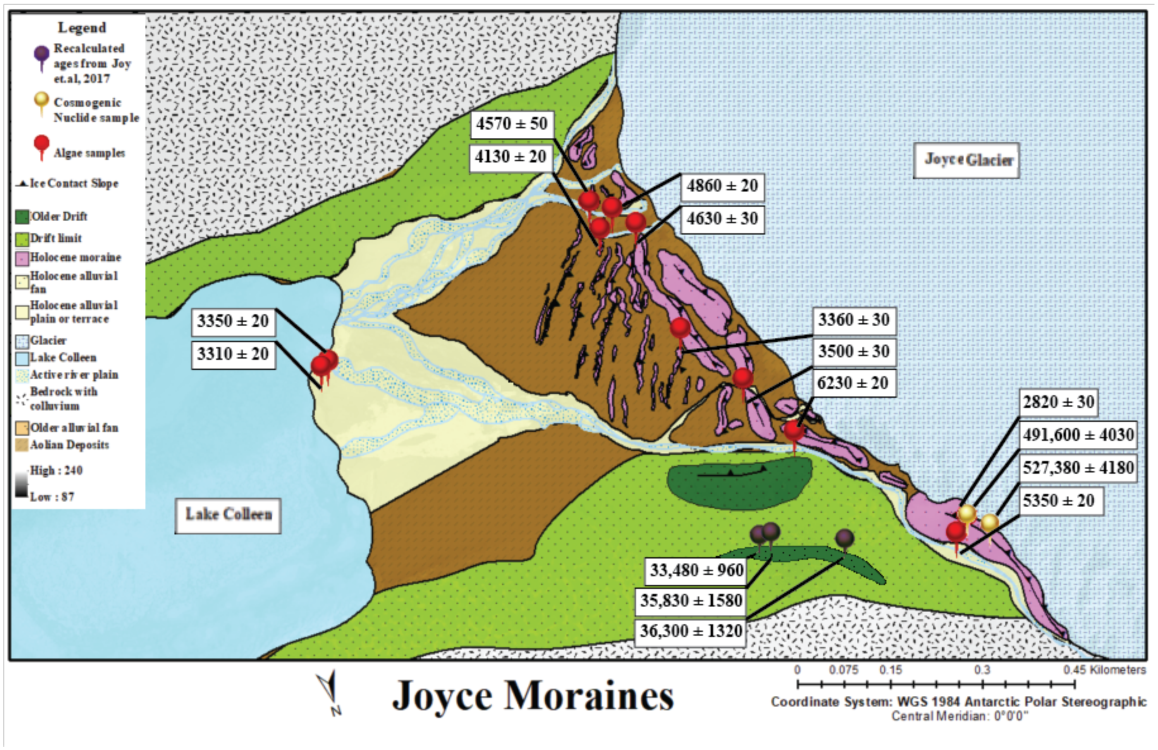

Figure 6. ^{14}C and ^{10}Be ages of samples collected from Joyce moraines

Map shows the ages of samples collected from landforms near Joyce Glacier. Radiocarbon samples from lacustrine algae, as well as beryllium exposure-age samples from this study and recalculated from Joy et al. (2017), are plotted in calendar years. The radiocarbon ages range from 3360-6230 years BP whereas cosmogenic samples on the moraines adjacent to the glacier range from 491,600-527,380 years BP. Samples near Lake Colleen have an average age of 3330 years BP.

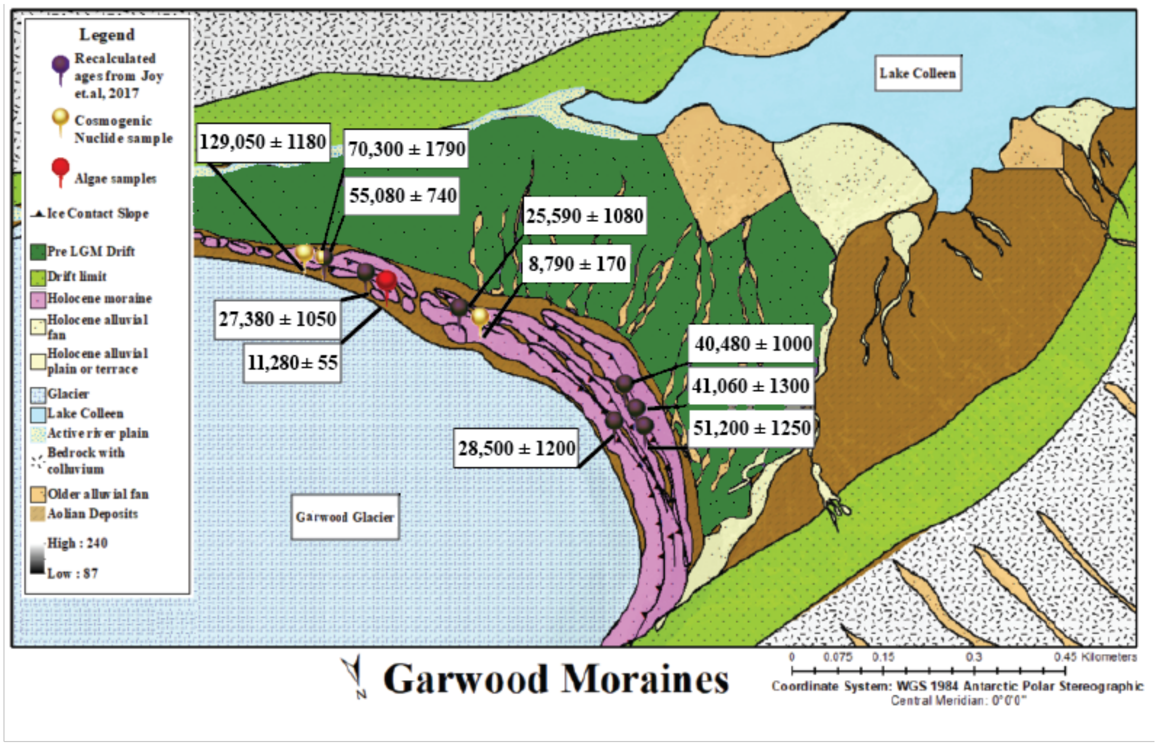

Figure 7. Calculated Ages of Samples Near Garwood

Apparent ages of samples recorded on the landform map above are based on radiocarbon samples, beryllium cosmogenic exposure samples and recalculated beryllium ages of samples published in the previous study by Joy et al. (2017).

Table 1. Results of radiocarbon dating of Garwood Valley samples

Sample	Lab #	14C	Error	δ13C	Location	Lat	Long	Elev	Description	Cal	Err 1σ
AB-17-33	OS-140523	3120	35	-5.35	Joyce	-78.02379	163.81676	370	In thrust moraine	3360	30
AB-17-42	OS-140252	9880	55	-6.87	Garwood	-78.02081	163.91887	399	In thrust moraine	11280	50
BH-17-50	OS-140258	4720	25	-11.49	Joyce	-78.01974	163.80189	401	In thrust moraine	5350	20
BH-17-51	OS-140714	2730	25		Joyce	-78.01994	163.80086	406	Top of thrust moraine	2820	30
BH-17-52	OS-140715	5450	35	-11.84	Joyce	-78.02186	163.81099	369	Inner belt thrust moraine	6230	20
BH-17-53	OS-140646	3300	20	-10.01	Joyce	-78.02281	163.81347	367	In thrust moraine	3500	30
BH-17-54	OS-140716	4140	30	-10.74	Joyce	-78.02547	163.81775	362	Base inner thrust moraine	4630	30
BH-17-55	OS-140717	3740	25	-11.25	Joyce	-78.02554	163.82031	361	Outer thrust moraine	4130	20
BH-17-56	OS-140718	4090	30	-10.18	Joyce	-78.02597	163.82048	360	Core of outer thrust moraine	4570	50
BH-17-57	OS-140719	4320	30	-13.22	Joyce	-78.02579	163.81909	357	Core inner thrust moraine	4860	20
BH-17-59	OS-140720	3110	25	-9.3	Joyce	-78.02478	163.84161	361	Ridge by Lake Colleen	3350	20
LM-17-22	OS-140759	3060	20	-12.03	Joyce	-78.02473	163.84216	356	In thrust moraine	3310	20

Table 2. Cosmogenic nuclide sample information measured in quartz

Sample name	Latitude (DD)	Longitude (DD)	Elevation (m)	Thickness (cm)	Density (g cm-2)	Shielding	Erosion rate (cm yr-1)	[Be-10] (atoms g-1)	+/- (atoms g-1)
GAR-17-2	-78.02154	163.92404	380	1.38	2.7	0.995844	0	391,377.7491	6,805.07053
GAR-17-3	-78.02141	163.92282	390	2.69	2.7	0.995041	0	898,598.408	946.4809537
GAR-17-6	-78.01988	163.91315	393	1.17	2.7	0.995634	0	64,078.06509	17,465.57853
JCE-17-5	-78.01971	163.79948	405	1.8	2.7	0.98063	0	3,358,523.577	43,350.5445
JCE-17-6	-78.01994	163.80086	408	1.72	2.7	0.984369	0	3,180,828.342	56.87692424

Table 3. Table of calculated ages for cosmogenic exposure age samples

The columns labeled "Interr" and "Exterr" refer to the internal and external errors respectively, where the internal errors refer to the errors possible in lab procedures and equipment uncertainty and external refers to error possible in the overall cosmogenic nuclide procedure with respect to changes in the natural system such as magnetic field variability, solar flares, etc.

Sample name	Nuclide	St Age(yr)	Interr(yr)	Exterr(yr)
GAR-17-2	Be-10(qtz)	55,080	737	1,140
GAR-17-3	Be-10(qtz)	129,051	1,182	2,388
GAR-17-6	Be-10(qtz)	8,789	165	214
JCE-17-5	Be-10(qtz)	52,7381	4,182	10,283
JCE-17-6	Be-10(qtz)	491,608	4,031	9,567

CHAPTER FOUR

DISCUSSION

4.1 Formation of Moraines and Implication for Chronology

Examination of the sediments, stratigraphy, and morphology of moraines adjacent to Joyce Glacier indicate that they were formed by glaciotectonic reworking of pre-existing lake and fan sediments. Sediments, including layers of algae, initially were deposited in horizontal or near-horizontal layers and were pushed and thrust upwards in faulted blocks and folds by the advancing glacier. This disturbance is observed in sections within the moraines at my field site and thus indicates that the landforms can be classified as thrust moraines. These landforms are commonly found in the Dry Valleys region and often indicate an active or advancing glacier (Fitzsimmons,1996). These moraines are formed by the thrusting and faulting of frozen blocks of sediment in front of an advancing glacier. This often results in ice-cored moraines and disturbance of the sediment stratigraphy.

The glaciotectonic origin of these moraines has implications for the radiocarbon and beryllium chronologies. My radiocarbon ages are of algae that were buried in lacustrine sediments, possibly from higher levels of Lake Colleen. Subsequently, these sediments were thrust into the moraines as the glacier advanced. Because the sediments were laid down before the moraines formed, the ^{14}C ages of the algae act as maximum-limiting ages for moraine formation. The youngest date offers the closest constraint to the timing of glacial advance.

Using this context, I can interpret the ages from the Joyce and Garwood moraines. The ages for the Joyce moraines range from 6230 ± 20 years BP to 2820 ± 30 years BP.

Thus, the youngest moraine must have formed at some time after 2820 years BP. I only have one date from the Garwood moraines, and it indicates that the moraine closest to the ice margin formed after 11,280 years BP. Several outboard moraines exist, but lack algae for dating. The results suggest that both Joyce Glacier and Garwood have advanced in the present interglacial and, in at least the case of Joyce Glacier, into the late Holocene. Moreover, the chronology does not exclude the possibility that the glaciers are continuing to advance today.

A key question is if thrust moraines are reliable landforms from which to collect cosmogenic nuclide samples from surface boulders. It is possible that some boulders on the moraine crests were derived from pre-existing sediments that have been uplifted to their current position through the glaciotectonic processes. Alternatively, the boulders could have dropped onto the crest from the ice margin once the moraine already had formed.

Two large granitoid boulders embedded in the crest provided material for ^{10}Be exposure dating of the Joyce moraines. The boulders yielded generally internally consistent ages of 491,610 ± 4030 and 527,380 ± 4180 years BP. However, the exposure ages are significantly older than the age of the moraine, obtained from the maximum-limiting age of 2820 years BP provided by algae in the same moraine segment. One sample was adjacent to dated algal layers that likely extended beneath the dated boulder. Both boulders also rested atop a moraine that included a thick section of stratified sediments, with algae dating to 5350 years BP. Thus, the exposure age should be younger than the algae, but that is not the case. This indicates that the two samples, despite yielding similar ages, inherited most of their beryllium concentrations prior to moraine formation and are unreliable indicators of moraine age. In Antarctic exposure dating, internal agreement of boulder ages on a landform has been used as a measure of accuracy. Due to the general agreement between the two dated boulders, the age assigned to the landform could have been easily misinterpreted to be older than its actual age. This points to the value of using multiple chronologic methods when dating Antarctic moraines.

Interpretation of exposure ages of boulders on the moraines in front of Garwood Glacier is less straightforward. An algae sample collected from within the inner thrust moraine yielded a result of 11,280 years BP, whereas an exposure sample obtained from Joy et al. (2017) on the same moraine yielded an age of 27,380 years BP. Other erratics resting on the inner moraine, although not on the same segment, have ages of 28,500 and 25,590 years BP(Joy et al.,2017). Thus, although the exposure ages are generally consistent, they are considerably older than the maximum-limiting radiocarbon age of 11,280 yr BP. The outer two moraines yield dates of 40,480-51,200 years BP(Joy et al.,2017 and thus study). Whether these dates are accurate remains to be tested. As the thrust moraines curve around the Garwood terminus towards Garwood Stream, it becomes more difficult to separate ridges. An erratic from this sector of the moraines produced an age of 129,050 years BP. Finally, a sample with an age of 8790 years BP came from a separate boulder moraine that is draped across the broad inner thrust moraine. At face value, this age is consistent with the radiocarbon date of algae, and suggests that the boulder moraine dates to ≤8790 years BP.

While several factors such as erosion, shifting or rolling of samples can affect the scatter in calculated ages, all boulders sampled were large, stable and on the moraine crests. In this case, the inconsistency between the radiocarbon and exposure ages may be indicative of the poor reliability of exposure dates from thrust moraines. This is a result of the incorporation of previously exposed deposits into the landforms during their formation, as boulders on the valley floor can be raised onto a moraine during thrusting of proglacial sediments. This would result in dates that are older than the age of thrusting of the moraine sediments and therefore result in inaccurate conclusions about the timing of glacial events. It is also possible that boulders with significant prior exposure dropped off the ice margin onto already formed moraines.

4.2 Holocene Advance of Alpine Glaciers

There are limited studies of Holocene alpine glacier behavior in the Antarctic. The available data usually exists as by-products of larger projects and are understated in the conclusions. One of the main goals of this study was to contribute to a more robust chronology of Holocene glacial behavior. The ages of the Joyce and Garwood moraines, younger than 2810 and 11,670 years BP, respectively, indicate that they formed in the Holocene. Other studies that document Holocene alpine glacier expansion include limited radiocarbon dates of algae within Suess Glacier thrust moraines that date to 2880-6800 BP (Stuiver et al., 1981; Hall and Denton, 2000). In addition, several alpine glaciers are currently overriding deltas laid down during the maximum of the last ice age. For example, Salmon Glacier has advanced onto the back of a delta that is dated to 16,000 years BP (Jackson et al., 2017), and Rhone Glacier is overriding its delta also dating to about 16,000 years BP (Stuiver et al., 1981).

Why would alpine glaciers advance in the Holocene? Antarctic glaciers lack a direct sensitivity to warmer temperatures because of the lack of surface melting ablation zones. Over 90% of ice loss on glaciers in this area is due to sublimation (Chinn, 1993). Instead, warming climate increases the capacity for water vapor in the surrounding air masses and thus precipitation increases (Simpson, 1934). This results in net growth and advance of terrestrial glaciers.

Available evidence suggests that glacial advance in warm periods, such as the Holocene, is not limited solely to these alpine glaciers but rather is also reflective of terrestrial-based EAIS outlets during warmer interglacial periods (Stuiver et al., 1981; Denton et al., 1989; Higgins et al.,2000). Records of this synchronous behavior can be observed in the geomorphic evidence left behind by Taylor Glacier, such as the merging of moraines from expanded alpine and outlet glaciers (Higgins et al., 2000). This suggests that as the Antarctic continues to warm, increased accumulation will cause thickening and advance not only of alpine glaciers but also of terrestrial-terminating EAIS outlets.

CHAPTER FIVE

CONCLUSIONS

- Examination of the sediments, stratigraphy, and morphology of moraines adjacent to Joyce Glacier indicate that they were formed by thrusting of pre-existing lake and fan sediments.

- Radiocarbon ages of algae within these sediments range from ~2820-6230 years BP. These dates afford maximum-limiting ages for moraine formation, indicating that these landforms are <2820 years BP. Joyce Glacier must have advanced to this position at or since this time, which contrasts with the ages provided by the cosmogenic samples from surface boulders, which are 491,600 and 527,380 years BP.

- A radiocarbon sample from an inner moraine at Garwood Glacier produced a maximum-limiting age of 11,280 years BP, which contrasts with the exposure age sample on the same moraine with an age of 27,380 years BP. We infer that the exposure age must suffer from inherited nuclides. Thus, exposure samples collected from erratics on thrust moraines should be interpreted with care.

- Evidence for Holocene glacial advance supports the idea that increased accumulation during interglacial times causes the advance of land-terminating glaciers in the McMurdo sector of the Transantarctic Mountains.

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