PROJECT DESCRIPTION: COLLABORATIVE RESEARCH: TERRESTRIAL EXPOSURE-AGE CONSTRAINTS ON THE LAST GLACIAL MAXIMUM EXTENT OF THE ANTARCTIC ICE SHEET IN THE WESTERN ROSS SEA

INTRODUCTION

We propose to collect glacial-geological and geochronological data from ice-free regions in coastal areas of northern Victoria Land that will constrain the nature and timing of past changes in the thickness of major glaciers that drain into the northwestern Ross Sea. This is important because during the Last Glacial Maximum (LGM) ca. 15,000 - 18,000 years ago, these glaciers were most likely confluent with grounded ice from both the East and West Antarctic Ice Sheets that expanded across the Ross Sea continental shelf to near the present shelf edge. Thus, thickness changes at these glaciers were most likely controlled in part by the extent and thickness of Ross Sea ice, and the data we propose to collect can potentially provide information on the LGM position of the grounding line in the western Ross Sea, the time that position was reached, and ice thickness changes that occurred before and after that time. This, in turn, is important because the Ross Sea housed a significant proportion of the excess Antarctic ice volume at the LGM, so understanding past ice sheet change in this region is necessary for quantifying the Antarctic contribution to past sea level changes. In particular, hypotheses regarding ice sheet change during the LGM in the northern and central Ross Sea are central to evaluating the potential Antarctic contribution to rapid sea level rise during meltwater pulse 1-A (MWP-1A) ~14,600 years ago. Our proposed work would provide new geological and geochronological data that are directly relevant to evaluating these hypotheses.

In this proposal, therefore, we aim to show that:

1. Glacial-geological and geochronological observations from so far nearly unstudied sites in northern Victoria Land can provide important constraints on ice thickness changes, and therefore also on the extent and timing of grounding line advance and retreat, in the western Ross Sea during the LGM that are not available from existing marine and terrestrial data sets;

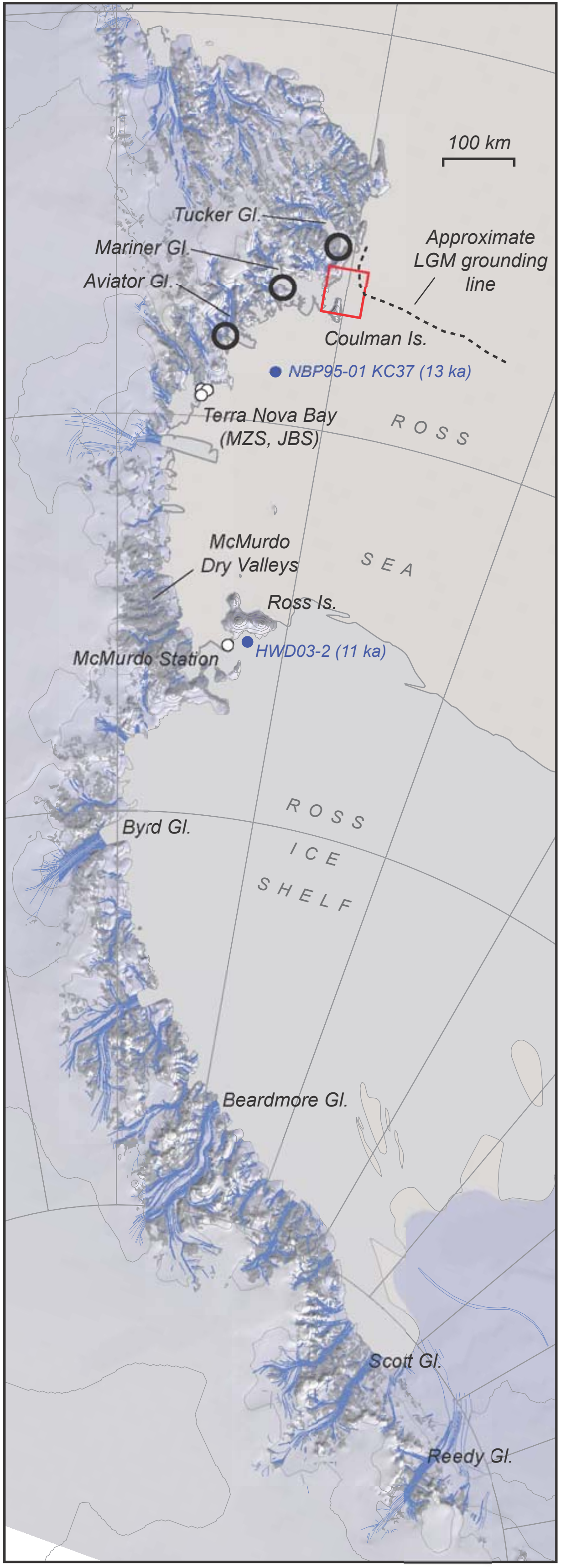
2. Available information about our proposed sites, evaluated in light of our and others' experience in similar past research, indicates a high likelihood that a recoverable record of ice sheet change exists at these sites; and

3. We have available to us adequate resources and strategies to overcome likely potential challenges imposed by geological and geomorphic factors at these sites.

Overall, we argue that the geological and geochronological data we seek to gather are valuable to not only the broad research objective of understanding past Antarctic ice sheet change, but also to specific and targeted questions regarding the relationship of rapid ice sheet and sea level changes. These data are important; obtaining them is feasible; and, in fact, we would be remiss in not exploiting all available sources of terrestrial geological data that might pertain to the important question of LGM ice sheet extent and thickness in the Ross Sea.

LAST GLACIAL MAXIMUM ICE SHEET CONFIGURATION IN THE ROSS SEA

Marine geophysical data and sediment cores provide the only direct constraints on the northernmost extent of LGM grounded ice in the Ross Sea. Multibeam bathymetry from cruise NBP98-01 (Shipp et al., 1999) shows north-south-trending seafloor lineations, interpreted as evidence of grounded Ross Sea ice, between Coulman Island and the mainland and extending ca. 30 km north of the northern tip of Coulman Island (Figure 1). Based on this observation, seismic-stratigraphic evidence of a depositional grounding-zone wedge near this position, and the sedimentology of nearby cores, Shipp et al. (1999) and Anderson et al. (2002) argued that the northernmost extent of the lineations was the terminal LGM grounding line position. Sparse multibeam coverage north of this zone displays iceberg furrows that may overprint glacial lineations, indicating the possibility of more extensive advances either early in the LGM or during previous glacial maxima (Shipp et al., 1999; Anderson et al. 2002). The trough offshore of Tucker Inlet shows east-west-trending glacial lineations, indicating presumable LGM advance of the Tucker Glacier grounding line onto the shelf, but it is unclear whether an expanded Tucker Glacier was confluent with



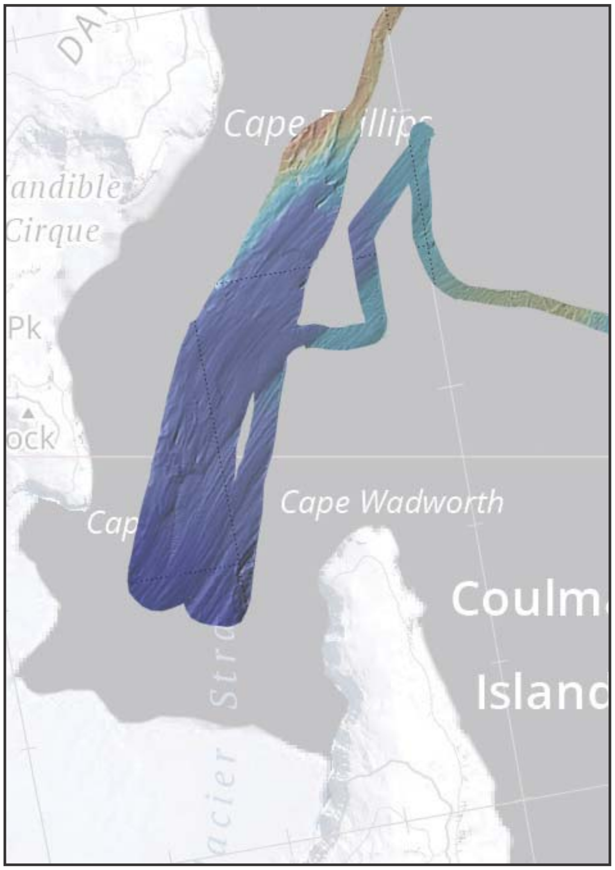


Figure 1. Left panel, map of the western margin of the Ross Sea and Ross Ice Shelf generated from the Antarctic Digital Database. The black circles show locations of proposed field sites at the mouths of large glaciers flowing through the Transantarctic Mountains into the Ross Sea. The blue circles show locations of marine sediment cores in the western Ross Sea that provide radiocarbon age constraints on LGM-to-present grounding line retreat. Accompanying ages are interpreted as dates that the site became free of grounded ice and are given in calendar years BP according to proposed age corrections in the source papers and the INTCAL09 calibration (Domack et al., 1999; McKay et al., 2008). Right panel, multibeam bathymetry collected on NBP08-01 (from GMRT synthesis via GeoMapApp) showing mega-scale glacial lineations whose northern margin is interpreted as the northernmost extent of grounded Ross Sea ice at the LGM (Shipp et al., 1999). Background image is Polar Geospatial Center Map ANT-REF-MS2006-006. Location of this panel is shown by the red box in left panel.

grounded Ross Sea ice. Also, the pattern of glacial lineations in this area is interpreted to indicate that the grounding line was strongly controlled by bathymetry, lying farther south in troughs than on intervening banks (Anderson et al., 2002). Radiocarbon ages on foraminifera from glaciomarine sediments near the continental shelf edge (Taviani et al., 1993) of ~25-40 ka are interpreted as evidence that at least some of the continental shelf remained free of grounded ice at the LGM. To summarize, it is highly likely that the LGM grounding line lay at least ~30-50 km north of Coulman Island, it may have locally advanced several tens of km farther, but it is unlikely that it advanced to the shelf edge.

The chronology of Ross Sea grounding line advance to its LGM position and subsequent retreat is based primarily on radiocarbon ages on the acid insoluble organic fraction of marine sediment core samples (Domack et al., 1999; Anderson et al., 2002; Licht and Andrews, 2002; McKay et al., 2008). Specifically, these studies attempted to date grounding line retreat from the core sites as recorded by a lithologic transition from subglacial to glaciomarine sediment; ages from the basal glaciomarine facies provide minimum limiting ages for deglaciation of the sites. These ages are subject to large corrections to account for the presence of recycled carbon in the acid insoluble fraction, but many ages from the central and outer Ross Sea show that glaciomarine conditions prevailed well south of Coulman Island at 11-13 ka (Domack et al., 1999; Licht and Andrews, 2002; McKay et al., 2008; see Figure 1. Note that all ages in this proposal are given in calendar years; we accept radiocarbon ages as computed in source papers and convert to calendar ages using the INTCAL09 calibration when required). Overall, the marine radiocarbon chronology clearly shows that significant retreat from the maximum LGM grounding line position took place before ca. 13 ka. On the other hand, it provides very few constraints on the timing of grounding line advance to its LGM position. Licht and Andrews (2002) proposed, based on ages of reworked foraminifera in till, that grounding line advance was not complete until after ca. 16.8 ka.

On land, glacial-geological and geochronological data from the coastal McMurdo Dry Valleys (Figure 1) record landward flow of thickened Ross Sea ice into this region during the LGM. Assuming that thickening of Ross Sea ice in the McMurdo region is associated with grounding line advance across the Ross Sea shelf and vice versa, these data provide an indirect record of overall grounding line advance and retreat. Many radiocarbon ages on reworked marine shells and fossil penguin eggshells (Hall and Denton, 2000; Emslie et al., 2007) indicate ice-free conditions in this region between ~45 and ~30 ka. Radiocarbon ages between 28-15 ka from lake highstand deposits in the Dry Valleys require impoundment of these lakes by thickened Ross Sea ice that blocked the seaward ends of the valleys (Hall and Denton, 2000). The youngest of these ages coincide with exposure ages on associated moraines, indicating the onset of ice surface lowering at 14-15 ka (Brook et al., 1995). Similar glacial-geologic observations near the present grounding lines of major glaciers that flow through the southern Transantarctic Mountains (Reedy, Scott, Beardmore, and Hatherton Glaciers; see Figure 1; Todd et al., 2010; Bromley et al., 2010; Bromley et al., 2012; Denton et al., 1989; Bockheim et al., 1989) as well as related exposure-age and radiocarbon chronologies (Todd et al., 2010; Bockheim et al., 1989) also record significantly thicker grounded ice in the Ross Sea at the LGM and document its subsequent thinning. These data from the southern Transantarctic Mountains are less directly relevant to the extent and thickness of grounded ice in the outer Ross Sea at the LGM that we focus on in this proposal, but are important because they demonstrate the effectiveness of the general strategy, that we propose to use in this project, of inferring the past ice thickness in the Ross Sea from glacial-geological records adjacent to inflowing glaciers.

To summarize, both marine and terrestrial data provide extensive evidence for changes in the past extent and thickness of grounded ice in the western Ross embayment, adjacent to the Transantarctic Mountains, from the McMurdo Dry Valleys-Terra Nova Bay region in the north to the Reedy Glacier in the south. Conway et al. (1999) and subsequently McKay et al. (2008) have used this information to assemble a chronology of ice sheet thinning and grounding line retreat in the western Ross embayment between ~13 ka – the deglaciation of the northernmost core thought to have a reliable radiocarbon chronology, between Coulman Is. and Terra Nova Bay -- and the late Holocene. The part of this story that is lacking, however, and that we propose to address in this proposal, is the question of what happened prior to ~13 ka when grounded Ross Sea ice lay near its maximum extent.

A ROSS SEA CONTRIBUTION TO MELTWATER PULSE 1A?

The importance of understanding changes in ice sheet extent and thickness in the Ross Sea prior to 13 ka has also been highlighted by recent research into the source of meltwater pulse 1A (MWP-1A), a rapid rise in sea level of ca. 14 m at approximately 14.6 ka. Carlson and Clark (2012) provide a detailed and comprehensive summary of this research. First, it is difficult to account for this amount of sea level rise by known meltwater inputs from Northern Hemisphere ice sheets, and, second, “sea-level fingerprinting” studies based on inversions of global relative sea level observations indicate a significant Antarctic source for this sea-level rise (Clark et al., 1996; Clark, 2002; Bassett et al., 2005; Carlson and Clark, 2012). As there is little evidence for significant ice surface lowering in inland regions of Antarctica during this time (Bentley et al., 2010, 2011; Stone et al., 2003; Price et al., 2007; Ackert et al., 1999), the outer and central Ross Sea represents one of the two regions of Antarctica where ice volume changes are most likely to have made a significant contribution to MWP-1A (the other is the Weddell Sea embayment). At present, geological and geochronological data are insufficient to evaluate the hypothesis that large changes in grounding line position and/or ice thickness, that contributed significantly to MWP-1A, occurred in the Ross Sea at 14.6 ka. Mainly, this is because nearly all geochronological data on the rate of grounding line retreat (from the marine radiocarbon record) or ice thinning (from the terrestrial record) are more recent than this. Exceptions are exposure ages recording the LGM highstand in the extreme southern Transantarctic Mountains (Reedy Glacier; Todd et al., 2010) and the radiocarbon record of thickening and thinning of Ross Sea ice in the coastal McMurdo Dry Valleys (Hall and Denton, 2000). However, these sites are far removed (~500 km or more) from the LGM grounding line position in the Ross Sea, and using these data to infer the LGM grounding line position or the ice thickness in the central and outer Ross Sea requires large model extrapolations.

The question of whether large ice volume changes in the Ross Sea occurred at 14.6 ka and contributed to MWP-1A is contentious and it is not the purpose of this proposal to assess the arguments on both sides of the issue in detail. Rather, the central premises of this proposal are: i) that understanding ice extent and thickness during the LGM in the outer Ross Sea is important; and ii) that the best way to address this issue with geological evidence is to obtain such evidence from sites that are as close as possible to the LGM grounding line position. Thus, we propose to locate sites in northern Victoria Land where large glaciers flow into the Ross Sea near the latitude of the LGM grounding line position inferred from marine-geological data. Guided by successful past studies at similarly situated glaciers in the southern Transantarctic Mountains, we will apply glacial-geologic mapping and cosmogenic-nuclide exposure-dating methods at these sites to reconstruct past ice thickness changes, thereby providing new constraints on ice extent and thickness in the adjacent Ross Sea.

A currently active Antarctic field project (ANT-1042974 to N. Lifton, ANT-1043485 to J. Curtice, ANT-1043517 to P. Clark, ANT-1043018 to D. Pollard) also aims to address the question of what happened in the central Ross Sea during MWP-1A by developing an improved exposure-age chronology of already well-mapped LGM deposits of Ross Sea drift at sites in the McMurdo Sound and Terra Nova Bay region. As discussed above, these sites provide important, but indirect constraints on LGM ice thickness changes in the outer Ross Sea. We view our present proposal as complementary to this research and argue that our approach of seeking out new terrestrial records to the north will provide additional important, and more direct, constraints on ice thickness and extent changes when the Ross Sea grounding line was near its LGM position.

POTENTIAL TERRESTRIAL GLACIAL-GEOLOGIC RECORDS FROM THE OUTER ROSS SEA

In this section, we describe our search for new sites in northern Victoria Land where suitable geological records might exist. Overall, we seek ice-free areas adjacent to major glaciers that flow through the eastern escarpment of the Transantarctic Mountains into the Ross Sea. As discussed above, this overall approach has been successfully applied at a number of sites in the southern Transantarctic Mountains. To evaluate the suitability of potential sites for this purpose, therefore, we used criteria developed from our and others’ past exposure-dating research in similar contexts (e.g., Stone et al., 2003; Todd et al., 2010; Ackert et al., 1999; Brook et al., 1995; Bentley et al., 2010; Bromley et al., 2012; Balco et al., 2013.). First, potential exposure-dating sites should be as close to the glacier of interest as possible; this ensures that evidence of past ice margin changes at the site will be directly related to ice thickness changes in the main glacier trunk rather than reflecting changes in the mass balance of smaller, locally derived glaciers or alpine snowfields. Second, proximity to a large trunk glacier thick enough to sustain melted and therefore erosive basal conditions allows a large supply of subglacially derived sediment that may be deposited in the form of moraines or drift. Smaller, higher, and thinner glaciers are more likely to be

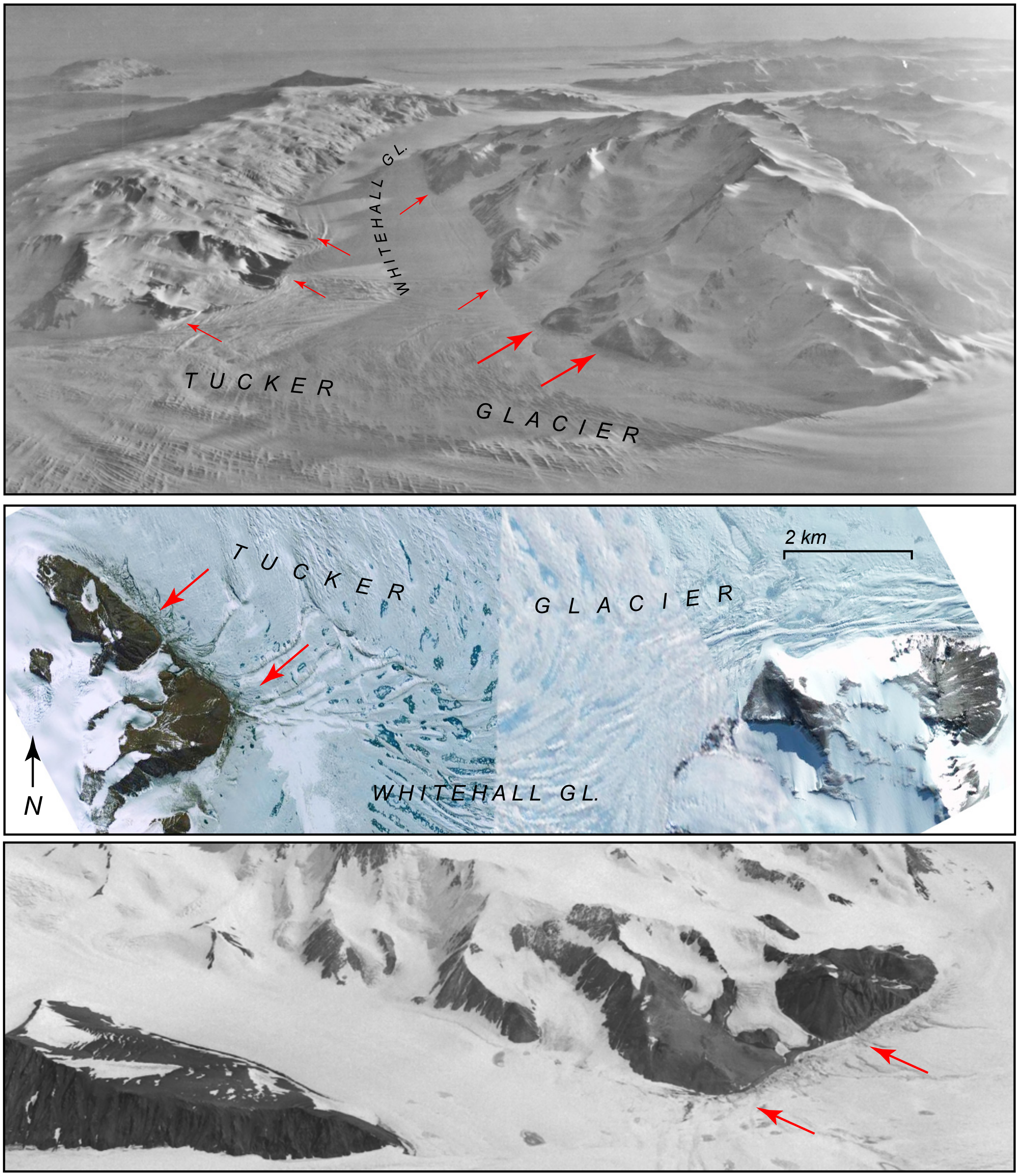


Figure 2. Ice-free areas near the confluence of the Tucker and Whitehall Glaciers. Top panel, U.S. Navy aerial photo TMA 1377, R128, looking south from the Tucker Glacier up the Whitehall Glacier. Coulman Island is visible in background at left. Middle panel, Google Earth image of the Tucker-Whitehall confluence. Lower panel, U.S. Navy photo TMA 346, L232, looking SW from the Tucker-Whitehall confluence. This shows a low-level moraine sequence of the Tucker Glacier, which is presumably part of the Whitehall Moraine of Harrington et al. (1963, 1968). The pair of thick red arrows in all images indicate the field area of primary interest; arrows point to same locations and have same orientation in all photos. The thinner arrows in the upper image point to other potential field sites of interest.

frozen to their beds, which decreases the available sediment supply. Third, ice-free areas must be relatively gently sloping so that moraines or drift can accumulate during ice surface lowering; steep and rugged outcrops are not conducive to the preservation of glacial deposits. Finally, it must be safe and logistically feasible to access the sites.

In northern Victoria Land between Terra Nova Bay and the likely LGM grounding line position north of Coulman Island, suitable major glaciers include, from north to south, the following (Figure 1): The Tucker Glacier flows into the Ross Sea ~60 km north of Coulman Island, slightly north of the proposed LGM grounding line position of Shipp et al. (1999) and Anderson et al. (2002); the Mariner Glacier flows into the Ross Sea adjacent to Coulman Island; and the Aviator Glacier flows into the Ross Sea south of Coulman Island and near the site of core NBP 95-01 KC37 (Domack et al., 1999), the northernmost extent of the existing marine radiocarbon chronology for grounding line retreat (McKay et al., 2008).

<u>*Tucker Glacier.*</u> A cluster of ice-free sites just upstream of the present grounding line of the Tucker Glacier, on the south side of the glacier at its confluence with the Whitehall Glacier, meets all requirements. These comprise several square km of ice-free area divided among several distinct nunataks (Figure 2). They are located in a region of blue ice with surface ridges and flow stripes indicating convergent ice flow, presumably the result of persistent ablation due to topographically controlled katabatic winds. Slopes of these nunataks are gentle and aerial photos indicate cover by a mixture of bare bedrock, colluvial deposits, patterned ground, and moraines (Figure 2).

The only visits to these sites that we are aware of were by i) the New Zealand Geological Survey Antarctic Expedition in the 1957-58 International Geophysical Year, who made a Sno-Cat and ski traverse from Cape Hallett Station across and up the Tucker Glacier (Harrington et al., 1963; 1967); and ii) a USGS field party that landed at or near the site by helicopter in 1964 (Crowder, 1968). The IGY party mapped the bedrock geology of the sites (granodiorite on the west side of the Whitehall Glacier; mafic volcanics on the east side) and also reported glacially transported erratic boulders at elevations up to 400 m on the north side of Tucker Glacier. At the south side, they reported a prominent moraine complex (the "Whitehall Moraine;" see Figure 2), "that appears to have been deposited by the Tucker ice stream." Although they did not report moraine elevations, they noted several distinct ridges or benches and speculated, presumably on the basis of weathering characteristics, that the highest was "as old as the last glaciation of the Quaternary." They did not report erratics above the moraine complex on the south side of the Tucker Glacier, although it is not clear whether or not they made an extensive search. The 1964 USGS group did not describe any surficial deposits. Based on satellite imagery, oblique air photos, and the traverse route of the IGY expedition, ice in the convergence zone of the Tucker and Whitehall Glaciers appears minimally crevassed. Thus, it is most likely feasible to access this site by Twin Otter landing on the Whitehall Glacier and foot, ski, or snow machine travel among the various nunataks.

To summarize, these sites are located in an area where first principles suggest a glacial-geologic record of past thickness changes of the Tucker Glacier, and observations from these sites indicate that such a record, comprising at least a moraine sequence and perhaps scattered erratics or drift at higher elevations, is in fact present. Access to this site appears feasible. As the Tucker Glacier discharges into the Ross Sea slightly north of the proposed LGM grounding line location based on marine-geophysical data, this is a potentially important site for constraining the location of the LGM grounding line. Mapping and dating the possibly extensive geologic record of glacier change at this site is a primary objective of our research plan.

<u>*Mariner Glacier.*</u> There are very few ice-free sites adjacent to the Mariner Glacier. Of these, the majority are steep bluffs lining the glacier trough. Many are overhung by ice cliffs and display evidence of rockfall. These are highly unlikely to accumulate or retain glacial deposits, and they are difficult and dangerous to access. The only potentially suitable site we have identified is along the southern edge of the Mariner Glacier near its confluence with the Meander Glacier (Figure 3). This site comprises five bare rock ridges mapped as granite or granodiorite of the Admiralty intrusive suite intruding metasediments of the Robertson Bay Group (Gair et al., 1969). The lower ends of these ridges appear coarsely streamlined, but are steep and air photos show no evidence of moraines or other glacial deposits.

We are not aware of any previous visits to these sites. For the most part they abut heavily crevassed glacier ice. Access by fixed-wing aircraft appears unlikely given imagery available to us; landing in uncrevassed areas at the center of the Mariner or Meander Glaciers would require extensive foot travel through heavily crevassed areas to access the sites. Thus, it appears most likely that safe and efficient access to this site would only be possible by helicopter. However, the site is 180 km from the nearest likely potential base for helicopter operations (Mario Zucchelli or Jang Bogo Stations at Terra Nova Bay).

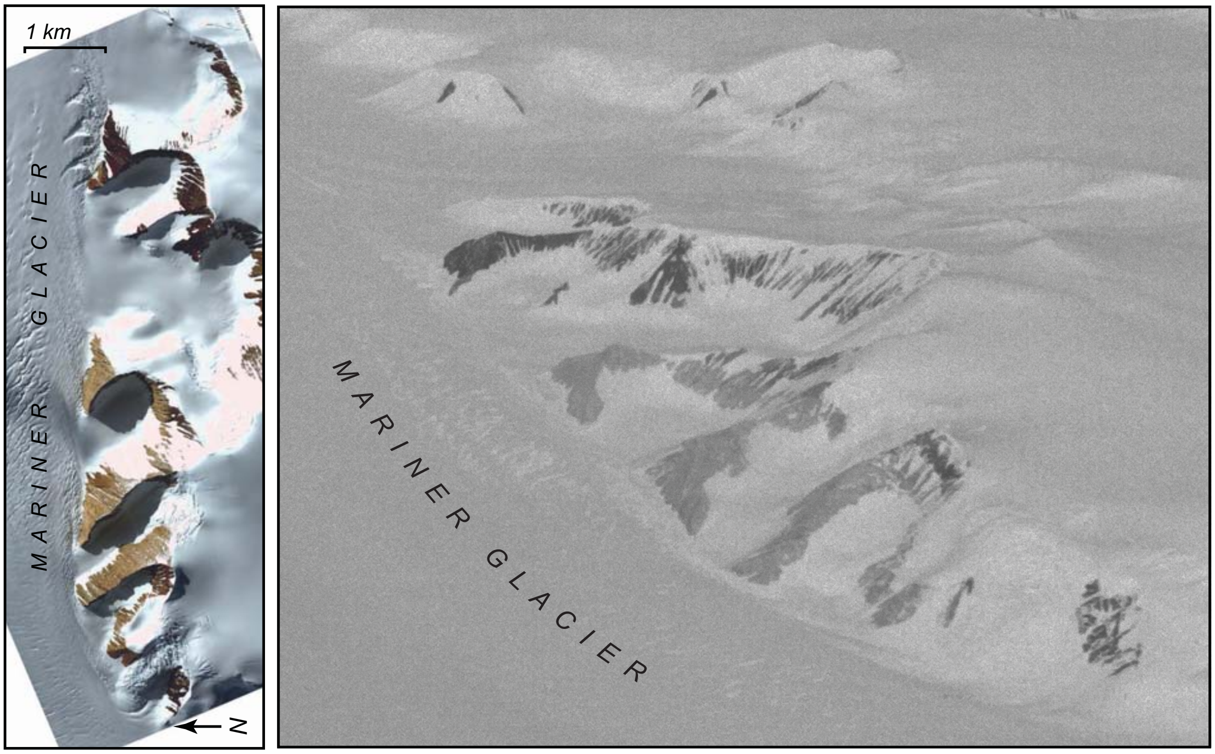


Figure 3. Ice-free sites at the southern margin of the lower Mariner Glacier (see Figure 1 for location). Left panel, Google Earth image. Right panel, U.S. Navy photo TMA 365, L220. The field sites of potential interest are the ridges that descend toward the glacier margin.

To summarize, this site is located in a potentially extremely valuable location for our proposed study, and appears to be the only site where terrestrial geological evidence for past changes in the thickness of the Mariner Glacier could be obtained. Given our proposed strategy of making cosmogenic ^{14}C measurements on bedrock samples (see discussion below), constraints on past ice thickness change could very likely be obtained from this site even in the absence of extensive glacial drift. However, given our present knowledge of available aircraft resources, we do not see that access to this site is possible. Thus, in the current proposal we have requested Twin Otter support for a reconnaissance flight to this site to gather more information about likely geological conditions and whether a landing is possible.

Aviator Glacier. The physiography of the Aviator Glacier is similar to that of the Mariner Glacier in that the majority of ice-free areas near the lower glacier are steep bedrock bluffs that are unlikely to either preserve significant accumulations of glacial drift or permit safe access. The exception is a ridge system, mapped as granitic rocks of the Granite Harbor Intrusives (Gair et al., 1969), that borders the southern side of the glacier near its present grounding line (Figure 4). This ridge system includes gently sloping and apparently coarsely streamlined bedrock terrain immediately adjacent to the glacier shear margin. We are not aware of previous visits to these sites. Available aerial and (low-resolution) satellite photos do not display obvious moraines, but the relatively gentle slope of these ridges and their location immediately adjacent to a large glacier indicates a high likelihood of drift and/or erratic deposition during times of glacier thickening. In addition, granite bedrock here would be amenable to our strategy of supplementing exposure ages on glacially transported clasts with cosmogenic ^{14}C measurements on bedrock samples (see discussion below).

Apparently uncrevassed snowfields outboard of the Aviator Glacier shear margin separate the various ridges at this site. It appears possible that the largest of these snowfields would be suitable for a Twin Otter landing. In addition, this site is 85 km from Mario Zucchelli and Jang Bogo Stations at Terra Nova Bay, so helicopter access to this site would be possible if based out of these stations. As we have not yet initiated discussions with Italian or Korean scientists regarding potential collaboration to facilitate this, our logistics request includes three days of Twin Otter support for i) a reconnaissance flight, and ii), if a landing is feasible, two day trips for mapping and sample collection.

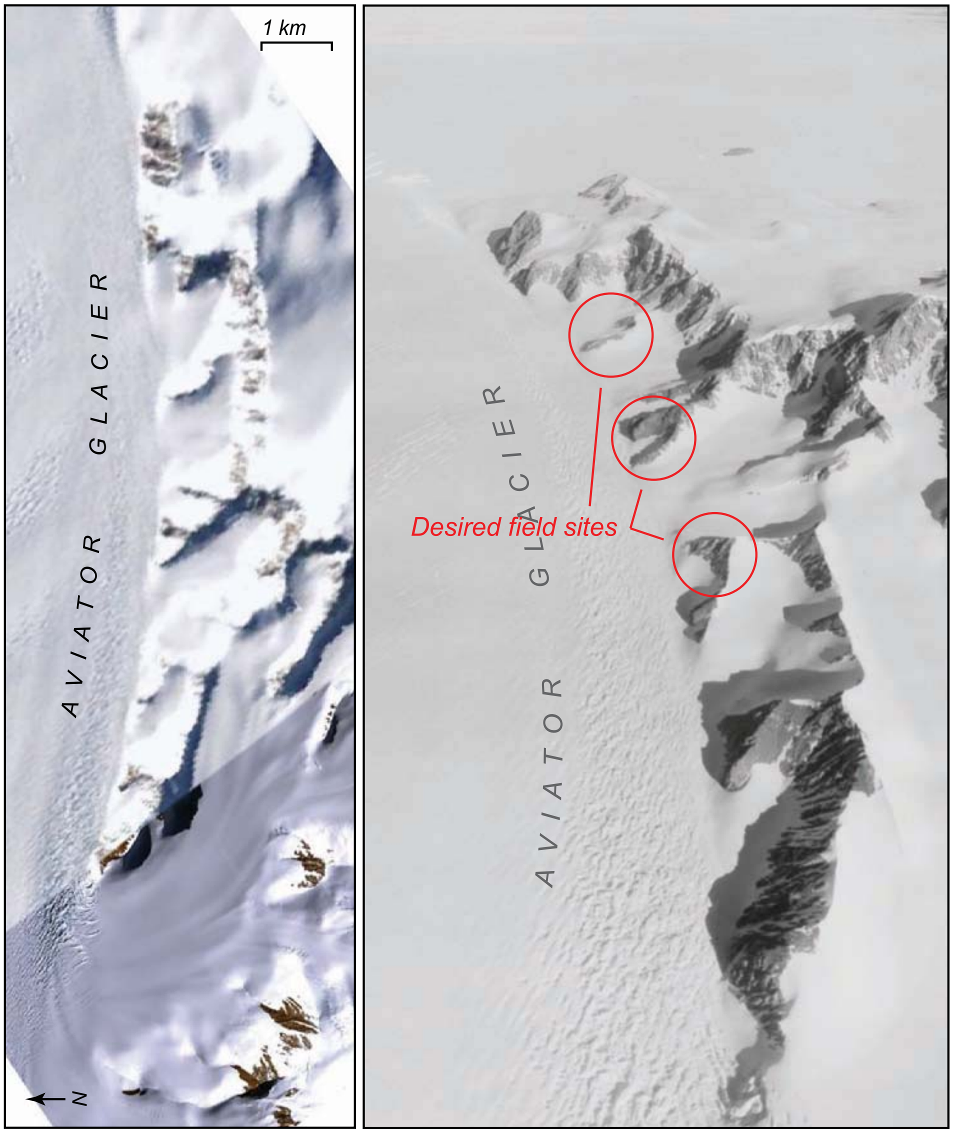


Figure 4. Ice-free areas at the southern margin of the lower Aviator Glacier. Left panel, Google Earth image. Right panel, U.S. Navy photo TMA 442, L351. View is from west to east: the Aviator Glacier flows toward the Ross Sea in background. The landward end of the Aviator Glacier Tongue is visible at upper left in the photo.

To summarize, this site occupies an important location for obtaining an exposure-age record of ice thickness change in the Ross Sea near the northernmost extent of the existing marine radiocarbon chronology of grounding line retreat. A record of past ice thickness change at the mouth of the Aviator Glacier, dated by a method completely independent of radiocarbon dating of marine sediments, would be an extremely valuable complement to the marine chronology. Access to these sites appears possible. Although we are not aware of any evidence as to whether or not glacial deposits are present at this site, its overall physiography appears favorable for their accumulation.

RESEARCH STRATEGY: GLACIAL-GEOLOGIC MAPPING AND EXPOSURE DATING

Our research strategy at these sites will consist of i) locating and mapping glacial landforms and deposits indicative of past thickness changes in the glaciers bordering the sites; and ii) determining their age. In the mapping portion of the project, we will use standard geomorphic and sedimentological field methods to locate, describe, and map glacial landforms and surficial deposits (e.g., Todd et al., 2010; Bromley et al., 2010; 2012). The geochronological part of the project will primarily utilize cosmogenic-nuclide exposure-dating methods. These methods rely on the fact that the majority of rock debris carried by Antarctic glaciers is derived from subglacial erosion of deeply exhumed bedrock surfaces that have not experienced geologically recent exposure to the surface cosmic ray flux. When this material is carried to glacier margins and exposed by ice surface lowering, it becomes newly exposed to the surface cosmic ray flux. Cosmic-ray interactions with minerals containing suitable target elements (the most commonly used of which is quartz) then cause accumulation of trace nuclides within the mineral crystal lattice, for example ^{10}Be, ^{3}He, and ^{14}C, that are diagnostic of cosmic ray exposure. As the production rates of these nuclides are known, their concentration provides an estimate of the age since the rock samples in question were exposed by ice surface lowering. Balco (2011) gives a detailed summary of the method and its application to glacial chronology in Antarctica and elsewhere. In favorable circumstances, therefore, cosmogenic-nuclide exposure ages of glacially transported clasts from a particular nunatak display older exposure ages with increasing elevation, and the age-elevation array records past ice sheet thinning at that location (e.g., Stone et al., 2003).

The chief potential complication with this method is that of cosmogenic-nuclide “inheritance,” or “prior exposure.” Past studies have found that many erratic and bedrock samples from Antarctic nunataks contain larger cosmogenic-nuclide inventories than can be accounted for by the time since they were most recently exposed by ice retreat (e.g., Stone et al., 2003; Sugden et al., 2005). This is also common in the Arctic (e.g., Briner et al., 1996; Goehring et al., 2008). It occurs because much of the Antarctic ice sheet is frozen to its bed, so subglacial erosion is negligible during periods of ice cover. Thus, the cosmogenic-nuclide concentration in bedrock surfaces continues to increase during ice-free periods, but is never reset by subglacial erosion. In addition, glacially transported clasts deposited during one ice-free period can remain in place while covered by frozen-based ice and emerge again during subsequent interglaciations; alternatively, they can be re-entrained by overriding ice and exposed again on a different nunatak. Our goal in this project is to reconstruct the most recent deglaciation in our field area, so erratics with prior exposure would present a serious complication. However, many previous exposure-dating studies provide clear guidance on how to deal with this issue, as follows.

First, these studies have shown that the proportions of “fresh” erratics -- whose exposure ages record the most recent deglaciation -- and “pre-exposed” ones have a clear relationship to the glaciological context of a site. For example, in the Ford Ranges (Stone et al., 2003), the exposure-dating sites bordered the lower reaches of major through-flowing glaciers (the Boyd and Arthur Glaciers) draining the entirely-ice-covered interior of Marie Byrd Land, and the relative frequency of pre-exposed erratics was relatively low (88% of erratics analysed in the entire study had Holocene exposure ages). In the Marble Hills (Todd et al., 2005), on the other hand, the exposure-dating site lay well inland, adjacent to locally derived ice draining nearby higher elevations in the Ellsworth Mountains. At this site, only 38% of erratics had Holocene exposure ages. In the present project, we are guided by these and similar studies in selecting target sites at low elevation near the termini of major glaciers flowing in deep troughs. These characteristics act to maximize the likelihood that thickened LGM ice removed deposits of past interglaciations, and also maximize the chance that erratics delivered to the site will have originated in regions of active subglacial erosion.

Thus, our first strategy to address the issue of prior exposure is to select sites where past research suggests that it will be minimized. However, at one of our sites (at the Tucker-Whitehall confluence), air photos show, in addition to bare rock surfaces, talus, colluvium, and patterned ground adjacent to the ice margin. This suggests that if LGM ice covered the site (which, of course, remains to be established) it was frozen-based and did not remove pre-existing surficial deposits. In that case we would expect to find multiple superimposed generations of glacial drift, and to face the challenge of distinguishing among them to generate an exposure-age record of the most recent deglaciation, rather than some previous one. We have three field and analytical strategies for addressing this challenge. The first one is based on the results of past exposure-dating studies that analysed a large number of erratics in elevation transects from single nunataks. These results typically show an array of Holocene exposure ages that define a monotonic age-elevation relationship, and a scatter of older ages that show no such relationship (Todd et al., 2005; Stone et al., 2003; Bentley et al., 2010, Balco et al., 2013; Todd et al., 2010). This is expected if the youngest erratics that record the most recent deglaciation are linked by a common age-elevation relationship, but the others may have survived varying durations of ice cover or been initially exposed at other sites. The large number of samples analysed in these studies lends confidence to this interpretation. We will follow this strategy in the present study, with the goal of collecting enough data that we can clearly identify an array of samples that define the most recent deglaciation. Previous work suggests that this requires ~10-15 exposure ages in each elevation transect.

Our second strategy for addressing the issue of inheritance is borrowed from that of Ackert et al. (2007), who used an analytical strategy to weed out pre-exposed erratics. They collected samples from a high elevation, inland site near an ice divide, where bedrock surfaces were deeply weathered and showed little evidence of subglacial erosion. Based on the considerations above, they anticipated that most erratics would be pre-exposed. They used a two-tiered analytical strategy in which they began by measuring cosmogenic ^{3}He in quartz, which is rapid and inexpensive, but imprecise due to temperature-dependent diffusive loss of He. This served as a rapid-screening method to weed out samples with ages significantly older than the LGM. In agreement with expectations from the geomorphic and glaciological characteristics of the site, they found that 95% of erratics had prior exposure. They then made precise, but more time-consuming and expensive, ^{10}Be measurements only on the resulting pre-screened set of samples. We have recently used this strategy in an exposure-dating project in the Pensacola Mountains (see Results of Prior Research below) and we have included a budget for ^{3}He measurements so that we can apply it in the present project as well.

Our final strategy involves measurements of in-situ-produced cosmogenic ^{14}C in bedrock surfaces. Like the commonly used cosmic-ray-produced radionuclides ^{10}Be and ^{26}Al, ^{14}C is produced in situ in the quartz mineral lattice by high-energy neutron spallation (Lifton et al., 2001 and references therein). However, its half-life is two orders of magnitude shorter (5730 years compared to 0.7 and 1.4 Ma for ^{26}Al and ^{10}Be respectively). This is important because cosmogenic ^{14}C concentrations in bedrock surfaces retain less “memory” of past periods of exposure and burial than do longer-lived nuclides. In many cases, the majority of the ^{10}Be inventory in bedrock surfaces or erratics that have been repeatedly exposed and covered by frozen-based ice reflects periods of exposure prior to the current one. Because of its short half-life, this is not the case for ^{14}C (e.g., Miller et al., 2006; Briner et al., 2013 in press).

Figure 5 shows this relationship. Given continuous exposure for several times the ^{14}C half-life (> ~30,000 years), cosmogenic ^{14}C concentrations in quartz in a bedrock surface will reach an equilibrium concentration where production is balanced by decay and loss to surface erosion. At the low bedrock surface erosion rates observed in Antarctica (ca. 0.2-2 m/Myr; see Balco and Shuster, 2009), this equilibrium concentration is only weakly dependent on the erosion rate (varying the erosion rate within these bounds has only a 3% effect on the concentration). In this project, we are interested in determining whether ice-free sites were ice-covered at the LGM. If they were not, they would have experienced continuous exposure for at least the last ~30,000 years, and quartz in bedrock surfaces would display cosmogenic ^{14}C concentrations at steady state with respect to the production rate at the sample elevation (Figure 5). Note that the elevation dependence of the steady state ^{14}C concentration in quartz in Antarctica has been directly measured in the Antarctic Dry Valleys (N. Lifton and CRONUS-Earth project, personal communication), so potentially uncertain scaling extrapolations to estimate this value are minimized. If the samples did experience ice cover for a time at the LGM, even if no subglacial erosion took place, ice cover exceeding several meters thickness would halt nuclide production, and the ^{14}C concentration would be reduced by radioactive decay. If deglaciation occurred at ca. 15 ka, the subsequent time would not be sufficient to re-establish steady state, so an elevation transect of ^{14}C concentrations in quartz in bedrock would show a discontinuity at the maximum elevation reached by the LGM ice surface (Figure 5). White et al. (2011) described a similar approach, although it is important to note that our approach involves identifying a discontinuity in a ^{14}C elevation transect rather than comparing a measured ^{14}C/^{10}Be ratio to the (relatively uncertain) production ratio. Thus, their statement that one cannot detect periods of ice cover prior to ~15 ka does not apply to our proposed approach.

This aspect of cosmogenic ^{14}C systematics is extremely important for the present proposal because the sites we propose to visit are small in area and, except in the case of the Tucker-Whitehall Glacier sites, we do not know whether any glacial deposits will be present. Thus, given the high likelihood that the longer-lived nuclides in bedrock surfaces will show significant prior exposure, in the absence of glacial deposits it might not be possible to generate a chronology of the most recent deglaciation using ^{10}Be or ^{26}Al. However, mapped bedrock lithologies (granite and granodiorite of the Admiralty intrusives and quartz-rich metasediments of the Robertson Bay Group; Gair et al., 1969; Harrington et al., 1968; Sturm and Carryer, 1970) indicate that we can collect elevation transects of cosmogenic ^{14}C measurements in quartz from bedrock at each site. Given only these data and no other information, we can use the approach outlined in Figure 5 to estimate the maximum ice thickness reached during the LGM, which fulfills one important goal of this proposal. In addition, if we can also obtain an independent chronology of glacier thinning using ^{10}Be in glacially transported clasts, comparison of ^{10}Be and ^{14}C concentrations may permit estimating the timing of glacier thickening prior to the LGM using the method of "burial dating" with the ^{10}Be/^{14}C pair (the feasibility and precision of this approach depends on the actual timing of events, which we do not know in advance; see Goehring et al., 2013a; Goehring et al., 2011; White et al., 2011). Overall, including cosmogenic ^{14}C measurements in this project requires significant additional resources, but we view it as extremely important in i) mitigating the risks inherent in visiting small sites where we are unsure if a sedimentary record of past glacier advance and retreat exists, and ii) potentially allowing reconstruction of both glacier thickening prior to the LGM and thinning after the LGM.

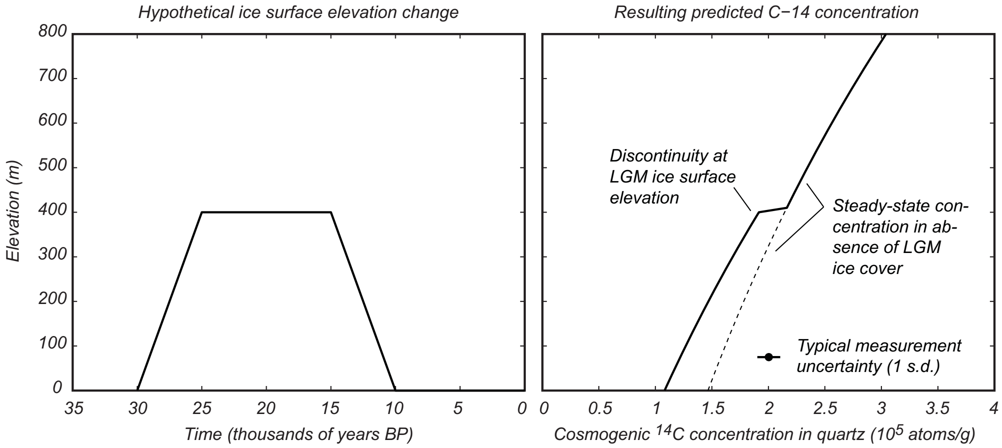


Figure 5: Predicted elevation dependence of the cosmogenic ^{14}C-in-quartz concentration in bedrock partially ice covered at the LGM. Ice thickness change history at left implies ^{14}C concentrations in right panel. A discontinuity between steady-state and sub-steady-state concentrations indicates the maximum elevation of LGM ice cover.

To summarize, many previous studies involving exposure-dating of Antarctic glacial deposits indicate that the key challenge we are likely to face in this project is that of prior cosmic-ray exposure due to recycling of previously exposed glacial deposits and preservation of repeatedly exposed surface materials by non-erosive, frozen-based ice during glacial periods. This creates a risk that we might not achieve our primary goal of developing an exposure-age chronology of LGM-to-present glacier change at our sites. However, as described above, these studies also provide extensive guidance in how to mitigate this risk. Our research plan is designed to take advantage of this guidance and, in addition, employ the relatively newly developed technique of in-situ-produced cosmogenic ^{14}C measurements to reduce the risk further. Overall, we argue that even in the unfavorable case of a sparse sedimentary record and significant prior exposure, these strategies will deliver new information about the extent and timing of LGM-to-present glacier change at our sites, and thus important constraints on ice thickness and extent in the outer Ross Sea during the LGM.

RESEARCH PLAN AND DIVISION OF RESPONSIBILITIES

Personnel. Personnel involved in this project include co-PIs Greg Balco (Berkeley Geochronology Center), Claire Todd (Pacific Lutheran University), and Brent Goehring (Purdue University); an undergraduate from Pacific Lutheran University who will participate in fieldwork and other aspects of the proposed research as discussed below; and a field mountaineer. Balco and Todd are knowledgeable in glacial geology and geomorphology as well as cosmogenic-nuclide geochemistry. They have six and four field seasons, respectively, experience in geologic and geochronologic fieldwork, similar to that proposed here, in remote regions of Antarctica. Goehring is also a specialist in geologic and geomorphic applications of cosmogenic-nuclide geochemistry, and is particularly important to this project because of his expertise in analysis of cosmogenic ^{14}C in quartz, expertise which is only shared by a few researchers in the US. He has not previously conducted fieldwork in Antarctica.

In addition, Dr. Nat Lifton is a co-PI of the Purdue University portion of this proposal with Goehring. This is necessary because Goehring has a postdoctoral appointment at present (a promotion to research scientist is expected to take effect before the proposal start date), and Purdue administrative policies do not permit a sole co-PI with this status. Thus, Lifton's participation in the proposal is budgeted at the minimum level necessary to comply with these administrative requirements.

Fieldwork. We propose a single Antarctic field season. All five project personnel will participate in fieldwork. The primary focus of the field season will be to map surficial deposits and collect exposure-dating samples in the Tucker Glacier - Whitehall Glacier confluence region. Available aerial and satellite photo coverage, as discussed above, indicates to us that a Twin Otter landing on the Whitehall Glacier is feasible, and that the Tucker-Whitehall convergence zone is relatively uncrevassed and will permit foot or snow machine travel between ice-free areas on both sides of the Whitehall Glacier. Thus, we propose to establish a field camp at this site, with access by Twin Otter, for a four-week season.

Our secondary objectives will be to conduct reconnaissance fieldwork at the Mariner Glacier and Aviator Glacier sites. As described above, access to the Mariner Glacier sites does not appear feasible without helicopter support, so in this proposal we have requested only Twin Otter time for a reconnaissance flight to determine whether a landing is possible and, if possible, gain information about whether glacial deposits are present. At the Aviator Glacier sites, a Twin Otter landing appears potentially feasible on snowfields near the outcrops of interest, and the sites are within helicopter range of manned stations at Terra Nova Bay. In addition, the relatively gently sloping bedrock areas at this site, where we expect a potential record of glacier change to exist, are small enough to permit reconnaissance mapping and sample collection in day trips. Thus, pending logistical review of this proposal, we have requested three days of Twin Otter support for reconnaissance and day trips to these sites.

Sample analysis. Analytical work for this project will occur upon completion of fieldwork and throughout year 2 of the project, and is likely to involve measurements of cosmogenic ^{3}He, ^{10}Be, and ^{14}C in quartz.

Sample preparation for ^{3}He measurements involves only crushing of rock samples and handpicking of ~0.25 g of quartz (or other target mineral), which is most likely straightforward in the lithologies we expect to encounter. ^{3}He extraction and analysis employs laser heating under vacuum and analysis in a noble gas mass spectrometer; two such systems are available at BGC (see Facilities and Resources). Thus, Balco, Todd, and Todd's undergraduate student will carry out initial sample preparation tasks at PLU and BGC, and Balco will perform ^{3}He measurements at BGC.

^{10}Be measurements include more extensive sample preparation to isolate large samples (~20 g) of pure quartz, followed by wet chemical extraction of Be and analysis by accelerator mass spectrometry (AMS). Balco, Todd, and Goehring are all experienced at these tasks. In this project, Balco will have primary responsibility for carrying out sample preparation and Be extraction at wet chemistry laboratories located at BGC and UC-Berkeley, and AMS analysis will be carried out at the Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory. At the exposure ages we expect to measure in this project (late glacial and early Holocene), expected ^{10}Be concentrations are two to three orders of magnitude above typical analytical blanks, and analyses are thus expected to be routine.

Cosmogenic ^{14}C measurements use the same pure quartz separate prepared for ^{10}Be measurements, followed by vacuum heating, purification of evolved CO_2, and AMS analysis (Lifton et al., 2001). This will take place in an extraction line constructed for this purpose by Goehring and Nat Lifton at Purdue. AMS analysis for ^{14}C will be carried out at the Purdue Rare Isotope Measurement Laboratory. Past performance of the extraction procedure and estimated ^{14}C concentrations in the samples we propose to collect imply likely measurement precision of ~5-8% (see Goehring et al., 2013b).

Supporting research and analysis. Supporting research and analysis tasks in this project involve mapping and GIS analysis and lithologic and sedimentological analysis of surficial deposits. This will be primarily focused at PLU and will employ GIS facilities there; the undergraduate researcher at PLU will take responsibility for part of this work under the close mentorship of Todd.

Glaciological model interpretation. The ultimate goal of this project is to use records of glacier thickness change near the mouths of major glaciers flowing into the Ross Sea to gain information about the past thickness of Ross Sea ice. Relating these two things requires a physically based glacier modeling strategy. To accomplish this for the data we propose to generate in the present project, we will use a steady-state, flow-band model developed by Claire Todd and others, previously applied to the similar problem of inferring ice thickness in the southern Ross Sea from exposure-age data at Reedy Glacier (Todd et al., 2005; Todd et al., 2007) and also to glaciers in the Pensacola Mountains (Hegland et al., 2012). Claire Todd will have primary responsibility for this part of the project. In previous Antarctic research, she has successfully involved undergraduate students in working with the flowline model (see results of prior research below), and we anticipate this would continue in the present project. The data we propose to generate in this project will be from one site on each glacier, so is not expected to support, by itself, well-constrained model inversions for past glacier profiles. Instead, our objective is simply to use physically justifiable reasoning to quantitatively estimate the range of ice surface elevations and/or grounding line positions in the Ross Sea downstream of our sites that is compatible with our observations given expected past changes in sea level and surface mass balance. Overall, this project is strongly focused on data collection, and our modeling efforts will be secondary to the primary goal of collecting geological and geochronological data; however, some element of model interpretation is required to ensure quantitatively reasonable interpretations. In addition, we note that the currently active project of Clark, Lifton, Curtice, and Pollard (described above) already includes a large modeling component directed at reproducing past ice sheet changes in the entire Ross Sea catchment. Their work will produce model predictions that can be directly compared with the data that we propose to generate.

Undergraduate education and research. As described in more detail below, this project will support Claire Todd's ongoing program of undergraduate education and research in glacier change. Thus, one member of the project team will be a PLU undergraduate who, under Todd's supervision, will participate fully in preparation for fieldwork, fieldwork, sample preparation and geochemical analysis, and data analysis. To accomplish this, we have budgeted: i) to include the undergraduate in Antarctic fieldwork; ii) for the undergraduate to travel to BGC and/or Purdue to participate in sample preparation and learn about cosmogenic-nuclide measurements; and iii) to present the results of an independent research project at a national scientific meeting. These goals are modeled on successful similar work in prior Antarctic research (see below).

POTENTIAL OUTCOMES: INTELLECTUAL MERIT

The primary outcome of this project will be to improve understanding of a period of Antarctic ice sheet history that is i) relatively unconstrained at present; and ii) potentially extremely important in understanding past ice sheet-sea level interactions. In particular, the data we propose to gather can be used to address the general question of how the Antarctic ice sheet behaved at last-glacial-maximum conditions, and the specific question of whether or not ice volume changes in the Ross Sea contributed to rapid sea level rise during MWP-1A.

POTENTIAL OUTCOMES: BROADER IMPACTS

The primary broader impact of this project is that it will support Claire Todd's ongoing program of undergraduate education and research in the field of glacier change. Todd is a tenure-track professor at Pacific Lutheran University (PLU), a liberal arts college focused primarily on undergraduate education of a socio-economically diverse group of students, 25% of whom are first-generation college students, 25% of whom are from low-income backgrounds (per FAFSA classification), and 97% of whom receive some form of financial aid. PLU has an institutional commitment to recognizing the unique and specific obstacles that first-generation and low-income college students face in navigating the new world of college, and acting intentionally to connect these students with the resources they need. PLU also maintains a close relationship to the neighboring Joint Base Lewis-McChord, serving veterans in matriculating and non-matriculating programs, and partners with the US Department of Veterans Affairs to offer full-tuition to veterans through the Yellow Ribbon Program. The PLU Geosciences Department has graduated several veterans in recent years.

For the past six years, Todd has focused her teaching and student mentoring at PLU around research in glacier change in Antarctica, in the Peruvian Andes, and in the Pacific Northwest. During this period, she has supervised 18 students in summer and academic-year research projects on glacier change, glacier hydrology, and glacier-climate interactions both in the Washington Cascades and Mount Rainier, and in previous Antarctic research (see results of prior research below). This overall program is the foundation for independent research projects for the students and provides locally and globally relevant source material for courses in geoscience, environmental science, and meteorology.

The present project would support this ongoing research program by providing an opportunity for PLU undergraduates to participate in Antarctic glacier change research. It would offer a rare opportunity to involve undergraduates in many different aspects of the scientific process: preparing for fieldwork; glacial geologic mapping and sample collection in the field; interpreting glacial-geologic data, comparing data with quantitative model predictions; and presenting results at a national conference. Undergraduate participation in this project would also be supported at the departmental and division level at PLU via the senior capstone research project requirement in the Geosciences department as well as the opportunity to interact with a broader community through a summer program in PLU's Division of Natural Sciences.

To summarize, this aspect of the project would support i) undergraduate education and research; ii) early career faculty development; and iii) outreach, through PLU's institutional focus on socio-economic diversity, to students from backgrounds underrepresented in the geosciences.

An additional potential broader impact of this proposal will be to bring Brent Goehring, an early-career researcher with world-class expertise in cosmogenic ^{14}C analysis, into the Antarctic research commmunity. This technique offers potential extremely important advances in the overall field of reconstructing past Antarctic ice sheet change from geological and geochronological data.

RESULTS OF PRIOR RESEARCH

G. Balco and C. Todd*: Collaborative Research: Last Glacial Maximum and deglaciation chronology for the Foundation Ice Stream and southeast Weddell Sea Embayment.* PIs Greg Balco (BGC), Claire Todd (PLU), and Howard Conway (University of Washington). $681,620 among three institutions. 8/15/2009 - present.

This project involved two field seasons in the Pensacola Mountains, and its primary aim is to reconstruct LGM-to-present ice sheet change in the Weddell Sea sector of Antarctica by generating an exposure-age chronology for ice thickness changes at nunataks adjacent to the Foundation Ice Stream (FIS). So far we have exposure-age results from the Williams Hills, ~70 km upstream of the present FIS grounding line, and the Schmidt Hills, near the present grounding line. Results from the Williams Hills are straightforward and indicate an LGM ice surface elevation greater than 500 m above present, and 500 m of thinning between 11 ka and 5 ka (Figure 6).

Results from the Schmidt Hills are more complex. Based on field evidence at this site for the preservation of multiple generations of erratics by frozen-based ice during periods of ice cover, we applied the cosmogenic-^{3}He-in-quartz screening method described by Ackert et al. (2007). As expected, apparent ^{3}He exposure ages ranged widely between 2-200 ka. We then made cosmogenic ^{10}Be measurements in all samples (15) with apparent ^{3}He exposure ages less than 25 ka. Surprisingly, we found that samples with apparent ^{3}He exposure ages of 2-25 ka yielded ^{10}Be exposure ages between 0.2-1.6 Ma. Thus, we have not found any record of LGM ice cover or LGM-to-present deglaciation at this site. In light of the clear evidence for LGM ice cover and Holocene deglaciation 70 km away at the Williams Hills, this is confusing. Thus, the challenge in this part of the project is to attempt to discern whether or not the Schmidt Hills were covered by ice, and we are pursuing this further via: i) experiments to determine the diffusivity of ^{3}He in these samples and thus the possibility that poor ^{3}He retention is the result of long burial during periods of ice cover; and ii) possible cosmogenic radiocarbon measurements in collaboration with Brent Goehring at Purdue. Exposure-age samples from a third site, the Thomas Hills, an additional ~100 km upstream on the FIS, remain to be analysed.

A second focus of this project was to use both glaciological and ice-penetrating radar observations to learn about the dynamics of small glaciers and snowfields adjacent to our exposure-dating sample sites, with the idea of using these data to improve the interpretation of exposure-age data near the present ice margin as a record of recent ice sheet changes. These results have been reported in a paper (Campbell et al., 2013).

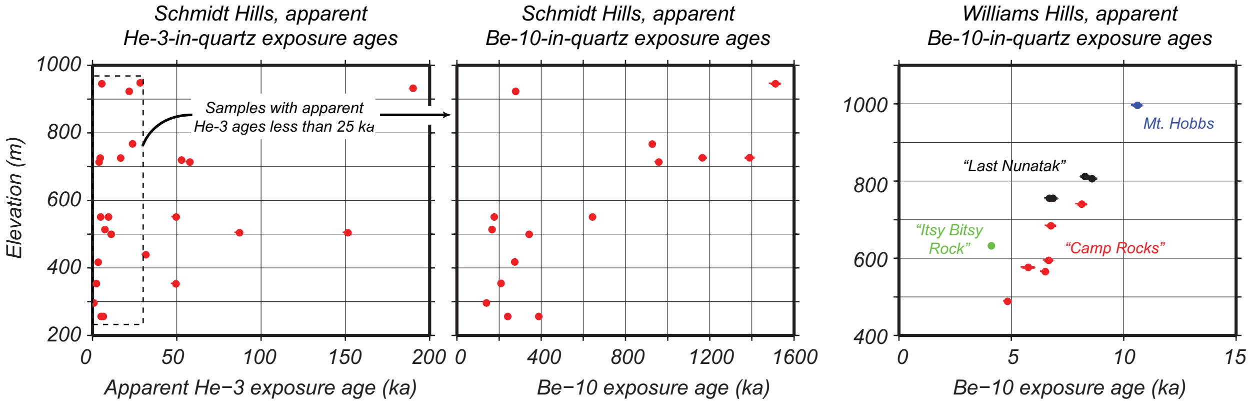


Figure 6. Exposure-age results from sites adjacent to the Foundation Ice Stream in the Pensacola Mountains. Left panel, apparent ^{3}He-in-quartz exposure ages from the Schmidt Hills. Middle panel, ^{10}Be ages on samples with the youngest apparent ^{3}He ages. Right panel, ^{10}Be exposure ages from the Williams Hills.

<u>*Intellectual merit:*</u> The exposure-age data so far generated by this project provide new information about LGM-to-present ice sheet change in the Weddell Sea region, an area where little such information is available and that contributes significant uncertainty in understanding the Antarctic contribution to past sea level change. The glaciological and radar-stratigraphic portion of the project may provide a foundation for possible future applications of the idea that the shallow stratigraphy of ice adjacent to nunataks may contain a record of past ice surface elevation change.

<u>*Broader impacts*</u>: Primary broader impacts of this project are in the areas of early-career faculty development, graduate student education, and undergraduate research and education. During the period of this project, co-PI Claire Todd transitioned from a temporary to a tenure-track position at PLU. The project provided primary support for University of Washington graduate student Kat Huybers and partial support for University of Maine graduate student Seth Campbell. It supported three undergraduate capstone research projects at PLU (two of which included participation in fieldwork). With one exception (Balco et al., 2012) all publications and abstracts resulting from this project so far have been student-authored (Vermeulen et al., 2011; Hegland et al., 2012a,b; Huybers et al., 2012; Campbell et al., 2013). Additional broader impacts included a range of K-12 outreach activities by Todd (in the Tacoma, WA region) and Campbell (in Maine).

B. Goehring: Goehring has not previously been a PI of NSF-funded research.

N. Lifton (see explanation above in 'Personnel' section): *Collaborative Research: Arctic sensitivity to climate perturbations and a millennial perspective on current warming derived from shrinking ice caps (1549864). Co-PI Nathaniel Lifton.* $123,251 (subcontract to U. Colorado). 09/01/2012-08/31/2015.

<u>*Intellectual Merit*</u>: Fieldwork as part of this award is scheduled to commence Summer 2013. In situ ^{14}C analyses under this grant will begin upon return from the field. As part of this work, a PhD student is compiling previously published exposure ages from Baffin Island and Greenland (see below).

<u>*Broader Impacts:*</u> A significant portion of a PhD student's training will be derived from this award, including training in in situ ^{14}C analyses by Lifton and Goehring. The exposure age compilation will also be of value to the broader community by compiling multiple decades of work in a consistent manner to foster comparison with other paleoclimate records.