NSFPLR-NERC: GEOLOGICAL HISTORY CONSTRAINTS ON THE MAGNITUDE OF GROUNDING LINE RETREAT IN THE THWAITES GLACIER SYSTEM

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1. SUMMARY. We propose to obtain geological evidence from the Thwaites-Pine Island glacier system (henceforth, the 'Thwaites system') that will show whether and when glaciers were less extensive than they are at present. This is important due to concern that currently observed grounding line retreat in the Thwaites system may be irreversible and lead to globally significant sea-level impacts. At present, evaluating this possibility relies on forward model predictions initialized with the current state of the glacier. In contrast, we aim to obtain information about past glacier changes that can show whether glaciers have been less extensive than they are at present under past climate states similar to or warmer than exist now, and, if so, under what conditions they readvanced. This will help to establish limits on the possible future behaviour of the glacier system, and also provide records of past glacier change that can be used as model validation targets.

First we will focus on Thwaites system glacier change during the last several thousand years. Existing geological evidence from ice-free areas in the region (discussed below) implies that glaciers were likely thinner than present during the last 5,000 years, presumably due to grounding-line retreat inboard of present positions, and subsequently readvanced and thickened to the present configuration. If this hypothesis is true, it implies that at least one grounding-line retreat episode that took place under climate conditions similar to present was, in fact, reversible. Determining whether this took place, and, by comparison to paleoclimate, paleoceanographic, and sea-level records, establishing under what boundary conditions it took place, is critically relevant to answering the question of whether or not present grounding-line retreat is irreversible and therefore to predicting the likely magnitude of future sea level rise from the Thwaites system. To achieve this, we will apply cosmogenic-nuclide exposure-dating of subglacial bedrock recovered by drilling. The presence of significant cosmogenic-nuclide concentrations in subglacial bedrock is direct, unambiguous evidence that the ice sheet was less extensive in the past, and provides evidence for when and how often this occurred.

We will also pursue two linked investigations. First, we will utilize raised shoreline and shallow-marine deposits in ice-free areas to reconstruct relative sea-level (RSL) changes during the past several thousand years in Pine Island Bay and adjacent areas. This information is necessary both in establishing boundary conditions for forward model simulations of present change and in evaluating the role of sea-level change in hypothesized coeval grounding-line fluctuations. Second, we will seek to obtain geological evidence for glacier changes in the more distant past, specifically addressing the question of whether or not irreversible grounding-line retreat in the Thwaites Glacier system took place during past Pleistocene interglacial periods when climate was likely similar to or warmer than present.

To summarize, in this project we will apply geologic investigations to establish boundary conditions necessary for forward model development (e.g., geologically recent sea-level changes) as well as past behavior of the glacier system useful for model validation and testing (e.g., limits on past glacier changes during climate states similar to or warmer than present). Our results will thus contribute to program themes 1, 2, and 4 ("Boundary conditions", "External drivers of change", and "Past change").

2. PAST GROUNDING LINE FLUCTUATIONS IN THE THWAITES SYSTEM. In this section, we describe evidence that grounding-line fluctuations in the Thwaites system took place during climate states similar to or warmer than the present, mainly focusing on the Holocene period (the last 11,700 years), during which surface climate in Antarctica was approximately similar to present. There are two sources of geological information about Holocene glacier changes in the region. First, the marine sedimentary record from the Amundsen Sea shelf shows that following the Last Glacial Maximum (LGM) ca. 15-25 ka (ka = thousands of years ago), grounding lines retreated to near present positions by 11.5-7 ka (Smith et al., 2011; 2014, Kirshner et al., 2012, Hillenbrand et al., 2013). However, with the exception that seafloor features beneath Pine Island Ice Shelf have been interpreted to suggest reduced late Holocene glacier extent compared with the present (Graham et al., 2013), existing data from the marine record provides little information on grounding line positions after 7 ka.

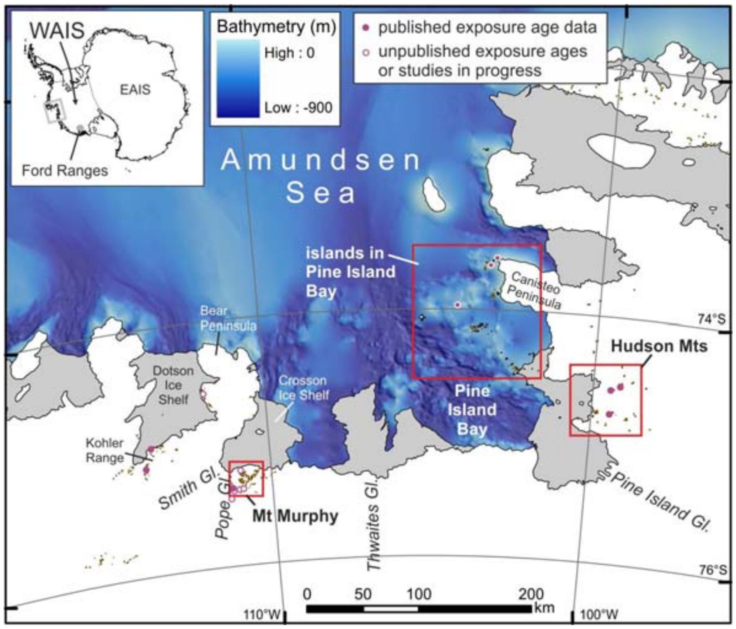

Figure 1. Map of Amundsen Sea Embayment showing locations mentioned in text and highlighting locations of previous glacial-geology and geochronology research in the region. Significant ice shelves are shown in gray. The red boxes show our proposed target areas for subglacial bedrock recovery and exposure-dating (Mt. Murphy and the Hudson Mountains) as well as relative sea-level reconstruction (islands in Pine Island Bay).

Second, glacial-geochronology studies at nunataks adjacent to lower Pine Island Glacier (Hudson Mts.: Johnson et al., 2014) and lower Thwaites and Smith Glaciers (Mt. Murphy area: Lindow et al., 2014; ongoing NERC-funded work by PIs Johnson and Rood) used cosmogenic-nuclide exposure-dating to reconstruct ice thickness change (section 4 below describes this method). Fig. 2 shows data from the Hudson Mts. and also from the only other sites along the outer coast of West Antarctica where enough data exist to reconstruct a continuous thinning history (the Ford Ranges to the west, bordering Sulzberger Bay; see Fig. 1 inset). All sites in coastal West Antarctica systematically show steady thinning during the early- to mid-Holocene, reaching present ice surface elevations between 3-6 ka, depending on the location. No site shows any record of late Holocene change. At other Amundsen Sea coastal sites, exposure ages have only been measured at single elevations, so do not provide continuous thinning histories (Johnson et al., 2008; Lindow et al., 2014), but all these ages are early Holocene as well (including ages for samples recently collected by Johnson adjacent to Pope Glacier). Overall, no record of late Holocene glacier change exists above the present ice surface anywhere in coastal West Antarctica.

There are two possible reasons that there is no such record. One, ice thicknesses did not change during the late Holocene. Two, ice was thinner than present during the late Holocene and subsequently thickened. In the latter scenario, a geologic record of late Holocene ice thickness change likely exists, but is hidden below the ice surface.

We argue that the second scenario is most likely. First, stable ice thickness for millennia appears unlikely given dynamic late Holocene boundary conditions, including RSL change forced by eustatic and glacioisostatic effects, climate and oceanographic changes (e.g., Walker et al., 2007), and changes in ice shelf extent elsewhere in Antarctica (e.g., Domack et al., 2005). Second, the expected relation between RSL and grounding-line position (RSL fall should cause grounding line advance; e.g., Gomez et al., 2010) suggests that the time delay between eustatic sea-level change and glacioisostatic rebound in the late Holocene would cause a grounding-line retreat-advance cycle. Water addition to the ocean due to deglacial ice sheet melt was essentially complete by ca. 5 ka (Lambeck et al., 2014), but isostatic rebound due to early Holocene ice loss in West Antarctica is still continuing (Groh et al., 2012; Whitehouse et al., 2012; Scheinert et al., 2016 also observed extremely high uplift rates at Mt. Murphy, but noted that Mt. Murphy is a volcano possibly subject to magmatic uplift). Thus, late Holocene RSL fall, which would favor grounding line advance, is expected at least locally in West Antarctica. In the Thwaites area, raised marine features in Pine Island Bay (see discussion below) imply late Holocene RSL fall.

Bradley et al. (2015) considered this scenario in detail for the Weddell Sea and found that a late Holocene retreat-advance cycle improved model-data agreement for GPS-measured uplift rates. Full-glacial-cycle ice sheet model simulations (generously made available to us by David Pollard and Lev Tarasov) show this "overshoot" behavior locally in marine embayments throughout Antarctica, in particular the Weddell Sea and the Siple Coast, but it has not to our knowledge been considered or modeled systematically for the Amundsen Sea region.

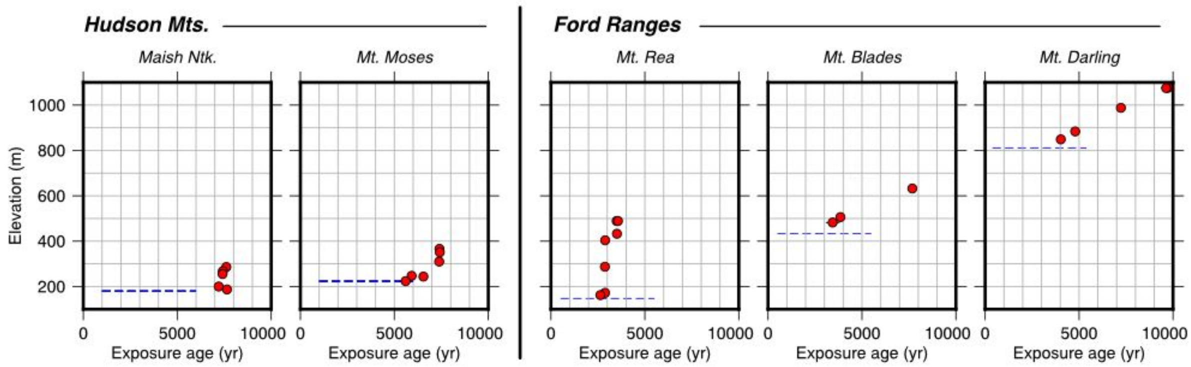

Figure 2. Exposure ages from ice-free areas along the outer coast (Pine Island Bay and Sulzberger Bay) of West Antarctica (Fig. 1). Hudson Mts. data from Johnson et al. (2014); Ford Ranges from Stone et al. (2003). Red circles, ^{10}Be exposure ages from glacial erratics. Blue lines, present ice surface elevation at each site. All sites show early Holocene thinning from a thicker LGM configuration, reaching present thickness 3-6 ka. However, there is no late Holocene record above the present ice surface anywhere in coastal West Antarctica.

To summarize, existing geologic evidence from ice-free areas in the Thwaites system and elsewhere in coastal West Antarctica suggests that glacier grounding lines in this region retreated inland of present positions in the late Holocene, under climate conditions similar to present, and subsequently readvanced. However, despite the importance of this possibility as an analogue for current grounding-line retreat, at present we have zero direct evidence for changes in thickness or grounding line position in the Thwaites system between the middle Holocene and the beginning of 20th-century satellite observations. This leads to the primary focus of this project on two questions. Did Thwaites system grounding lines retreat inland of their present position, and then readvance, in the last few thousand years? If so, how are these events related to potential sea-level or oceanographic forcings? We address the first question in objective 1 below. In objective 2 we will produce a record of Holocene RSL change. Reconstructing Holocene paleoceanographic changes that may have forced glacier change is not included in this proposal, because that is the subject of ongoing BAS research by J. Smith (NERC grant M013081/1) and is also an element of other proposals to the Thwaites program.

On a longer time scale, a large body of research, mainly ice sheet model simulations and inference from global eustatic sea-level data, focuses on the hypothesis that catastrophic grounding line retreat, potentially leading to total deglaciation of all marine-based parts of West Antarctica (so-called "collapse"), took place during Pleistocene interglacial periods when climate was similar to or warmer than present, specifically MIS 5 (~125 ka) or 11 (~400 ka) (summarized in DeConto and Pollard, 2016 and Dutton et al., 2015). Existing geologic evidence clearly requires grounding line retreat into interior West Antarctica at some time in the last ~750 ka (Scherer et al., 1998), but is equivocal as to when this took place or how extensive it was. Determining whether or not catastrophic grounding line retreat took place in West Antarctic marine embayments, including the Thwaites system, during interglacial periods is important in the present context because it establishes validation targets for model simulations that aim to use past interglacial climates as analogues for a warmer future (see, for example, Schaefer et al. 2016). Thus, in objective 3 below we focus on obtaining direct geologic evidence for thinning and grounding line retreat in the Thwaites system on a longer time scale than the late Holocene alone.

3. OVERVIEW OF RESEARCH OBJECTIVES. Our plan to investigate whether and when the Thwaites glacier system was less extensive than at present has three objectives, as follows.

Objective 1. To produce a chronological record of late Holocene ice thickness change. We hypothesize that if no geologic record of late Holocene ice thickness change exists above the present ice surface in coastal West Antarctica, it must be below the present ice surface. We will access this record using cosmogenic-nuclide exposure-dating of subglacial bedrock, using a drill system recently developed for this purpose, at two locations near present grounding lines in the Thwaites system. Thickness changes at these sites are likely to be dynamically linked to grounding-line positions of adjacent glaciers.

Objective 2. To produce a chronological record of RSL change during the Holocene. A record of past RSL variation constrains past ice mass change and is also an important boundary condition for modeling grounding line and ice thickness fluctuations leading to the modern configuration. Currently there is no RSL record for the Amundsen Sea Embayment. We will produce this record by mapping raised marine deposits on islands in Pine Island Bay and dating them using radiocarbon in fossil organic material.

Objective 3. To determine whether extensive grounding line retreat in the Thwaites system is unprecedented, rare, or common over multiple glacial-interglacial cycles. We will address this using cosmogenic-nuclide exposure-dating of subglacial bedrock at a site in the interior Thwaites catchment where (i) model simulations show that ice thickness is dynamically linked to the Thwaites grounding line position, and (ii) cosmogenic-nuclide concentrations in subglacial bedrock likely record evidence for glacier change over the past hundreds of thousands of years. Measurements of a range of cosmogenic nuclides will provide constraints on whether, when, and how often ice surface lowering due to grounding line retreat occurred in the past.

4. COSMOGENIC-NUCLIDE EXPOSURE-DATING OF SUBGLACIAL BEDROCK. We will use this technique in objectives 1 and 3. Here we summarize the method and the information that it can provide.

4.1. Overview. Cosmogenic-nuclide exposure-dating relies on the measurement of trace nuclides (in this project we will use ^{3}He, ^{10}Be, ^{14}C, ^{21}Ne, ^{26}Al, and ^{36}Cl), that are produced by cosmic-ray bombardment within rocks and minerals exposed at the Earth's surface. This method is commonly used to date glacial deposits exposed above the present Antarctic ice sheet, because significant production of these nuclides only occurs within a few meters of the Earth's surface, whereas glacially transported clasts are typically quarried at the glacier bed where they have not been exposed to the cosmic-ray flux. Thus, cosmogenic-nuclide concentrations in glacial deposits are proportional to the age of the deposit (see summaries in Dunai, 2010 and Balco, 2011). In the Thwaites system this method has been used to reconstruct early to mid-Holocene ice thickness change in the Hudson Mts. (Fig. 2). Also, a field project led by Johnson in 2015-2016 (NERC grant K012088/1) collected a similar set of samples at Mt. Murphy, adjacent to Pope and lower Thwaites Glaciers (Fig. 1), and analyses are in progress. Thus, although we propose to collect some additional exposure-dating samples from ice-free areas in Pine Island Bay and the Hudson Mts. to improve the existing data set, most exposure-age data that could potentially be collected from areas above the present ice surface in the Thwaites system have already been collected.

In this proposal, on the other hand, we want to determine when glaciers were less extensive, not more extensive, than present. Any direct geological evidence for past glacier retreats or collapses is below the glacier surface at present. To investigate this, we aim to obtain exposure-age data from below the present ice surface. The basic principle of this approach is that the presence of significant cosmogenic-nuclide concentrations in subglacial bedrock is direct and unambiguous evidence that the bedrock was ice-free in the past. Using coordinated measurements of a variety of cosmogenic nuclides with different half-lives, at different depths both below the ice surface and below the bedrock surface, we can obtain evidence for whether, when, and how often areas that are now covered by ice were ice-free in the past.

4.2. Subglacial bedrock recovery drilling. We propose to use two drill systems recently developed by the U.S. Ice Drilling Design and Operations (IDDO) program for subglacial bedrock recovery drilling. Both are commercial minerals exploration rigs, originally designed for rock coring, that have been adapted for access drilling through firn and ice and for Antarctic field use.

The smaller system is the "Winkie" drill, a highly portable drill rig (Fig. 3; man- or horse-packable in commercial applications), with design capacity for collecting 33 mm core at up to 120 m total depth, and transportable by Twin Otter or light helicopter. In the 2016-17 season, the Winkie drill was used in the Ohio

Range (PI: Sujoy Mukhopadhyay) to collect 5 short bedrock cores of ~0.5 m length and one sample of loose rocky debris overlying bedrock, beneath 12-28 m of ice, in 8 attempts. We will use the Winkie drill for objective 1.

Figure 3. Left, 8m rock core recovered from beneath 150 m of ice at Pirrit Hills in 2016-17 using the ASIG drill (J. Stone photo). Right, Winkie drill at Ohio Range in 2016-17 (IDDO photo).

The larger system is the "Agile Sub-Ice Geological" (ASIG) drill. It has a design capacity of 6 m of bedrock core beneath up to 700 m of ice and is transportable by ground traverse, LC-130, or multiple helicopter or Twin Otter flights. In the 2016-17 field season, it was deployed to the Pirrit Hills in central West Antarctica (PI: John Stone) by traverse from WAIS Divide. One of two coring attempts at this site was successful and yielded 8 m of bedrock core from beneath 150 m of ice (Fig. 3). We will use the ASIG drill for objective 3.

4.2. Cosmogenic-nuclide exposure-dating of subglacial bedrock. The most important aspect of this approach is that the presence of significant nuclide concentrations in subglacial bedrock is direct and unambiguous evidence that the bedrock was ice-free in the past. Nuclide production decreases approximately exponentially with depth below the ice or rock surface (with an *e*-folding length of ~1.5 m in ice or ~0.6 m in rock, such that production is < 1% of surface production under 7 m of ice). Production beneath even a few meters of ice is negligible compared to surface production.

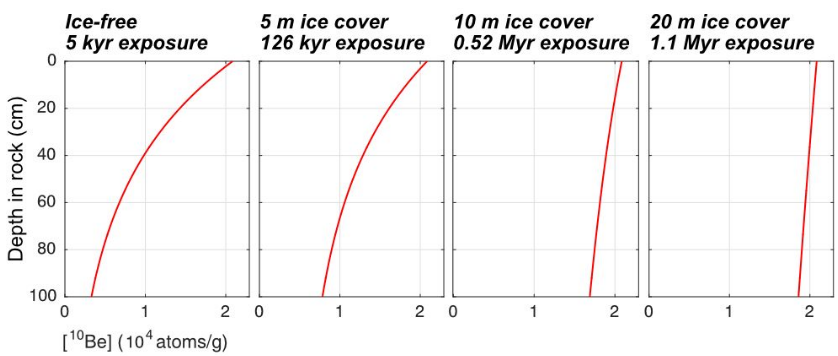

Figure 4. Depth profiles of cosmogenic ^{10}Be in bedrock exposed under different ice thicknesses for different durations, so that the bedrock surface concentration is the same in all cases. Subsurface ^{10}Be concentrations distinguish between a short ice-free period and long residence under thin ice. Although this is drawn for ^{10}Be, the relationship is the same for other nuclides.

If one can collect a core sample even a few tens of centimeters long beneath the bedrock surface, the variation in nuclide concentrations with depth provides information about the thickness of ice that covered the site at the time nuclide production took place. This is important because with only one surface measurement, one could not distinguish between a short period of exposure under ice-free conditions and a longer period of exposure under thin ice cover. As shown in Fig. 4 (also see Schaefer et al., 2016), one can distinguish these two scenarios by measuring nuclide concentrations at multiple depths below the rock surface. The drilling systems that we will use are designed to recover core samples for this purpose.

Measurements of cosmic-ray-produced radionuclides with different half-lives provide information about when surface exposure took place. For example, objective 1 focuses on reconstructing late Holocene ice thickness changes near present grounding lines. It would be unlikely that we could unambiguously identify Holocene exposure periods using cosmogenic ^{10}Be produced in quartz (half-life, $t_{1/2}$: 1.4 million years), because any ^{10}Be concentration we observed could have been produced either in the Holocene or during past interglaciations, for example MIS 5 (80-130 ka) or 11 (ca. 420 ka). On the other hand, cosmogenic ^{14}C, which is also produced in quartz, has a half-life of 5730 years. Any ^{14}C inventory produced in a past interglacial period will have been long lost by radioactive decay, so cosmogenic ^{14}C concentrations in subglacial bedrock are uniquely diagnostic of Holocene exposure (Goehring et al., 2011). Similar approaches for associating observed surface exposure with particular past warm periods can be developed using other nuclides with different half-lives, such as ^{36}Cl ($t_{1/2}$ = 0.3 My) or ^{26}Al ($t_{1/2}$ = 0.7 My); this approach is discussed in detail by Schaefer et al. (2016) and also below, as it relates to objective 3.

Cosmogenic-nuclide exposure-dating of subglacial bedrock has been successfully applied once, to bedrock recovered from the base of the GISP2 ice core in central Greenland. Schaefer et al. (2016) measured cosmogenic ^{10}Be and ^{26}Al concentrations in this core and showed that the presence of significant quantities of these nuclides required the near-complete absence of the Greenland Ice Sheet (GrIS) during at least some middle or late Pleistocene interglacial periods. This, in turn, is important to efforts to model GrIS response to present and future climate: nearly all such modeling studies using warm Pleistocene interglacials as analogues for future climate (e.g., Tarasov and Peltier, 2003; Fyke et al., 2014) do not predict complete GrIS disappearance, but the cosmogenic-nuclide measurements show that it must have happened. We argue that similar constraints on whether catastrophic grounding line retreat into West Antarctic marine basins took place in the past are likewise critical for validation of model simulations that aim to evaluate the likelihood of this event in the future.

5. HOLOCENE CHANGES IN GROUNDING-LINE POSITION (Objective 1). We will address this objective by cosmogenic-nuclide exposure dating of subglacial bedrock recovered by shallow drilling adjacent to ice-free areas near present grounding lines in and adjacent to the Thwaites glacier system. If glacier grounding lines were inboard of their present positions in the past, glaciers near and inland of present grounding lines were thinner at that time. In turn, bedrock in such areas that is not exposed at the surface now would have been exposed. To detect this, we will predominantly rely on in-situ-produced cosmogenic ^{14}C, because, as discussed above, its short half-life means that its concentration is diagnostic of surface exposure during the Holocene, and cannot be inherited from previous Pleistocene interglacial periods (MIS-5e or earlier).

5.1. Site selection. Here we require drilling sites that are adjacent to ice-free areas on nunataks near glacier grounding lines in or near the Thwaites system. The reason is that local weather and mass balance conditions suitable for maintaining ice-free areas close to glacier surfaces at present have likely been similar throughout the Holocene, which indicates that a change in the overall glacier surface elevation near these sites would also result in a change in the extent of the ice-free areas. Although, in general, ice-free areas are rare in the Thwaites system, we identify two sites that meet these needs. First, the Hudson Mts. are a group of nunataks adjacent to lower Pine Island Glacier (Figs. 1, 5). Results from two sites in the Hudson Mts. (Fig. 2) show early Holocene ice surface lowering at this site coeval with grounding line retreat across the continental shelf (Johnson et al. 2014). This observation, as well as the proximity of the sites to the present grounding line, lead us to conclude that retreat of the Pine Island Glacier grounding line would lead to thinning at nunataks in the Hudson Mountains.

Mt. Murphy, a coastal volcanic massif on the west side of the Thwaites embayment, occupies an analogous position to the Hudson Mts. with respect to the Thwaites Glacier grounding line. However, the eastern side of Mt. Murphy that is closest to Thwaites Glacier and adjoins the Crosson Ice Shelf (Fig. 1) is blanketed by locally derived mountain glacier ice and lacks ice-free areas. Thus, it is unlikely that changes in grounding line positions would create new ice-free areas at this location. However, on the western side of Mt. Murphy, ice-free ridges emanating from Kay Peak extend down to near the present grounding line of Pope Glacier (Fig. 6) . Thus, the Hudson Mts. and the west side of Mt. Murphy are the sites most closely associated with the Thwaites system where we can potentially obtain information about past grounding line changes, and we propose to work at both of these sites.

Choosing specific drilling sites also requires detailed information about subglacial bedrock topography adjacent to ice-free areas. Ideally, we would choose sites where exposed ridges extend below the present ice surface: targeting ridgetops increases the likelihood that rock surfaces will be ice-free when ice is thinner. To identify these sites and choose drilling targets, we will perform ice-penetrating radar surveys at both the Hudson Mts. and Mt. Murphy target areas in advance of drilling (see details below).

Finally, bedrock must be suitable for ^{14}C measurements. ^{14}C is usually measured in quartz, and both extraction procedures and production rate estimates are well established for this nuclide/mineral pair (Lifton et al., 2001; Pigati et al., 2010a; Goehring et al., 2014; Lifton et al., 2015; Borchers et al., 2016). Our target ridge at Kay Peak (sampled by Johnson in 2016), is a quartz-rich gneiss, which is ideal.

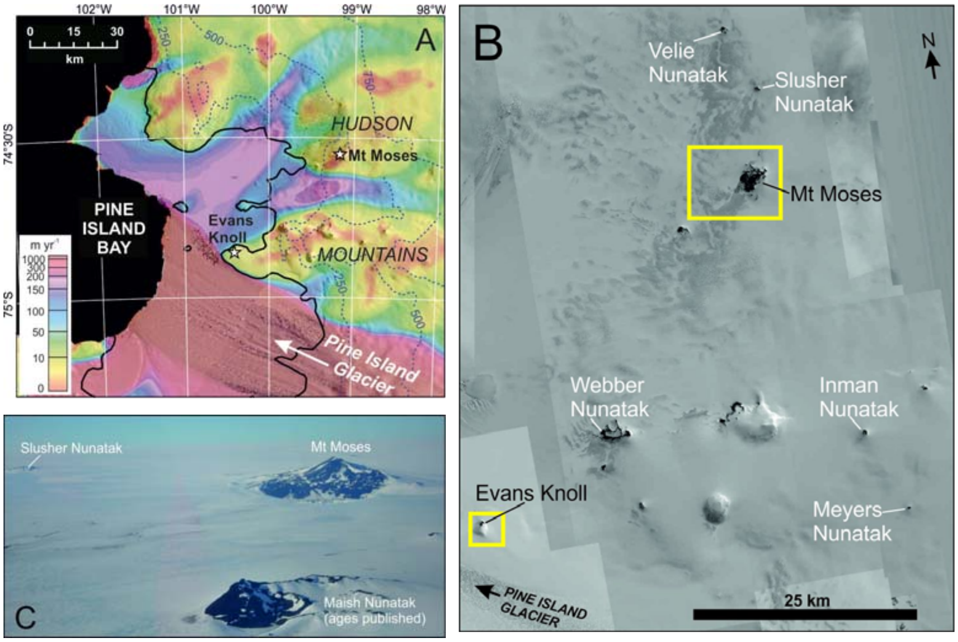

*Figure 5. **A**, Map of lower Pine Island Glacier and the Hudson Mountains. Black line is 2011 grounding line; colors show ice velocity (Rignot et al., 2011). Stars highlight two potential drill sites, but actual site selection will be based on survey in season 1. **B**, Satellite image of the Hudson Mts. Boxes highlight same sites as in A. **C**, Oblique aerial photograph of Mt. Moses and nearby nunataks showing typical topography.*

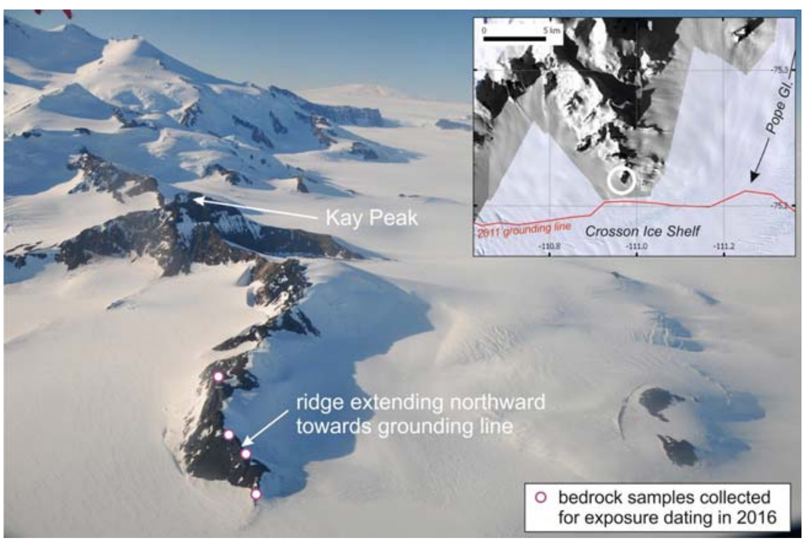

Figure 6. Proposed drilling site at the north ridge of Kay Peak, a subpeak of Mt. Murphy (main Mt. Murphy massif is visible in background). Inset shows location of 2011 grounding line (Rignot et al., 2011) in relation to proposed site (open white circle in inset). We expect that the ridge extends subglacially to the north (toward the viewer in this image), providing potential targets for bedrock recovery drilling. Johnson travelled around the north end of the ridge by Ski-doo in January 2016, collected samples for exposure-dating, and camped on the eastern side (at left in this image).

Hudson Mountains bedrock is primarily basalt and not known to be quartz-bearing, but a limited set of samples available to us contain olivine phenocrysts. Pigati et al. (2010) developed and validated a procedure for cosmogenic ^{14}C extraction from olivine, indicating that if quartz is absent in Hudson Mts. bedrock as we expect, we can achieve objectives at this site using ^{14}C measurements in olivine. The ^{14}C production rate in olivine is not well established (theory suggests it is compositionally dependent but similar to that in quartz at ca.16 atoms/g/yr), but that is not an obstacle here because we can locally calibrate the production rate for the lithology of interest by measuring ^{14}C in bedrock above the ice surface where the Holocene deglaciation history is already known from ^{10}Be measurements on glacial deposits. Thus, this site requires ^{14}C and also ^{10}Be measurements on samples above the present ice surface as well as subglacial samples. As an additional redundancy, measuring ^{14}C in plagioclase, also found in Hudson Mts. basalts, is theoretically feasible, and we are now conducting experiments to establish extraction methods and production rates. Finally, cosmogenic ^{3}He is routinely measured in olivine (e.g., Goehring et al., 2010; Blard et al., 2014). This nuclide is stable so not necessarily diagnostic of Holocene exposure as is ^{14}C, but we will measure it in ice-free and subglacial samples to ensure that we obtain all available information about the bedrock exposure history.

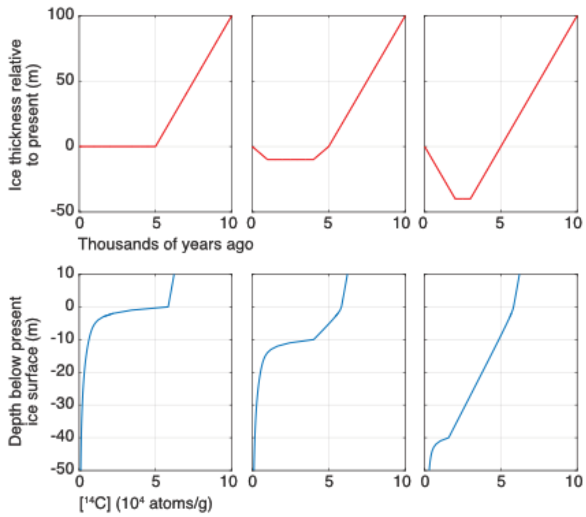

Figure 7. Expected cosmogenic ^{14}C concentrations in subglacial bedrock for late Holocene ice sheet change scenarios. Upper panels show hypothetical ice thickness changes. The leftmost shows the null hypothesis: early Holocene thinning to the present configuration and zero change thereafter. Center and right show scenarios including a late Holocene retreat-advance cycle. Lower panels show corresponding ^{14}C concentrations at the bedrock surface, as a function of depth below the present ice surface. The [^{14}C]-depth relationship in subglacial bedrock is diagnostic of the timing and duration of the retreat-advance cycle. In particular, observing subglacial [^{14}C] in excess of that predicted by the no-change scenario would clearly disprove the null hypothesis of late Holocene stability. Note that here we assume zero subglacial erosion during the final thickening event, because high accumulation rates and surface temperatures in the -10° to -20° C range that ice in the target depth range (< ~50-80 m) predict that the bed will remain below freezing.

5.2. Analytical and interpretive strategy. Our strategy for reconstructing ice thickness changes is based on the idea that a given ice thickness history implies a relationship between bedrock ^{14}C concentration ([^{14}C]) and depth below the present ice surface. The null hypothesis of zero late Holocene ice thickness change predicts that surface [^{14}C] in subglacial bedrock will decrease rapidly with depth below the ice surface following the exponential attenuation of the cosmic-ray flux (left panel of Fig. 7). If we observe higher concentrations at any depth than predicted by this null hypothesis, a thinning-thickening cycle must have occurred. Then, by comparing observed [^{14}C] with that predicted for different thickness change histories (Fig. 7, center and right panels), we can reconstruct the pattern and timing of change. Although for clarity Fig. 7 shows [^{14}C] only in the bedrock surface, an ice thickness history also predicts diagnostic variations in [^{14}C] below the bedrock surface (see Fig. 4). We will collect bedrock core samples, so we can also use this information to improve the thickness change reconstruction. Overall, although the relationship between the ice thickness change history and bedrock [^{14}C] is not mathematically unique, and also we will sample this relationship at discrete depths at each site, both (i) the depth below the ice surface to which we find [^{14}C] characteristic of surface exposure, and (ii) the variation in [^{14}C] with depth below the ice surface, closely constrain the magnitude and duration of any thinning event.

To summarize, at the Hudson Mts. and Mt. Murphy sites we will first conduct radar survey to map the subglacial continuation of exposed ridges and identify drill sites. We will use the Winkie drill to collect subglacial rock core samples from a range of depths; drill performance in the 2016-17 season suggests that at each site we can sample at least 5 depths. We will measure ^{14}C (and, potentially, ^{3}He as discussed above) concentrations in the recovered samples, compare the results to concentrations expected for the null hypothesis of late Holocene stability as well as other ice thickness change scenarios, and determine which scenarios are consistent with the observations.

6. RELATIVE SEA-LEVEL CHANGES IN THE THWAITES-PINE ISLAND EMBAYMENT (Objective 2). Glacioisostatic rebound, documented in the geologic record as RSL change, continues for thousands of years after deglaciation. Typically, deglaciation and unloading causes local RSL fall, providing a potential stabilizing feedback on grounding-line change. Thus, knowledge of coeval RSL change is needed for understanding the dynamic significance of Holocene grounding-line fluctuations in the Thwaites system. It is also important in establishing boundary conditions for past-to-present model simulations and inversions of satellite gravity data, and, in addition, validating glacioisostatic adjustment (GIA) models. Currently we have effectively zero knowledge of LGM-to-present RSL change in the entire Amundsen Sea region (see Whitehouse et al., 2012a,b, whose GIA model is only constrained by one point from the whole ASE; also Larter et al., 2014).

6.1. A Holocene RSL record for Pine Island Bay. We will generate a record of Holocene RSL change using the established method of surveying and dating raised marine features on islands in and around Pine Island Bay. Dozens of islands (Fig. 8) sprinkled throughout the bay are ice-free and distributed so as to record both regional RSL change and potential site-specific variations due, for instance, to differences among major glaciers in the timing of grounding-line retreat. Islands are up to 120 m elevation, likely sufficient to capture the full range of Holocene RSL change (typically < 30 m throughout Antarctica: Miura, 1998; Bentley et al., 2005; Baroni and Hall, 2004; Hall et al., 2004; Hall, 2010; Watcham et al., 2011; Hodgson et al., 2016). We examined satellite imagery of a subset of these islands and found that apparent raised marine landforms and sediments are common. For example, a flight of at least ten raised beaches occurs on the largest of the Schaefer Islands, and raised beaches also occur in the Backer, Edwards, and Lindsey Islands.

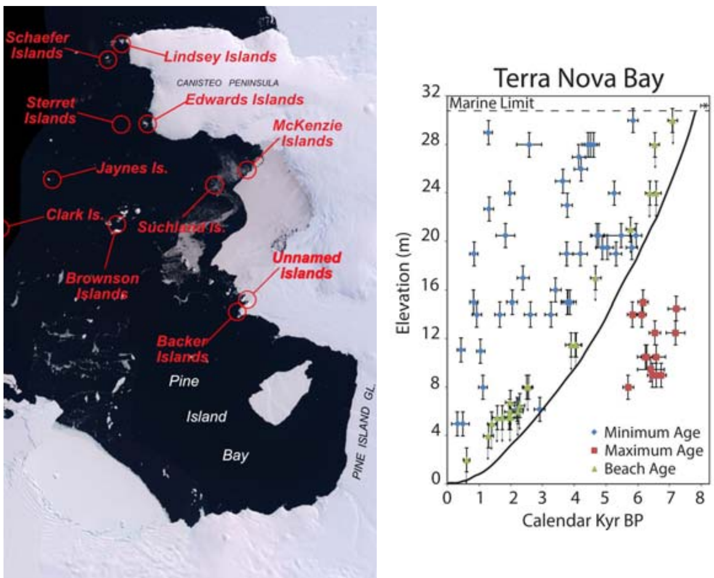

Figure 8. Left panel, LIMA image of Pine Island Bay (see box in Fig. 1) showing islands and island groups where satellite imagery shows raised marine deposits. Right panel, example RSL curve for Terra Nova Bay, Antarctica (Baroni and Hall, 2004, recalculated with INTCAL13 and delta-R of Hall et al., 2010). This is shown as an example of the data we will generate in this project. The RSL curve must lie between minimum-limiting (blue) and maximum-limiting (red) ages. Green symbols are dated raised beaches; because beaches form slightly above sea level by storm waves, RSL must fall ~1-2 m lower. Star in upper right corner is the age of the oldest dated sample from Terra Nova Bay (penguin remains above the marine limit), from which we infer deglaciation at ~8 ka.

We will construct RSL curves by radiocarbon dating of organic material in landforms and sediments that have a genetic relationship to past sea level. Based on past experience in the Ross Sea region (Hall and Denton, 1999; Hall et al., 2004; Baroni and Hall, 2004), the South Shetland Islands (Hall, 2010), and Greenland (Hall et al., 2008, 2010) we expect datable material in three settings. One, marine sediments may occur above present sea level. These sediments, which commonly contain marine fauna such as *Adamussium colbecki* or *Laturnula elliptica*, afford minimum estimates for sea level. Two, flights of raised beaches occur in favorable locations. Beaches are constructed close to sea level, although typically slightly above due to storm waves (Hall et al., 2004). Our experience shows that datable material, such as shell fragments, penguin bones and skin, elephant seal skin, and seaweed, is common within the beaches. Adelie rookeries are widespread in Pine Island Bay (Lynch and LaRue, 2014; Harris et al. 2015); our past work near rookeries (Baroni and Hall, 2004), leads us to expect abundant datable penguin remains. Radiocarbon dates on Antarctic beaches usually provide true ages for the landform and related sea level within error of the dating method, although replication is necessary to rule out reworking of non-contemporaneous material. Three, organic remains deposited on beaches, for example in situ penguin guano and remains in abandoned nesting sites (e.g., Baroni and Orombelli, 1991), moulted elephant seal skin (Hall et al., 2006), or whale bone (Hall, 2010; Watcham et al., 2010) provide maximum estimates for sea level. Together, these three groups of data yield tight constraints on past RSL change (Fig. 8). Note that knowledge of the marine carbon reservoir effect is also necessary for accurate dating; we will use the Holocene (0-7000 yr) delta-R value of 729 +/- 121 yr for the Southern Ocean (Hall et al., 2010).

6.2. Additional constraints on Holocene grounding line changes. Extrapolation of RSL curves to the elevation of the marine limit, often indicated by a shoreline notch or upper limit of marine sediment or wave-washed bedrock, yields an age estimate for deglaciation (Fig. 8). To complement this information, as well as to independently constrain the Holocene grounding line retreat history inferred from marine sediment cores (Smith et al., 2011; Hillenbrand et al., 2013), we will date grounding-line retreat through Pine Island Bay via ^{10}Be and ^{14}C-in-quartz surface exposure dating of erratics and bedrock collected above the marine limit. At present, there exist only four such exposure ages from islands, two of which are considered reliable deglaciation ages (Lindow et al., 2014; Johnson et al., 2008).

7. PLEISTOCENE INTERGLACIAL COLLAPSE OF THE THWAITES SYSTEM (Objective 3). Here we will apply cosmogenic-nuclide exposure-dating of subglacial bedrock to determine whether or not retreat of the Thwaites system grounding line into the interior of West Antarctica occurred during Pleistocene interglacial periods. The basic concept - that significant cosmogenic-nuclide concentrations in subglacial bedrock are unambiguous evidence that the ice sheet was thinner in the past -- is the same as for objective 1. The difference is that for this objective we require a site with negligible subglacial erosion during glacial and interglacial periods. Hundreds of meters of ice thickening during glacial periods at coastal sites (Stone et al., 2003) could permit basal ice to reach the pressure-melting point and erode bedrock surfaces (Sugden et al., 2005), removing the surface bedrock that carries any cosmogenic- nuclide evidence for past interglacial exposure (note that this possibility does not affect objective 1, because LGM thickening and erosion would predate the late Holocene time range of interest). Thus, for this objective we require a site where (i) exposed bedrock indicates a suitable lithology, (ii) the ice thickness is dynamically linked to the Thwaites grounding line position, and (iii) surface climate is cold enough that basal melting is unlikely to have occurred at target drilling depths during glacial periods.

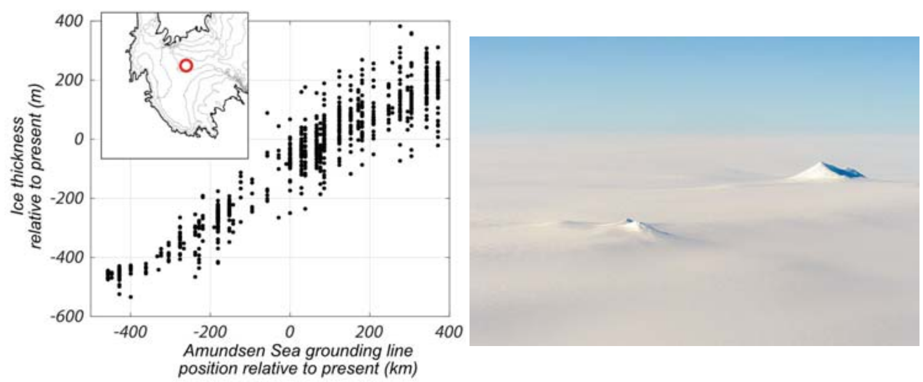

Fig. 9. Left, correlation between grounding line position in the Amundsen Sea and ice surface elevation in the Mts. Moore/Woollard area (red circle on map) in a model simulation (see text; each point is a model time step). Right, oblique aerial photograph of Mt. Woollard.

We identified a site meeting these criteria by using the 4.9-Myr ice sheet evolution model of Pollard and DeConto (2009; David Pollard kindly provided model output) to estimate the correlation between grounding line position in the Amundsen Sea Embayment and ice thickness at several nunataks in interior West Antarctica. We find a strong correlation (Fig. 9) at Mts. Moore and Woollard, located in the upper Thwaites system 300 km from WAIS Divide camp. Bedrock at these nunataks is quartz-bearing and suitable for measurement of a full range of cosmogenic nuclides: rock samples from Mt. Woollard held in the U.S. Polar Rock Repository are gneiss intruded by dikes of granitic composition, and those from Mt. Moore are metasediments with extensive quartz veining. As the ice temperature at WAIS Divide is below -30 °C to ~2 km depth (Cuffey and Clow, 2014), it is unlikely that target drill sites (< 250 m depth) would approach the melting point even given thickening during glacial periods.

Our approach at this site will be similar to that at the grounding line sites discussed above, except geared towards recovering a longer record of potential interglacial exposure. In the first field season we will perform radar mapping of subglacial topography, geologic mapping and sampling to establish the suitability of various lithologies for the needed measurements, and glaciological observations needed for drill planning. We then propose to collect subglacial bedrock samples at several depths between ~100-250 m depth (the target depth range reflects a balance between the expected sensitivity to grounding line migration shown in Fig. 9 and drilling time estimates based on the 2016-17 deployment). Differences in analytical strategy in relation to objective 1 above include: (i) collection of longer cores (6 m or more) necessary to verify the hypothesis of negligible subglacial erosion via measurement of muon-produced nuclide inventories (Stone et al., 1998; Ploskey and Stone, 2012), as well as (ii) measurement of a variety of nuclides with different half-lives, including ^{14}C (5.7 kyr), ^{36}Cl (301 kyr), ^{26}Al (0.7 Myr), ^{10}Be (1.4 Myr), and ^{21}Ne (stable), needed to provide information on the timing and duration of past exposure events. Measurements of these nuclides together, even lacking any other information, can provide constraints on the cumulative duration of periods of exposure and ice cover during the past several million years, as well as limits on when exposure periods may have occurred. In combination with model simulations or other glaciological or paleoclimate evidence for WAIS collapse during certain interglacials, these data can be used to quantitatively test specific ice sheet change hypotheses (see, for example, Schaefer et al. 2016).

8. RESEARCH TASKS. Specific tasks in this project include (i) radar survey and other reconnaissance in advance of drill site selection; (ii) subglacial bedrock recovery drilling; (iii) mapping and dating of raised marine features on islands; and (iv) cosmogenic-nuclide measurements.

8.1. Ice-penetrating radar survey. The objective of radar surveys will be to map bed topography, with target precision +/- 2 m or better depending on depth, between the ice margin and ~100 m depth (for coastal shallow drilling sites) or ~300 m depth (Mts. Moore/Woollard). We will use single-channel radar systems, with various antenna frequencies appropriate to target depths, coupled to differential GPS and post-processed using industry-standard software (see Facilities and Resources). Performance of these systems is discussed in Campbell et al. (2012a, 2012b) and Winter et al. (2016). Survey plans will be adapted to each target location and designed for rapid identification of subglacial ridges via coarse grid survey, followed by denser survey over ridges potentially suitable for drilling. At Mt. Murphy, our aim is to map the subglacial continuation of a specific, preselected ridge within a small (ca. 0.5 km^2) area, which could be conducted either on skis or by Ski-doo, depending on the mode of access to the site (helicopter or Twin Otter). At the Hudson Mts. and Mts. Moore/Woollard, we must survey a larger region around several nunataks, so we will tow radar by Ski-doo, which allows ~100 km of 50/100 MHz grid line to be collected per day. 1000 km of widely spaced lines around likely nunataks will identify major subglacial ridges. We will then collect finer grids in a nested pattern to highlight detail along suitable ridge crests. We will conduct common-midpoint surveys within nested grids to calculate EM propagation velocities needed for velocity-corrected bedrock topography models and best-possible depth-to-bedrock estimates; this technique can yield decimeter accuracy given suitable conditions. Besides the main goal of mapping subglacial topography, we will also collect any information available about englacial structure and the nature of the ice/sediment/bedrock interface that might be relevant to drill site selection or the glaciology of the site, although it is important to note that the spatial resolution of any radar surface imaging is very coarse in relation to the size of rock coring drill-bits (< 5 cm).

8.2. Geological and glaciological reconnaissance of drill sites. Ice-free areas at Kay Peak were mapped by PI Johnson in 2015-16 and we have in hand enough samples to establish bedrock suitability for cosmogenic-nuclide measurements. However, we have access to only a very small number of bedrock samples from the Hudson Mts. Thus, during radar survey prior to drilling there, we will also perform geological reconnaissance, including sampling bedrock and glacial deposits (including those potentially needed to intercalibrate nuclide production rates) as well as mapping bedrock surface condition and distribution of unconsolidated surface material or glacial drift. We will also collect glaciological data needed for site selection and drilling planning, including firn density profiles and surface velocity and mass balance measurements by repeat survey of a grid of stakes emplaced at likely drill sites during the first field season.

8.3. Subglacial bedrock recovery drilling. As discussed above and in the IDDO Drilling Support Letter, we will use the Winkie drill system for shallow drilling at sites near grounding lines, and the ASIG drill system for deep drilling at interior sites.

8.4. Mapping and dating of raised marine features in Pine Island Bay. We propose two field seasons for this work, ideally helicopter-supported (see Logistical Requirements and Field Plan). To capture potential spatial variability in RSL change, we will work at five island groups (Lindsey, Schaefer, Edwards, Brownson, and Backer Islands) as well as Jaynes and Clark Islands (Fig. 8). We have examined high-resolution satellite imagery of four of these island groups and found suitable features in all cases.

We will map features onto high-resolution satellite imagery and measure elevations using differential GPS (target vertical precision < 0.5 m). Sampling for radiocarbon dating by hand excavation will focus on the stratigraphic context of each sample; this approach elsewhere has allowed us to identify multiple generations of sea-level change in single beach ridges (Gardner et al. 2006). Based on our past experience, the desired precision of RSL determinations, and the possibility of reworked material, we estimate that our proposed 5 RSL curves will require ~150 dates in total. We will also collect samples of bedrock and/or glacial deposits (if present) from portions of islands lying above the marine limit, for cosmogenic-nuclide exposure-dating aimed at improving the chronology of Holocene deglaciation of Pine Island Bay. Rocks in the area are predominantly quartz-bearing granitoids (Gohl, 2010; Lindow et al., 2014, 2016) so are suitable for both ^{10}Be (erratics) or ^{14}C (bedrock) measurements.

8.5. Cosmogenic-nuclide sample preparation and analysis. We will measure several nuclides in this project, including ^{3}He (in olivine and possibly other minerals), ^{10}Be (quartz), ^{14}C (quartz and olivine, possibly plagioclase), ^{21}Ne (quartz), ^{26}Al (quartz), and ^{36}Cl (feldspars and biotite). Several laboratory facilities suitable for mineral separation and wet chemical extraction, accelerator mass spectrometers, and noble gas mass spectrometers are available for this purpose (see Facilities and Resources). Particularly important to this project is the ^{14}C extraction facility at Tulane University (directed by PI Goehring). This proposal relies on a large number (~100) of ^{14}C-in-quartz measurements, which historically has not been possible at existing facilities. It will be possible here due to significant advances in automation and associated improvements in throughput and reproducibility at the Tulane facility (Goehring et al., 2016; Fig. 10), which completed over 100 measurements in calendar year 2016 and is expected to increase throughput due to furnace upgrades in the coming year.

Without knowledge of the number and length of bedrock cores that will be recovered, we cannot precisely determine the total number of measurements needed, or the relative distribution of measurement types. We derived our analytical budget by assuming that 4, 6, and 3 cores will be recovered at Kay Peak, the Hudson Mts. and Mts. Moore/Woollard, respectively, and also budgeting for (i) exposure-dating of new samples of glacial deposits collected from Pine Island Bay and the Hudson Mts., and (ii) analysis of bedrock samples above the present ice surface needed to establish continuity between exposure histories above and below the present ice surface. We also budget replicate analyses of a fraction (~10%) of samples both for interlaboratory standardization and, potentially, for verifying detections of short periods of exposure if needed. Laboratory and AMS facilities used for particular analyses will be determined both by sample flow (samples exiting Antarctica as BAS cargo will receive initial processing and most analytical work in the UK, and US-bound samples in the US) and by the expertise and analytical performance of specific laboratories (for example, the University of Washington laboratory has better established facilities for ^{36}Cl extraction than others, and the Purdue/PRIME Lab accelerator facility has better ^{26}Al beam current performance than others).

9. SUMMARY: INTELLECTUAL MERIT. This proposal addresses the 'Boundary conditions,' 'External drivers of change,' and 'Past change' themes of the Thwaites Glacier research program.

9.1. Boundary conditions. Boundary conditions characterized by our proposed work include RSL change in the past several thousand years as well as the trajectory of changes in glacier extent and grounding line position during the past several thousand years and leading up to the present time. This information is necessary to (i) adequately model present crustal rebound, (ii) prescribe in model simulations future crustal motion that is an ongoing response to past mass redistribution, and, potentially, (iii) to initialize or spin-up predictive glacier change models.

9.2. External drivers of change. We will generate information about past changes in relative sea level and ice mass distribution that (i) can be compared to coeval oceanographic and glacier changes in efforts to diagnose causes of glacier change, and (ii) have an effect on present and ongoing vertical crustal motions and, potentially, other ongoing processes associated with ice sheet response to past climate or oceanographic changes.

9.3. Past change. We will obtain direct geological evidence that can contribute to answering two important questions about past changes in the Thwaites glacier system, both of which are necessary for defining validation targets for model simulations that aim to predict future change. First, did reversible grounding line fluctuations, as suggested by geologic evidence from ice-free areas in the region, occur during the middle and/or late Holocene under climate conditions similar to the present? Second, did catastrophic grounding line retreat in the Thwaites system occur in previous interglacial periods that are likely analogues for potential future climate?

10. BROADER IMPACTS.

*10.1. Public engagement and outreach (US)***.** This is focused at the lead US institution, Tulane University, in New Orleans. Much of New Orleans is below sea level and protected from flooding by levees and flood control works. New Orleanians are acutely aware of flood hazards, but public awareness is largely focused on short-term drivers of flood hazard such as (i) catastrophic engineering failures during storms, and (ii) seawater incursion due to coastal land loss. Global sea-level rise, on the other hand, is viewed in media coverage and overall public awareness as slower and less imminent (Durham, 2014). Tulane University is a leader in raising awareness regarding coastal land loss, but so far is less engaged with issues of far-field, global sea-level rise. We view the potentially more immediate threat posed by hypothesized collapse of the Thwaites glacier system (Christianson et al., 2016; Parizek et al., 2013) as an important and timely opportunity to improve focus on global sea-level change awareness both in New Orleans via Tulane and also, potentially, in the other coastal regions represented by proposal PIs.

10.1.1. Mobile, dynamic, physical sea-level visualization. This component draws from two iconic phenomena in the urban environment: historical flood markers and mobile promotional vehicles. It is common practice in coastal and riverine cities throughout the US, UK, and elsewhere to mark the height of significant historical floods on buildings, telephone poles, or other structures, both in an *ad hoc* way by individual building owners or as the centerpiece of a museum or riverfront park. This practice provides a sense that city residents have endured shared hardships, a powerful reminder of vulnerability to natural processes, and a spur to planning and preparedness against future flooding. We want to start with this idea, migrate it from past to future sea-level rise scenarios, and realize it as a mobile, dynamic visualization tool that attracts and fixes public attention. As a model for how we might do this, we look to mobile promotional vehicles used as advertising tools; many such vehicles, including the Oscar Meyer Wienermobile, the Hershey's Kissmobile, and the Planters Peanutmobile, have been in continuous use for decades and represent a proven and effective method for attracting public attention.

Our design concept is a vehicle-mounted, continuously-adjustable, pneumatic or articulated mast, resembling those seen on mobile news vans, linked to GPS and LiDAR topographic data (available statewide in Louisiana). An indicator on the vehicle can therefore dynamically indicate present sea level, historical flood levels, and potential inundation under future ice sheet change scenarios, as the vehicle travels around portions of New Orleans, or another coastal city, that lie below sea level now or potentially could in future. Note that a pneumatic mast is needed in many portions of New Orleans just to reach modern sea level. To address the engineering and visual-communication design problems of how to best communicate information about sea-level change with such a device and to prototype the device itself, PI Goehring will collaborate with multiple departments/programs in Tulane University's School of Science and Engineering, including its Maker Space, a development environment for science and engineering ideas focusing on undergraduate collaboration. Goehring will lead a team of Earth and Environmental Science, Engineering, and Communications students in an independent study course focused on design and construction of the sea level visualization tool as well as outreach applications in the local school system (Goehring serves as an Earth science liaison to the Science and Engineering High School).

10.2. Public engagement and outreach (UK). This element will focus on outreach to schools through the existing '*Think Geophysics*' initiative run by Woodward at Northumbria University, which builds on the *nu*STEM project led by Northumbria (currently funded at £1.2 million by the Higher Education Funding Council for England). *nu*STEM targets gender imbalance in physics at UK universities (a recent Institute of Physics survey found that 21% of students are female) by changing the way young people engage with science during their school years and path to university, and works with 40 partner schools, aiming to engage over 100,000 young people by 2025. '*Think Geophysics*' will adapt the *nu*STEM cradle-to-career blueprint to environmental geochemistry and geophysics, aiming to inspire young people, particularly women and underrepresented groups, into science careers through the following actions:

Engage pupils at 20 partner schools through '*Think Geophysics*' workshops that cover climate change in Antarctica including sea level rise, introduce key concepts in geochemistry and geophysics, and allow children to explore these themselves through hands-on activities.

Help young people to explore scientific concepts of climate change through media not traditionally used in the teaching of geochemistry and geophysics. In conjunction with a local artist, bespoke workshops will be developed to creatively interpret changing Antarctic climates.

Link to Centres, museums, festivals and events to target young people's support networks and bring '*Think Geophysics'* to new audiences, specifically the Cambridge Science Festival (an established annual event attracting 25,000); the Annual Big Bang Fair at the The Centre for Life, Newcastle; and the Imperial Festival and Imperial Fringe at Imperial College London and Natural History Museum (Nature Live talks).

Utilize the 'Think' digital presence to enhance learning from the workshops, show real-life applications and associated career pathways. This includes activities for children and parents to continue learning outside of school, resources for teachers, case studies of students studying these subjects and geologists working in the field, and engagement through video, podcasts and social media.

We will utilize the existing monitoring approaches developed by *nu*STEM to assess engagement. In addition, we will assess the success of the art initiative through approaches for impact assessment adopted by the UK Arts and Humanities Research Council.

10.3. Embedded journalist. For outreach and public engagement via print and online media, we will work with Douglas Fox, a freelance science writer who has been reporting on Antarctic research since 2007. He has participated in four Antarctic field seasons aboard ships and at inland deep field camps, and written over 40 articles on Antarctic science for major print and online publications including *National Geographic*, *Scientific American*, *Discover*, *Wired*, and *The Atlantic*. We propose that Fox will join one of the two field groups undertaking subglacial bedrock recovery drilling in the second project season (2020-21), and subsequently report on this aspect of the project, as well as other parts of this project and Thwaites Glacier research generally, in online and print outlets in both the US and UK (see attached letters of collaboration).

10.4. Other broader impacts. Goehring, Campbell, and Rood are early-career scientists. The project will support graduate and undergraduate research at Tulane, the U. of Maine, U. of Washington, and BAS/Imperial College London, and a postdoctoral researcher at Imperial.

11. RESULTS FROM PRIOR NSF SUPPORT

*11.1. Hall. Deglacial Chronology of the Northern Scott Coast from Relative Sea-Level Curves (PLR-9909104, $173,641).*This project determined timing of deglaciation and relative sea-level change in the western Ross Sea. *Intellectual Merit:* We produced relative sea-level (RSL) curves from Antarctica and perfected methods for dating small amounts of organic remains associated with raised beaches, expertise that we will use in this project. Two RSL curves, each based on >80 radiocarbon dates, also constrain ice retreat to ca. 8 ka (Fig. 8), helping to show that Ross Sea deglaciation was largely Holocene. Resulting publications include Baroni and Hall (2004), Hall et al. (2004); Gardner et al. (2006), a graduate thesis (Gardner, 2002), and review papers (e.g., Hall et al., 2013). *Broader Impacts:* This work supported one graduate and 3 undergraduate students, initiated an enduring international collaboration with Italian Antarctic Program researchers; and provided data, photographs, and experiences used in University and K-12 classrooms as well as other professional and public venues.

11.2. Balco and Goehring: COLLABORATIVE RESEARCH: Terrestrial Exposure-Age Constraints on the last Glacial Maximum Extent of the Antarctic Ice Sheet in the Western Ross Sea (PLR-1341420, PLR-1460449, PLR-1341364; $420,708 among 3 institutions). PIs Balco, Goehring, and Claire Todd (Pacific Lutheran University). This project aims to determine the timing of Antarctic ice sheet advance and retreat to and from its maximum extent in the Ross Sea embayment at the last glacial maximum. *Intellectual Merit*: Geological mapping and exposure-age data show modest (~300 m) thickening of outlet glaciers draining into the outer Ross Sea, advance to the LGM grounding line position at ca. 25 ka, and early Holocene retreat. So far no data support the hypothesis that large changes in Ross Sea ice thickness were related to Meltwater Pulse 1A at 14.5 ka. An important methodological advance, critical to this proposal, is the successful use of the high-throughput Tulane ^{14}C extraction system to unambiguously constrain LGM ice thickness using a dense elevation transect of ^{14}C measurements on bedrock (Fig. 10). Thus, LGM ice thickness data can be obtained from nunataks lacking glacial deposits, which improves overall LGM ice volume reconstructions. *Broader Impacts:* This project has contributed to the program of undergraduate teaching and research in glacier and environmental change led by Claire Todd.

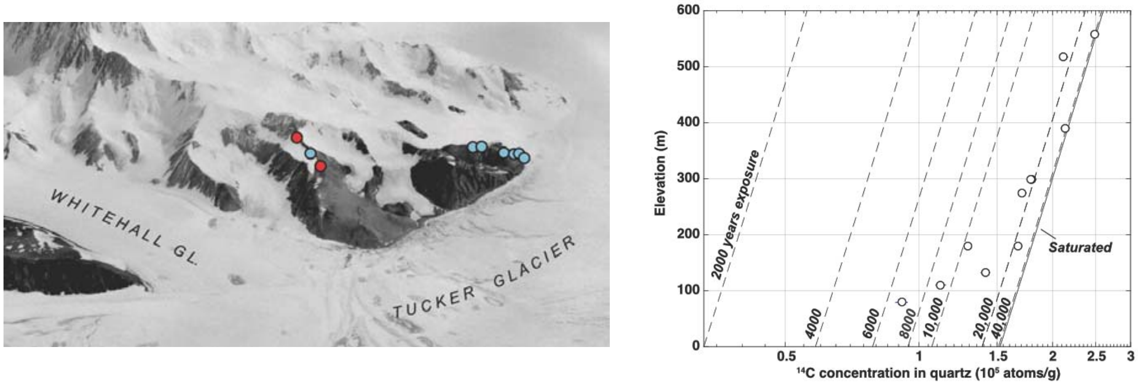

Figure 10. ^{14}C-in-quartz data for bedrock near the Tucker Glacier, northern Victoria Land. Left panel, sample locations on ice-free ridges; right panel, measured [^{14}C] against elevation with saturation concentration and isolines of exposure age (the ^{14}C production rate, and thus the concentration for a given exposure age, increases with elevation). Samples above 300 m show the "saturation" concentration at which decay balances production; this requires ca. 30 kyr uninterrupted exposure and precludes LGM ice cover. Lower samples (and one higher-elevation sample adjacent to a snowfield) have concentrations well below saturation, indicating LGM ice cover. Thus, the LGM ice thickness was 300 m greater than preset. In the left panel, saturated sites are shown in red and unsaturated in blue.

11.3. Stone: EXPROBE-WAIS: Exposed rock beneath the West Antarctic Ice Sheet: A test for interglacial ice sheet collapse (NSF PLR-1341728; $376,812). This project uses cosmogenic-nuclide measurements on subglacial bedrock to determine the extent of ice cover during past warm climates. *Intellectual Merit:* During the 2016-17 Antarctic field season the ASIG drilling system was used to obtain 8 m of bedrock core (Fig. 3) from beneath 150 m of ice cover in the Pirrit Hills, West Antarctica. Ice sheet models indicate bedrock at this depth would have been exposed during past collapses of the WAIS, so data from the core will provide direct evidence for or against extensive deglaciation during warm interglacials in the past. Analyses of cosmogenic ^{10}Be, ^{26}Al, ^{36}Cl, ^{14}C and ^{21}Ne are in progress and initial results will be in hand by April 2017. We also recovered 8 m of ice core above the bedrock interface. Stable isotope and trapped gas analysis in this ice will help establish the time at which ice last overran the surface. *Broader Impacts:* Contributes to the education of three graduate students, and two undergraduate research students who are carrying out associated cosmogenic nuclide projects. Eighteen undergraduate students have carried out similar projects in the University of Washington Cosmogenic Nuclide lab during the past 10 years, including two who took part in Antarctic reconnaissance fieldwork in the Pirrit Hills in 2013.

11.4 Campbell: Geophysical Survey of McMurdo Ice Shelf to Determine Current Infrastructure Stability and for Future Planning (NSF EP-ANT-15-36; $98,500). Applies ice-penetrating radar and shallow coring on the McMurdo Ice Shelf (MIS) to assess meteoric ice thickness, basal conditions, and englacial structures. *Intellectual Merit:* 1300 km of radar data contribute to the extensive, high-resolution model of the ice shelf, including mapping the brine extent, identifying jump unconformities and basal fractures, and inferring salinity gradients from mapping of the brine and ice shelf bottom. Overall results indicate that the MIS is currently stable, but identify several locations where long-term monitoring is needed. *Broader Impacts:* Results disseminated in presentations, a CRREL Technical Report, and one paper (Campbell et at., 2017). One early career scientist and one undergraduate student were involved in data processing, interpretation, and manuscript preparation.