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Lessons learned from shallow subglacial bedrock drilling campaigns in Antarctica

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Abstract

We review successes and challenges from five recent subglacial bedrock drilling campaigns intended to find evidence for Antarctic Ice Sheet retreat during warm periods in the geologic past. Insights into times when the polar ice sheets were smaller than present serve as guiding information for modeling efforts that aim to predict the rate and magnitude of future sea level rise that would accompany major retreat of the Antarctic Ice Sheet. One method to provide direct evidence for the timing of deglaciations and minimum extent of prior ice sheets is to extract subglacial bedrock cores for cosmogenic nuclide analysis from beneath the modern ice sheet surface. Here we summarize the lessons learned from five field seasons tasked with obtaining bedrock cores from shallow depths (<120 m beneath ice surface) across West Antarctica since 2016. We focus our findings on drilling efforts and technology and geophysical surveys with ground-penetrating radar. Shallow subglacial drilling provides a high risk, high reward means to test for past instabilities of the Antarctic Ice Sheet, and we highlight key challenges and solutions to increase the likelihood of success for future subglacial drilling efforts in polar regions.

1. Introduction

In their special report entitled *The Ocean and Cryosphere in a Changing Climate*, the Intergovernmental Panel on Climate Change highlights the need to better understand whether ongoing and projected ice mass loss is irreversible (Meredith and others, 2019). Therefore, exploring periods throughout geologic history that enable us to gain insight into the reversibility of ice mass loss is critical. Uncovering any evidence that parts of the Antarctic Ice Sheet have recovered from a smaller-than-present configuration would thus be important in suggesting a tipping point for runaway retreat has not yet been reached. Ice mass gain after a period of accelerated loss can be observed in the recent past (mid-to-late Holocene) and throughout deeper time (last and previous interglacials) via access to the ice-bed interface made possible by subglacial drilling. Once an access hole through the ice has reached within several meters of the bedrock, a rock-coring system can then be used to retrieve a sample of the upper 1–2 m of underlying bedrock for cosmogenic nuclide exposure dating. Evidence of above-background levels of targeted cosmogenic nuclides indicates prior exposure of the bedrock at or near the surface because cosmic radiation can penetrate as much as 5–10 m of ice cover (Spector and others, 2018; Balco and others, 2023). Therefore, the depth below the current ice surface at which nuclides are measured indicates ice sheet thinning of at least that magnitude.

Subglacial drilling has been attempted in parts of West Antarctica and Greenland (e.g. GreenDrill) with success at depths of tens to hundreds of meters (e.g. Spector and others, 2018; Balco and others, 2023; Balter-Kennedy and others, 2023). Thus far, sites in East Antarctica and the Antarctic Peninsula have yet to be drilled. In West Antarctica in 2016/17, a team retrieved an 8 m rock core at 150 m depth at Pirrit Hills, West Antarctica (Spector and others, 2018) using a drill system intended to reach depths up to 700 m. Following the successful extraction of a subglacial bedrock core at Pirrit Hills, a workshop was convened in 2019 to prioritize drill sites across Antarctica that would capture past extents of the ice sheet (Spector and others, 2019). Of particular interest were sites that may record periods of time with a climate similar to present. The field campaigns discussed here targeted periods during the Pleistocene, for which it has been hypothesized that the ice volume of the West Antarctic Ice Sheet (WAIS) may have been greatly reduced (Scherer and others, 1998; Kopp and others, 2009; Lau and others, 2023). More recently, there is evidence for retreat



and readvance during the late Holocene after recent studies revealed evidence for retreat of the WAIS in both the Weddell Sea sector (Bradley and others, 2015; Kingslake and others, 2018) and the Ross Sea sector (Venturelli and others, 2020, 2023). Once the geographic scope of sites was narrowed down based on targeted geologic time periods, specific targets for future drill sites were further refined on how well they met the following criteria: (1) past ice volume fluctuations at the drill site occurred on a regional scale representing larger ice sheet dynamics, not simply local ice dynamics, (2) the rock types at each site must be appropriate for cosmogenic nuclide measurements to determine if glacial thinning occurred at the site, (3) the upper few meters of the subglacial bedrock surface (where the cosmogenic nuclide record is preserved) must have remained free from erosion that would otherwise erase or obscure results by removing rock that would archive cosmogenic nuclides (Spector and others, 2018) and (4) the bedrock must be above sea level when deglaciated to prevent shielding of cosmogenic rays caused by water (Granger, 2014). Additional considerations for site selection from a logistical perspective included the need to select sites that: (1) allowed for ground-penetrating radar (GPR) imaging of subglacial topography at targeted depths, (2) have limited crevassing for site-safety considerations and (3) could be reached by small plane support such as a Twin Otter or Basler. For an extensive review of these criteria and an overview of the sensitivity analysis for sites to capture past deglaciation events of the WAIS, see Spector and others (2018, 2019).

Here we focus on lessons learned from five shallow drilling (<120 m) campaigns (Fig. 1) carried out since 2016/17. Four were undertaken at Ohio Range, Mount (Mt.) Murphy, Hudson Mountains and Enterprise Hills. Drilling at the fifth site, Mount (Mt.) Waesche, is planned for 2024/25 and we include the site here to highlight the advantages of a pre-drilling season dedicated to reconnaissance and GPR data collection. We discuss the success and challenges related to the use of GPR for drill site selection and the Winkie Drill system and its evolution. For the five sites, we provide a brief site description and summary of key take-aways from each field season. Additional details related to the scientific significance of each site and an overview of radar surveys with corresponding GPR data and drilling efforts are found in the supplemental material.

2. Drilling and radar overview

2.1 Drilling technology

A variety of technologies provide access to the ice-bed interface including those that melt through ice [e.g. clean-access, hot-water drilling (Tulaczyk and others, 2014; Priscu and others, 2021)] and those that permit the collection of ice [e.g. ice coring (see Boeckmann and others, 2021) or ice augering (see Rix and others, 2019)]. The tools used and timeframe targeted for subglacial access efforts depend on conditions at the site (blue ice vs firn), the depth to bedrock and the logistical support available.

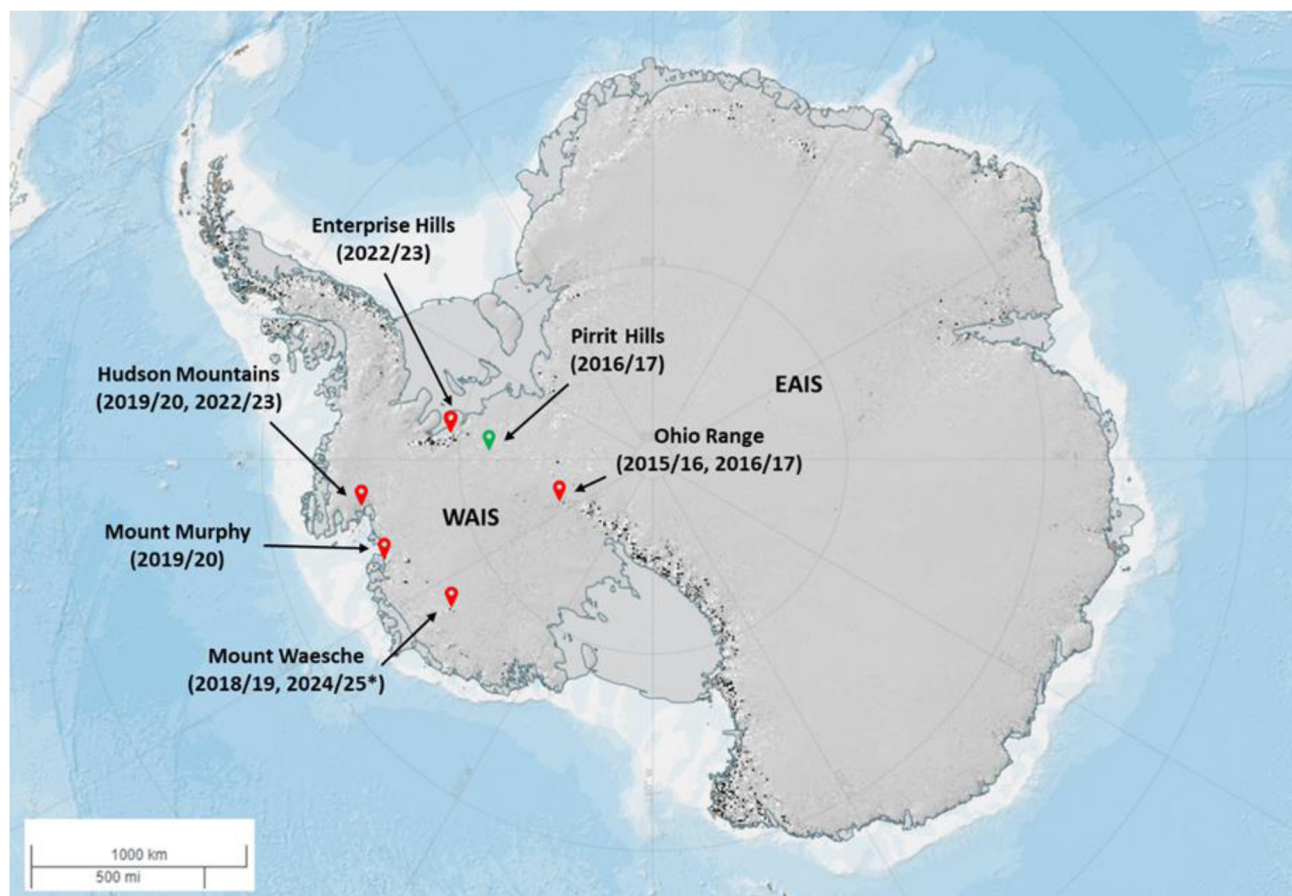


Figure 1. Overview map of Antarctica showing study locations and campaign dates of subglacial drill sites. Previously drilled sites include Ohio Range, Mt. Murphy (Kay Peak), Hudson Mountains (Winkie Nunatak), and Enterprise Hills. A reconnaissance geophysical survey was conducted at Mt. Waesche in 2018/19 with drilling proposed to begin in 2024/25 as noted by the asterisk. Red pins indicate Winkie Drill sites. The green pin indicates an additionally mentioned drill site that used the Agile Sub-Ice Geologic Drill (ASIG), capable of drilling to depths of 700 m. WAIS – West Antarctic Ice Sheet. EAIS – East Antarctic Ice Sheet. Textured gray represents the current ice-sheet surface (from Reference Elevation Model of Antarctica [Howat and others, 2019]). Shaded gray areas outlined in blue represent ice shelves. Bathymetry (blue and white shades) is from GEBCO2019 global dataset (GEBCO group, 2019). The basemap was created from the SCAR Antarctic Digital Database.

Here, we focus primarily on the use and evolution of the Winkie Drill, a commercially available rock coring system that can reach depths of 120 m and has had demonstrated success in extracting bedrock cores at depths up to 50 m. In addition, the Winkie Drill system is commonly used for drilling efforts in remote, polar environments because of logistical considerations related to the size and weight of the system and the support provided by the U.S. Ice Drilling Program (IDP). For the United States Antarctic Program, the Winkie Drill system is operated by the IDP, a National Science Foundation funded program to provide planning support, drill equipment and services and drill operators for field campaigns. See Boeckmann and others, 2021 for a comprehensive overview of the initial criteria for selecting the Winkie Drill for polar subglacial drilling efforts.

2.2 Ground-penetrating radar surveys

All subglacial bedrock recovery drilling projects so far have targeted sites adjacent to exposed bedrock nunataks where the surface topography indicates that exposed ridges are likely to continue into the subsurface and the outcropping bedrock is suitable for analysis. Continental-scale digital elevation models such as Bedmap 2 and 3 (Fretwell and others, 2013; Fremant and others, 2023) and BedMachine (Morlighem, 2022) are not expected to be accurate at these locations, so small-scale, ground-based GPR surveys are necessary for drill site selection (e.g. Balco and others, 2023). GPR is the preferred tool for such surveys over alternatives such as airborne radar because GPR systems can easily be transported to remote field sites and collect high resolution data for near surface drilling targets. GPR is used to trace subglacial nunatak ridges and to pinpoint topographic features to target

for drilling and the surveys provide observations of ice thickness, crevasse detection and englacial stratigraphy.

When conducting GPR surveys, radar technicians generally have several goals in mind. First, teams will survey larger areas (hundreds of meters to kilometers) to map prominent subglacial bedrock ridges and ice thickness. Additionally, these larger spatial surveys can place local drill site englacial stratigraphy and ice thicknesses into broader context. Once a general area is selected based on the initial survey, a secondary survey is made to pinpoint target drill sites over a smaller area and in higher resolution. If buried crevasses are a concern, a crevasse-detection survey may be carried out as well for site safety. Although large crevasses may be apparent in surveys using lower frequency antennas, there remains the possibility of missing the detection of smaller or shallow crevasses or stress fractures, multiple crevasses in close proximity or crevasses that run parallel to the lines of an initial GPR survey. As a general practice, it is best to survey the potential drill site at multiple orientations relative to the known crevasses (perpendicular, oblique and parallel) as this may reveal additional crevasses that went undetected.

3. Study sites

Shallow drilling (<120 m) to recover subglacial bedrock has been attempted at five sites in Antarctica thus far (see Table 1; Fig. 1). The five sites span a range of glaciological settings and we provide insight into the challenges associated with shallow subglacial bedrock drilling from both geophysical and technical perspectives in various glaciological environments. The Ohio Range and Mt. Waesche sites are situated in the center of the thickest parts of the WAIS, whereas Mt. Murphy, Hudson Mountains and

Table 1. Summary of shallow subglacial drilling campaigns at five sites in Antarctica

Drill site	Ohio Range	Mt. Murphy	Hudson Mountains	Enterprise Hills	Mt. Waesche
Season of drilling	2016/17	2019/20	2022/23	2022/23	2024/25*
Preseason with GPR survey	2015/16	–	2019/20	–	2018/19
Total days of GPR survey	9	2	5 and 5	6	14
Drill used for access hole	Kovacs ice auger	Badger-Eclipse Drill	Badger-Eclipse Drill	Modified Kovacs ice augers	Badger-Eclipse Drill*
Drill used for recovering bedrock cores	Winkie Drill	Winkie Drill	Modified Winkie Drill ^a	Modified Winkie Drill ^a	Modified Winkie Drill*
Drill affiliation	US Ice Drilling Program	US Ice Drilling Program	US Ice Drilling Program	Durham University, UK	US Ice Drilling Program
Team size	5	6	6	4	6
Total days on site	24	19	28	26	–
Total days of drilling	12	16	11	11	–
Ice type	Blue ice	Firn/glacial ice	Firn/ glacial ice	Blue ice	Blue ice
Ice-bed interface	Frozen, free of meltwater or debris in overlying ice at five of six sites	17–20 cm thickness of clay-rich sediment in basal ice	Clay-rich sediment and local basalt fragments in basal ice	Frozen, clean interface with pieces of in situ weathered bedrock	To be determined
Bedrock lithology	Granite	Biotite gneiss	Basalt	Quartzite	Volcanic
Number of access holes drilled	6	4	1	6	–
Number of cores recovered	6	4	0 ^b	4	–
Type of cores	5 bedrock, 1 sediment	4 bedrock, 1 rock/debris-rich ice	–	4 bedrock	–
Length of cores (cm)	38, 67, 28, 57, n.a., 60	114, n.a., 137, 128	–	10, 47, 26, 5	–
Diameter of cores (mm)	33	33	–	33	–
Depth below ice sheet surface (m)	12.1, 12.9, 25.5, 26.5, 27.0 (sediment), 28.3	35.8, 36.3 (rock/ice), 39.4, 40.9	–	10.8, 24.1, 29.5, 9.5	<100*

^aModifications to the Winkie Drill are described in sections 3.3 (Hudson Mountains) and 3.4 (Enterprise Hills).

^bNo bedrock cores were recovered, but an access hole through 49.6 m of ice was drilled.

*Indicate a planned drilling season.

Enterprise Hills are situated nearer the coast. The latter three are therefore expected to record changes in thickness of marine-terminating outlet glaciers near their grounding lines, in contrast to the Ohio Range and Mt. Waesche sites that will record ice thickness changes far inland. A summary of the details for each field site is included in Table 1.

3.1 Ohio range (drilled 2016/17)

3.1.1 General site description

The Ohio Range is a ~50 km long escarpment located within the interior West Antarctica near the West Antarctic Ice divide (Fig. 2). A blue ice ablation zone with supraglacial debris occurs at the base of the escarpment at ~1500 m. Cosmogenic nuclide exposure dates of subaerial bedrock samples along the Ohio Range escarpment and nunataks range from 2 to 7 Ma (millions of years) indicating ice free conditions with low erosion rates (Mukhopadhyay and others, 2012). Exposure ages of erratics indicate the most recent high stand occurred ~12 ka about 125 m above the present ice elevation and that several nearby nunataks were ice covered (Ackert and others, 2007). The extent of previous low stands in this high elevation region of WAIS was unknown, however, the exposure data indicate the region experienced delayed elevation changes relative to down-glacier environments consistent with model results (Ackert and others, 2007). Drilling was targeted on subglacial granite bedrock ridges extending from Bennet Nunataks in a blue ice area (Fig. 2).

3.1.2 Key takeaways from radar and drilling efforts

The drill sites at Ohio Range were characterized by frozen conditions at the bed as expected from the sites location and elevation. See section 4.3 (Fig. 8) for an example of the frozen interface when the team drilled into steeply dipping rock that was extracted with an ice wedge. Although surface melt was observed and linked to supraglacial debris that covered much of the ablation area at the drill site, it was not found at ice-bed interface. Cold ice resulted in greater GPR signal return strength in surveys as meltwater within or at the base of ice can increase attenuation and complicate radargram interpretations. However, at deeper sites, estimates of ice thickness from GPR surveys included greater uncertainties due to geometric spreading of radio waves reflecting off more complex subglacial topography (Moran and others, 2003; Lapazaran and others, 2016). This results in false bed reflectors that can impact ice thickness estimates by several or more meters.

From a drilling perspective, this was the first attempt at using the converted Winkie Drill system to extract subglacial bedrock samples. The team found that the Winkie Drill was not successful in drilling through ice and had to rely on Kovacs auger extensions to create boreholes from depths between 10 and 30 m. The augers performed well at depths of 30 m or less. However, a borehole attempted at a greater depth (56 m) was unsuccessful due to a failure of the Kovacs auger connection points due to the weight of multiple Kovacs flights. It was noted that the augers bent throughout the season and this was partially due to misalignment between borehole and drive shaft. It was recommended that a shorter auger section be used for drilling the initial pilot hole. This first season highlighted the difficulty of drilling to depths greater than 50 m and the importance of beginning to drill at shallower depths and then progressing to deeper depths when possible. When drilling at greater depths, the time necessary to troubleshoot drill-related issues increases, as does the time required for the drill to reach bedrock and return to the surface.

3.2 Mt. Murphy (drilled 2019/20)

3.2.1 General site description

Mt. Murphy is a volcanic massif situated between the western lateral margin of Thwaites Glacier and the eastern lateral margin of Pope Glacier (Fig. 3). Exposed bedrock ridges on the north side of Mt. Murphy are the closest location to Thwaites and Pope Glaciers where ice thickness changes associated with grounding line retreat or advance would be expected to cause changes in the extent of bedrock exposure that could be detected by subglacial bedrock exposure dating. Drilling was undertaken at the foot of a ridge extending northwards from Kay Peak, where quartz-bearing bedrock (exposed basement rocks) suitable for cosmogenic-nuclide analysis outcrops at the ice margin (Johnson and others, 2020; Balco and others, 2023).

3.2.2 Key takeaways from radar and drilling efforts

Overall, this project was successful in that multiple bedrock cores were collected as planned, and the cores were subsequently used to show that this site experienced ice thinning during the middle Holocene followed by thickening to present conditions (Balco and others, 2023). From the perspective of drilling operations, several successes were also achieved. First, it was a successful application of on-the-fly site selection by radar survey immediately (one day) in advance of drilling, which shows the feasibility of this strategy for sites with relatively simple geometry where the surface

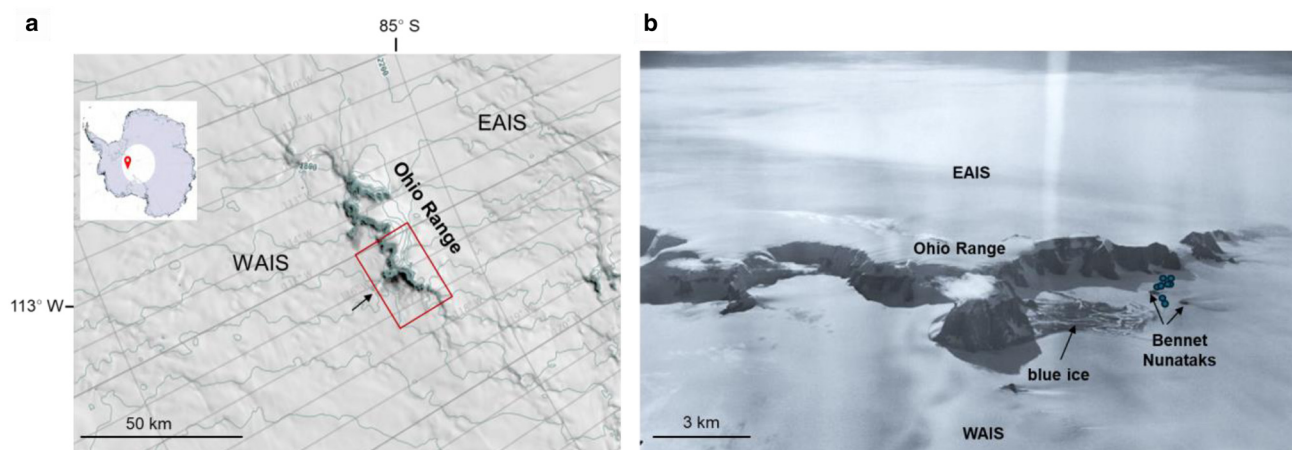


Figure 2. (a) Overview map of Ohio Range from Landsat Image Mosaic of Antarctica (LIMA) satellite imagery showing topographic lines spaced at 100 m intervals. The red box indicates the area photographed in the right panel. The black arrow is oriented in the direction at which the photo in the right panel was taken. (b) aerial photograph of the Ohio Range showing the location of Bennet Nunataks and the East and West Antarctic Ice Sheets (EAIS and WAIS, respectively). The blue dots indicate drill site locations. Photo ID: TMA CA05750009, USGS, 26 December 1959.

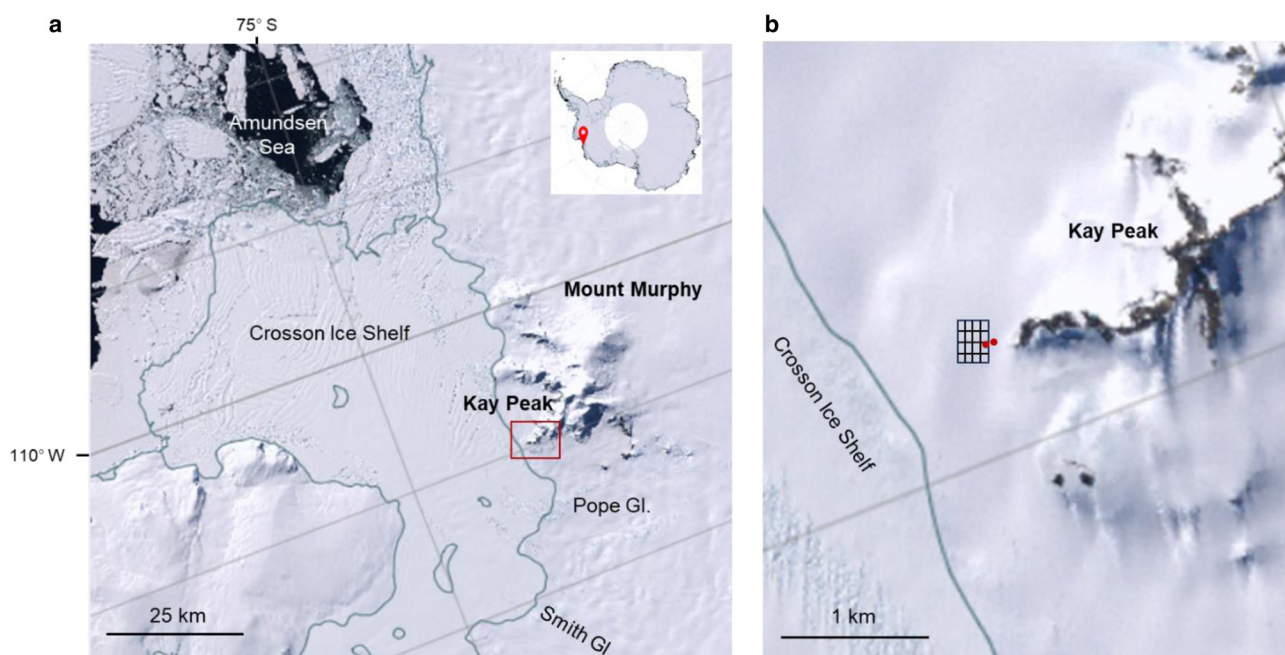


Figure 3. (a) Overview map of Mt. Murphy. The red box indicates the enhanced image in panel (b). The outlined light gray area indicates the ice shelf. (b) Location map for Kay Peak. The black lines in a grid indicate location of the GPR survey. The red dots are the approximate location of the drill sites. Images for both panels are from the Landsat Image Mosaic of Antarctica (LIMA).

topography strongly suggests the presence of suitable subglacial bedrock targets. At Mt. Murphy, this approach proved feasible with a highly experienced radar technician, although we do not recommend this strategy due to the likelihood of unknown subsurface complexities such as complicated basal geometry, off-axis reflections, and crevassing, each resulting in difficult-to-interpret radar data and additional time for radar surveys. Second, adaptation of the Winkie system to firn-covered sites using the Eclipse drill, casing, and packer was also a success, which greatly expanded the possible range of Antarctic and other sites accessible using the Winkie system.

On the other hand, this project also exposed some key limitations that significantly impacted drilling. First, warm ambient temperatures at the low-elevation site created difficulty in keeping drilling equipment, in particular the Eclipse sonde and the Winkie drilling fluid, below freezing. Warm drilling equipment and fluid degrades drill performance, damages the borehole, and creates the risk of equipment loss by freezing into the hole. Although this was mitigated by working during nighttime hours (where the lower sun angle reduced air temperatures and direct solar heating) and burying drill fluid drums in the firn, continued problems with warm fluid and refreezing of borehole water eventually prevented core collection in the final borehole. Second, continuing difficulties with transport of cuttings derived from ice-rock-clay mixtures in the basal ice greatly slowed drilling by requiring repeated halts and rod trips to unclog bit waterways and other parts of the fluid system blocked by flocculated cuttings (rod tripping entails removing or replacing drill rod from the borehole to access the coring assembly or drill bit). This appeared to be primarily caused by: (1) poor dispersion of clay cuttings in the drill fluid (Isopar-K) itself and/or immiscible fluid/water mixtures created by failure to maintain the fluid temperature below freezing, and (2) difficulties in filtering ice chips that were likely also exacerbated by the warm fluid.

3.3 Hudson mountains (drilled 2022/23)

3.3.1 Site description

The Hudson Mountains are a series of volcanic peaks adjacent to Pine Island Glacier (Fig. 4). The chosen drill site was located at

the southern end of Winkie Nunatak, which is situated ~10 km from the present margin of Pine Island Glacier and less than 50 km upstream of the current grounding line. The nunatak comprises a narrow, exposed ridge top ~1 km long, rising ~500 m above the surface of the adjacent Pine Island Glacier. Bedrock at Winkie Nunatak is composed of subaerially deposited basaltic bedrock with a weathered and eroded surface. Mineralogically, the rock is appropriate for cosmogenic nuclide dating using in situ ^{14}C (Pigati and others, 2010) and ^{36}Cl (Evans and others, 1997) in olivine and feldspar, respectively. Near-surface conditions at the drill site were similar to those at Mt. Murphy with snow and firn overlaying ice. High resolution satellite imagery revealed crevassing near Winkie Nunatak.

3.3.2 Key takeaways from radar and drilling efforts

Overall, the field campaign experienced several obstacles that ultimately prevented the successful extraction of bedrock cores. One major obstacle was related to crevassing directly over potential drill sites. Since this region is experiencing ongoing rapid change, conditions had changed since the previous season when a reconnaissance GPR survey was undertaken. Thus, the initial plan to GPR survey the site for two days immediately prior to drilling had to be increased to five days to properly map out crevasse hazards. At sites with snow and firn, we recommend that future teams are equipped with GPR systems appropriate for not only imaging ice thickness but also for detecting and flagging near-surface crevasses. This will allow for GPR to be used in tandem (not in place of) traditional field safety methods that include probing the area for crevasse hazards. In addition, when working at sites located near grounding lines or shear margins, the potential for changing near-surface conditions from year to year requires that a GPR survey be conducted the same season as drilling operations even if a reconnaissance season is carried out in previous years. Teams should have an inventory of backup drill sites as well, in case the first-choice site is not drillable due to crevassing.

A second obstacle was the need to drill at greater depth below the ice surface than originally planned because of the heavily crevassed terrain over the subglacial bedrock ridge at shallower depths.

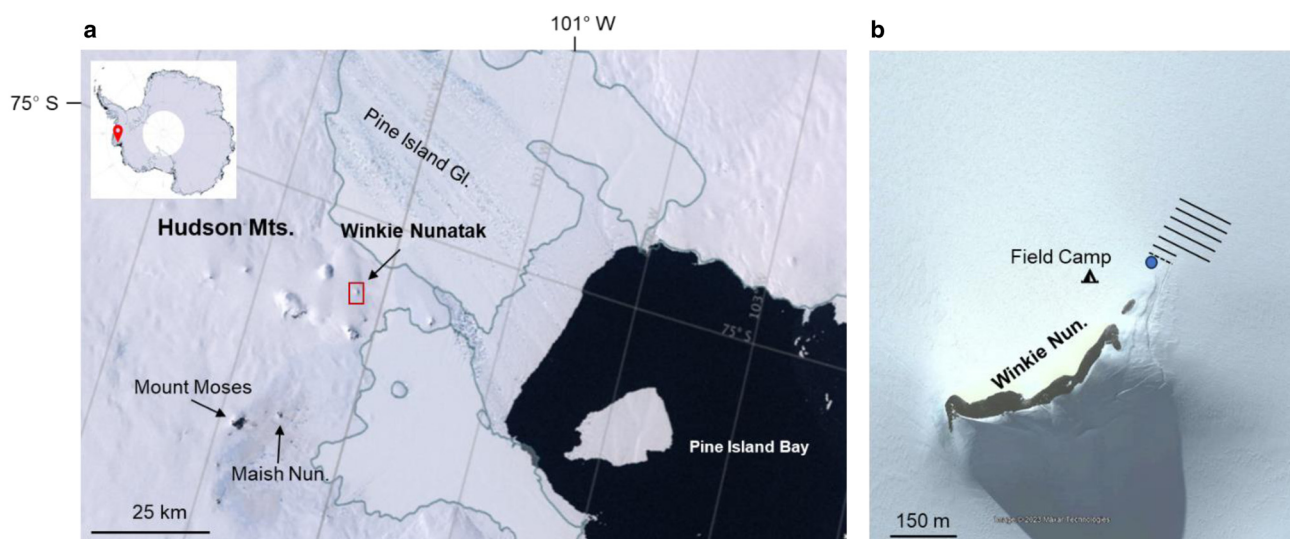


Figure 4. (a) Overview of Hudson Mountains from the Landsat Image Mosaic of Antarctica (LIMA). Textured gray represents the current ice-sheet surface and shaded gray areas outlined in blue represent ice shelves. The red box indicates the location of Winkie Nunatak. (b) Enhanced image of Winkie Nunatak with black lines indicating GPR survey described in radar survey section. Dotted black line indicates location of GPR survey in Fig. S4. The blue dot indicates the location of the drill site. Imagery from Google Earth: © 2023 Maxar.

Crevassing also dictated that a drill site on the upstream flanks of the ridge was chosen, rather than on the ridge crest. Drilling to greater depths was time consuming and resulted in insufficient time to attempt drilling further boreholes. At this site, the basal zone was found to contain frozen sediment and clay which prevented the team drilling to bedrock. Since selecting a site from GPR surveys with a clean ice-bed transition is inherently difficult, off ridge-crest drilling should be discouraged as there is a greater likelihood of encountering subglacial sediment in such settings. Finally, adding to these obstacles was the loss of two out of five weeks of field time, due to delays getting into the field. This further compounded the difficulties described above.

3.4 Enterprise hills (drilled 2022/23)

3.4.1 Site description

The Enterprise Hills, composed of Paleozoic quartzites of the Crashsite group, form the northern rim of Horseshoe Valley, a

large ice-filled valley in the Heritage Range of the Ellsworth Mountains (Fig. 5). Ice in Horseshoe Valley flows in a general northwest direction toward the modern grounding line which is situated at Hercules Inlet. In several places, glaciers cross the escarpment edge and flow in a more northerly direction toward the grounding line. One such glacier is Plummer Glacier and at its distal end this glacier merges with an extensive area of blue ice that is found all along the leeward side of the Enterprise Hills. At the mouth of Plummer Glacier is a small nunatak, 40–60 m above present-day ice. Prior to deployment to the field, this nunatak (informally named Plummer Nunatak) and a nearby small outcrop were identified as the highest priority target for drilling in the Enterprise Hills. Although there are additional rock outcrops in closer proximity to the grounding line at Hercules Inlet this site was selected for two main reasons: (1) available satellite imagery suggested less extensive snow and firn cover and numerous rock outcrops directly next to blue ice zones (a prerequisite for drilling with the available system), (2) several

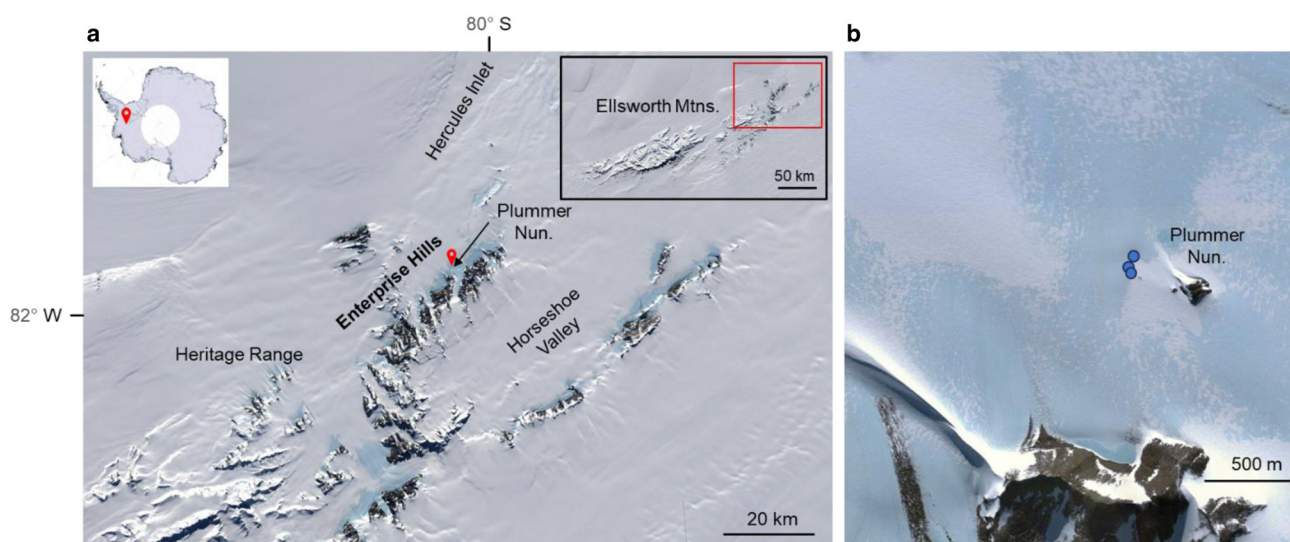


Figure 5. (a) Overview of Enterprise Hills. The red pin in the main image indicates the location of Plummer Nunatak. The red box in the inset map in the upper right highlights the area shown in the main image. (b) Enhanced map showing blue ice area around Plummer Nunatak. Blue dots indicate drill site locations. Base maps for both panels were created from Google Earth: Imagery © 2023 Maxar.

potential sites in close proximity were identified which, given the lack of a dedicated radar survey season prior to the drilling season, increased chances of finding a viable drill site once on the ground.

3.4.2 Key takeaways from radar and drilling efforts

Overall, the season was a success, with the team able to extract multiple cores from the site using the modified Winkie Drill system. Preseason on-site training from experienced drillers at the IDP contributed to this success. However, a more extensive GPR survey by an experienced technician could have identified a drill site with a more favorable configuration of subglacial topography (i.e. a gently dipping ridge crest), and would have avoided several days being dedicated to troubleshooting GPR operational issues. Side reflections in the radargrams made ascertaining accurate depths difficult, and this was exacerbated by the lack of GPR experience in the team. Fig. S5 shows the GPR-estimated ice thickness and the actual drill-depths and highlights the increasing inaccuracy of ice thickness estimates at increasing depths. In contrast, the drill sites were all located on blue ice that made assessment of site safety straightforward. From a drilling perspective, the ice augers used to create boreholes performed well to ~30 m depth, similar to the experience of the team at the Ohio Range site. With the modified Winkie Drilling system (see section 3.3 above), the team found that the presence of any ice and/or liquid water within the drill fluid circulation loop could be avoided through improved fluid management.

3.5 Mt. Waesche (to be drilled 2024/25)

3.5.1 General site description

The Mt. Waesche massif consists of two coalesced, undissected volcanic shields and is located on the high plateau of West Antarctica in the Executive Committee Range, a line of volcanoes projecting through the WAIS in Marie Byrd Land (Fig. 6). The oldest known deposits at Mt. Waesche are dated at 2.0 ± 0.1 Ma (Panter, 1995). Although much of the volcanoes are ice-covered, the southern flank of the massif exhibits a remarkable set of well-exposed and preserved scoria cones and lava flows (Fig. 6b) with a range of geochemical compositions, related to a pulse of eruptive activity between 0.2 and 0.1 Ma (Dunbar and others, 2021; Panter and others, 2021; Wilch and others, 2021). The volcano is

currently in a dormant state but is potentially still active (Dunbar and others, 2021). These young volcanic rocks are ideally suited, both in terms of age and composition, to constraining interior WAIS elevations during the Last Interglacial using a combination of $^{40}\text{Ar}/^{39}\text{Ar}$ and cosmogenic dating.

Present-day regional ice flow is southward from a dome centered on the northern Executive Committee Range where ice elevations reach 2200 m. WAIS surface elevations near Mt. Waesche are ~2000 m above sea level and the ice-covered summit caldera reaches 3200 m above sea level. A combination of ice flow processes and local winds have resulted in a notable local ablation (blue ice) area that occurs to the southwest of Mt. Waesche (Fig. 6b). This blue ice area, which is 8 by 10 km in extent, contains numerous englacial tephra layers that represent a repository of local and distal volcanism (Dunbar and others, 2021). The geometry of tephra layers indicates that in some areas the local ice has undergone complex deformation, likely as a result of interacting with subglacial bedrock topography. Work at Mt. Waesche seeks to better understand both the tephra stratigraphy and complex deformation using GPR survey information.

3.5.2 Preparations for upcoming drill season

IDP will deploy their Eclipse and Winkie Drill equipment at Mt. Waesche in the upcoming drilling season. The drilling objective is to collect eight subglacial bedrock cores (at least 0.5 m in length) from depths ranging from 30–100 m. In advance of the drilling season, IDP plans to test new downhole coring tools with improved bit clearance as a potential solution to the bit plugging and glazing that has negatively impacted drilling efforts at other sites (e.g. Hudson Mountains, section 3.3). If successful, new tooling may substantially increase the likelihood of recovering multiple bedrock cores in a single field season by improving drill performance in sediment rich basal environments. Additionally, IDP plans to rely on a new full-face ice drilling bit which can provide faster access to the bed at greater drill depths than the Eclipse drill that has previously been used.

Detailed grid surveys were carried out in 2018/19 to obtain 3-D radargrams of the sites. The advantage of 3-D imaging for drill site selection is to map out potential near-surface hazards, to better reduce ice thickness estimates in areas with complex

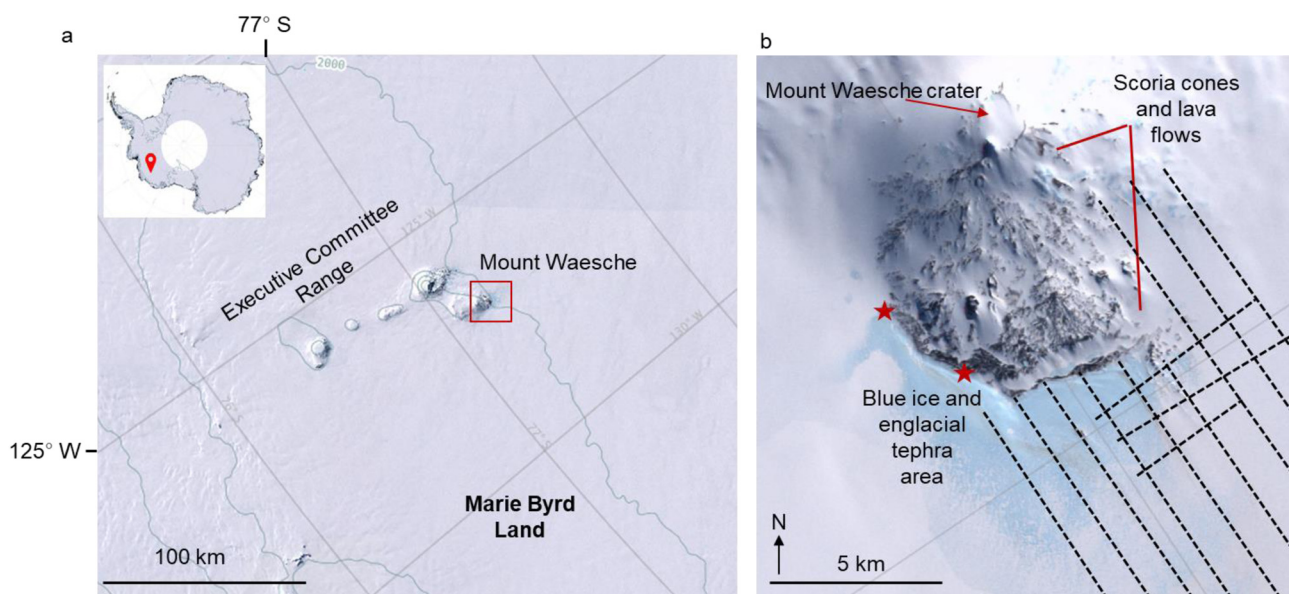


Figure 6. (a) Overview map of Mt. Waesche. The red box indicates the location of Mt. Waesche in panel (b). Topographic lines are spaced at 500 m intervals. (b) Enhanced image of Mt. Waesche showing GPR survey from 2018/19 (black dashed lines) and future drill site locations (red stars). The images from both panels are produced from the Landsat Image Mosaic of Antarctica (LIMA).

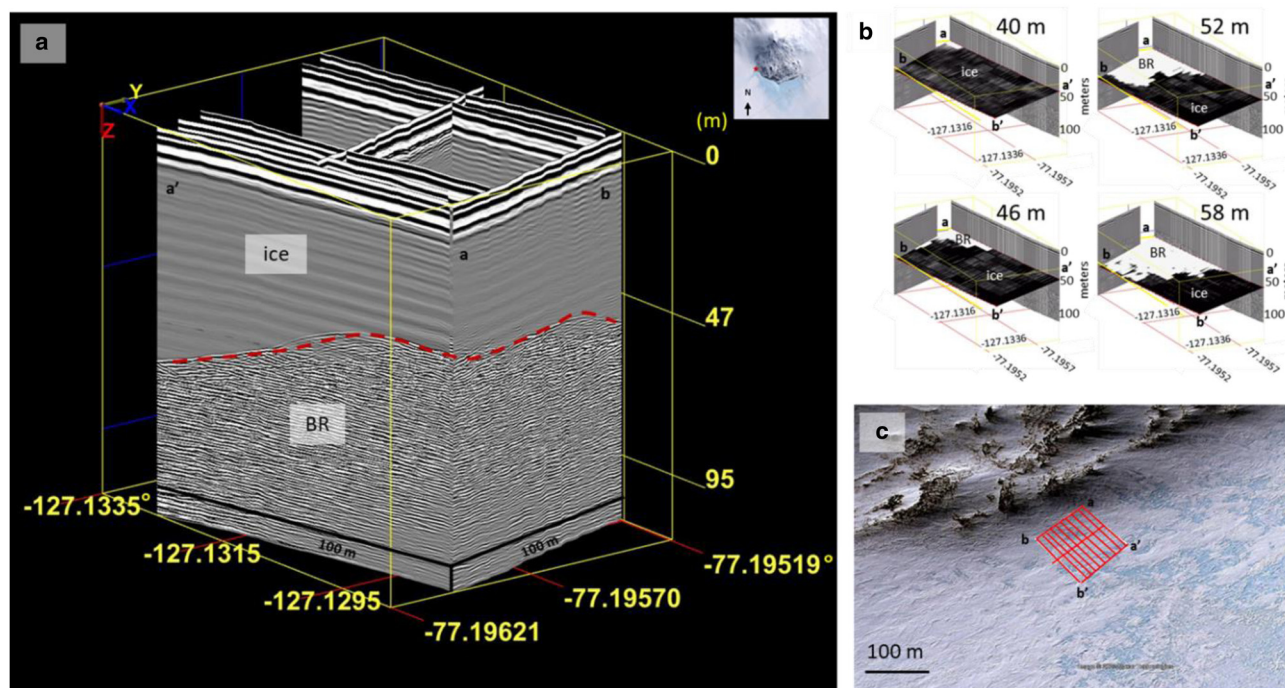


Figure 7. (a) A 3-D-processed radargram collected in 2018/19 used for drill site selection for the upcoming field campaign. The radar profiles were time-zero corrected, distance normalized to flag survey points (spaced at 10 m intervals) and migrated to increase ice thickness estimates and reduce the noise to signal ratio. (b) example of 3-D radar profile shown in slices at various depths beneath the ice surface (40, 46, 52, 58 m). On the horizontal plane, the darker colors indicate ice and the areas of white indicate bedrock (BR). Note that the ratio of bedrock to ice increases with depth. Orientation of a – a' and b – b' can be found in panel (c). (c) Image showing location of GPR survey (red lines) near the flank of Mt. Waesche. Imagery from Google Earth: Imagery © 2023 Maxar.

subglacial topography, and to preselect multiple target drill sites. The targeted drill sites are noted in Figure 6b and an example of the 3-D radargrams from one of the drill sites is shown in Figure 7. A reconnaissance GPR season is advantageous at a site like Mt. Waesche because the drill site is located over slow-moving blue ice so the complications presented by crevassing are not an issue like at other sites such as the Hudson Mountains.

4. Discussion and recommendations

We have discussed in detail the results and efforts of drilling campaigns and radar surveys at five sites in Antarctica. Decisions regarding drill site selection, what equipment to use in various glaciological settings, and the necessary time to complete the objectives of a field campaign are complex and need to be considered carefully well in advance of reaching the field site. It is essential to use as much information as possible for each site from a glaciological, geological, technical and logistical perspective. To improve the likelihood of success in future subglacial bedrock drilling efforts, we have the following recommendations.

4.1 Recommendations for future site selection

Here we highlight the importance of field site conditions when considering scientific objectives. Sites described in this overview were targeted based on sensitivity analysis and the likelihood of recording broader, regional ice volume change (Ohio Range, Mt. Waesche) and others because they were ideally located to capture grounding line retreat (Mt. Murphy, Hudson Mountains). However, some of these sites presented significant challenges with logistics as well as field safety due to heavy crevassing near targeted drill locations. For example, Winkie Nunatak (Hudson Mountains) is located adjacent to the shear margin of Pine Island Glacier and the drill site was situated over snow and firn. Although the field site was surveyed in December 2019, changes in ice flow dynamics in the subsequent three years resulted in

heavy crevassing at ideal drilling locations when the site was resurveyed in January 2023. Therefore, it was deemed necessary to drill at a location that was safer, but with the consequence that it was more challenging to reach bedrock due to the greater ice thickness and steepness of subglacial topography. Conversely, at Enterprise Hills, a site was selected on blue ice where crevasse hazards could be mitigated or avoided completely. However, that site was not an optimal location to capture grounding line retreat in the Weddell sector of Antarctica. This demonstrates the need to consider the tradeoffs between selecting sites that best serve to answer a specific science question but are in regions with less favorable glaciological conditions (snow and firn sites, crevassing, proximity to ice streams and margins) compared with sites that will ease logistical constraints based on proximity to field stations and are in more favorable glaciological settings (blue ice), but may not fully capture certain elements of the proposed scientific question.

4.2 Recommendations for future GPR surveys

Since drilling efforts began in Antarctica with the Winkie Drill at Ohio Range in 2016/17, GPR technology has improved so that systems are capable of imaging englacial features (stratigraphy, crevasses) at higher resolution, are more compact and easier to transport so that teams have the option to use multiple systems, and data can be processed quickly in the field to provide real-time imaging of the ice-bedrock interface. GPR is widely used in cryosphere studies and an essential tool for drill site selection and safety when carrying out fieldwork on glaciers. Here we summarize key takeaways when considering the use of GPR for drill site selections.

- 1) We recommend that a dedicated radar specialist is included in every field team. The radar operator should have sufficient field experience with equipment and the knowledge and preparation for rapid data processing in the field. Although GPR

systems are relatively user friendly and are often borrowed and used by teams without a dedicated radar technician, properly interpreting radargrams in the field with limited time is difficult. Challenges include properly identifying the depth to bedrock, crevasse detection, and interpreting englacial stratigraphy. In addition, it is rare that GPR systems do not require troubleshooting in the field because of the harsh conditions in which they operate.

- 2) Although GPR is a powerful tool for imaging englacial stratigraphy and providing depth estimates, greater survey depths, coupled with complex subglacial topography, will lead to a larger uncertainty in the depth estimate because of geometric spreading of the radar signal and side reflections (e.g. Moran and others, 2003; Lapazaran and others, 2016). We recommend sufficient time is given to carry out a detailed GPR grid survey over the intended drill site with additional time needed for processing the data in the field. The amount of time needed will vary based on site complexity and radar technician experience.
- 3) GPR surveys should be planned in advance of the field season using satellite imagery and digital elevation models of the ice surface as well as adjacent ice-free areas to save time once on site in the field. When on the ground, a survey can first be conducted at points of interest with the technician starting a transect at the ice surface-nunatak transition and surveying away from exposed bedrock to trace the depth of subglacial topography. Based on those results, a grid survey can be set up over an area of interest to map the area in greater detail (see Figs. S3, S4, S5).
- 4) GPR can also be used for crevasse detection at sites with snow and firn cover but should not be relied on to reveal all hazards at a field location. Crevasse may go undetected for numerous reasons including the angle at which the radar is towed over a crevasse, the frequency of antenna used for surveying, the post-processing techniques used in the field, and the experience of the radar technician interpreting radargrams. A GPR crevasse survey is best used after site safety has been established by conventional techniques (visual inspection and

probing by an experienced field mountaineer/field guide). Given the weight of the drilling equipment, it is essential to identify and flag major crevasse systems that may hamper drilling efforts or create safety concerns for field personnel. Crevasse hazards at sites with snow and firn cover highlight the importance of conducting a GPR survey in the same season as drilling if the area is in an area of rapid ongoing glaciological change. For sites where drilling will be conducted on slow-moving blue ice, a reconnaissance survey season may be appropriate because surface conditions are unlikely to change much from year to year.

4.3 Recommendations for future subglacial drilling campaigns

Substantial engineering development of the Winkie Drill has made it an effective tool for collecting shallow (<120 m) subglacial samples on logistics-constrained projects. Drill operational and site selection recommendations are summarized below for future drilling campaigns.

- 1) Subglacial drilling with the Winkie Drill requires that the basal ice-bed contact are sealed as this prevents contamination of the subglacial environment (Doran and Vincent, 2011) as well as maintaining a closed fluid circulation system. At interior sites such as the Ohio Range, this was not an issue. At one coastal site, Mt. Murphy, meltwater from the local nunatak made its way to the ice-bed interface and complicated drilling efforts that ultimately resulted in abandoning that access hole. Figure 8 shows the difference in the ice-bed interface between these two sites.
- 2) If possible, selecting a drill site with blue ice that is free of fractures is an effective strategy to reduce the necessary drilling equipment. Subglacial drilling at blue ice site does not require a separate electro-mechanical access drill and casing system to seal the outer borehole surface since competent blue ice is impermeable to drill fluid. It is also noteworthy that access drilling using the Winkie Drill is more efficient compared to a standard electro-mechanical drill such as the Eclipse drill.

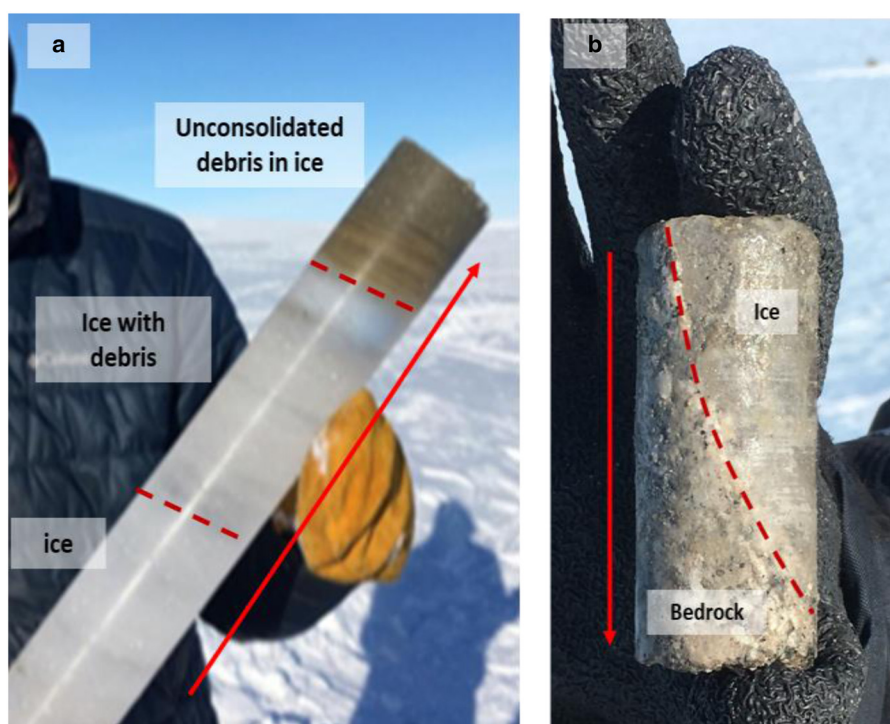


Figure 8. (a) A photo of a core collected from Mt. Murphy that illustrates increasing debris density down core. These fine debris and clay material can delay or hamper drilling efforts for the Winkie Drill system. (b) Photo of a core collected from Ohio Range. The core was recovered with the basal ice frozen directly to the bedrock. The red arrow in each photograph is pointing downcore.

- 3) Warm ambient temperatures degrade drill performance and increase the risk of equipment loss by freezing in the hole for both access and subglacial drilling operations. If ambient temperatures approaching -4°C (25°F) are anticipated, we recommend using a fluid chiller to cool drill fluid. It is also recommended to use a windscreen or drilling tent to shade the access drill during surface operations.
- 4) Transporting and positioning drill equipment, drilling an access hole, and collecting a subglacial core from a single borehole constitute a substantial time commitment of days to more than a week. Therefore, it is recommended to complete a detailed GPR survey to select a drill site and not relying solely on estimates from models such as BedMachine or BedMap as this can greatly improve the efficiency of subglacial drilling efforts.
- 5) It is recommended that drilling campaigns start with a shallow core first (10–20 m) and then progress to drilling at deeper sites if successful. This approach increases the likelihood of success as it allows the drill operator to efficiently troubleshoot site-specific challenges while also tuning drilling parameters without excessive tripping times. Additionally, drilling a shallow core and obtaining an exact depth to bedrock will serve as a ground-truth point for GPR estimates of ice thickness when applied in post-processing. For example, at Enterprise Hills (Fig. S5), a shallow drill site was GPR-estimated at 10 m depth and the actual drill depth was 10.8 m. However, at a deeper site GPR estimated at 21 m, the actual drill depth was 29.5 m. This is a nearly 30% under estimation by the GPR due to the steepness of the subglacial terrain and limited time for post processing. At the Hudson Mountains, additional time was allotted for post-processing GPR data due to other delays and the GPR estimated depth of 43 m underestimated the drill depth of 49.6 m by $\sim 15\%$ (drilled into debris-filled ice that was likely within 1 m of bedrock; Fig. S4).
- 6) Drilling through subglacial sediment and clay overburden can stall drilling and substantially impact the time required to reach bedrock. Any information available on subglacial topography or drill site lithology should be leveraged to select a drill site that prioritizes a clean transition from ice to bedrock. A detailed GPR survey can mitigate drilling risk by targeting subglacial topography that minimizes sediment accumulation (such as ridges or domes). At present, GPR cannot differentiate between bedrock and debris-covered bedrock at the ice-bed interface. To address this issue from a technological perspective, it is recommended that future development focus on improving chip transport of clay and sediment to prevent bit plugging. One possible solution is to implement a drilling fluid additive that reduces clay flocculation to prevent aggregation of sediments on the downhole bit and tooling. Another option is to investigate an alternative core barrel assembly with oversized fluid circulation waterway to improve chip transport.

5. Conclusion

Despite the challenges presented by subglacial geologic drilling in polar environments, the method remains the only conclusive means by which to test for past instabilities of existing ice sheets. The implementation of the Winkie Drill to recover bedrock from shallow sites has been successful at many locations, and results from some of those studies provide direct evidence for past ice volume changes of AIS (Balco and others, 2023). Future drilling campaigns in Antarctica will continue to use the Winkie Drill (Mt. Waesche) as well as other systems such as with the INCISED program which will use a newer drill system, the percussive rapid access isotope drill (P-RAID; Timoney and others, 2020). In Greenland, the GreenDrill Program will target subglacial

bedrock sites at depths of hundreds of meters after a successful campaign in 2023 using the Winkie and ASIG drills. Given the urgency to reduce uncertainties in future contributions of the Antarctic Ice Sheet to sea level rise, we expect continued and increasing efforts to collect subglacial bedrock samples to constrain past ice volume changes at more locations in Antarctica and Greenland. Our recommendations for radar surveys and drilling efforts will increase the likelihood of success for such future endeavors.

Supplementary material. The supplementary material for this article can be found at <https://doi.org/10.1017/aog.2024.12>

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References

- Ackert Jr RP, Mukhopadhyay S, Parizek BR and Borns HW (2007) Ice elevation near the West Antarctic ice sheet divide during the last glaciation. *Geophysical Research Letters* **34**(21), 1–6. <https://doi.org/10.1029/2007GL031412>
- Balco G and 12 others (2023) Reversible ice sheet thinning in the Amundsen Sea Embayment during the Late Holocene. *The Cryosphere* **17**, 1787–1801. <https://doi.org/10.5194/tc-17-1787-2023>
- Balter-Kennedy A and 10 others (2023) First Results from GreenDrill: Exposure dating in sub-ice material from Prudhoe Dome, northwestern Greenland [conference presentation]. AGU 2023, San Francisco, CA USA, Dec. 11–15. Available at <https://agu.confex.com/agu/fm23/meetingapp.cgi/Paper/1314764>
- Boeckmann GV and 6 others (2021) Adaptation of the Winkie Drill for subglacial bedrock sampling. *Annals of Glaciology* **62**(84), 109–117. <https://doi.org/10.1017/aog.2020.73>
- Bradley SL, Hindmarsh RC, Whitehouse PL, Bentley MJ and King MA (2015) Low post-glacial rebound rates in the Weddell Sea due to Late Holocene ice-sheet readvance. *Earth and Planetary Science Letters* **413**, 79–89. <http://doi.org/10.1016/j.epsl.2014.12.039>
- Doran PT and Vincent WF (2011) Environmental protection and stewardship of subglacial aquatic environments. In Siegert MJ and Kennicutt MC (eds), *Antarctic Subglacial Aquatic Environments*. Geophysical Monograph Series,

- V. 192. American Geophysical Union, pp. 149–157. <https://doi.org/10.1002/9781118670354.ch9>
- Dunbar NW and 5 others** (2021) Active volcanoes in Marie Byrd Land. In Smellie JL, Panter KS, Geyer A (eds), *Volcanism in Antarctica: 200 Million Years of Subduction, Rifting and Continental Break-up*, vol. 55. London: Geological Society of London Memoirs, pp. 759–783. doi: [10.1144/m55-2019-29](https://doi.org/10.1144/m55-2019-29).
- Evans JM, Stone JOH, Fifield LK and Cresswell RG** (1997) Cosmogenic chlorine-36 production in K-feldspar. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* **123**(1–4), 334–340. [https://doi.org/10.1016/S0168-583X\(96\)00714-8](https://doi.org/10.1016/S0168-583X(96)00714-8)
- Freund A, Pritchard H, Fretwell P and Bodart J** (2023) Bedmap3: new data and gridded products of Antarctic ice thickness, surface and bed topography (No. EGU23–13665). Copernicus Meetings.
- Fretwell P and 6 others** (2013) Bedmap2: improved ice bed, surface and thickness datasets for Antarctica. *The Cryosphere* **7**(1), 375–393.
- GEBCO Bathymetric Compilation Group 2019** (2019) The GEBCO_2019 Grid – a continuous terrain model of the global oceans and land. British Oceanographic Data Centre, National Oceanography Centre, NERC, UK. doi: [10.5285/836f016a-33be-6ddc-e053-6c86abc0788e](https://doi.org/10.5285/836f016a-33be-6ddc-e053-6c86abc0788e)
- Granger DE** (2014) Cosmogenic nuclide burial dating in archaeology and paleoanthropology. In: Holland HD and Turekian KK (Eds). *Treatise on Geochemistry*, 2nd Edn. Oxford: Elsevier, pp. 81–97. <https://doi.org/10.1016/B978-0-08-095975-7.01208-0>
- Howat IM, Porter C, Smith BE, Noh M-J and Morin P** (2019) The reference elevation model of Antarctica. *The Cryosphere* **13**, 665–674. <https://doi.org/10.5194/tc-13-665-2019>
- Johnson JS and 10 others** (2020) Deglaciation of Pope Glacier implies widespread early Holocene ice sheet thinning in the Amundsen Sea sector of Antarctica: Earth and Planetary Science Letters, v. 548. <https://doi.org/10.1016/j.epsl.2020.116501>; corrigendum available at <https://doi.org/10.1016/j.epsl.2021.117221>
- Kingslake J and 9 others** (2018) Extensive retreat and re-advance of the West Antarctic ice sheet during the Holocene. *Nature* **558**(7710), 430–434. <https://doi.org/10.1038/s41586-018-0208-x>
- Kopp RE, Simons FJ, Mitrovica JX, Maloof AC and Oppenheimer M** (2009) Probabilistic assessment of sea level during the last interglacial stage. *Nature* **462**(7275), 863–867. <https://doi.org/10.1038/nature08686>
- Lapazaran JJ, Otero J, Martín-Español A and Navarro FJ** (2016) On the errors involved in ice-thickness estimates I: ground-penetrating radar measurement errors. *Journal of Glaciology* **62**(236), 1008–1020. <https://doi.org/10.1017/jog.2016.93>
- Lau SC and 10 others** (2023) Genomic evidence for West Antarctic ice sheet collapse during the Last Interglacial. *Science (New York, N.Y.)* **382**, 1384–1389. doi: [10.1126/science.ade0664](https://doi.org/10.1126/science.ade0664)
- Meredith M and 12 others** (2019) Polar regions. In Pörtner H-O and 12 others (eds), *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*. Cambridge, UK and New York, NY, USA: Cambridge University Press, pp. 203–320. <https://doi.org/10.1017/9781009157964.005>
- Moran ML, Greenfield RJ and Arcane SA** (2003) Modeling GPR radiation and reflection characteristics for a complex temperate glacier bed. *Geophysics* **68**(2), 559–565. <https://doi.org/10.1190/1.1567225>
- Morlighem M** (2022) *MEaSURES BedMachine Antarctica, Version 3 [Data Set]*. Boulder, Colorado, USA: NASA National Snow and Ice Data Center Distributed Active Archive Center. <https://doi.org/10.5067/FPSU0V1MWUB6>
- Mukhopadhyay S, Ackert Jr RP, Pope AE, Pollard D and DeConto RM** (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**, 243–251. <https://doi.org/10.1016/j.epsl.2012.05.015>
- Panter KS** (1995) Geology, Geochemistry and Petrogenesis of the Mount Sidley Volcano, Marie Byrd Land, Antarctica. PhD: New Mexico Tech, 208.
- Panter KS** (2021) Antarctic volcanism: petrology and tectonomagmatic overview. In Smellie JL, Panter KS and Geyer A (eds), *Volcanism in Antarctica: 200 Million Years of Subduction, Rifting and Continental Break-up*, vol. 55. London: Geological Society of London Memoir, pp. 43–53. doi: [10.1144/m55-2020-10](https://doi.org/10.1144/m55-2020-10)
- Pigati J, Lifton N, Jull A and Quade J** (2010) Extraction of in situ cosmogenic ¹⁴C from olivine. *Radiocarbon*, **52**(3), 1244–1260. doi: [10.1017/S0033822200046336](https://doi.org/10.1017/S0033822200046336)
- Priscu JC and 10 others** (2021) Scientific access into Mercer Subglacial lake: scientific objectives, drilling operations and initial observations. *Annals of Glaciology* **62**(85–86), 340–352. <https://doi.org/10.1017/aog.2021.10>
- Rix J, Mulvaney R, Hong J and Ashurst DA** (2019) Development of the British Antarctic survey rapid access isotope drill. *Journal of Glaciology* **65**(250), 288–298. <https://doi.org/10.1017/jog.2019.9>
- Scherer RP and 5 others** (1998) Pleistocene collapse of the West Antarctic ice sheet. *Science (New York, N.Y.)* **281**(5373), 82–85. <https://doi.org/10.1126/science.281.5373.82>
- Spector P and 5 others** (2018) West Antarctic sites for subglacial drilling to test for past ice-sheet collapse. *The Cryosphere* **12**(8), 2741–2757. <https://doi.org/10.5194/tc-12-2741-2018>
- Spector P and 10 others** (2019) Drilling priorities to determine the past extent of the Antarctic Ice Sheet. Ice Drilling Program Subglacial Access Working Group Science Planning Workshop, March 29–30, 2019, Herndon, Virginia, USA, 1–10.
- Timoney R and 7 others** (2020) A low resource subglacial bedrock sampler: the percussive rapid access isotope drill (P-RAID). *Cold Regions Science and Technology* **177**, 103113. <https://doi.org/10.1016/j.coldregions.2020.103113>
- Tulaczyk S and 10 others** (2014) WISSARD at Subglacial Lake Whillans, West Antarctica: scientific operations and initial observations. *Annals of Glaciology* **55**(65):51–58. <https://doi.org/10.3189/2014AoG65A009>
- Venturelli RA and 9 others** (2020) Mid-holocene grounding line retreat and readvance at Whillans ice stream, West Antarctica. *Geophysical Research Letters* **47**(15), e2020GL088476. <https://doi.org/10.1029/2020GL088476>
- Venturelli RA and 10 others** (2023) Constraints on the timing and extent of deglacial grounding line retreat in West Antarctica. *AGU Advances* **4**(2), e2022AV000846. <https://doi.org/10.1029/2022AV000846>
- Wilch TL, McIntosh WC and Panter KS** (2021) Marie Byrd land and Ellsworth land: volcanology. In Smellie JL, Panter KS and Geyer A (eds), *Volcanism in Antarctica: 200 Million Years of Subduction, Rifting and Continental Break-up*, vol. 55. London: Geological Society of London Memoir, pp. 515–576. doi: [10.1144/M55-2019-39](https://doi.org/10.1144/M55-2019-39)

Supplementary Information

Lessons learned from shallow subglacial bedrock drilling campaigns in Antarctica

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1. Drilling Technology

The Winkie Drill system uses jointed pipes, driven from the surface, to collect samples using traditional diamond coring bits. The drill produces a 48.1 mm borehole and 33.5 mm core with a continuous core length of 1.52 m. The drill can be equipped with four bit designs to be used for a variety of ice-bed conditions (Fig. S1). The three main components of the system are 1) powerhead and frame, 2) drill string and core barrel, and 3) circulation system. The circulation system for the subglacial drill included modifications for cold operation and fluid recovery. Isopar K, a paraffin-like, relatively non-toxic hydrocarbon solvent used in industrial cleaning applications and with a density of 760 kg m⁻³, was selected for the circulation fluid after several studies noted its advantages for use in polar environments (Talalay, 2011; Sheldon and others, 2014; Liu and others, 2016). The “used” Isopar K must be contained, filtered, and recycled. For this, a tank with several filtration socks is assembled to capture the Isopar K and a light-weight piston pump is used to circulate the fluid through the borehole. When first developed, the Winkie Drill used standard commercial components for every subsystem except for the circulation system. Since the drill system was field tested in 2016/17, parts of the equipment have changed to meet the demands and challenges associated with collecting subglacial bedrock cores. We document the evolution of the Winkie Drill in section 3 of the main text.



Fig. S1. Winkie Drill is equipped with four bit designs. The #10 diamond-impregnated bit is used in hard bedrock formations. The geoset bit is used in soft rock formations or when sediments are entrained in the ice. The polycrystalline diamond compact (PDC) bit can be used in similarly soft rock formations but has had limited success when ice is present in the kerf. The hybrid impregnated bit is made from the same material as the standard #10 diamond-impregnated bit but includes a relief angle behind the leading edge. This bit can cut ice and transition into bedrock. Figure reproduced from Boeckmann and others, 2020; Fig. 4.

The weight of the required drilling system for a field campaign is driven by the targeted depth at which a team intends to drill and surface conditions at the drill site. This is because a large portion of the total weight is from the drill rods and drill fluid. Additionally, drill sites that contain firm or fractured blue ice require a pilot drill and casing to contain the drill fluid. See Table S1 to calculate the approximate weight of equipment based on targeted drill depths and glaciological conditions.

Table S1. Estimated weight for required drilling equipment. The weight of necessary equipment will scale to the intended depth of drilling.

Equipment	Weight (kg)	Notes
Drill Rig & Equipment	1000	Modified IDP Winkie Drill system
Drill Generators	200	Weight for two Honda 5 kW Generators
Drill Rod	40	Weight per 15 m of rod section
Drill Fluid	45	Weight required per 15 m depth drilled
Fuel	340	Weight for two 200 L drums

Pilot Drill*	590	IDP Badger-Eclipse Drill
Casing*	83	Weight per 15 m section of casing
Packer Equipment*	90	Inflatable packer and compressor

* A pilot drill and associated equipment are necessary for drilling at sites with firm or fractured blue ice.

2. Radar Technology

The choice of GPR system and antennas depends upon the target drill depths, with deeper targets requiring lower frequency radar systems. Low-frequency antennas (5-100 MHz) have the capability to image hundreds-to-thousands of meters depth, primarily depending on frequency choice, transmitter power, and sample rates. Higher-frequency antennas (200-900 MHz) can image tens-to-hundreds of meters of depth and are often used for imaging near-surface features or shallow ice thicknesses. Often, shallow radar surveys are carried out over small areas (~100-500 m²) using a grid system. Grids are created using stakes spaced at set intervals (usually every 10, 25, or 50 m) and located for post processing using GPS systems. The grid system allows for distance normalization of radar profiles, a post-processing method that enables the user to more accurately geolocate subglacial features of interest. Targeted ice thickness depths for grid surveys range from 10 to 150 m. See Table S2 for a summary of the GPR hardware and basic settings used at each field site.

Table S2. Summary of ground-penetrating radar (GPR) hardware and basic settings used for data collection at five sites in Antarctica. GSSI - Geophysical Survey Systems Incorporated. S&S - Sensors and Software. Two GPR surveys were conducted in the Hudson Mountains. Data for the 2019/20 survey is given in brackets.

Drill site	Ohio Range	Mt. Murphy	Hudson Mountains	Enterprise Hills	Mt. Waesche
Season	2015-2016	2019-2020	(2019/20) 2022-2023	2022-2023	2018-2019
GPR Make	GSSI	GSSI	(S&S) GSSI	S&S	GSSI
GPR Model	3207, 50400S	3207, 50400S	(PulseEKKO) 50200HS, 50400S	PulseEKKO	3207, 50400S
GPR Antenna (MHz)	100, 400	100, 400	(100, 200) 200, 400	100	100, 400
GPR Receiver	SIR-4000	SIR-4000	(Digital Video Logger) Panasonic® Toughpad G2	Digital Video Logger	SIR-4000
Scan Rates (scans/second)	12-90	12-90	12-110	12	12-90

Sampling Rates (samples/scan)	1024-4096	1024-4096	(4,000ns/300m) 1024-4096	1440	1024-4096
Bandpass Filter (MHz)	25-350, 100-800	25-350, 100-800	(40-80, 120-240) 65-800,100-800	20-200	25-350, 100- 800

3. Study Sites

For each site, we provide the scientific justification for drilling and an overview of the drilling and radar campaigns (if applicable). See main text for a site description and the key takeaways from radar and drilling efforts.

3.1 Ohio Range

Scientific justification

The Ohio Range is part of the Transantarctic Mountains that divides the WAIS and East Antarctic Ice Sheet (EAIS). This location was selected for subglacial bedrock recovery drilling because ice sheet models indicated the potential of the site to record evidence of low stand glacial ice during the Plio-Pleistocene (Pollard and Deconto 2009, 2012). The Pliocene is of interest because it is the most recent period in which global temperatures were warmer than present and atmospheric CO₂ concentrations may have been slightly higher than current levels (e.g. Haywood and others, 2000; Jiang and others, 2005), potentially providing an analog for future WAIS behavior. Therefore, cosmogenic nuclide inventories in subglacial bedrock cores recovered from this site provide evidence of ice-free conditions at periods of interest in the past. Simple two stage models of the observed cosmogenic nuclide concentrations in the recovered cores provide constraints on minimum exposure and cover. Similar to the adjacent exposed bedrock on the Bennet nunataks, the cosmogenic nuclide concentrations of the recovered subglacial samples indicate a complex exposure history with at least several hundred thousand years of integrated exposure and cover. Bedrock exposure ranges from 300 ka (thousands of years) to 2000 ka and ice cover from 150 to 200 ka (Mason, 2018; Middleton and others, 2018).

Radar survey

In preparation for subglacial drilling, extensive 400MHz and 100 MHz GPR surveys were conducted in 2015/16 and 2016/17 to map subglacial topography and englacial stratigraphy surrounding Tuning and Bennett Nunataks (Fig. S2). These data were collected to locate subglacial ridge crests or rises with minimal entrained debris in the ice above to assure success of drilling shallow (<30-50 m) ice cores to extract subglacial bedrock samples. In addition, data was used to interpret local flow dynamics during advance and retreat of ice elevation in the Ohio Range and provide ice depth information for constraining numerical ice models. GPR data was supplemented with ice ablation and velocity measurements obtained from stakes installed during 2015/16 to better characterize local glaciological conditions using methods similar to those by Campbell and others, (2013).

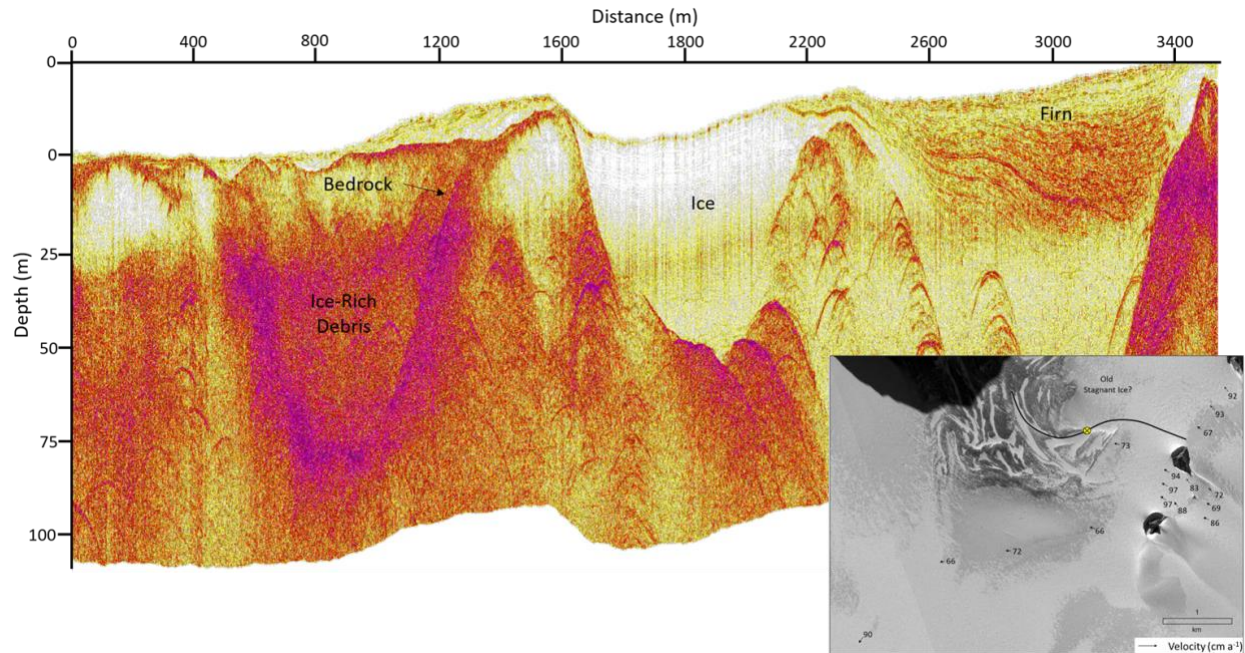


Fig. S2. Example 100 MHz radar profile collected in 2015/16 that crosses a complex area of ice, firn, and bedrock (see inset). For depth estimates, a relative permittivity of 3.1 was assumed. The profile has been distance and surface normalized and stacked to improve signal to noise ratios. The values in the inset map indicate velocity measurements and ice flow direction. Imagery © 2023 Maxar

Drilling efforts

The 2016/17 season was the first deployment of the Winkie drill system in Antarctica to attempt to extract a bedrock core. The drilling goal was to collect 50+ cm subglacial bedrock samples from six discrete boreholes ranging in depth from 10 m to 30 m beneath the ice surface. If the drill performed well, the team would attempt a borehole to 50 m depth. All drilling operations were carried out through blue ice, which simplified the drill fluid circulation system because non-fractured blue ice can contain the drilling fluid. The drill was first tested by using air circulation to clear ice chips but this proved to be ineffective and the team switched to Kovacs augers to create access boreholes to the underlying bedrock. The team successfully drilled for 12 days following a planned procedure: 1) drilling an access hole to the bedrock surface using Kovacs augers driven by the Winkie Drill, 2) configuring the Winkie Drill for wet drilling, using a geoset bit (Fig.S1) for the first coring run, 3) drilling with the geoset bit until penetration was no longer possible due to bit dulling then collecting the core, 4) replacing the geoset bit with a diamond impregnated bit and coring to the desired depth, 5) moving the Winkie Drill to the next drill site. This resulted in the extraction of five bedrock cores that varied in length from 28 cm to 67 cm. The successful boreholes were drilled through ice at depths between 12.1 and 28.3 m (Table 1). One additional core of sediment was collected (rather than bedrock) from 27.0 m when attempting to reach bedrock.

The project was successful, and a list of recommendations were made during post-season discussions that included using a remote power source and an electric motor for the drill and a drill enclosure. Enclosing the drill would prevent weather interruptions and issues from blowing snow entering parts of the drill system. Moving to a remote power source would

alleviate the noise and exhaust generated by the engine mounted to the Winkie Drill. In addition, the team found that drill system upgrades could be made to address the process known as rod tripping. Rod tripping entails removing or replacing drill rod from the borehole to access the coring assembly or drill bit. Rod tripping is necessary to clear the drill bit if it becomes clogged with ice or mud, or to recover a drilled core. This is especially relevant for deeper boreholes (>30 m) where rod tripping speed is a main driver of drilling production rate. The team suggested that a mechanism should be added to the system to make rod tripping less physically demanding and more efficient for the operators given the targeted drilling depths.

3.2 Mt Murphy

Scientific justification

Mt. Murphy is located between the Thwaites and Pope Glaciers in the Amundsen Sea region of West Antarctica, an area of rapid glacier thinning in recent decades that has been a focus of studies of the Antarctic contribution to present and future sea-level rise (Scambos and others, 2017). These and other Amundsen Sea glaciers overlie over deepened subglacial basins, so that present-day grounding line retreat has the potential to initiate a positive feedback response in which retreat into the basin increases the water depth at the calving face, which increases the calving rate and spurs further retreat. This so-called marine ice sheet instability is hypothesized to be a potential trigger for irreversible ice loss from a substantial portion of West Antarctica in the coming decades to centuries, with possibly significant impacts on global sea level (Thomas and others, 1979; Bamber and others, 2009).

Subglacial bedrock drilling at Mt. Murphy (and also in the Hudson Mountains and Enterprise Hills described in section 3.3 and 3.4) was motivated by the observation that cosmogenic-nuclide exposure age datasets in many regions of Antarctica including the Amundsen Sea indicate rapid thinning to the present ice surface elevation between 8 - 4 ka ago, but provide no evidence of thicker ice after that time (see Johnson and others, 2022). Thus, either the ice thickness has been perfectly stable in this region for over 4 ka – which is unlikely given dynamic late Holocene boundary conditions, including changing relative sea level and oceanographic conditions – or the ice sheet thinned to a configuration smaller than present, with grounding lines inboard of present positions, and then thickened to the present configuration. The possibility that thinning and grounding line retreat inboard of present positions took place earlier in the Holocene and did not lead to irreversible retreat is important in understanding the significance of present thinning in this region, so the drilling project was intended to determine whether a late Holocene retreat-advance cycle did or did not take place.

Radar survey

A radar survey for the selection of the first drill site was conducted in the one day immediately prior to drilling. A radar line collected with a ski-towed 100 MHz antenna (Fig. S3) that crossed the subglacial extension of the ridge several times was used to select an initial drill site so that drill assembly and site preparation could begin at the same time as a more detailed radar survey was conducted. The area available for site survey was limited by a prominent bergschrund 100-200 m from the ice margin that separated a crevasse-free area below the bergschrund from an extensively crevassed area between the bergschrund and the ice margin. As the ice thickness at the bergschrund was ~30 m, this precluded drilling at any sites shallower

than that depth. Further radar surveying, mainly including a 70 by 100 m grid survey with 10-meter line spacing (see Fig. S3) established that the subglacial ridge dropped away from the nunatak fairly steeply, leaving approximately a 70-meter long section of subglacial ridge between the bergschrund and the maximum ice thickness deemed efficient for drilling operations at approximately 60 m. Thus, the grid survey was used to select several drill sites along this ridge segment with ice thicknesses interpreted from the radar between 35-60 m.

An important element of the radar survey at this site was that radar survey and drill deployment were taking place simultaneously – drilling commenced less than one day after the beginning of the radar survey – and under deep field conditions, so it was not possible to apply advanced processing techniques to the radar data to optimize bedrock depth estimates. As such, only rapid and low-overhead processing techniques such as stacking (which improves signal-to-noise ratio) and a simple migration algorithm based on bedrock hyperbolae (which corrects incorrect bedrock slopes influenced by side reflections) were used. Regardless, four out of six drill holes successfully recovered bedrock core.

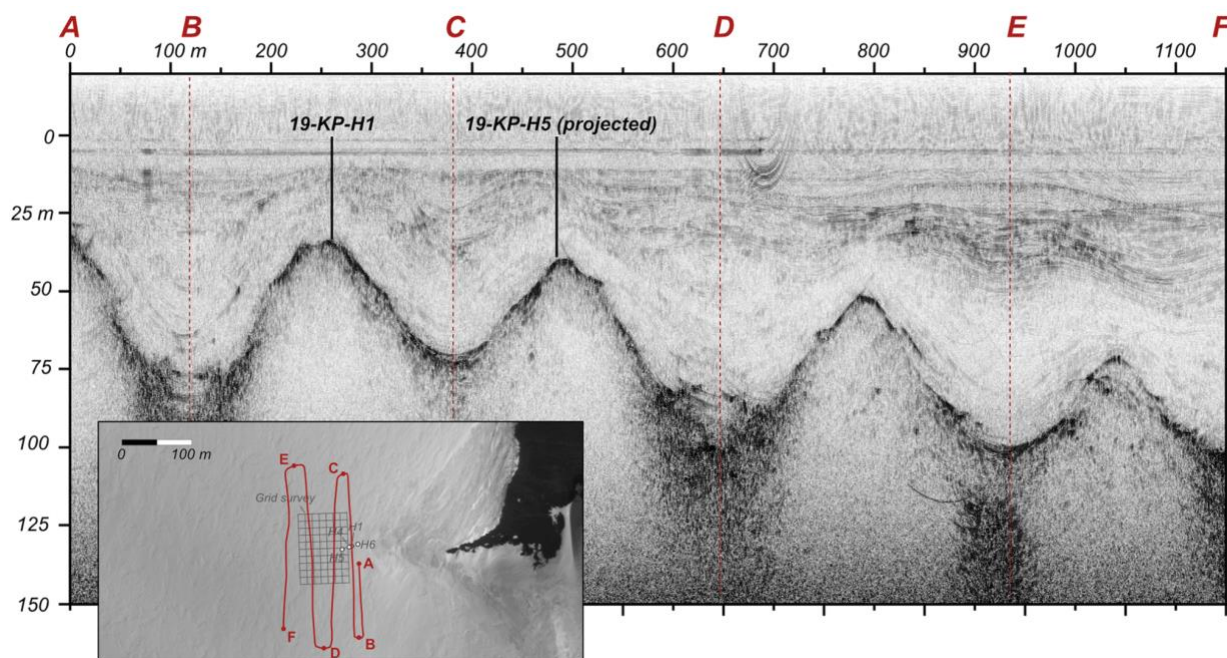


Fig. S3. Example 100 MHz radar profile collected prior to drilling in 2019/20 that crosses the subglacial portion of Kay Peak Ridge four times (see inset map). The profile has been distance normalized (RADAN, 2017), and a Kirchhoff migration (Schneider, 1978, Özdemir and others, 2014) was applied to improve bedrock depth estimates. Core 19-KP-H1 lies on the radar line, as shown, and the nearest projected location of 19-KP-H5 is also shown. The location of the grid survey that was also used for drill site selection is shown in gray. This figure is reproduced from Balco and others, 2023.

Drilling efforts

The primary difference between the Winkie drill deployment at this site and previous deployment in the Ohio Range was the addition of casing and pilot drill equipment needed for drilling through firn. Blue ice without fractures is impermeable, so drilling fluid can circulate to the surface without sealing the borehole walls. In contrast, firn is permeable and incapable of

containing pressurized drill fluid, so achieving fluid circulation for rock coring requires the use of borehole casing and a packer system, as well as a separate drill for creating the borehole to place the casing. For the Mt. Murphy project, this was achieved by using the IDP Badger-Eclipse cable-suspended ice coring drill (henceforth Eclipse drill). This drill produces an oversized borehole that accommodates casing large enough to pass the Winkie Drill rods and rock coring tooling. Thus, the Eclipse drill was used to create an access hole deep enough to reach ice of sufficiently high density ($> 870 \text{ kg m}^{-3}$) to form a seal with an inflatable packer. The use of two drill systems had significant advantages in that 1) rock coring at one site could take place at the same time as access hole drilling at a second site, which greatly improved efficiency, and 2) high-quality ice core could be collected without delaying rock coring operations. However, the addition of the Eclipse drill, borehole casing pipe, and packer system increased the total drill system weight. For example, the Winkie Drill equipment for a 60 m blue ice site weighs approximately 2600 kg; the additional Eclipse drill and casing weighs approximately 1000 kg. Other Winkie upgrades for this field season included replacing the 2-stroke gasoline powerhead engine with an electric motor and controls, adding a tripod and capstan winch for easier rod tripping, and improved fluid tank and mud pumps for drill fluid circulation and handling.

The drilling objective was to collect six 1.5 m bedrock core samples ranging in depth 10 m to 60 m from the ridgeline extending from Kay Peak. The team of six arrived onsite after a 2-week logistics delay. Drilling proceeded at a rapid pace for 16 days following the general procedure: 1) drill the access hole as deep as possible with the Eclipse drill until dirty ice or bedrock prevents further ice coring; 2) move the Eclipse drill to the next site and install the Winkie Drill, casing, and packer system; 3) use the geoset bit to penetrate through dirty ice, clay and overburden; 4) after penetrating into competent rock, replace the geoset bit with impregnated bit to retrieve bedrock core. Unexpectedly, the most time-consuming part of this process proved to be penetrating the relatively thin (70-120 cm) dirty ice and sediment layer overlying bedrock, which required repeated rod tripping for bit cleaning and maintenance of fluid circulation. Six access holes were drilled to depths between 31-58 m. One was abandoned because of the presence of liquid meltwater, apparently sourced from runoff from the adjacent exposed bedrock ridge. A second was abandoned because the bed was not encountered at the maximum practical depth for rock coring - the borehole missed the subglacial ridge. Rock cores with a minimum length of 1.2 m were collected from three of the other holes, and a 10-cm bedrock surface sample from the final hole.

Finally, although the ability to simultaneously operate both access and coring drills permitted high productivity in a very short field season, it also demanded long workdays and continuous effort by field personnel: a minimum of 10 hours were spent in active work at the drill site each day, with only one weather break. Although safety issues were fortunately not experienced during this field season, the resulting fatigue risked contributing to mistakes and/or poor decision-making practices. This level of effort should not be considered sustainable for planning future field seasons.

3.3 Hudson Mountains

Scientific justification

The Hudson Mountains are situated adjacent to Pine Island Glacier and are in the same sector of Antarctica (the Amundsen Sea sector) as Mt. Murphy (Section 3.2). The apparent lack of late-Holocene exposure ages from currently exposed sites in the Hudson Mountains (Johnson and others, 2014 and Nichols and others, 2023) indicates either ice sheet stability since the mid-Holocene or a phase of ice sheet thinning below present followed by thickening (with associated grounding line retreat and readvance) in the Amundsen Sea sector. A relative sea level record reconstructed from islands located in the Amundsen Sea suggests that no broad spatial scale, major readvance of the grounding line occurred during the last 5 ka (Braddock and others, 2022). Cosmogenic nuclide concentrations in subglacial bedrock cores collected from nearby Mt. Murphy (see Section 3.2) suggest that tens of kilometers of grounding line retreat inland of its present position likely accompanied upstream ice sheet thinning of at least 30 to 35 meters of ice in the previous 5 ka (Balco and others, 2023). Subsequent readvance and ice thickening must have occurred at Mt. Murphy for the adjacent glaciers such as Thwaites to expand to their modern-day limits. To determine if the thinning of glaciers near Mt. Murphy was a unique, local event or a broader, regional ice volume loss in the region, a second site was selected for subglacial drilling efforts because of its proximity to the neighboring Pine Island Glacier.

Radar survey

In the 2019/20 season, a team of two scientists and two field guides visited the Hudson Mountains with the goals of 1) undertaking radar surveys to identify suitable site(s) for subglacial bedrock recovery drilling and 2) collecting surficial bedrock samples to determine if the mineral composition of the rocks is appropriate for cosmogenic dating and to constrain the above-ice deglacial history. Upon completion of the initial surveys, the site near the shear margin of Pine Island Glacier at Winkie Nunatak (-74.8595° , -99.7833°) was selected. It is in an area with snow and firn cover. This site was intended to be drilled the following year, however, due to delays caused by the Covid-19 pandemic, the second (drilling) field season was carried out in 2022/23. Because of the two-year delay in returning to the site, and the consequent likelihood of significant change in near-surface ice conditions as this the drill site is located close to the active shear margin of the rapidly retreating Pine Island Glacier, a GPR technician joined the drill team to resurvey the site. First, the team carried out a survey on foot in search of visible signs of crevassing at the surface but found no obvious signs of slumping or collapsed snow bridges. Following this initial inspection, the team conducted a repeat survey of the same area near Winkie Nunatak surveyed in 2019/20 by establishing a gridded flag system over an area of 150 m by 300 m (Fig. S4) using two GPR antenna systems. One antenna was better suited to detect near-surface crevasses in greater resolution (400 MHz antenna) while the other system could image ice thickness at greater depths (200 MHz Hyperstacking antenna). The GPR systems were hand-towed across the survey area at approximately 1 m s^{-1} . Nearest to the nunatak, where ice was thinnest ($<30 \text{ m}$), the radar surveys revealed multiple large extensional crevasses that ran over the targeted subglacial ridge top at oblique angles. These crevasses were covered by snow bridges that were probed and found to be only 0.5 m thick. Crevassing had been detected in the 2019/20 season, but it was difficult to discern from the resulting radargrams if there was one large crevasse or multiple that were closely packed in the shallow ice region nearest to the nunatak because the antenna used was intended for penetrating to greater depths but in lower resolution. More extensive probing and additional GPR surveys

revealed that it would not be advisable for the team to drill over the ridge crest because of crevasse safety concerns. It was decided that the team would therefore drill on the flank of the ridge, to a GPR-estimated depth of ~45 m (Fig. S4). Additional GPR surveys would be carried out simultaneously with drilling efforts in order to locate a second, shallower drill site that would provide further constraints on the degree of past ice sheet thinning.

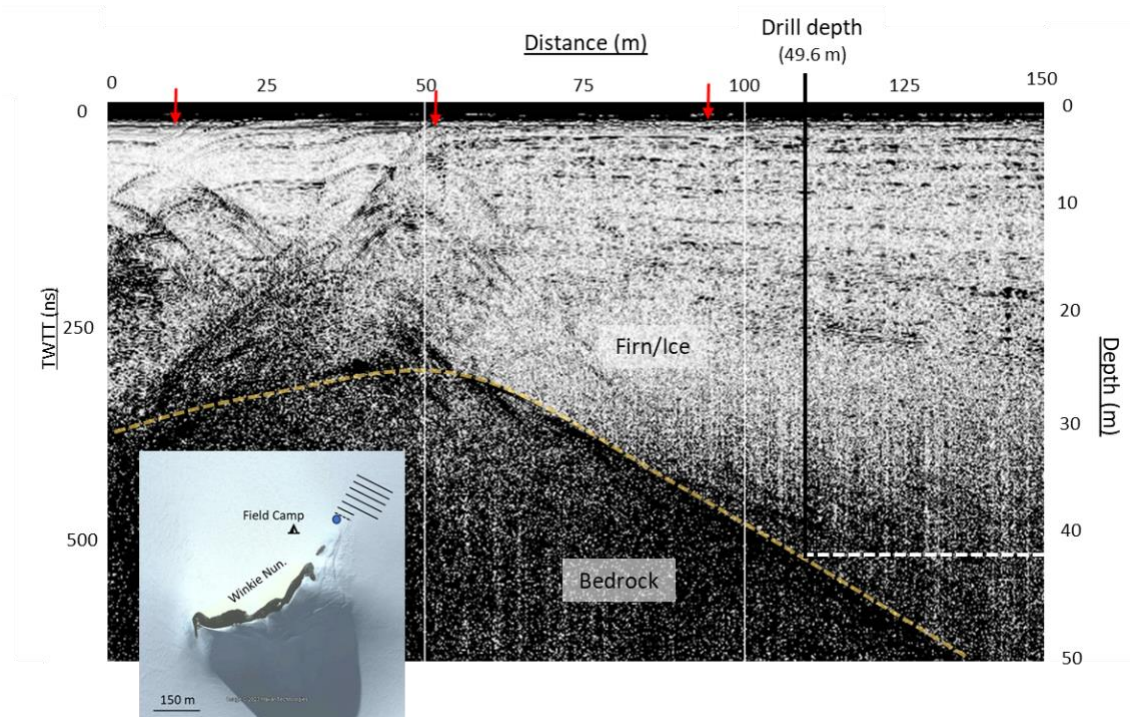


Fig. S4. Example 200 MHz Hyperstack radar profile collected prior to drilling in 2022/23 that crosses the subglacial ridge top of Winkie Nunatak (see inset map). The profile has been stacked and distance normalized. White vertical lines at 50 and 100 m indicate the location of flagged survey points spaced at 50 m intervals. The red arrows on the horizontal axis indicate the location of crevasses. The location of the drill site is shown with a black line with the corresponding estimated depth shown by the dashed horizontal white line. In the inset map, the location of the grid survey that was also used for drill site selection is shown by the black lines. The red line shows the location of the radargram in this profile and the direction the GPR was towed is indicated by the red arrow direction. Inset image: Imagery © 2023 MAXAR.

Drilling efforts

In the 2022/23 season, the IDP deployed its modified Winkie and Eclipse drills to the Hudson Mountains with the objective of collecting three subglacial bedrock cores of varying depths (<30 m, 30 - 50 m, > 50 m). The drilling techniques and equipment deployed at Winkie Nunatak closely followed the strategy previously used at Mt. Murphy but with several upgrades focused on improving system efficiency. To improve the drill fluid circulation system, an insulated settling tank paired with an air-to-liquid process chiller was implemented. The focus of these upgrades was to settle fine clay contaminants and maintain subfreezing drill fluid during coring operations as the team expected similar ice-bedrock conditions to Mt. Murphy given the sites proximity to the coast. Throughout the season, the process chiller performed well and reduced the risk of

freezing the drill string downhole. Additional upgrades were also made to the Winkie rod handling system including a powered capstan winch and custom foot clamp to improve operator safety while reducing rod tripping cycle time in deeper boreholes. To reduce logistics burden, drilling equipment was cached at a field depot following the Mt. Murphy season for two years prior to being deployed at Winkie Nunatak. Although this reduced the logistics burden of drill camp input, over-wintering was harsh on drill equipment, meaning that it required several days of additional field diagnostics and troubleshooting prior to use.

Due to delays traveling to the field site and safety concerns arising from the crevasse field described above, the team decided mid-season to focus on drilling a single borehole at ~45 m below the ice surface. Since the subglacial ridge was covered by firn, not blue ice, the Eclipse drill was again used to drill a 48 m access hole for the inflatable packer and casing system. This access method using a field-proven coring drill continued to be reliable and efficient for firn-covered sites. After access drilling was complete, the Winkie Drill was assembled at the drill site. A total of nine coring attempts were executed over four days of drilling, yielding only 1.6 m of ice and debris-rich ice core. Coring runs were typically cut short after only 5 - 10 cm due to loss of penetration or fluid circulation. Upon inspection at the surface, coring bits were normally glazed with fine clay which effectively plugged core bit waterways. A variety of different bits, penetration rates, and drill fluid circulation rates were tried without any noted improvement. Despite maintaining clean, cold drill fluid, no improvements in coring frozen clay were noted as compared to the Mt. Murphy season. Fluid circulation blockages at the bit and core barrel caused by fine clay created substantial drilling delays and was a contributing factor in not recovering a bedrock core at this site. After 28 days on site, including 11 days of drilling activity, one borehole through 49.6 m depth of ice was drilled, yielding 1.6 m of clay rich mixed media core. Ultimately, a bedrock core was not recovered from the borehole due to a combination of drilling challenges caused by clay rich overburden and time constraints that prevented an attempt at drilling at a second site.

3.4 Enterprise Hills

Scientific justification

As outlined above, the Holocene evolution of WAIS has been widely discussed with increasing focus on the potential for significant retreat beyond present day grounding lines in several sectors of the Antarctic ice sheet, with direct geological evidence of such behavior documented in the Ross Sea and Amundsen Sea sectors. The Weddell Sea is another sector where retreat-readvance behavior has been postulated, but direct glacial-geological evidence does not yet exist. A zone of grounding line retreat inland of its present position was hypothesized by Kingslake and others (2018) based on modeling. This zone encompasses a 1500 m deep sedimentary basin with a retrograde bed slope that underlies major ice streams draining into the southern part of the Weddell Sea embayment (Ross and others, 2012).

Radar results

A localized GPR survey was undertaken focused on the area around the small patch of exposed bedrock ~350 m northeast of Plummer Nunatak. The area around this exposure was

predominantly blue ice with patches of wind-blown snow up to 2 m thick. Because the drill site is on blue ice, where crevasses are clearly visible and easily avoided, there were no concerns about crevassing at Enterprise Hills. To characterize the sub-ice topography, a PulseEKKO Pro GPR system with 100 MHz antennas was used to survey the identified drill site(s). Due to loss of some components during transit, it was not possible to connect any GPS system to the digital video logger, meaning that survey lines had to be marked out by hand prior to collecting GPR. This greatly increased the effort involved and limited time dedicated for additional radar surveying. As a result, only two potential drill sites were surveyed (Fig. S5). The antennas, transmitter, and receiver were attached to a plastic sledge and hand-towed across the survey area at approximately 1 m s^{-1} .

The GPR survey clearly identified the ice-bedrock transition at depths of interest. A subglacial bedrock ridge was identified extending away from the small rock outcrop near Plummer Nunatak. Unfortunately, the crest of this ridge remained at a near constant depth ($\sim 10 \text{ m}$) for the entirety of its length before it passed below a steeper blue ice slope on which set-up of the drill rig would have been problematic. To increase the range of depths to be sampled, a decision was made to drill away from the ridge crest. In doing so, it was difficult to accurately assess the true depth to bedrock, likely due to the steep nature of the local sub-ice topography introducing off-nadir reflectors giving a negative bias to the estimated ice thicknesses (e.g. Lapazaran and others, 2016). Interpretation of the profiles was also hampered by the absence of a specialist with GPR knowledge within the field team.

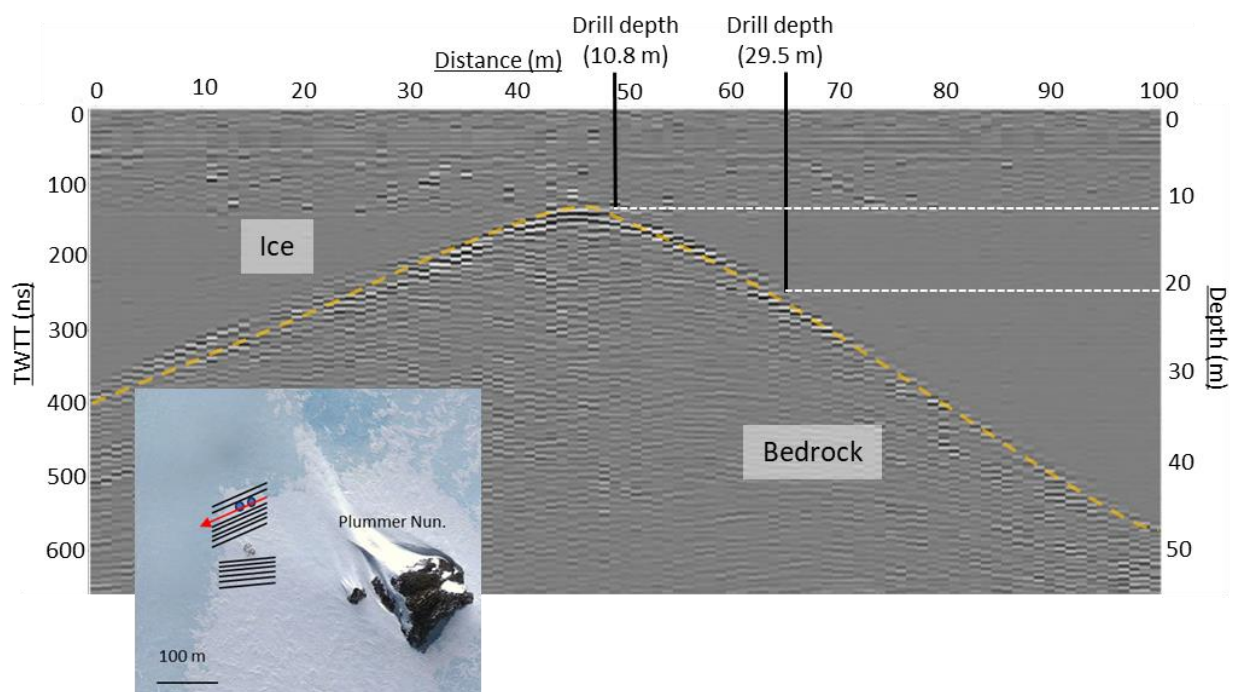


Fig. S5. Example 100 MHz radar profile collected prior to drilling in 2022/23 that is located near Plummer Nunatak (see inset map). The profile has been distance normalized to survey flags spaced at 25 m intervals. Location of the drill sites are shown with black lines with the corresponding estimated depth shown by the dashed horizontal white line. In the inset map, the location of the grid survey that was also used for drill site selection is shown by the black lines with and a red line shows the location of the radargram in this profile and the direction the GPR was towed is indicated by the red arrow direction. Blue

dots in the inset map indicate drill site locations from radar profile. Inset map created from Google Earth: Imagery © 2023 Maxar.

Drilling efforts

Two sites, bracketing this zone, were selected for sub-glacial drilling to test for Holocene retreat-readvance in the Weddell Sea. The first of these sites, in the Enterprise Hills (-79.9439° , -81.4314°), was visited in the austral summer of 2022/23 and the second site at the Pensacola Mountains will be visited in 2023/24. Drilling was undertaken with a Winkie Drill system purchased by Durham University. Modifications follow Boeckmann and others. (2020) but are less extensive than the systems used at Mt. Murphy (section 3.2) and Hudson Mountains (3.3 section). In practice the system is most like that used at the Ohio Range in 2016/17. As such it requires ice that is frozen to the bed and, as it cannot core where firn is present, it can only be deployed at sites with blue ice at the surface. These logistical limitations strongly influence site selection. A total of six access holes (7 – 29.5 m) were produced using modified Kovacs ice augers during 11 days of drilling activity by a team of four. For most access hole locations, a pit was excavated in the snow cover to allow the drill rig to be set up directly on blue ice. Of the six access holes, four attempts were made at rock coring. At one site, fluid circulation could not be established which is thought to be the result of fluid draining into a bedrock crack and another site was deemed to be too shallow to justify the effort to core given time constraints. A total of four rock cores (5 – 47 cm) were collected, consisting of medium-fine grained quartzites. These cores spanned depths of 9.5 – 29.5 m below present-day ice levels. In all holes we encountered a practically clean bedrock interface with the small amount of loose material encountered interpreted as being *in situ* pieces of weathered bedrock. No clasts or debris were observed in the ice column.

Several issues were encountered that impacted and/or disrupted drilling activities with the most significant of these being related to fluid circulation and the mud pump. Specifically, there was a persistent issue with liquid water being present in the fluid circulation loop that were attributed to either: 1) small ice chippings, either left over from augering or produced during coring activities enter the loop. These are subsequently melted due to frictional heating (in the pump or downhole) or within warm drill fluid, and/or 2) direct production of liquid water due to frictional heating at the drill head and/or melting of the borehole wall due to warm drill fluid. Regardless of the source of the water it had several noticeable impacts. Firstly, it could refreeze within the pump when not in use, this would prevent the pump from starting unless it was heated sufficiently to melt any ice present. Secondly, if water was not quickly and efficiently flushed from the borehole it can accumulate and re-freeze at the bottom of the borehole (drill fluid being less dense than water). This occurred at one site where the resulting ‘ice plug’ was unknowingly re-cored in the subsequent core run. Finally, when rod tripping at another drill site after completion of an initial short (~5 cm) coring run, liquid water refroze on the outside core barrel and froze the drill string to the borehole wall. This required considerable time and effort to free. We also noted the presence of fine rock particles within the drill fluid which could impact on its effectiveness either through clogging of fluid pathways on the drill bit or by contributing to accumulation of clay and/or ice agglomerations in the fluid. Other issues encountered included the loss of a core barrel at the first site due to “pack off”. This is where fluid circulation is not maintained for a sufficient duration to clear chippings from the hole. The chippings settle around

the drill string causing it to become stuck in the borehole. There was also an issue with the inverter drive, used to control the mud pump, malfunctioning. This required that the pump be connected directly to the generator. Finally, the starter mechanism for the two-stroke gas engine failed due to a broken plastic component, presumably made brittle by the cold temperatures.

Despite these issues, there were considerable periods when the drill rig was performing well and producing core. Our modified ice augers worked without issue to 30 m depth and the intention is to test them deeper in the coming field season. The main modifications for the 2023/24 field campaign relate to a simplified pump design and improvements to the fluid management system including improved monitoring of fluid temperature, a settling tank, and a baffled circulation tank. These modifications should reduce the presence of cuttings as well as ice/water in the drill fluid during and after downhole circulation.

3.5 Mt. Waesche

Scientific justification

Mt. Waesche lies near a dome of WAIS in central Marie Byrd Land. Changes in ice elevation there reflect past changes in WAIS extent and volume (Ackert and others, 1999, 2013). The timing and occurrence of lower ice elevations at interior sites in West Antarctica have implications for the WAIS contribution to past and future sea level changes but is generally unconstrained. The presence of cosmogenic nuclides in subglacial bedrock is clear evidence for past exposure and thus, lower ice elevation than at present. In addition, the direct dating by $^{40}\text{Ar}/^{39}\text{Ar}$ of lava flows that extend beneath the ice margin provide independent evidence for lower ice elevations at the time of eruption. The ages, lithologies, and physical settings of young volcanic rocks at Mt. Waesche provides a unique opportunity to determine WAIS elevation during the last interglacial. A set of Eemian interglacial-age lava flows, examined and sampled during the 2018/19 field season, extend below the present ice surface. Previous work at Mt. Waesche demonstrated that the local volcanic rocks are suitable for cosmogenic nuclide dating (Ackert and others, 1999, 2013). Successful sampling of young lava flows below the current ice sheet level, and analysis of the cosmogenic nuclide profile, will allow us to determine if WAIS volume was significantly smaller during the last interglacial period.

Radar survey

In the 2018/19 season, a reconnaissance team conducted a geophysical survey to map subglacial topography over the blue ice zone on the southern flank of Mt. Waesche. At Mt. Waesche, GPR is critically important in order to produce maps of the subglacial lava flow topography to guide drilling, as well as to trace tephra horizons in englacial stratigraphy over the kilometer to tens-of-kilometers scale. Collected radar data were processed in the field and throughout 2019 in preparation for the drilling season. The GPR data served several purposes: 1) the aim was to locate suitable sites, such as subglacial ridge crests or knobs, for drilling shallow ice cores (< 120 m depth below surface) to extract rock samples from below the ice-bed interface, 2) the data provide valuable insights into potential changes in local flow dynamics during periods of decreased ice thickness in the region by mapping the distribution of tephra layers and ice stratigraphy. 3) the GPR data provides information on regional ice depth to constrain numerical ice flow models. Finally, they enable identification of subglacial landforms,

including ponded lava that is indicative of ice-lava interaction at depths up to 700 m below the current ice elevation.

Over 14 days of GPR data collection, the team of six located two potential drilling locations at the targeted depths (Fig. 6b). The collected radar profiles allowed for the creation of 3-D radargrams of the sites. The advantage of 3-D imaging for drill site selection is to map out potential near-surface hazards, to better reduce ice thickness estimates in areas with complex subglacial topography, and to preselect multiple target drill sites. To do this, a 100 m by 100 m grid system was established with radar profiles collected at 10 m intervals using a 100 MHz antenna towed by hand. The density of GPR data collected, along with sufficient time allotted for processing the data before drilling in an upcoming season, allowed for the creation of 3-D radargrams (example in Fig. 7). Additionally, lower frequency antennas (5, 10 MHz) were towed by snowmobile to image englacial stratigraphy at greater depths and over a larger spatial area (dashed black lines in Fig 6b).

References

- Ackert Jr RP and 6 others (1999) Measurements of past ice sheet elevations in interior West Antarctica. *Science* 286(5438):276-80. <https://doi.org/10.1126/science.286.5438.276>
- Ackert, Jr RP and 6 others (2013) Controls on interior West Antarctic Ice Sheet Elevations: inferences from geologic constraints and ice sheet modeling. *Quaternary Science Reviews* 65:26-38. <http://doi.org/10.1016/j.quascirev.2012.12.017>
- Balco, G and 12 others (2023) Reversible ice sheet thinning in the Amundsen Sea Embayment during the Late Holocene, *The Cryosphere*, 17, 1787–1801, <https://doi.org/10.5194/tc-17-1787-2023>.
- Bamber J L, Riva REM, Vermeersen LAB, Lebroco AM (2009) Reassessment of the Potential Sea-Level Rise from a Collapse of the West Antarctic Ice Sheet. *Science* 324,901-903. <https://doi.org/10.1126/science.1169335>
- Boeckmann GV and 6 others (2021) Adaptation of the Winkie Drill for subglacial bedrock sampling. *Annals of Glaciology* 62(84):109-17. <https://doi.org/10.1017/aog.2020.73>
- Braddock S, and 9 others (2022) Relative sea-level data preclude major late Holocene ice-mass change in Pine Island Bay. *Nature Geoscience* 15(7):568-72. doi.org/10.1038/s41561-022-00961-y
- Campbell S and 6 others (2013) Radar-detected englacial stratigraphy in the Pensacola Mountains, Antarctica: implications for recent changes in ice flow and accumulation. *Annals of Glaciology* 54(63):91-100. <https://doi.org/10.3189/2013AoG63A371>
- RADAN 7 Manual Geophysical Survey Systems (GSSI) (2017), Nashua, NH.

Haywood AM, Sellwood BW and Valdes PJ (2000) Regional warming: Pliocene (3 Ma) paleoclimate of Europe and the Mediterranean. *Geology* 28(12):1063-6.
[https://doi.org/10.1130/0091-7613\(2000\)28%3C1063:RWPMPO%3E2.0.CO;2](https://doi.org/10.1130/0091-7613(2000)28%3C1063:RWPMPO%3E2.0.CO;2)

Jiang D, Wang H, Ding Z, Lang X, and Drange H (2005) Modeling the middle Pliocene climate with a global atmospheric general circulation model. *Journal of Geophysical Research: Atmospheres* 110(D14). <https://doi.org/10.1029/2004JD005639>

Johnson, JS and 8 others. (2014). Rapid thinning of Pine Island Glacier in the early Holocene: *Science*, v. 343, p. 999–1001, <https://doi.org/10.1126/science.1247385>.

Johnson, JS and 12 others (2022) Review article: Existing and potential evidence for Holocene grounding line retreat and readvance in Antarctica, *The Cryosphere*, 16, 1543–1562, <https://doi.org/10.5194/tc-16-1543-2022>

Kingslake J and 9 others (2018) Extensive retreat and re-advance of the West Antarctic Ice Sheet during the Holocene. *Nature* 558(7710):430-4. <https://doi.org/10.1038/s41586-018-0208-x>

Lapazaran JJ, Otero J, Martín-Español A and Navarro FJ (2016) On the errors involved in ice-thickness estimates I: ground-penetrating radar measurement errors. *Journal of Glaciology* 62(236):1008-20. <https://doi.org/10.1017/jog.2016.93>

Liu N, Xu H, Yang Y, Han L, Wang L and Talalay P (2016) Physicochemical properties of potential low-temperature drilling fluids for deep ice core drilling. *Cold Regions Science and Technology* 129:45-50. <http://doi.org/10.1016/j.coldregions.2016.06.004>

Mason ZE, (2018) Subglacial Cosmogenic Exposure Constraints On The History Of The West Antarctic Ice Sheet. University of California, Davis.

Middleton JL, Mason Z, Mukhopadhyay S, Putnam A., Ackert RP. and Campbell SW, (2018) December. Cosmogenic nuclides suggest long-term Pleistocene exposure of subglacial bedrock at the Ohio Range in the West Antarctic Ice Sheet. In AGU Fall Meeting Abstracts (Vol. 2018, pp. C22B-05)

Nichols, KA and 11 others (2023) Offshore-onshore record of Last Glacial Maximum–to–present grounding line retreat at Pine Island Glacier, Antarctica. *Geology*, 51, (11): 1033–1037. <https://doi.org/10.1130/G51326.1>

Özdemir C, Demirci Ş, Yiğit E and Yilmaz B (2014) A review on migration methods in b-scan ground penetrating radar imaging. *Mathematical Problems in Engineering* 2014, 280738. doi: 10.1155/2014/280738

Pollard D and DeConto RM (2009) Modelling West Antarctic ice sheet growth and collapse through the past five million years. *Nature* 458(7236):329-32. <https://doi.org/10.1038/nature07809>

Pollard D and DeConto RM (2012) Description of a hybrid ice sheet-shelf model, and application to Antarctica. *Geoscientific Model Development* 5(5):1273-95. <https://doi.org/10.5194/gmd-5-1273-2012>

Ross N and 9 others (2012) Steep reverse bed slope at the grounding line of the Weddell Sea sector in West Antarctica. *Nature Geoscience* 5(6):393-6. <https://doi.org/10.1038/ngeo1468>

Scambos TA and 10 others (2017) How much, how fast?: A science review and outlook for research on the instability of Antarctica's Thwaites Glacier in the 21st century. *Global and Planetary Change*;153:16-34. <http://doi.org/10.1016/j.gloplacha.2017.04.008>

Schneider WA (1978) Integral formulation for migration in two and three dimensions. *Geophysics*. 43(1):49-76.

Sheldon, S, Popp, T, Hansen, S and Steffensen, J (2014) Promising new borehole liquids for ice-core drilling on the East Antarctic high plateau. *Annals of Glaciology* 55(68), 260–270. doi: 10.3189/2014AoG68A043

Talalay, PG (2011) Drilling Fluids for Deep Coring in Central Antarctica. Technical Report PRC 12-01. China: Polar Research Center, Jilin University, 1–73

Thomas R, Sanderson T and Rose K (1979) Effect of climatic warming on the West Antarctic ice sheet. *Nature* 277, 355–358 <https://doi.org/10.1038/277355a0>