Drilling priorities to determine the past extent of the Antarctic Ice Sheet

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Subglacial Access Science Planning Workshop 2019

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1. Introduction and priority research questions

The response of the Antarctic ice sheets to warmer-than-present climates is a pressing scientific question due to its linkage to global sea level. Evidence of former cosmic-ray exposure in subglacial bedrock can reveal the dimensions of ice sheets and glaciers under warmer climate conditions in the past. Recent projects at the Pirrit Hills and the Ohio Range in Antarctica have now demonstrated the feasibility of recovering intact bedrock cores for isotope measurements, which provide strong constraints on the glacial history of the sites. As the number and geographic distribution of sites expands, this approach has the potential to constrain the history and dynamics of ice sheets under various past warmer climates. Major questions address three critical time periods:

How big was the Pliocene Antarctic ice sheet? Reconstructions of the Pliocene Antarctic ice sheet envisage a dramatically smaller WAIS, largely confined to bedrock highlands, and major ice loss from the Wilkes, Aurora and Recovery Basins of East Antarctica (e.g. Pollard et al., 2015; de Boer et al., 2015). With atmospheric greenhouse gas concentrations now at Pliocene levels, it is critical to verify these model projections, and the associated implications for sea level rise. This can be resolved by strategic subglacial exposure measurements with stable and long-lived cosmogenic nuclides, focused on key sites in West and East Antarctica (Figure 1). Data from the Ohio Range and Pirrit Hills already bear on the question, and prospective projects at other sites in West and East Antarctica will add further constraints.

What happened to the West Antarctic Ice Sheet (WAIS) during warm and/or prolonged late Pleistocene interglacials such as Marine Isotope Stages (MIS) 5e and 11? Does collapse always lead to the same ice-sheet configuration, or do the Ross, Weddell, and Amundsen Sea catchments act independently in response to differences in their ocean margins? These questions can be answered by comparing the exposure histories of presently subglacial bedrock surfaces recovered from different sectors of the ice sheet. In addition, knowledge of interior elevations provide constraints on interglacial ice volumes. Proof-of-concept projects are underway, and will likely establish whether past interglacial ice sheets were like the present-day WAIS, or radically smaller. However, more detailed work at additional sites, at multiple depths below the present ice surface, will be required to establish former interglacial WAIS configurations. We envisage sampling at key sites within the Ross, Amundsen and Weddell catchments, and along the divides that separate them. As noted above, initial projects using both the ASIG and Winkie drills have been completed and were very successful; it is clear these techniques are widely applicable. Because preservation of the cosmogenic nuclide record requires cold-based, non-erosive ice cover, this work is likely to be within the depth range and working capabilities of these existing drill systems. At present, the Winkie drill has only been used to depths of ~30m. Realizing the full potential of the Winkie Drill (~120 m) will be critical to obtaining continuous profiles that overlap with the capabilities of the ASIG drill.

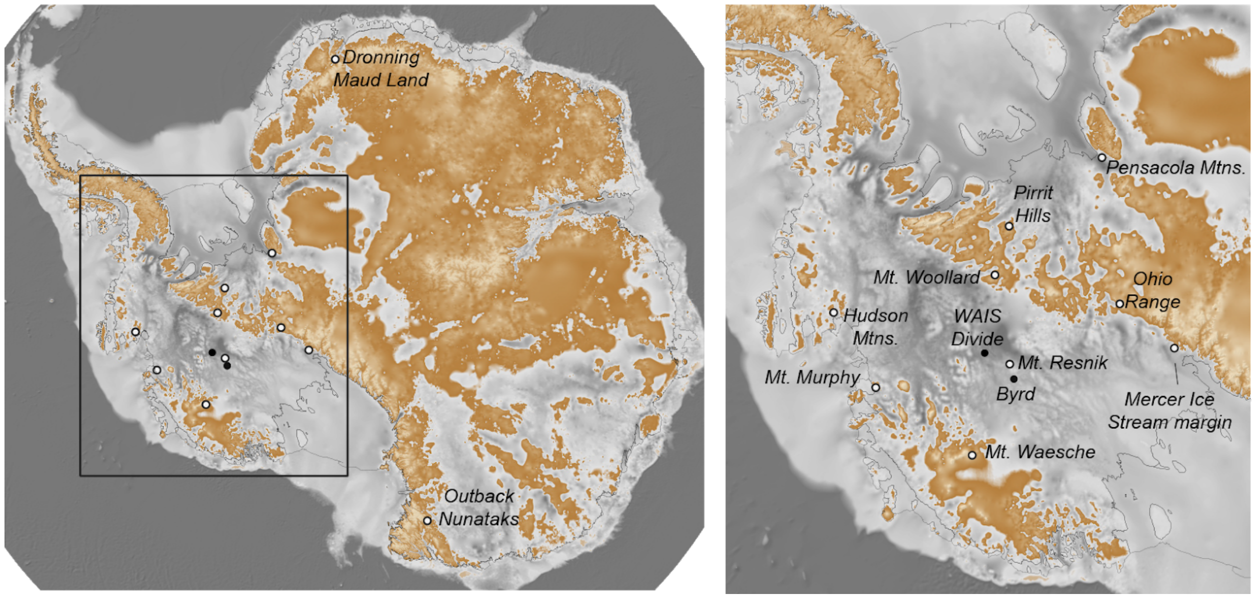

Figure 1. Map of the subglacial topography of Antarctica (Fretwell et al., 2013). Grays represent areas below sea level; oranges represent areas above sea level. Circles represent sites mentioned in the text.

Was the WAIS smaller than present during the late Holocene? The recent discovery of radiocarbon in till from beneath the Siple Coast ice streams (Kingslake et al, 2018), along with evidence of Holocene grounding-line fluctuations in the Weddell Sea sector (e.g. Siegert et al., 2013), have focused attention on grounding-line stability and the ability of the WAIS to recover from a reduced state. At sites far from the isostatic influence of ice sheets, there is evidence of eustatic sea level changes during the late Holocene that cannot be explained by melt of the northern hemisphere ice sheets (e.g., Lambeck et al., 2014). Thus, the sensitivity of WAIS grounding lines to changes in boundary conditions is a key concern under a warming climate. Measuring in situ cosmogenic ^{14}C and optically-stimulated luminescence signals on subglacial bedrock cores provides a means of investigating this sensitivity by allowing mapping of regions exposed by Holocene grounding-line retreat and subsequently re-covered by late Holocene advance. Ice-sheet models predict thinning and thickening in response to Holocene grounding-line retreat and re-advance of tens to hundreds of meters at sites near the present-day ice-sheet margin, depths which are within the capabilities of the Winkie and ASIG drills.

2. Direct observational evidence of past ice-sheet thickness and strategies to gather it

2.1 Strategies for subglacial sampling

The primary aim is to collect subglacial bedrock cores, with a secondary aim of collecting basal ice for studies of atmospheric gas content. The Winkie and ASIG drills are currently available for these purposes, while the RAID drill is under development for potential deeper drilling plans. A key consideration in these applications is the need for preliminary subsurface characterization of potential drill sites. This should be achieved through reconnaissance studies utilizing ground-based ice-penetrating radar to identify appropriate subglacial bedrock features, in concert with targeted sampling of surficial bedrock and erratics for initial cosmogenic nuclide analyses (Spector et al., 2018). Once appropriate subglacial drill targets are selected, initial shallow investigations using the Winkie drill are recommended, with possible subsequent deeper efforts using the ASIG if the signal of past exposure extends to depths of ~100 m. Both the ASIG and Winkie drills have large and heavy components that scale with hole depth.

Therefore, very lightweight techniques for reconnaissance sampling of subglacial bedrock surfaces would be a worthwhile investment in the future, and is discussed in more detail in Section 4.

Potential drill sites should be evaluated based on three primary criteria, which have been discussed in detail by Spector et al. (2018). First, past changes in ice-thickness at the drill site must have been related to the extent and configuration of the broader ice sheet, rather than the local ice flow or meteorology. Second, subglacial drilling must target rock types in which useful cosmogenic nuclides can be measured. If, for example, drilling returned low-grade metasedimentary rock, which is known to outcrop in West Antarctica, it would be challenging or potentially impossible to make the measurements necessary to determine whether the site has deglaciated in the past. Third, the cosmogenic-nuclide record, which is primarily produced in the top-most few meters of bedrock, must have remained continuously preserved and protected from erosion.

At a given site it is essential to collect multiple bedrock cores spanning a range of depths beneath the ice surface. This allows for the magnitude of past drawdowns to be established and for exposure and ice-cover histories to be compared over a range of depths. Such depth transects, combined with samples collected above the present-day ice surface allow ice-thickness variations over full glacial-interglacial cycles to be constrained.

Boreholes drilled for the initial purpose of recovering subglacial bedrock cores will be available to other scientists for logging or installation of geophysical instruments. Some shallow holes, however, may not be fluid filled, and therefore any borehole activity would need to occur immediately following drilling. For more details on these techniques, refer to whitepaper on East Antarctica in this series.

2.2 Analyses on recovered subglacial bedrock and basal ice

Cosmogenic-nuclide measurements: The discovery of significant concentrations of cosmogenic nuclides in subglacial bedrock surface would provide direct and unambiguous evidence of past exposure by ice-sheet thinning, and would place limits on the timing, frequency, and magnitude of past deglaciations. Where possible, a suite of nuclides with different decay rates (e.g. C-14, Cl-36, Al-26, Be-10, Ne-21, He-3) should be measured on recovered samples because each nuclide provides information about past exposure and ice-cover on different time scales. Constraints on the bedrock erosion history, which is required for accurate interpretation of the glacial history, can be obtained by measuring depth profiles of these isotopes in cores that extend several meters below the surface, beyond the depth of spallation-produced nuclides.

Analysis of the basal ice: Where possible, the basal ice directly overlying the bedrock should be collected for analysis of both the ice and trapped atmospheric gases. In the case that the ice is very old, this will allow for dating of its deposition or, if it is late-Pleistocene in age, direct correlation with other Antarctica ice cores. Many subglacial drilling projects will presumably want to quickly auger, rather than slowly core, through the majority of the ice column. In such cases, recovery of basal ice will require the total ice thickness to be accurately known from radio-echo sounding so as to determine the depth to switch from augering to ice coring.

Luminescence dating: This method has the potential to reveal the most recent time a bedrock surface was exposed to sunlight if it occurred within the last several glacial-interglacial cycles. This is important because cosmogenic-nuclide measurements potentially may not provide this information under certain scenarios of repeated exposure and ice-cover. Luminescence dating requires subglacial bedrock core tops be collected and stored in the dark. Because the luminescence signal is contained in the uppermost few millimeters of a rock surface, it can be removed by even small amounts of erosion. Therefore, this method should complement but not supplant the other methods described here.

Analyses for volcanic rock: Given the abundance of exposed (LeMasurier and Rex, 1989; Paulsen and Wilson, 2010) and subglacial (van Wyk de Vries et al., 2017) volcanoes within West Antarctica, some subglacial drilling projects will likely target and recover volcanic rocks. High-precision $^{40}Ar/^{39}Ar$ dating, as well as other methods (e.g., ^{36}Cl exposure dating), are capable of determining eruption ages of rocks of varied lithology that are as young as <10 kyr from Antarctica volcanoes (Panter et al., 1994; Wilch et al., 1999; Harpel et al., 2004). The $^{40}Ar/^{39}Ar$ ages provide a maximum age for the exposed surfaces, and together with cosmogenic exposure ages, constrain the duration of ice burial since the eruption. Even with the very limited geochronology for exposed West Antarctic volcanoes (see Paulsen and Wilson, 2010 for a review) previous work indicates significant volcanism in the region since ~14 Ma. A more comprehensive temporal assessment of West Antarctic volcanoes could identify lava flows that may have formed during times of glaciological interest for the WAIS (e.g. the Pliocene or Pleistocene interglacial periods). $^{40}Ar/^{39}Ar$ ages and volcanic lithofacies analyses of subglacial bedrock would reveal evidence for subaerial (e.g., welded tephra, lava flows) or subglacial (e.g., hyaloclastites) eruptions, providing more constraint for the geometries of past ice sheets. Lastly, should basal ice above bedrock contain tephra layers, the combination of $^{40}Ar/^{39}Ar$ ages and tephrochronology geochemical analyses could be used to determine the age of the oldest ice for that region.

3. Subglacial drill targets for determining the timing and magnitude of past deglaciations

3.1 Sites to test for Pliocene and Pleistocene deglaciation

Mt Waesche: Mt. Waesche is a late Pleistocene volcano near the dome of the WAIS in Marie Byrd Land. Local net ablation results in exposed bedrock and an adjacent blue ice area on the southern flank of the volcano. Ice elevation changes here place constraints on WAIS volume and deglaciation histories. Previous work has shown that the WAIS surface was ~40 m higher about 10 ka and up to 80 m higher at earlier times in the late Pleistocene (Ackert et al. 1999). Notably, lava flows exposed near the WAIS margin range in age from 150 ka to 350 ka. Assuming that these flows extend below the WAIS, any cosmogenic nuclides detected in rock cores from beneath the WAIS margin would record exposure sometime during the last two glacial cycles. During the 2018-19 field season an extensive GPR survey mapped the subglacial topography along the ice margin and the subaerial lava flows were mapped and sampled for $^{40}Ar/^{39}Ar$ and cosmogenic ^{3}He measurements. Based on the GPR data and the lithologies of the mapped lava flows, several potential drilling sites with ice thickness <100 m were identified. Drilling to collect rock cores up to 80 m beneath the ice surface with the Winkie Drill, as well as additional GPR surveys targeting deeper sites potentially accessible with the ASIG drill, is funded and scheduled for the 2020-21 season.

Wilkes Subglacial Basin/Outback Nunataks: The primary difference between ice sheet model simulations that call for catastrophic shrinkage of the EAIS during the mid-Pliocene warm period and those that do not is that the former predict extensive grounding line retreat in marginal subglacial basins around East Antarctica, in particular the Wilkes and Aurora Basins. This prediction is testable using subglacial bedrock exposure dating because an ice-free Wilkes Basin requires hundreds of meters of ice sheet thinning in the vicinity of the Outback Nunataks (Fig. 1), at the western margin of the Transantarctic Mountains in northern Victoria Land. A proposal (PIs Balco, Todd, and Campbell) for drill site reconnaissance in this area is pending logistics review at present. Pending the results of radar reconnaissance at potential drill sites, the large predicted thinning signal in this region would most likely make this project best suited to the ASIG drill system.

Mt. Woollard: Mt. Woollard is a nunatak located in central West Antarctica at the head of the Thwaites Glacier catchment. Ice-sheet models predict a strong relationship between local ice thickness and the position of the Amundsen Sea grounding line, and they depict hundreds of meters of thinning during many Pliocene and Pleistocene interglacial periods (Spector et al., 2018). The questions of whether and when such deglaciations occurred in the past, along with how much thinning they induced, can be addressed by a project to recover samples of basal ice and subglacial bedrock from a range of depths beneath the present-day ice surface. The most sensible plan would be initial sampling from shallow depths (down to ~100 m) using the Winkie drill, followed by deeper sampling with the ASIG drill if samples from ~100 m depth demonstrate past exposure.

Ohio Range: The Ohio Range Escarpment separates the WAIS from the EAIS near the head of the Mercer Ice Stream. The highest WAIS elevation at Ohio Range is ~125 m above the present ice level, and occurred between 10 ka and 12.5 ka (Ackert et al., 2007). Erratics on the peaks of nunataks projecting through a blue ice area outboard of the escarpment are consistent with ice cover during past WAIS highstands. ^{10}Be and ^{21}Ne exposure ages of granite bedrock on the nunatak peaks indicate millions of years exposure consistent with the deeply weathered nunatak surfaces. Although the data plot in the simple exposure field on ^{10}Be/^{21}Ne vs. ^{21}Ne diagrams, the concentrations are consistent with ice-cover histories predicted by ice sheet models (Mukhopadhyay et al., 2012). During the 2016-17 season, subglacial topography around the nunataks was mapped using GPR to select drilling targets for the Winkie and ASIG drills and constrain ice flow models. Additional bedrock samples were collected from the nunataks to better constrain changes in WAIS elevation. During the subsequent 2017-18 season, four bedrock cores were recovered using the Winkie Drill from depths ranging from 12 m to 28 m below the ice surface. The cores ranged in length from 30 - 50 cm in length. ^{10}Be, ^{26}Al and ^{21}Ne concentrations measured in the cores have a spallation dominated profile indicative of subaerial exposure. Calculations based on the ^{10}Be and ^{26}Al concentrations of the samples indicate that the subglacial bedrock was generally exposed for a long period (0.25 to 2 Myr) and has generally been ice covered for at least the last 200 kyr.

This was the first deployment of the Winkie Drill. Although an overall success, technical problems with the Winkie drill limited the depth of core recovery. Future modifications will be necessary to fully realize the potential of this drill. The Ohio Range remains an important target for deeper drilling with an improved Winkie drill (up to 100 m) and with the ASIG drill. Ice sheet models predict that maximum downdraw of the WAIS at this location is less than the depths obtainable with the ASIG drill which suggests that constraints on minimum ice thickness could be obtained here.

Mt. Resnik: Mt. Resnik is a prominent fully-subglacial peak that is of interest to an especially broad swath of the Antarctic scientific community. The peak is located in central West Antarctica between the WAIS Divide and Byrd logistical hubs, and it rises from one of the deepest portions of the bed to within ~300 m of the ice-sheet surface (Figures 1 and 2). The age of the peak is not known, but its magnetic anomaly suggests that it is a basaltic volcano (Behrendt et al., 2007). It is hypothesized that Mt. Resnik, or one of the other subglacial peaks in central West Antarctica (presumed to be volcanic), erupted as recently as the last ice age, exposing its summit above the ice (Iverson et al., 2017). Exposure of the peak may also have occurred during past warm climates of the Pliocene and Pleistocene, times when ice-sheet models indicate that the peak became an ice-free island (e.g. Pollard et al., 2015; Spector et al., 2018). If true, these volcanic and glacial histories imply that Mt. Resnik was exposed to marine and subaerial environments in the past, and may continue to harbor subglacial microbial life in an environment more extreme than the recently-explored habitats near the present-day grounding line (Christner et al., 2014). The possibility of active volcanism also suggests an elevated geothermal heat flux, which may affect ice flow and water production at the base of the present-day WAIS. These scenarios can be tested with an interdisciplinary project that combines (i) analyses of subglacial bedrock and basal ice to search for evidence of past exposure; (ii) petrologic and geochronologic measurements to determine the lithology and eruption age of the presumed volcano; (iii) clean-access sampling designed to reveal whether a microbial ecosystem persists beneath the ice; and (iv) geophysical measurements to determine the geothermal heat flux and detect seismic activity.

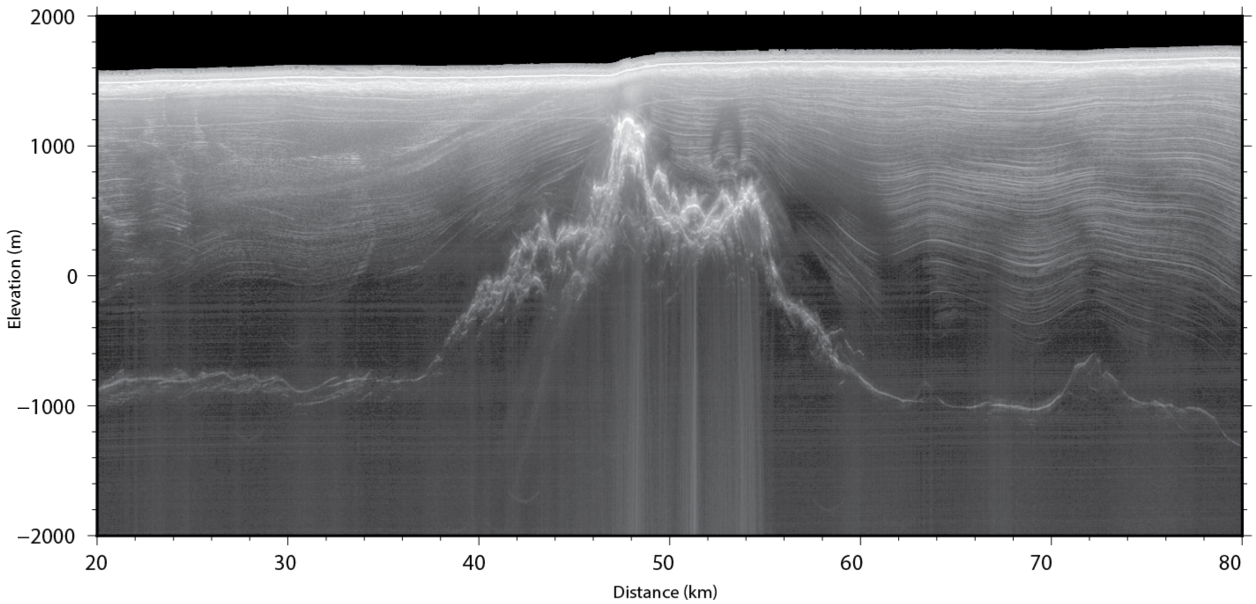

Figure 2. Radargram showing subglacial Mt. Resnik. Ice flow is from right to left. Credit: University of Texas Institute for Geophysics.

Dronning Maud Land: For over two decades, measurements of in situ cosmogenic nuclides from bedrock and erratics exposed at a range of altitudes on nunataks in both West and East Antarctica have enabled constraints on past ice thickness fluctuations across the continent. Western Dronning Maud Land (DML) has been a conspicuous hole in the spatial distribution of measurements to date, yet ice sheet models predict distinctive ice thickness differences between coastal and inland sites in western DML over Pliocene to Holocene time frames. Current NSF funding as part of an international collaboration is starting to remedy that data gap, through analyses of multiple nuclides along coast-inland and coast-parallel transects of nunataks. As these data accumulate, suggestions of potential Holocene or earlier exposure of currently subglacial bedrock surfaces could motivate subglacial drilling studies in key locations using a Winkie drill.

3.2 Sites to test hypothesis of Holocene grounding line retreat and re-advance in West Antarctica

This hypothesis predicts significant thinning directly upstream of the present-day grounding line, and can therefore be tested with subglacial bedrock samples recovered from near the WAIS margin in the Ross, Weddell, and Amundsen Sea sectors. Such work is already planned in the Amundsen Sea sector at Mt. Murphy and the Hudson Mountains (Figure 1) for the 2019-21 seasons as part of the International

Thwaites Glacier Collaboration. Two additional promising sites for are discussed below, which could establish whether a Holocene retreat-advance cycle occurred in the Ross and Weddell Sea sectors.

Mercer Ice Stream margin: The strongest evidence for Holocene grounding-line retreat and re-advance in West Antarctica comes from the finding of radiocarbon in till recovered from beneath the Siple and Gould Coast ice streams. The only ice-sheet model simulation consistent with this evidence (Kingslake et al., 2018) predicts > 1 km of Holocene thinning at nearby sites along the margin of Mercer Ice Stream. This scenario conflicts with geologic evidence from lower Reedy Glacier which suggests that ice levels were never lower than present during the Holocene (Spector et al., 2017; Todd et al., 2010). Direct and unambiguous evidence for or against a Holocene retreat-advance cycle can be obtained by recovering and analyzing subglacial bedrock samples from sites located between Scott and Reedy Glaciers along the margin of Mercer Ice Stream.

Pensacola Mountains: The large Foundation Ice Stream drains portions of both West and East Antarctica. The present grounding line is approximately adjacent to the Williams Hills, but in the Holocene it was possibly further upstream, closer to the Thomas Hills, and since then readvanced into the latest Holocene, with some models predicting > 100 m of ice thickness change (Kingslake et al., 2018). Existing surface chronology suggests that the modern ice surface elevation was reached during the mid-Holocene and thus ice thickness loss may have continued into the late Holocene prior to readvance. Additionally, the existing surface chronology demonstrates that the bedrock is potentially suitable for measurement of in situ radiocarbon, which is necessary to detect possible changes in Holocene ice thickness. Proposed work at this site is likely more than one year out.

4. Recommended investments in drill-site reconnaissance technology

Lightweight tools for exploratory subglacial bedrock sampling: With maintenance and improvements as needed, the existing suite of subglacial bedrock recovery drills are expected to be sufficient for most drilling projects within the coming decade. As discussed above, lightweight reconnaissance drilling to depths of ~100 m is necessary to establish whether deeper and more logistically-challenging drilling at a given site is warranted. Therefore we expect continued demand for the Winkie drill, and we think that the US IDP’s decision to build a second Winkie drill system was prudent. While the Winkie drill is much smaller than the ASIG drill, it still requires large and heavy components that scale with hole depth (e.g. drill rod, fluid, casing, etc.), so we think it is also advisable to investigate different technologies that might make reconnaissance drilling and minimal surface bedrock sample recovery lighter and more efficient, thus enabling more reconnaissance boreholes to be completed in a field season. For example, one potential approach might be to use a lightweight cable-suspended, electromechanical ice-coring drill to access the bed, followed by percussion hammering to obtain chips of the bedrock surface. Alternatively, one could envision a small-diameter, cable-suspended rock-surface corer with internal fluid pumping, akin to a miniature version of the device successfully used at the GISP2 borehole. In contrast to collecting long bedrock cores, these approaches would not provide detailed information about the exposure and erosion history of the site, but analysis of even small chips of bedrock would give an indication of whether the bedrock has been previously exposed by ice-sheet thinning, and thus whether deeper subglacial bedrock coring would be warranted.

Ice-penetrating radar solutions for the polar science community: It would be worthwhile to invest in ice-penetrating radar equipment that would be available to the polar science community. All of the potential future drilling projects described above would need to be preceded by ground-based ice-penetrating radar surveys to map the subglacial topography and identify promising bedrock drill targets. At present, this requires every project to (i) find and partner with someone with radar instruments and expertise and (ii) determine the proper equipment, settings, survey design, and post-processing methods to achieve the science goals. The task of mapping subglacial topography in a small region at the resolution necessary for drill site location is a relatively routine application of ground-penetrating radar that, in general, does not require advanced radar technology or new developments in data analysis. It would be simpler and more efficient if an academic institution with established radar capabilities and expertise, or an existing organization with an equipment pool infrastructure such as UNAVCO or IRIS PASSCAL, was funded to provide ground-penetrating radar equipment and expertise in support of the science goals of the polar community. Lack of access to geophysical expertise or equipment such as radar, LiDAR, seismic, and GPS technologies often act as a barrier-to-entry for early-career scientists and under-funded institutions. Much like seismic, LiDAR, and GPS, the community is in need of off-the-shelf radar solutions which are one of the most commonly deployed geophysical instruments in Polar projects. The development of a community radar resource will benefit numerous other Polar projects (Antarctic and Arctic) focused on localized glaciology, glacial geology, and coupled research programs.

Reconnaissance measurements for (likely) subglacial volcanoes: Drill targets that are likely volcanic (e.g. Mt. Resnik) would warrant additional reconnaissance measurements prior to subglacial drilling. Specifically, it would be important to establish whether the bed is wet or frozen as well as if any microbial matter can be detected in the ice above the bed. One potential approach would be to use small melt probes. Such devices could emplace vertical Raman Distributed Temperature Sensing (DTS) cables to determine the basal thermal state, and, if frozen, measure the geothermal flux. Additionally, they could sample the ice above the bed for microbial analysis without contamination by exogenous organisms. Development of these technologies is currently being supported by NSF and NASA. The relatively low cost and minimal logistical burden of this method could allow for a network of melt probes to be deployed around large and complex sites such as subglacial Mt. Resnik.

5. References

Ackert, R.P., Barclay, D.J., Borns, H.W., Calkin, P.E., Kurz, M.D., Fastook, J.L. and Steig, E.J., 1999. Measurements of past ice sheet elevations in interior West Antarctica. *Science*, *286*(5438), pp.276-280.

Ackert, R.P., Mukhopadhyay, S., Parizek, B.R. and Borns, H.W., 2007. Ice elevation near the West Antarctic Ice Sheet divide during the last glaciation. Geophysical Research Letters, 34(21).

Behrendt, J., Finn, C., Morse, D., and Blankenship, D.: One hundred negative magnetic anomalies over the West Antarctic Ice Sheet (WAIS), in particular Mt. Resnik, a subaerially erupted volcanic peak, indicate eruption through at least one field reversal, in: Antarctica: A Keystone in a Changing World, Proceedings of the 10th International Symposium on Antarctic Earth Sciences, Extended Abstract 030, 1–4, 2007.

Christner, B. C., Mikucki, J. A., Foreman, C. M., Denson, J., & Priscu, J. C. (2005). Glacial ice cores: A model system for developing extraterrestrial decontamination protocols. Icarus, 174(2), 572–584.

Christner, B. C., Priscu, J. C., Achberger, A. M., et. al.. (2014). A microbial ecosystem beneath the West Antarctic ice sheet. *Nature*, *512*(7514), 310–313.

de Boer, B., Dolan, A.M., Bernales, J., Gasson, E., Golledge, N.R., Sutter, J., Huybrechts, P., Lohmann, G., Rogozhina, I., Abe-Ouchi, A. and Saito, F., 2015. Simulating the Antarctic ice sheet in the late-Pliocene warm period: PLISMIP-ANT, an ice-sheet model intercomparison project. *The Cryosphere*, *9*, pp.881-903.

Fretwell, P., et al., 2013, Bedmap2: Improved ice bed, surface and thickness datasets for Antarctica, Cryosphere, 7(1), 375–393, doi:10.5194/tc-7-375-2013.

Harpel, C.J., Kyle, P.R., Esser, R.P., McIntosh, W.C., Caldwell, D.A., 2004, $^{40}Ar/^{39}Ar$ dating of the eruptive history of Mount Erebus, Antarctica: summit flows, tephra, and caldera collapse: Bulletin of Volcanology, v. 66, p. 687-702.

Iverson, N.A., Lieb-Lappen, R., Dunbar, N.W., Obbard, R., Kim, E. and Golden, E., 2017. The first physical evidence of subglacial volcanism under the West Antarctic Ice Sheet. *Scientific reports*, *7*(1), p.11457.

Kingslake, J., Scherer, R.P., Albrecht, T., Coenen, J., Powell, R.D., Reese, R., Stansell, N.D., Tulaczyk, S., Wearing, M.G. and Whitehouse, P.L., 2018. Extensive retreat and re-advance of the West Antarctic Ice Sheet during the Holocene. *Nature*, *558*(7710), p.430.

Lambeck, K., Rouby, H., Purcell, A., Sun, Y., & Sambridge, M. (2014). Sea level and global ice volumes from the Last Glacial Maximum to the Holocene. *Proceedings of the National Academy of Sciences*, *111*(43), 15296–15303. http://doi.org/10.1073/pnas.1411762111

LeMasurier, W.E., and Rex, D.C., 1989, Evolution of linear volcanic ranges in Marie Byrd Land, West Antarctica: Journal of Geophysical Research, v. 94, p. 7223-7236.

Mukhopadhyay, S., Ackert Jr, R.P., Pope, A.E., Pollard, D. and DeConto, R.M., 2012. Miocene to recent ice elevation variations from the interior of the West Antarctic ice sheet: constraints from geologic observations, cosmogenic nuclides and ice sheet modeling. *Earth and Planetary Science Letters*, *337*, pp.243-251.

Panter, K.S., McIntosh, W.C., and Smellie, J.L., 1994, Volcanic history of Mountain Sidley, A major alkaline volcano in Marie Byrd Land, Antarctica: Bulletin of Volcanology, v. 56, p. 464-473.

Paulsen, T.S., and Wilson, T.J., 2010, Evolution of Neogene volcanism and stress patterns in the glaciated West Antarctic Rift, Marie Byrd Land, Antarctica: Journal of the Geological Society, v. 167, p. 401-416.

Pollard, D., DeConto, R.M. and Alley, R.B., 2015. Potential Antarctic Ice Sheet retreat driven by hydrofracturing and ice cliff failure. *Earth and Planetary Science Letters*, *412*, pp.112-121.

Siegert, M., Ross, N., Corr, H., Kingslake, J. and Hindmarsh, R., 2013. Late Holocene ice-flow reconfiguration in the Weddell Sea sector of West Antarctica. *Quaternary Science Reviews*, *78*, pp.98-107.

Spector, P., Stone, J., Cowdery, S.G., Hall, B., Conway, H. and Bromley, G., 2017. Rapid early-Holocene deglaciation in the Ross Sea, Antarctica. *Geophysical Research Letters*, *44*(15), pp.7817-7825.

Spector, P., Stone, J., Pollard, D., Hillebrand, T., Lewis, C. and Gombiner, J., 2018. West Antarctic sites for subglacial drilling to test for past ice-sheet collapse. *The Cryosphere*, *12*(8), pp.2741-2757.

Todd, C., Stone, J., Conway, H., Hall, B. and Bromley, G., 2010. Late Quaternary evolution of Reedy Glacier, Antarctica. *Quaternary Science Reviews*, *29*(11-12), pp.1328-1341.

van Wyk de Vries, M., Bingham, R.G., and Hein, A.S., 2017, A new volcanic province: an inventory of subglacial volcanoes in West Antarctica, *In* Siegert, M.J., Jamieson, S.S.R., and White, D.A., (*eds*) Exploration of Subsurface Antarctica: Uncovering Past Changes and Modern Processes: Geological Society, London, Special Publication, 461.

Wilch, T.I., McIntosh, W.C., and Dunbar, N.W., 1999, Late Quaternary volcanic activity in Marie Byrd Land; potential $^{40}Ar/^{39}Ar$-dated time horizons in West Antarctic ice and marine cores: Geological Society of America Bulletin, v. 111, p. 1563-1580.