https://doi.org/10.5194/egusphere-2024-1452
Preprint. Discussion started: 12 June 2024

Detecting Holocene retreat and readvance in the Amundsen Sea sector of Antarctica: assessing the suitability of sites near Pine Island Glacier for subglacial bedrock drilling

Joanne S. Johnson[1], John Woodward[2], Ian Nesbitt[3], Kate Winter[2], Seth Campbell[3], Keir A. Nichols[4], Ryan A. Venturelli[5], Scott Braddock[3], Brent M. Goehring[6], Brenda Hall[3], Dylan H. Rood[4], Greg Balco[7]

[1]British Antarctic Survey, Cambridge, CB3 0ET, UK
[2]Department of Geography and Environmental Sciences, Northumbria University, Newcastle-upon-Tyne, NE1 8ST, UK
[3]School of Earth and Climate Sciences and the Climate Change Institute, University of Maine, Orono, ME 04469, USA
[4]Department of Earth Science and Engineering, Imperial College London, London SW7 2AZ, UK
[5]Department of Geology and Geological Engineering, Colorado School of Mines, Golden, CO 80401, USA
[6]Los Alamos National Laboratory, Los Alamos, NM 87545, USA
[7]Berkeley Geochronology Center, Berkeley, CA 94709, USA

Correspondence to: Joanne S. Johnson (jsj@bas.ac.uk)

Abstract. Unambiguous identification of past episodes of ice sheet thinning below the modern surface and grounding line retreat inboard of present requires recovery and exposure dating of subglacial bedrock. Such efforts are needed to understand the significance and potential future reversibility of ongoing and projected change in Antarctica. Here we evaluate the suitability for subglacial bedrock recovery drilling of sites in the Hudson Mountains, in the Amundsen Sea sector of West Antarctica. We use an ice sheet model and field data − geological observations, glaciological observations and bedrock samples from nunataks, and ground-penetrating radar from subglacial ridges − to rate each site against four key criteria: i) presence of ridges extending below the ice sheet, ii) likelihood of increased exposure of those ridges if the grounding line was inboard of present, iii) suitability of bedrock for drilling and geochemical analysis, and iv) accessibility for aircraft and drilling operations. Our results demonstrate that although no site in the Hudson Mountains is perfect for this study when assessed against all criteria, Winkie Nunatak (74.86°S / 99.77°W) is suitable. The accessibility, N-S orientation and basaltic bedrock lithology of its southernmost ridge make the nunatak a feasible site both for drilling and subsequent cosmogenic nuclide analysis. Furthermore, it is strewn with erratic cobbles at all elevations, providing constraints on the earlier Holocene deglacial history and time at which the ice sheet surface reached its present elevation. Such information is necessary for determining the maximum duration over which any Holocene grounding line readvance could have occurred.

1 Introduction

This paper describes geological and glaciological considerations needed for choosing a suitable site for a subglacial bedrock drilling campaign aimed at determining if and when the Antarctic ice sheet was ever smaller in the recent geological past than

https://doi.org/10.5194/egusphere-2024-1452
Preprint. Discussion started: 12 June 2024

it is today. Such considerations are broadly applicable to any similar study but due to its known instability, here we focus on part of the Pine Island-Thwaites Glacier system. Thwaites Glacier and its associated ice streams have the potential to contribute 65 cm to future sea level rise (Morlighem et al., 2020), and are of particular concern in this regard due to their potential vulnerability to runaway retreat (Joughin et al., 2014). Ice mass loss from Pine Island, Thwaites and surrounding glaciers in the Amundsen Sea sector continues to accelerate, and between 2003 and 2019 these glaciers contributed 7.5 mm to global sea level rise, dominating the total contribution from Antarctica during that period (Smith et al., 2020). However, we have only limited direct evidence for changes in ice sheet thickness in the Thwaites Glacier system between the mid-Holocene (~5,000 years ago) and the onset of 20th-century satellite observations (Balco et al., 2023). Hence, it is currently unknown whether (i) ice sheet changes similarly rapid to those of the past decades occurred more widely in the Amundsen Sea sector during the late Holocene, and (ii) if such rapid changes should be regarded as exceptional with respect to pre-observational history. These uncertainties limit our understanding of the drivers for such events (Jones et al., 2022). Determining whether the grounding line in this region ever retreated inboard of its present position during the past few millennia and subsequently readvanced (cf. Johnson et al., 2022) is necessary for understanding the possible range of glacier behaviours and mechanisms for recovery that could occur under the climatic conditions predicted for the next few centuries (Meredith et al., 2019). Similar studies are urgently needed elsewhere in Antarctica to determine how widespread Holocene retreat and readvance was, its extent and timing, and what drove such changes.

Glacial-geological evidence from above the ice sheet surface in the Pine Island-Thwaites Glacier system – specifically from the Hudson Mountains and Mt Murphy massif, the nearest exposed mountain peaks to Thwaites Glacier − suggests that the ice sheet surface in this region had lowered to its modern elevation by the mid- to late- Holocene (Adams et al., 2022; Johnson et al., 2014, 2020). The geological record of any subsequent changes in ice sheet surface elevation must therefore lie below the ice sheet and can only be accessed by subglacial drilling. At Mt Murphy, subglacial bedrock drilling recently revealed direct evidence for thinner than present ice during the late Holocene (Balco et al., 2023). However, the late Holocene ice sheet history in the Hudson Mountains is not yet known. Subglacial drilling enables recovery of bedrock cores (Spector et al., 2018; Braddock et al., 2024) from which the exposure history of the subglacial bedrock surface can be inferred by measuring the concentration of cosmogenic nuclides in minerals (typically quartz) extracted from a variety of depths within the cores (Schaefer et al., 2016). Any detectable presence of in-situ-produced cosmogenic nuclides in subglacial bedrock, with an exponential decrease in concentration with depth, would imply that it experienced near-surface exposure to cosmic radiation and therefore ice-free conditions, or only very thin ice cover (see Balco et al., 2023), in the past (Spector et al., 2018). The extent of ice sheet thinning below present at that time can be determined by collecting a series of bedrock cores along a transect trending inland perpendicular to the grounding line. This approach provides the ice sheet thinning history, but the relationship between thinning and associated grounding line retreat is likely to vary between glaciers due to differences in bathymetric and other boundary conditions (see section 5.3 of Johnson et al., 2021 for discussion). Thus, ice sheet modelling is usually required to establish this relationship for individual sites.

https://doi.org/10.5194/egusphere-2024-1452
Preprint. Discussion started: 12 June 2024

Subglacial bedrock recovery efforts have increased in the last decade, with successful attempts in both Antarctica and Greenland (Antarctica: Pirrit Hills, interior West Antarctica; Kuhl et al., 2020, Ohio Range, Transantarctic Mountains; Mukhopadhyay et al., 2020, Mt Murphy, Amundsen Sea embayment; Boeckmann et al., 2021 and Balco et al., 2023, Enterprise Hills, Ellsworth Mountains, SW Weddell Sea embayment; Braddock et al., 2024, and Neptune Range, Pensacola Mountains, S Weddell Sea embayment; Small et al., 2024. Greenland: GISP2 site; Schaefer et al., 2016 and Prudhoe Dome ice divide; Balter-Kennedy et al., 2023a). The primary aim of many of these campaigns was to search for evidence of ice sheet collapse during warm periods, particularly the last interglacial; as yet the only regions that have been drilled with the specific intention of recovering subglacial bedrock to seek evidence for *Holocene* exposure are the central Amundsen Sea and southern Weddell Sea sectors of Antarctica, and Prudhoe Dome in NW Greenland. Subglacial sediments documenting Holocene retreat inboard of present have been recovered by drilling in the Ross Sea sector (Kingslake et al. 2018; Venturelli et al., 2020, 2023).

2 Aims of subglacial bedrock drilling near Pine Island Glacier

In the austral summer of 2019-20, as part of the International Thwaites Glacier Collaboration, subglacial bedrock cores were recovered from near Kay Peak, which lies ~100 km west of Thwaites Glacier and adjacent to Pope Glacier (Fig. 1a). Cosmogenic nuclide analysis of the cores demonstrated that the ice sheet was at least 35 metres thinner than present at that site during the past few thousand years, implying that the grounding line of Pope Glacier had migrated inboard of its present position prior to the late Holocene and has since readvanced (Balco et al., 2023). Holocene retreat and readvance has been detected in other volumetrically significant sectors of Antarctica, for example in the Ross Sea sector (Venturelli et al., 2020, 2023; Neuhaus et al., 2021). It has also been postulated for the Weddell Sea sector based on ice sheet and glacial isostatic adjustment modelling and geodetic data (Bradley et al., 2015; Kingslake et al., 2018), and on geodetic data alone for the Totten-Denman region of the East Antarctic Ice Sheet (King et al., 2022).

The present paper describes the results of reconnaissance surveys undertaken prior to a second subglacial bedrock drilling campaign in the Amundsen Sea sector, targeting the Hudson Mountains in the eastern part of the Pine Island-Thwaites Glacier system (Fig. 1). We describe the approach and criteria used for choosing a suitable drill site. The Hudson Mountains are situated both adjacent to Pine Island Glacier (PIG) and in close proximity to islands in Pine Island Bay from which Relative Sea Level (RSL) records suggest steady retreat of PIG through the late Holocene (Braddock et al., 2022). This steady retreat contrasts with the synchronous retreat and readvance of Pope Glacier in the central Pine Island-Thwaites Glacier system detected using subglacial bedrock (Balco et al., 2023). The Hudson Mountains are thus a good site for testing whether the response of PIG to Holocene climate was similar to that of other glaciers in the system (and by inference whether the resolution of the PIG RSL record is insufficient to record a readvance on the scale of that detected at Pope Glacier).

https://doi.org/10.5194/egusphere-2024-1452
Preprint. Discussion started: 12 June 2024

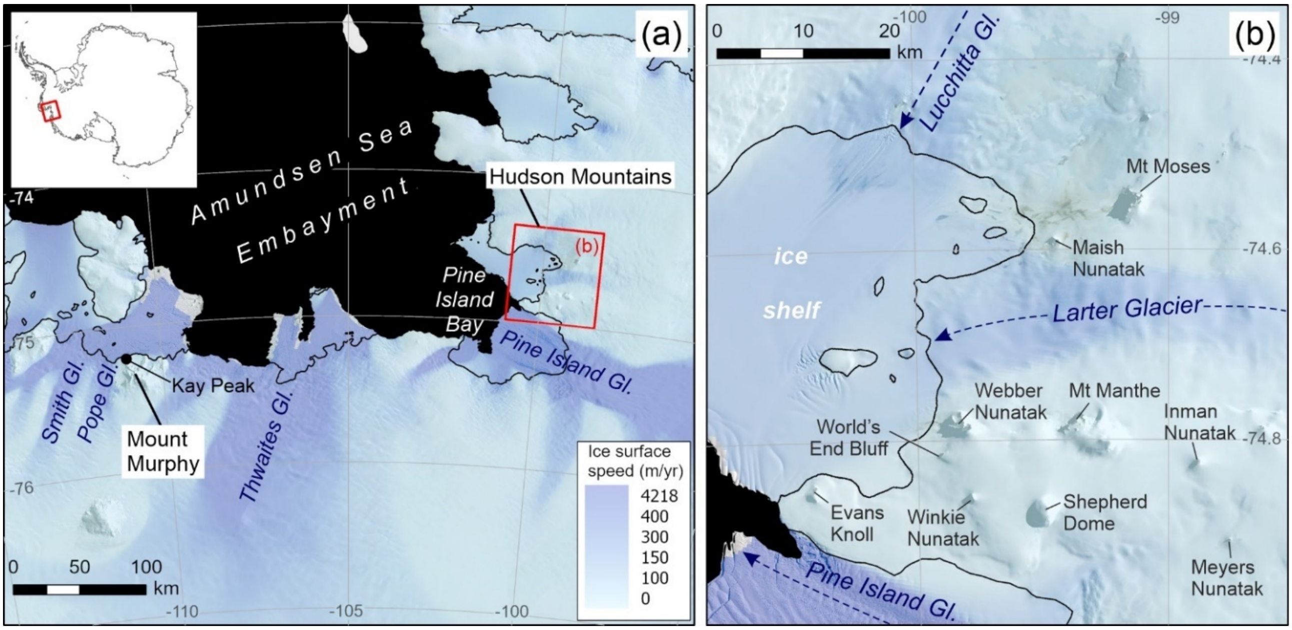


Figure 1: The location of the Hudson Mountains study site within the Amundsen Sea sector of Antarctica. **(a)** Map of Amundsen Sea Embayment, showing location of subglacial bedrock drilling sites near Kay Peak, Mt Murphy (Fig. 2) and Hudson Mountains. **(b)** Location of Hudson Mountains nunataks in relation to major glaciers. The grounding line (black) is from Rignot et al. (2016) and the coastline is from the SCAR Antarctic Digital Database [Accessed 15 May 2024]. Ice surface speeds (Rignot et al., 2017) are overlain on Landsat Image Mosaic of Antarctica (LIMA; Bindschadler et al., 2008) in panel (a) and a Landsat 8 Image acquired on 13 March 2022 (courtesy of USGS) in panel (b).

3 What makes a good subglacial bedrock drill site for detecting Holocene retreat-readvance?

A range of geological, glaciological, technical and practical considerations are needed when assessing the suitability of a site for subglacial bedrock recovery drilling (Spector et al., 2018; Briner et al., 2022). Successful detection of past ice sheet thinning from subglacial bedrock requires drilling at a site where (i) grounding line retreat would result in exposure of bedrock that is currently ice-covered, (ii) evidence for exposure would be preserved during subsequent ice cover, (iii) the bedrock lithology is suitable for both drilling and cosmogenic nuclide measurements, and (iv) safe access for a drill rig and operators is possible. Commonly, these criteria lead to selection of drill sites on the subglacial extension of exposed mountain ridges (Fig. 2), primarily based on the observation from the modern landscape that ridge tops are more likely to be ice-free than ridge flanks, as well as the relatively high confidence that the rock encountered by drilling will be the same lithology as the exposed ridge.

https://doi.org/10.5194/egusphere-2024-1452
Preprint. Discussion started: 12 June 2024

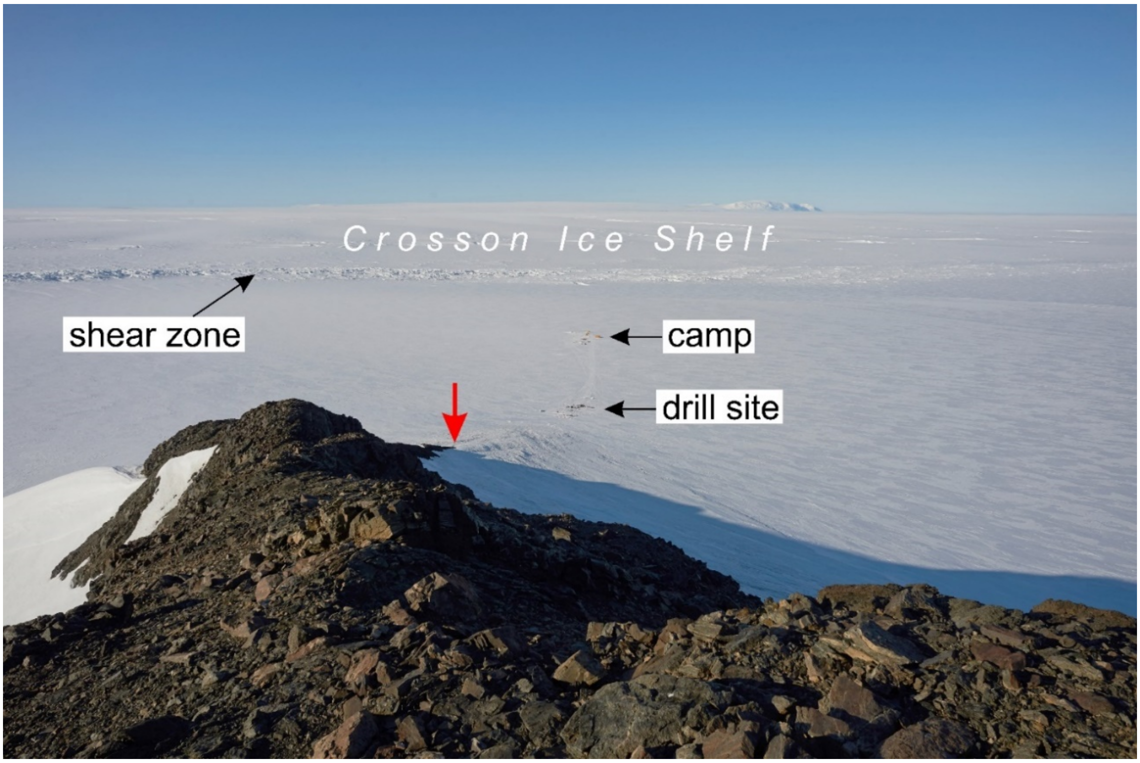


Figure 2: Photograph of a drill site at the Mt Murphy massif in the central Amundsen Sea Embayment. At the location marked by the red downward pointing arrow, the bedrock ridge (foreground) extends north from Kay Peak (Fig. 1a) below the ice sheet surface in a direction perpendicular to the present grounding line less than 2 km away (demarcated by shear zone crevasses). Its orientation and close proximity to the grounding line means the ridge is likely to have been more exposed during any past episodes of grounding line retreat than it is at present. Subglacial bedrock cores were recovered from this ridge in 2019-20 (see Balco et al., 2023).

Lithology is important mainly because some common lithologies do not provide suitable targets for cosmogenic nuclide measurement. Of the range of possible cosmogenic nuclides that can be commonly measured in rock (e.g. in situ ^{14}C, ^{10}Be, ^{36}Cl, ^{3}He), one – in situ ^{14}C – is particularly well-suited to investigating exposure on Holocene timescales due to its short half-life (Nichols, 2023). Holocene exposure has also been successfully detected using ^{10}Be, but only when there has been sufficient erosion to remove nuclides inherited from prior periods of exposure. At present, the in situ ^{14}C production rate and extraction procedures are best-known for quartz (e.g. Lifton et al., 2001). In situ ^{14}C measurement has therefore been largely restricted thus far to quartz-bearing rocks. However, it is theoretically possible to measure in situ ^{14}C in olivine (Pigati et al, 2010), and perhaps other mineral phases (Koester & Lifton, 2023), permitting detection of Holocene readvance at sites with non-quartz-bearing bedrock lithologies such as basalt, gabbro and dolerite. ^{10}Be extraction from pyroxene appears also to have potential in this regard (Balter-Kennedy et al., 2023b; Bergelin et al., 2024).

https://doi.org/10.5194/egusphere-2024-1452
Preprint. Discussion started: 12 June 2024

Given a site with suitable geometry and bedrock lithology, several technical factors are then important. These are mainly related to the fact that pressurised fluid circulation in the borehole is required for rock coring. To achieve fluid circulation, the rock to be cored, the rock-ice interface and the lowermost ~1-2 m of ice overlying the bedrock must be impermeable so that fluid leakage from the borehole cannot occur (Boeckmann et al., 2021). In previous subglacial drilling operations in Antarctica (e.g. GISP2, Pirrit Hills, Mt Murphy), this has not been a problem because the ice-rock interface has been well below freezing and any jointing or other flowpaths in the rock have been ice-filled and therefore leakproof. This is likely to be nearly always true for relatively shallow ice under Antarctic climate conditions. However, even if the ice temperature is well below freezing, conditions such as the presence of permeable firn near the base of a shallow borehole or crevassing extending near the bed could potentially allow fluid loss and preclude coring.

Figure 3: Equipment needed for shallow subglacial bedrock drilling. (a) In the foreground, all cargo (except snowmobiles and fuel) deployed for 2019-20 drilling campaign at Mt Murphy. **(b)** US Ice Drilling Program “Eclipse” ice drill in use at Mt Murphy. **(c)** US Ice Drilling Program “Winkie” drill, and associated equipment. The Eclipse drill is used to drill through ice to access the bedrock whilst the Winkie drill is used for bedrock recovery. Where the bedrock lies beneath clean blue ice, the Winkie drill can be used both to drill through the ice and recover the bedrock (see Braddock et al., 2024).

Lastly, a potential drill site must be accessible. Crevassing in and around a drill site can make safe access challenging for both the drill operators and researchers conducting the ground-penetrating radar (GPR) surveys during site selection. Bergschrunds

https://doi.org/10.5194/egusphere-2024-1452
Preprint. Discussion started: 12 June 2024

are often present adjacent to ice-free ridges and, even if not presenting a fall hazard, may also preclude drilling at shallow depths. These hazards are most significant in snow- or firn-surfaced areas; in blue ice areas, where snow is scoured away from the ice surface, crevassing can be clearly seen and avoided. Even in the absence of crevassing, the snow or ice surface must be flat enough to allow installation of the drill platform as well as to permit working and staging of equipment near it. In addition, a large flat area within a few kilometres of the drill site is needed to allow ski-equipped aircraft access via a skiway (unless helicopters are used); such access is required to deliver to the site, depending on which drill is to be used, several thousands of kilogrammes of drilling equipment – drill rig, drill rods, power supplies, drilling fluid – as well as standard field camp utilities (see Braddock et al., 2024). Figure 3 shows an example of the cargo needed for shallow subglacial drilling (up to ~100 m depth, as for this study). For deeper drilling, much more equipment (and fuel) is needed, requiring both a longer skiway for use by larger aircraft and a wider expanse of crevasse-free ground around the drill site for safe storage and drill operations.

4 Evaluation of candidate drill sites in the Hudson Mountains

4.1 Evaluation prior to field survey

The Hudson Mountains comprise 17 nunataks (Fig. 1b) dominated by basaltic volcanic rocks, the eruptive age of which is known for only two (Mt Manthe: 8.5 ± 1.0 to 5.6 ± 1.9 Ma, and Velie Nunatak: 3.7 ± 0.2 Ma; whole rock K-Ar dates reported in Rowley et al., 1990). Several have exposed rocky ridges extending below the modern ice surface making them potential drill sites. Prior to fieldwork, we examined both existing geological and geomorphological data from the nunataks and modelling studies to determine an order of priority for field survey.

4.1.1 Holocene exposure history

A temporally and spatially detailed picture of the above-ice exposure history is advantageous when choosing a drill site because this allows us to infer where late Holocene records of ice sheet configuration are most likely to be found (Johnson et al., 2022). Exposure history is determined by measuring the abundance of cosmogenic nuclides in the surfaces of either glacially deposited cobbles perched on the exposed portions of ridges (e.g. Stone et al., 2003; Mackintosh et al., 2007) or bedrock of those ridges (e.g. Johnson et al., 2019; Spector et al., 2019). Our knowledge of the Holocene exposure history of the Hudson Mountains is limited thus far to three studies, only two of which are sufficiently detailed to provide a profile of ice surface lowering (Johnson et al., 2014 and Nichols et al., 2023, cf. Johnson et al., 2008 which reports only two ages from a single feature). Johnson et al. (2014) reports a larger suite of cosmogenic nuclide surface exposure ages from Mt Moses and Maish Nunatak, both situated on the northern side of Larter Glacier (Fig. 1b). Although limited in number and situated within only 10 km of each other, these two nunataks together yielded a very well-constrained exposure history, including an estimate of when the modern ice sheet surface elevation was reached. The results show that, at both nunataks, following a period of very rapid thinning the ice sheet surface had lowered to its present elevation by the mid-Holocene (7.9 ka at Maish Nunatak and ~6 ka at Mt Moses). This finding is corroborated by a recently acquired suite of cosmogenic nuclide exposure ages from five additional nunataks, all situated adjacent to PIG (Nichols et al., 2023). Any record of late Holocene exposure at these sites – which would imply thinning below present elevation and grounding line retreat inboard of its present position – must therefore currently lie beneath the ice sheet surface, making these nunataks potentially suitable locations for our study. Thus, based on knowledge of Holocene exposure history alone, subglacial drilling at any of Mt Moses, Shepherd Dome, Evans Knoll or Maish, Inman, Meyers and Winkie Nunataks (Fig. 1b) would have the potential to reveal the late Holocene record of thinning in this region. The current lack of exposure histories from other peaks in the Hudson Mountains (for example, World's End Bluff and Webber Nunatak) does not necessarily rule them out as suitable drill sites, assuming that the ice sheet behaved similarly around them also. We therefore sought other types of data to inform our drill site selection.

4.1.2 Modelling

We used ice sheet model simulations to assess the sensitivity of ice cover to grounding-line retreat. This approach enabled us to consider where the grounding line would likely be situated relative to each nunatak during hypothetical periods of a smaller-than-present ice sheet, and to evaluate the orientation of individual ridges relative to the retreated grounding line. Subglacial bedrock that is most likely to yield evidence of thinning below present and subsequent rethickening during the late Holocene as a result of grounding-line retreat and readvance will be located off the end of currently exposed ridges that extend perpendicular to the former grounding line (see section 3).

The Net Sum Model (NSM) simulations from Larour et al. (2019), run using the Ice Sheet System Model (Larour et al., 2012), are suitable for the present study because they i) use a relatively high resolution (1 km) over the Hudson Mountains and ii) can simulate future grounding line positions analogous to those we would expect during periods when the ice sheet was smaller. Figure 4 shows the modelled versus observed modern grounding line positions near PIG, and modelled position for the year 2350. As expected, the model does not do a perfect job in reproducing the observations. For example, it is not physically plausible that the grounding line is presently situated between Maish Nunatak and Mt Moses, as simulated (model GL 0 yr; Fig. 4). However, closer to PIG, and around Evans Knoll, the observed and modelled modern grounding line positions correspond relatively closely, giving confidence in the model's ability in that region. The simulation for model year 2350 shows a much-retreated grounding line in many parts of the Hudson Mountains, particularly in the main glacial troughs (e.g. Larter Glacier) where it is predicted to migrate several tens of kilometres upstream of present. We use this future simulation as an analogy for a hypothetical grounding-line retreat inboard of its present position (followed by a readvance).

https://doi.org/10.5194/egusphere-2024-1452
Preprint. Discussion started: 12 June 2024

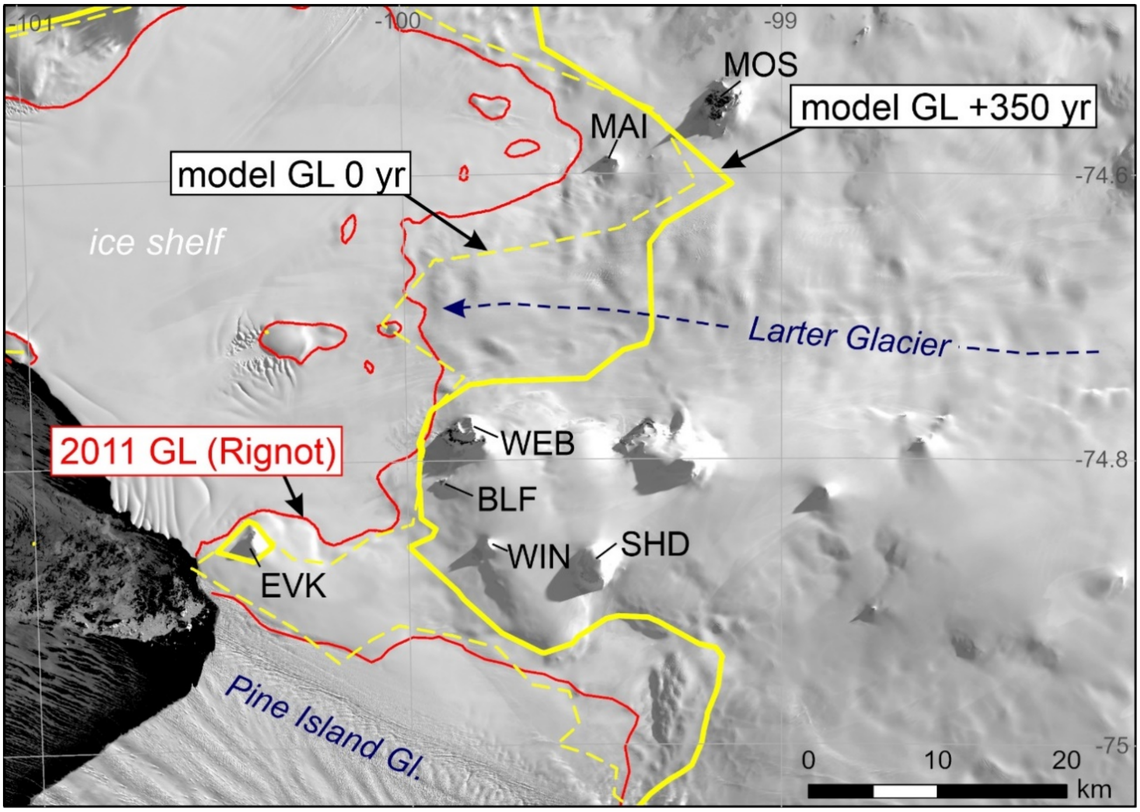


Figure 4: Position of present and modelled (future) grounding lines relative to nunataks in the Hudson Mountains region. The modern (2011) observed grounding line position is shown as a solid red medium-thickness line (Rignot et al., 2016). The modelled grounding line position at present-day (model GL 0 yr) is shown as a thin dashed yellow line, and at 350 years into the future (model year 2350) as a thick yellow line (model GL +350 yr). Both are from the NSM simulations of Larour et al. (2019). The underlying satellite image is Landsat-8, courtesy of USGS. Nunataks mentioned in the text are labelled as follows: EVK (Evans Knoll), BLF (World's End Bluff), WEB (Webber Nunatak), WIN (Winkie Nunatak), SHD (Shepherd Dome), MAI (Maish Nunatak), MOS (Mt Moses).

In the +350 yr future simulation (as well as in other future runs of Larour et al., 2019 not shown here), the modelled grounding line is retreated into the glacial troughs such that it passes within a few kilometres of some of the nunataks. In that situation, we would expect ice cover on N-S-oriented ridges of those nunataks to reduce as the grounding line retreated. For example, the +350 yr modelled grounding line position implies that ridges on the northern side of Webber Nunatak would be oriented perpendicular to it if the grounding line had retreated inboard of present (Fig. 4), making them potentially suitable sites from which to collect a transect of subglacial drill cores that could provide evidence of progressive late Holocene retreat. The model simulations also provide insight into what would become of Evans Knoll in a more retreated situation. At present, the grounding line skirts Evans Knoll on its western side, linking it to the mainland (Fig. 4). However, in the +350 yr model simulation, the knoll becomes an island rather than becoming more exposed. This implies that late Holocene records of ice sheet change are unlikely to be found in subglacial bedrock at that site.

Other models could be used to inform the selection of suitable subglacial drill sites. For example, models that predict ice sheet thickness changes through time may show which sites deglaciate the most during grounding-line retreat (e.g. the BISICLES ice flow model; Nias et al., 2019). However, the challenge with all models used for this purpose is that they must be of sufficiently high spatial resolution to resolve small-scale ice sheet changes around nunataks that are often only a few kilometres apart (Mas e Braga et al., 2021). Continent-wide ice sheet models are currently not capable of this, and even with nested domains at higher resolution, it is challenging (Johnson et al., 2021). This situation is, however, likely to improve in the near future as models evolve. In summary, based on the model comparison described above, the most suitable drill sites in the Hudson Mountains are those that are (i) currently situated in close proximity to the modern grounding line and (ii) unlikely to have become an island if the grounding line was situated inboard of its present location. They are Maish, Webber, and Winkie Nunataks, World's End Bluff and Shepherd Dome (Fig. 4).

4.1.3 Nunatak topography

The relative suitability of Maish, Webber, and Winkie nunataks, World's End Bluff and Shepherd Dome as drill sites can be further evaluated based on their present topographic shape. Prior to undertaking fieldwork, we used satellite imagery to assess this visually. Winkie Nunatak comprises a single ridge, Webber Nunatak has two ridges extending towards Larter Glacier and Maish Nunatak has three ridges which extend inland (see Figs. 6, 10 and 14). In contrast, neither World's End Bluff nor Shepherd Dome has any ridges. World's End Bluff is a partially ice-covered flat-topped feature with a near-vertical cliff face extending to ice shelf on its western side and Shepherd Dome consists of an ice dome with a few small patches of outcrop on its southern side. These two sites are thus not as suitable for drilling as Maish, Webber and Winkie Nunataks.

4.1.4 Bedrock lithology and structure

The lithology of the subglacial bedrock is important to know prior to drilling to ensure that enough of the target mineral can be collected for cosmogenic nuclide analysis (see section 3). Furthermore, to maximise the chance of successful core recovery, the bedrock structure − specifically permeability and consolidation − must be known. Although there is very little published information about the geology of the Hudson Mountains, they are known to be volcanics. Several are basaltic and contain olivine and feldspar phenocrysts (Rowley et al., 1990) making them potentially suitable for in situ ^{14}C cosmogenic nuclide analysis. Of the candidate drill sites, Webber Nunatak and Shepherd Dome consist of basaltic lava flows and hyaloclastite tuff, World's End Bluff is composed entirely of hyaloclastite tuff and Maish Nunatak consists of subaerial basaltic lavas (Lopatin & Polyakov, 1974; Rowley et al., 1990). In contrast, the lithology of Winkie Nunatak (basaltic lava; section 4.2.1) was unknown prior to our field survey. "Hyaloclastite" is used in this paper to include all hydroclastic fragmental rocks including hyaloclastite (*sensu stricto*), tuffs and lapilli tuffs, regardless of the specific mode of fragmentation (cf. White & Houghton, 2006).

https://doi.org/10.5194/egusphere-2024-1452
Preprint. Discussion started: 12 June 2024

Both basalt and hyaloclastite can be cored with typical rock drilling systems if joints and fractures in the rock are filled with ice. This has been the case in all previous Antarctic subglacial drilling campaigns and is likely in the Hudson Mountains since the candidate drill sites are all relatively low elevation (< 550 m asl) and experience melting at the ice margin as a result of solar heating during the austral summer. However, a weakly consolidated hyaloclastite could create several potential problems with core recovery, including core fragmentation, core loss during break-off, or loss of unconsolidated clay or fines to the drilling fluid (particularly a problem for hyaloclastite which is typically rich palagonite, a mixture of clay minerals; Stroncik & Schmincke, 2002). A well consolidated crystalline basalt, even if vesicular, will most likely yield a higher-quality and more complete core. Thus, from the perspective of bedrock lithology and structure alone, Maish Nunatak, Webber Nunatak, World's End Bluff and Shepherd Dome are probably plausible for successful drilling and core recovery, and depending on the results of our field survey, Winkie Nunatak may be also (Shepherd Dome and World's End Bluff were, however, discounted based on their unsuitable topography; section 4.1.3).

4.1.5 Summary

The results of the surveys undertaken *prior* to fieldwork are provided in Table 1. Taken together, they suggest that drilling into subglacial bedrock close to one or more of Winkie Nunatak, Webber Nunatak and Maish Nunatak will provide the best chance of obtaining evidence for/against a smaller ice sheet in the late Holocene in the eastern part of the Pine Island-Thwaites Glacier system. Our field reconnaissance field survey therefore focused on these three sites.

Site name	Latitude (DD)	Longitude (DD)	Ridges present?	Ridges sensitive to PIG grounding line migration?	Suitable bedrock lithology?*	Drill site safely accessible?*	Quartz-bearing erratics present on ridge?*
Winkie Nunatak	-74.86	-99.77	✓	✓	✓	✓	✓
Webber Nunatak	-74.77	-99.83	✓	(✓)	(✓)	✓	✓
Evans Knoll	-74.85	-100.41	(✓)	?	✓	✓	✓
World's End Bluff	-74.81	-99.91	x	N/A	N/A	N/A	N/A
Meyers Nunatak	-74.91	-98.75	✓	x	(x)	N/A	N/A
Inman Nunatak	-74.83	-98.87	x	N/A	N/A	N/A	N/A
Shepherd Dome	-74.88	-99.55	x	N/A	N/A	N/A	N/A
Maish Nunatak	-74.60	-99.34	✓	✓	✓	(x)	✓

Table 1: Suitability of sites in the Hudson Mountains for subglacial bedrock drilling. Each site was assessed against key criteria shown in the column headings. Asterisks indicate criteria that require field survey for full assessment. Key: ✓= yes; (✓) = probably, but with some challenges/caveats; ? = unclear; (x) = probably not (or at least not without major challenges); x = no; N/A = not applicable because site is ruled out based on other criteria.

https://doi.org/10.5194/egusphere-2024-1452
Preprint. Discussion started: 12 June 2024

4.2 Field survey of candidate drill sites in the Hudson Mountains

We conducted a ground-based survey of the Hudson Mountains in the austral summer of 2019-20. We used the criteria outlined in section 3 to establish the suitability for subglacial bedrock drilling of ridges at the three candidate drill sites, Winkie Nunatak, Webber Nunatak and Maish Nunatak. The results of our field survey (geological and glaciological observations, and sub-ice features from GPR surveys) are described here for each nunatak and summarised in Table 1. The bedrock lithology at each site was studied in detail following the fieldwork, using rock samples collected from the ridges. Details of the radar surveys are provided in Appendix A.

4.2.1 Winkie Nunatak

Winkie Nunatak (Fig. 5) is a ridge rising 110 m above the ice sheet surface that is composed entirely of basaltic pillow lavas, overlain by numerous granite erratics. The ridge is broadly oriented N-S and dips perpendicular towards PIG (Fig. 1), making it highly likely to have been more exposed during any periods when the grounding line was more retreated. The exposed part of the ridge is broad and rounded, with a gentle gradient (Fig. 5a).

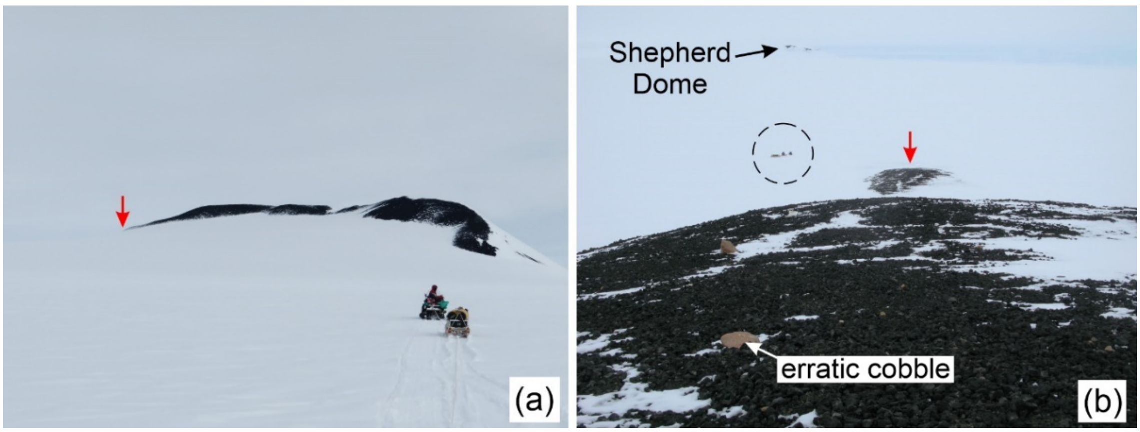


Figure 5: Topography and surroundings of Winkie Nunatak. **(a)** Photograph of Winkie Nunatak viewed from the north. Arrow indicates where the SE ridge extends below the ice surface. Sledge and snowmobile for scale. **(b)** View from Winkie Nunatak looking down the SE ridge towards Shepherd Dome. Red down-pointing arrow shows tip of ridge. Note erratic cobbles strewn on lava bedrock surface. Sledge and two snowmobiles (circled) for scale.

Accessibility: Although there is heavy crevassing on the western side of Winkie Nunatak and to the south (Fig. 6), access to the base of the ridge at its SE end was possible at the time of our survey without crossing crevassed ground by approaching the nunatak from the NE. The area between Winkie Nunatak and Webber Nunatak is several kilometres wide, snow- (and ice-) covered, and relatively flat, making it ideal for a skiway. This would permit the required access by ski-equipped aircraft (section 3). Using this skiway location would allow a camp to be situated within 5 km of the base of Winkie Nunatak, allowing for fast and safe transit between the camp and drill site for the drilling team.

https://doi.org/10.5194/egusphere-2024-1452
Preprint. Discussion started: 12 June 2024

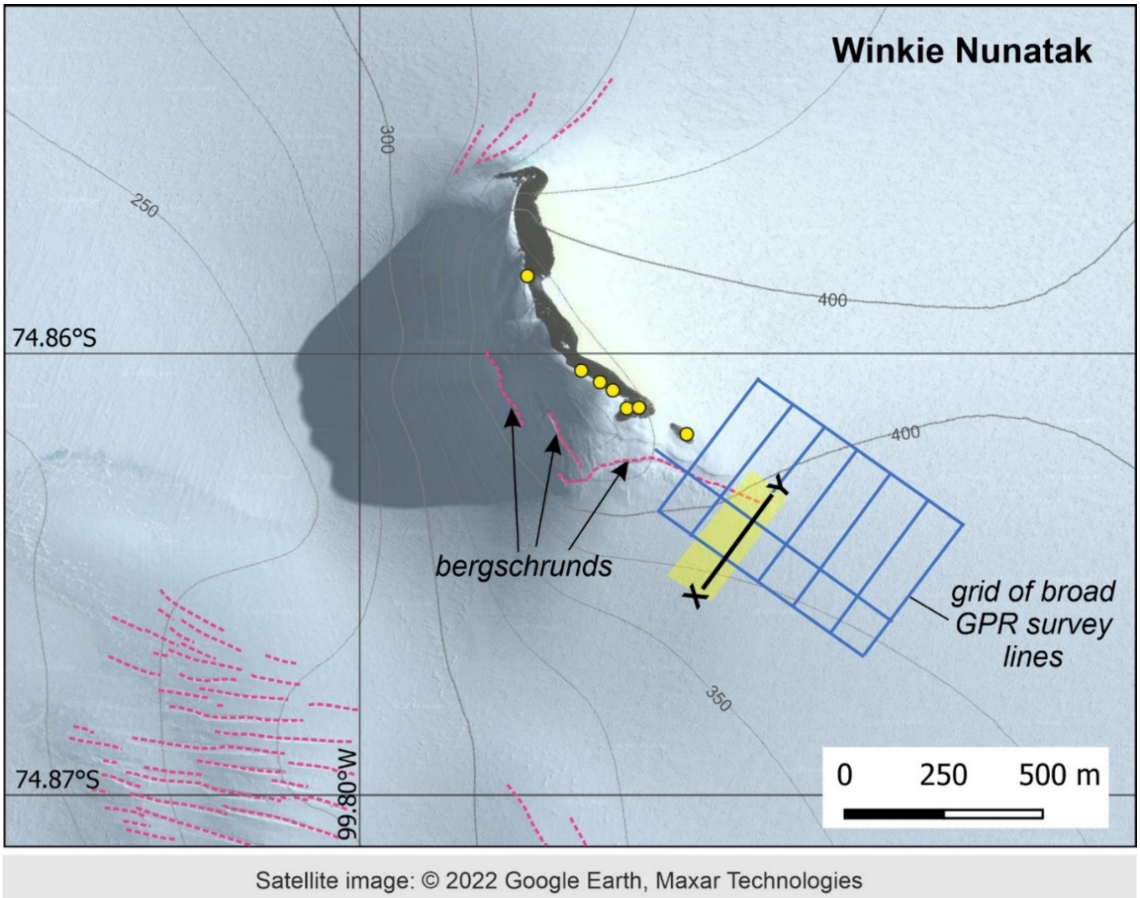


Figure 6: Satellite image of Winkie Nunatak, showing areas of known crevassing (pink dotted lines). Contours of surface elevation (at 25 m intervals) are from the REMA DEM (Howat et al., 2022). Satellite image ©2022 Google Earth, Maxar Technologies (imagery date: 16 February 2012). Locations of erratic cobbles dated by Nichols et al. (2023) are indicated by yellow circles. The location of radar profile (X-Y) in Fig. 8 is shown here inside a shaded yellow rectangle that outlines the coverage of our detailed survey grid (five lines; see Appendix A). The lines of the broader GPR survey (Appendix A) are also shown.

Bedrock lithology: Winkie Nunatak is comprised entirely of pillow basalt lavas, some of which are intact, that contain abundant olivine and plagioclase feldspars − but no pyroxene − in a finer-grained matrix (Fig. 7a and b). Both mineral phases are unweathered. Using a thin section of a sample taken from the central crystalline core of a pillow during the field survey (Fig. 7b and c), we measured the olivine crystals as 0.1-1.5 mm in diameter and plagioclase laths as 0.2-0.9 mm in length. We visually estimated their abundances as 10-15 % (olivine) and 20-25 % (feldspar). The phenocrysts are present, but less abundant, in the vesicular outer pillow rims. Due to their relatively large size, the olivines – and to a lesser extent the feldspars − would be straightforward to mechanically separate (using magnetic and density separation). Thus, although the bedrock at

https://doi.org/10.5194/egusphere-2024-1452
Preprint. Discussion started: 12 June 2024

Winkie Nunatak does not contain the most desirable mineral phase for ^{10}Be and in situ ^{14}C cosmogenic nuclide measurements (quartz), the presence of separatable olivine should make in situ ^{14}C dating feasible (section 3).

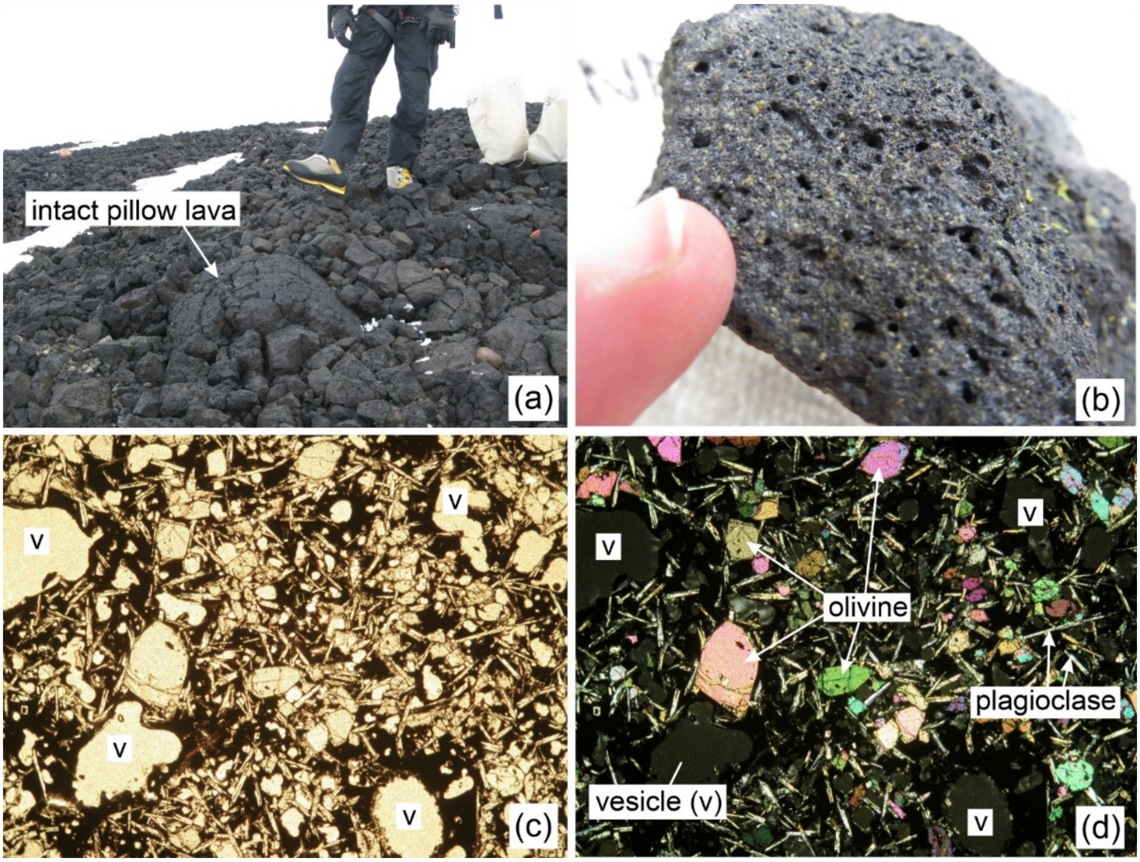
325


Figure 7: Photographs showing bedrock lithology at Winkie Nunatak. (a) Field photograph of pillow basalt. Person for scale. **(b)** Close-up photograph of lava, showing abundant olivine phenocrysts (green crystals). Fingertip for scale. **(c)** Thin section photograph of lava (sample UNN-204; British Antarctic Survey ID R19.1.12), shown in Plane Polarised Light (PPL). Field of view is 8 mm. **(d)** Thin section photograph of same lava as in panel c, shown between crossed polars (XPL). Field of view is 8 mm. v=vesicle (hole created by gas or steam during rock solidification after eruption)

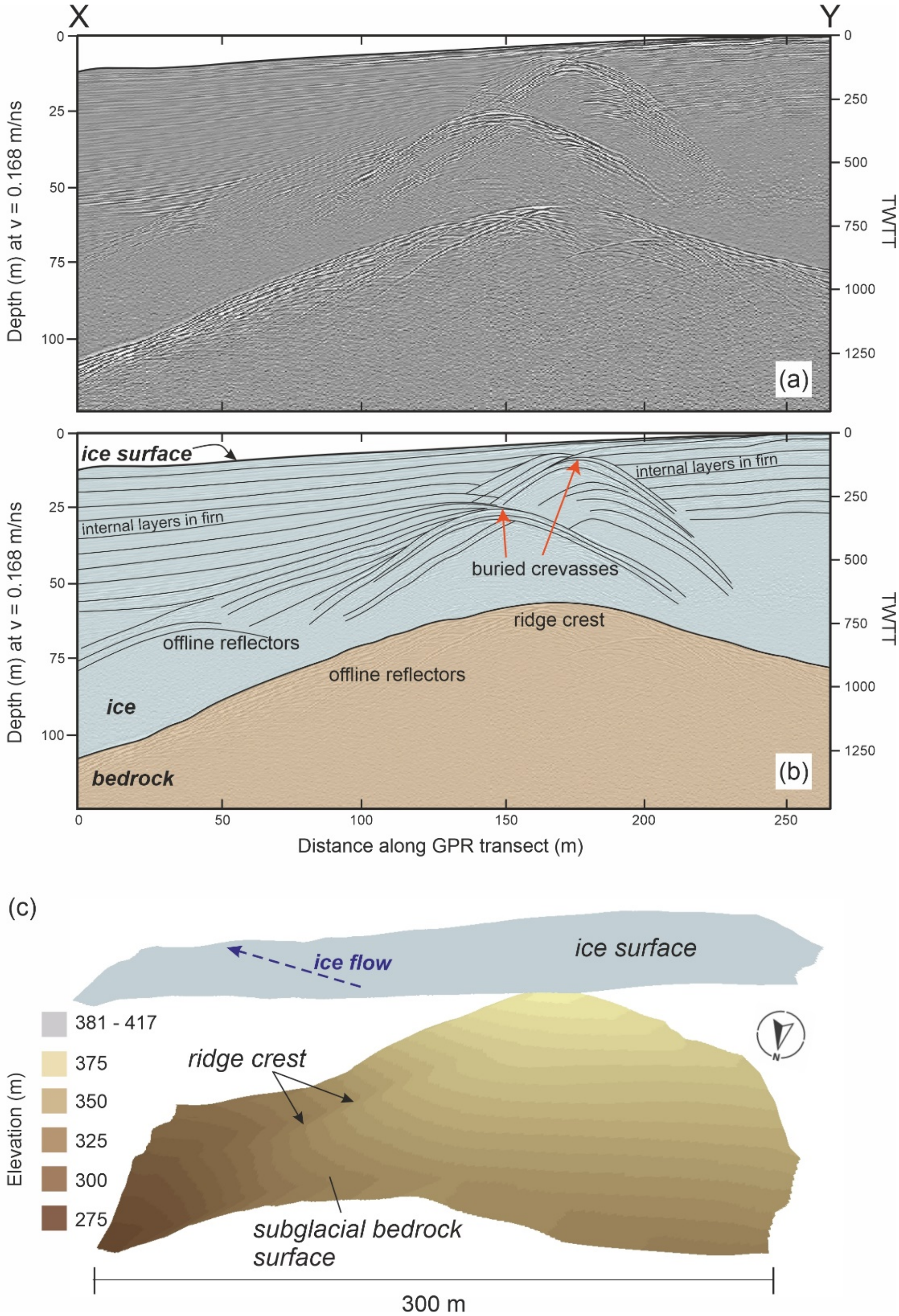
Glaciology: The ice sheet surface surrounding Winkie Nunatak consists of well-compacted firn covered by snow, with small sastrugi (< 30 cm high) covering most of the snow surface in the 2019-20 season. The ice surface slopes gently away to the SE from the end of the main ridge of Winkie Nunatak. Perpendicular to the ridge line, the ice slopes more steeply from the north, as it flows over the subsurface expression of the ridge towards the margin of PIG. A few large crevasses and a bergschrund are visible in satellite imagery (Fig. 6) and were also observed during fieldwork. Although well-bridged in 2019-20, these crevasses could limit or prevent access from both the northern end of the ridge and its SW side for drilling operations in future seasons. The GPR survey also showed some large crevasses running away from exposed bedrock ridge, parallel to

https://doi.org/10.5194/egusphere-2024-1452
Preprint. Discussion started: 12 June 2024

the crest of convexity in the ice surface. Subsequent surveys in 2022-23 (Braddock et al., 2024) revealed multiple additional large extensional crevasses running at oblique angles over top of the subglacial extension of the main ridge. These crevasses were covered only by thin (0.5 m-thick) snow bridges. It is likely that these new shallow crevasses are a result of the rapidly changing grounding line and ice margin position of PIG: the floating ice margin retreated past Winkie Nunatak between the 2019-20 season and the 2022-23 season as large icebergs calved from the terminus of the glacier (Joughin et al., 2021). Several similar calving events of PIG have been observed in the past decades (Jeong et al., 2016; Arndt et al., 2018).

Results of the GPR survey at Winkie Nunatak are shown in Fig. 8. The basal reflector indicates a well-defined ridge running out in line with the exposed ridge of Winkie Nunatak and dipping quickly to 60 m beneath the ice surface at the centre of the detailed grid shown in Fig. 6, 210 m from the lowest bedrock exposure (position marked by the down-pointing red arrow in Fig. 5b). Below the ice surface, the ridge crest gradually flattens, reaching a width of 20-30 m and widening further as it deepens towards the SE (Fig. 8). The subglacial ridge is covered by well compacted firn, likely transitioning to ice at depth. Layers are clearly visible in the firn (Fig. 8b). For the most part, the firn layers are continuous, though there are two large, buried crevasses visible in the profile, marking the extension of the bergschrunds that run across the south-facing slope of the nunatak (Fig. 6). Offline reflectors from the ridge obscure some lower internal ice reflectors near the bedrock surface, making it difficult to identify any near-bedrock layering in the ice column or at the ice-bedrock transition.

Our GPR observations suggest that, from a glaciological point of view, the subglacial ridge extending SE towards PIG is an ideal drill site for subglacial bedrock recovery drilling. The ridge crest is wide (Fig. 8c) and continues as a discrete ridge for over 300 m before it dips to an ice depth of >100 m. The centre of the ridge should thus be accessible for much of its length. The presence of large, buried crevasses may prevent drilling in certain locations on the ridge crest, but can likely be avoided. Alternatively, drilling away from the ridge crest could be considered. The continued dip below the ice surface of the exposed bedrock at the SE end of Winkie Nunatak suggests that the exposed bedrock is likely to be representative of the subglacial extension of the ridge.

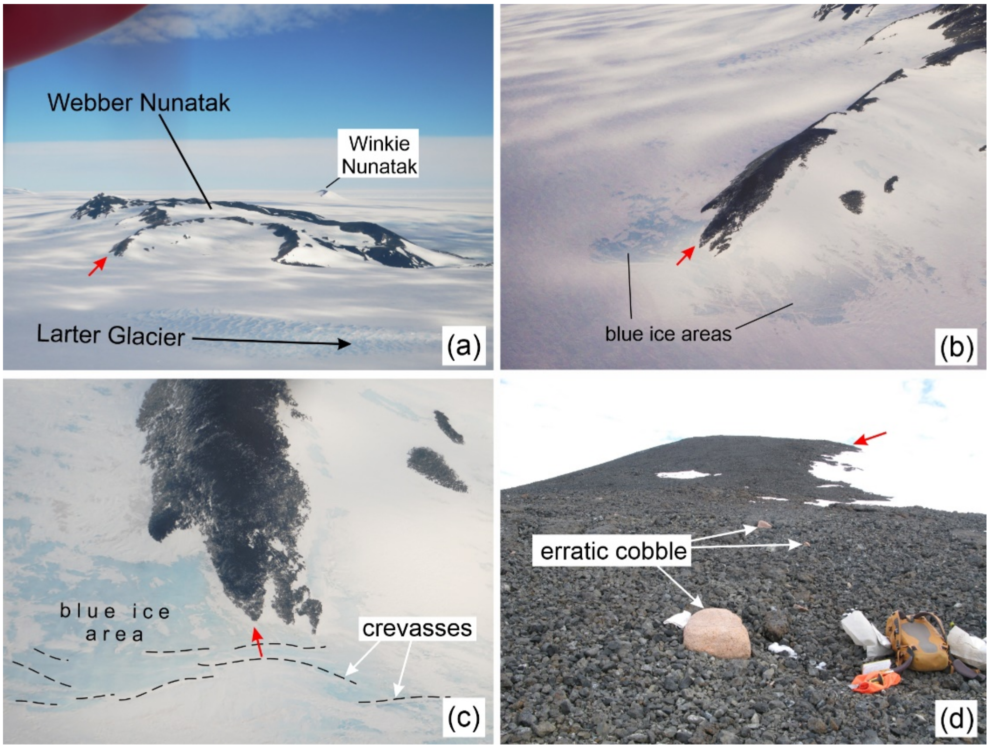


365 **Figure 8. GPR survey results from Winkie Nunatak. (a)** 2D radar profile (the location of profile X-Y is shown in Fig. 6). TWTT is two-way travel time. **(b)** 2D radar profile showing digitised basal topography and ice. Subsurface features including firn layers, crevasses and offline reflectors from basal bedrock are labelled. **(c)** Radar-based interpolation of the subglacial bedrock ridge at Winkie Nunatak (the area covered by these data is shown in Fig. 6).

https://doi.org/10.5194/egusphere-2024-1452
Preprint. Discussion started: 12 June 2024

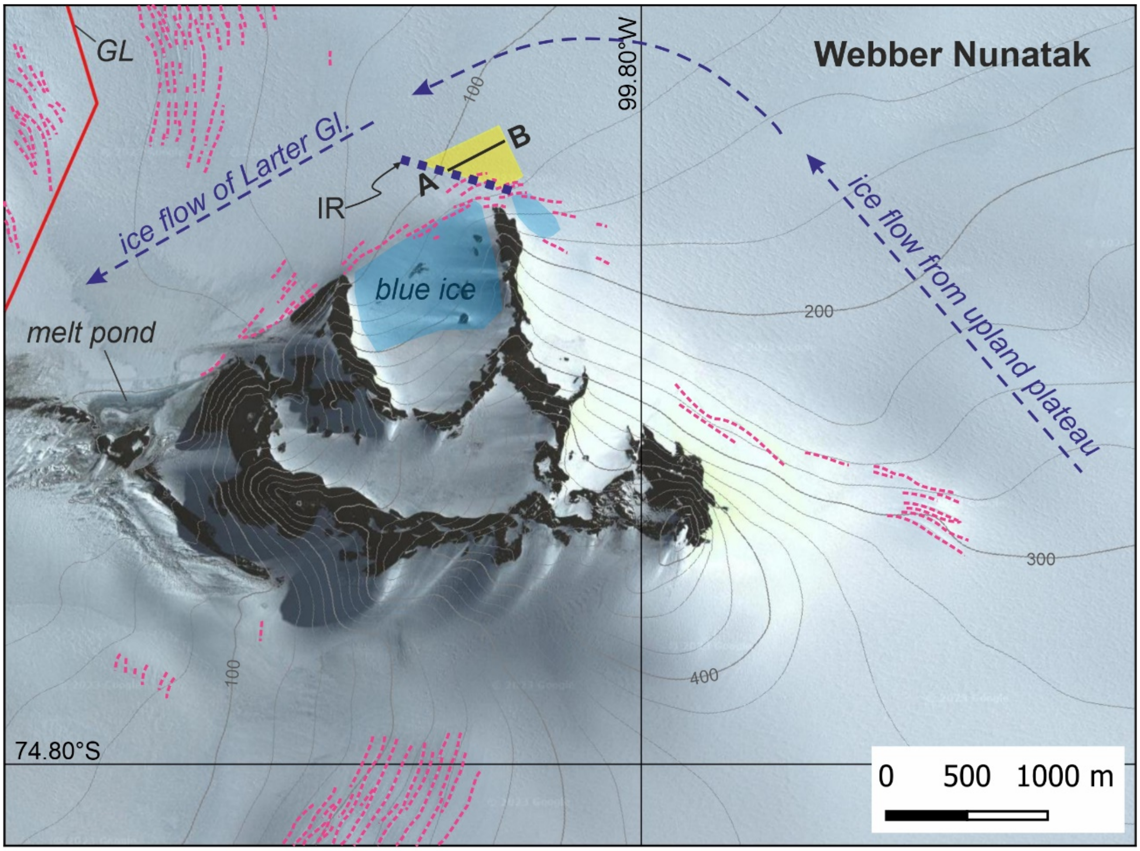
4.2.2 Webber Nunatak

Webber Nunatak (Fig. 9) is an eroded volcanic edifice situated adjacent to Larter Glacier which flows westward into an ice shelf (Fig. 1). The western margin of the nunatak is situated at the present grounding line (Fig. 1b). Two prominent ridges extend down to Larter Glacier on its northern side (Fig. 9a). Modelling suggests that, if the grounding line had ever retreated inboard of its present position during the Holocene, it would likely have retreated up the Larter Glacier trough (Fig. 4). Since these ridges are oriented perpendicular to that trough, they would be sensitive to ice sheet thickness changes resulting from such grounding line retreat; from this point of view, they make suitable drill sites. One of the ridges ('Ridge A'; Fig. 9a) descends relatively gently to a blue ice area where katabatic winds scour snow away from the ice surface. This is another feature making Ridge A suitable for drilling (section 3 and Fig. 3). The nunatak is composed of a sequence of lavas and stratified hyaloclastite, but in contrast to Winkie Nunatak, there are only a handful of erratic cobbles perched on its bedrock surfaces. These erratics are mostly quartz-bearing granitoids with a few gneisses (Fig. 9d), making them ideal for cosmogenic nuclide dating to determine the past exposure history of the ridge. Although they are only present on the lowermost 70 m of the two ridges, and predominantly on Ridge A, this should not present a problem for detecting a Holocene retreat and readvance because only erratics from close to the modern ice surface are needed to provide a constraint on the exposure history of the subglacial portion of the ridge (Johnson et al., 2022).



https://doi.org/10.5194/egusphere-2024-1452
Preprint. Discussion started: 12 June 2024

Figure 9. Topography and glaciology around Webber Nunatak. Short red arrows denote 'Ridge A' (see text), close to the candidate drill site. **(a)** Webber Nunatak viewed from Larter Glacier, showing candidate drill site (off end of Ridge A). Note extensive crevassing on Larter Glacier, preventing access by aircraft from the northern side. **(b)** Ridge A viewed from the air. **(c)** Close-up view of ridge A and the adjacent blue ice area, viewed from above. Several crevasses are visible extending perpendicular to the ridge. **(d)** The lower part of Ridge A, looking towards Larter Glacier. A few erratic cobbles are perched on the basalt rubble.



Satellite image: © 2022 Google Earth, Maxar Technologies

Figure 10. Satellite image of Webber Nunatak, showing areas of known crevassing and blue ice. Pink dotted lines and blue shaded areas show location of crevasses and blue ice, respectively. The location of the radar profile (A-B) shown in Fig. 12a and b is indicated by a shaded yellow box that outlines the survey area used to compile Fig. 12c. The dotted line labelled 'IR' shows the base of a ridge in the ice sheet surface. Numerous large crevasses were observed on the ridge slope to the SW of the line. Contours of surface elevation (at 25 m intervals) are from the REMA DEM (Howat et al., 2022). The solid red line (labelled 'GL') marks the location of the 2011 grounding line (Rignot et al., 2016). Satellite image ©2022 Google Earth, Maxar Technologies (imagery date: 16 February 2012).

Accessibility: In contrast to Winkie Nunatak, access to Webber Nunatak is more challenging due to the presence of several large crevasses close to its eastern end (Fig. 10). Furthermore, the downstream section of Larter Glacier on the northern side of Webber Nunatak is heavily crevassed making it impossible to land an aircraft there (Fig. 9a). The only way to access a drill site at the base of the ridges on the northern side of Webber Nunatak would therefore be from a camp situated in the broad flat

https://doi.org/10.5194/egusphere-2024-1452
Preprint. Discussion started: 12 June 2024

area between Winkie Nunatak and Webber Nunatak (Fig. 1b). The crevassing could then be avoided by driving in a wide berth around the eastern end of Webber Nunatak. Whilst feasible, this adds time for driving a few extra kilometres from the camp to the work area, but it would be impossible to bring the drill and associated equipment to the foot of those ridges by any other route. The work area at Webber Nunatak is also limited to a footprint extending a maximum of ~800 m from the northern ridges, due to the proximity to the shear zone of Larter Glacier (Fig. 9a). Care would also be needed to avoid smaller crevasses perpendicular to the base of the ridges on the northern side of the nunatak (Figs. 9c and 10); if these could not be avoided, it may alternatively be possible to bridge the crevasses using aluminium ladders to permit safe rope-free access to the drill site. These aspects mean that ridges on the northern side of Webber Nunatak could be workable, but access would not be as easy or as safe as at Winkie Nunatak.

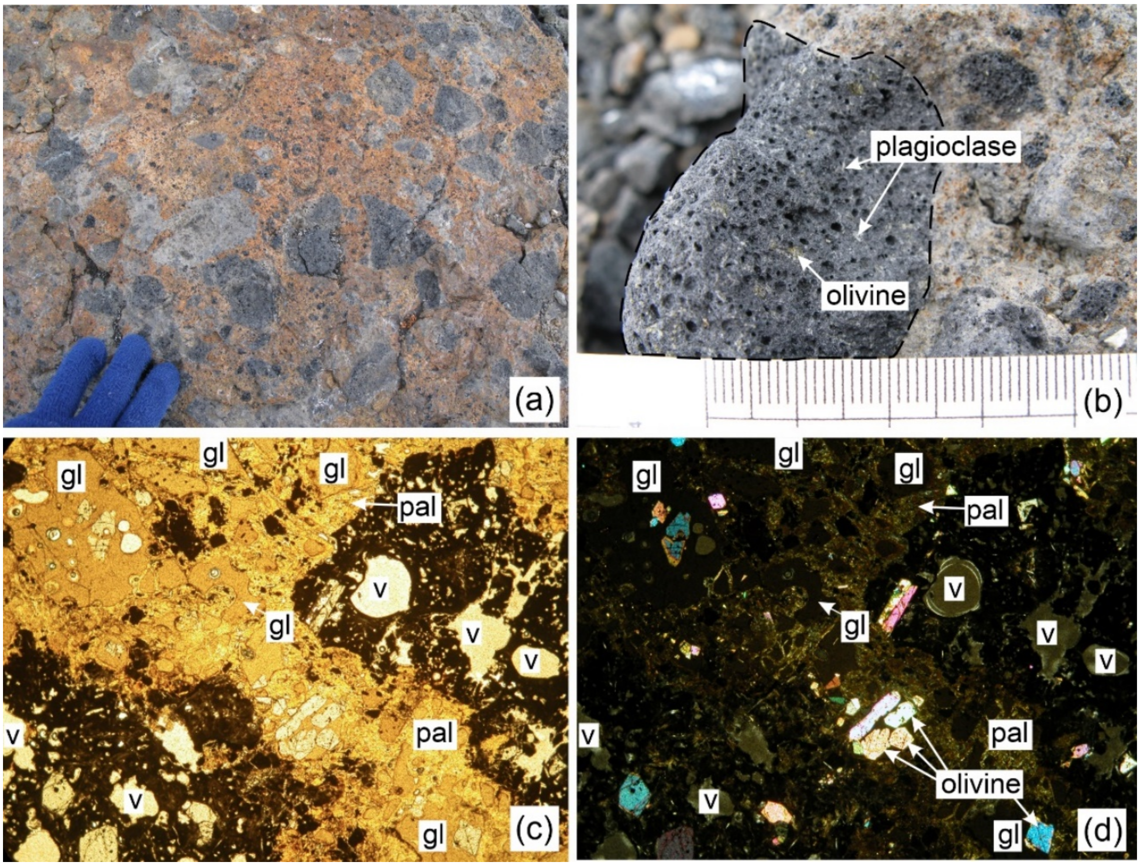


Figure 11. Photographs showing bedrock lithology at Webber Nunatak. (a) Field photograph of hyaloclastite at Webber Nunatak, from the base of a ridge that extends towards Larter Glacier close to a potential drill site. Large basalt clasts (grey) are surrounded by palagonitised glass matrix (orange). Gloved hand for scale. **(b)** Close-up field photograph of Webber Nunatak hyaloclastite, showing basalt clast (outlined by dashed line) containing abundant olivine and plagioclase phenocrysts. Scale bar increments are in mm. **(c)** Thin section photograph of hyaloclastite (sample WEB-211; British Antarctic Survey ID R19.2.11) in PPL. Field of view is 8 mm. v=vesicle, gl=glass (orange colour), pal=palagonite (yellow colour) **(d)** Thin section photograph of same hyaloclastite as in panel c, in XPL. Field of view is 8 mm. v=vesicle, gl=glass (in extinction), pal=palagonite (birefringent)

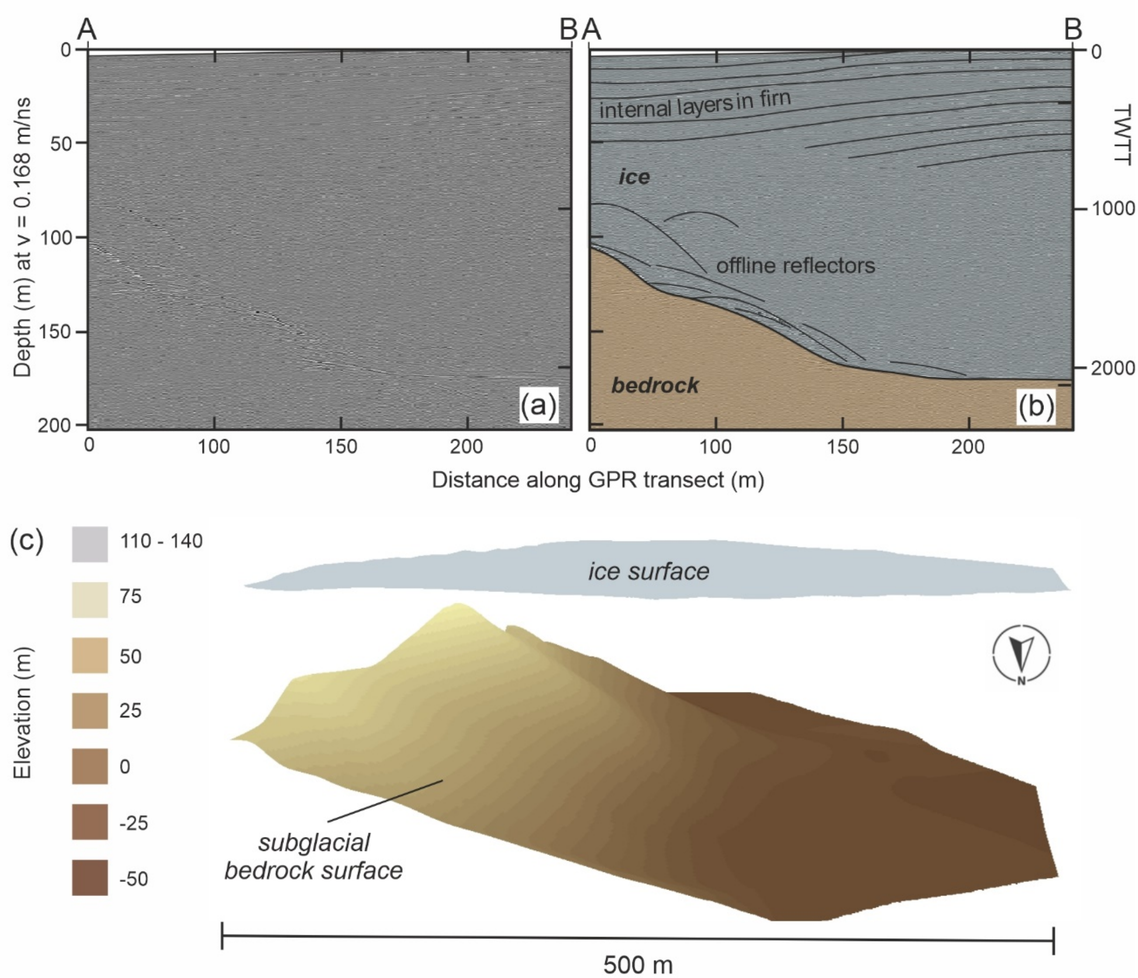
https://doi.org/10.5194/egusphere-2024-1452
Preprint. Discussion started: 12 June 2024

Bedrock lithology: The bedrock lithology of the lower ridges on the northern side of Webber Nunatak is massive (unstratified) hyaloclastite (Fig. 11). At Webber Nunatak, some of the glass within the hyaloclastite has been converted to clay minerals, specifically palagonite, by alteration (Fig. 11c; cf. fig. 4, Johnson & Smellie, 2007). Interspersed with the glass are fragments of basaltic lava that contain abundant olivine phenocrysts of 0.2-1.0 mm diameter (Fig. 11b) but no visible pyroxene or feldspar. The lava clasts are typically <6 cm in diameter. Presence of these lava clasts in any recovered drill core would allow measurement of cosmogenic ^{10}Be and in situ ^{14}C in olivine (see section 3), but such analyses would be dependent on recovering enough material: since the diameter of rock cores is typically only 2-5 cm, there would be a high likelihood of penetrating only (or predominantly) the glassy material that would be unsuitable for cosmogenic nuclide analysis. Thus, although it would theoretically be possible to measure cosmogenic nuclides in the Webber Nunatak bedrock, it would probably be extremely challenging, and potentially impossible.

Glaciology: The ice sheet surface at the base of Ridge A consists largely of blue ice with some firn, and patchy snow cover (Fig. 9). The blue ice is particularly extensive on the eastern side of the ridge. Numerous crevasses are present around the base of the ridge (Fig. 10). Some are >1 m wide and are filled with aerated unconsolidated snow and ice. Their depth was not discernible in the field, but we estimated they could be >2 m deep. During the 2019-20 seasons, the snow bridges of these crevasses were weak, likely due to the warm temperatures experienced in late 2019. The ice surface showed two elevations, with a higher area (which was heavily crevassed) and a lower, flatter area to the east. A steep slope separated the two areas, again with numerous crevasses, with the base of the slope trending NW from the end of the bedrock ridge. GPR surveys could only be safely conducted to the east of the ice ridge base. The results of our GPR survey at Webber Nunatak (Fig. 12) indicate that the main subglacial bedrock ridge trends to the NW, with the highly crevassed ice ridge marking its crest. It is fairly broad – rounded, rather than sharp-crested − beneath the ice surface (Fig. 12c). The bedrock ridge also appears to have been heavily eroded by ice moving NW from the plateau ice between Webber Nunatak, Mount Manthe and Shepherd Dome (Fig. 1b), before meeting Larter Glacier ice flowing WSW. There are few clearly discernible structures visible within the ice in the GPR data. Near the surface, a firn layer that extends to ~50 m below the modern ice sheet surface can be traced in places, and some offline bedrock reflectors are also apparent (Fig. 12a and b).

In summary, GPR and glaciological field observations suggest that drilling at the end of Ridge A at Webber Nunatak would be challenging due to the presence of large poorly bridged crevasses around the base of the exposed bedrock ridge. These would make access difficult, as well as reducing the options for recovering a closely spaced transect of subglacial bedrock cores. Furthermore, the evidence suggesting significant glacial erosion of the ridge by tributary ice from the plateau flowing into Larter Glacier indicates that near surface bedrock may have been eroded during the Holocene, reducing the scientific rationale for drilling here.

https://doi.org/10.5194/egusphere-2024-1452
Preprint. Discussion started: 12 June 2024



460 **Figure 12. GPR analysis of Webber Nunatak. (a)** and **(b)** 2D radar profile from Webber Nunatak, showing subglacial ridge crest (location of profile A-B is shown in Fig. 10). TWTT is two-way travel time. Panel (b) shows digitised basal topography and the ice surface and is annotated to show subsurface features (thin black lines). **(c)** Radar-based interpolation of the subglacial ridge.

4.2.3 Maish Nunatak

Maish Nunatak is situated on the northern side of Larter Glacier, ~3 km from the modern grounding line (Fig. 1b). Its bedrock is composed entirely of basaltic pillow lavas. Granite boulders and cobbles perched on the bedrock surfaces are much more numerous than at Winkie Nunatak or Webber Nunatak. Cosmogenic nuclide exposure dating of a suite of these cobbles (locations shown in Fig. 13b) showed that Maish Nunatak deglaciated rapidly in the early Holocene and that the modern ice surface elevation was reached by ~8 ka (Johnson et al., 2014). Maish Nunatak has three shallowly sloping ridges facing SE. These ridges are very low gradient (nearly horizontal) on their ice-proximal ends (Fig. 13). Their orientation is not perfect for detecting past changes in grounding line position because they slope inland away from the modern grounding line and are

https://doi.org/10.5194/egusphere-2024-1452
Preprint. Discussion started: 12 June 2024

protected by the higher elevation summit of the nunatak that lies on the side closest to the grounding line. Nevertheless, existing exposure ages from the easternmost and westernmost ridges appear to have captured ice sheet thinning that reached the modern surface elevation in the early Holocene. Thus, drilling at this site should permit detection of Holocene grounding line retreat and readvance if it occurred.

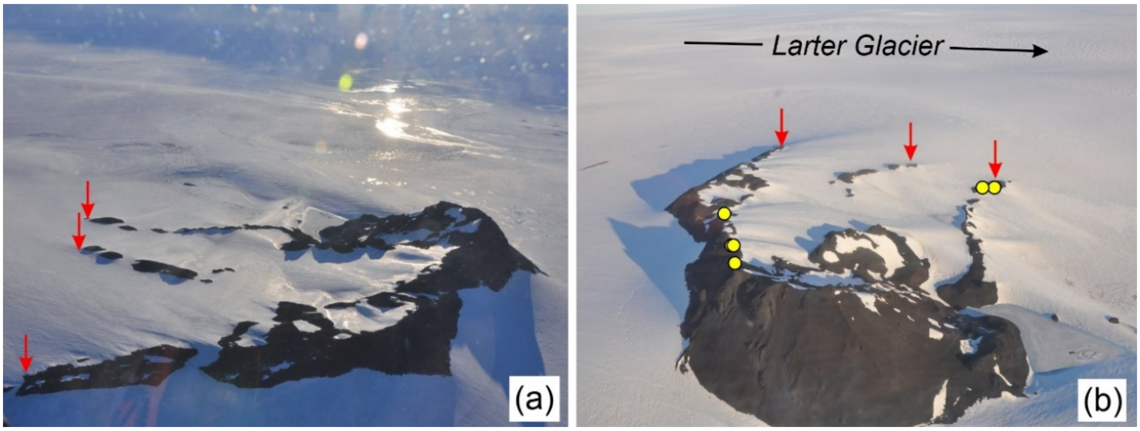


Figure 13. Topography and surroundings of Maish Nunatak. (a) View from the air, looking SW. Arrows indicate the tips of three low-gradient bedrock ridges described in the text. **(b)** View looking approximately SE, towards Larter Glacier. Circular symbols indicate the locations of erratic cobbles sampled for ^{10}Be exposure dating in an earlier study (Johnson et al., 2014). Both photographs were taken in 2010 by James Smith (British Antarctic Survey).

Accessibility: There is very little crevassing visible from the ground or in satellite imagery in the immediate vicinity of Maish Nunatak (Fig. 14). However, despite this and its suitability for drilling based on the surveys undertaken prior to fieldwork (proximity to the grounding line, three ridges with a low gradient and well-constrained early Holocene exposure history), our visit highlighted considerable challenges for access by a drilling team. Firstly, the nearest accessible location for ski-equipped aircraft is on the SE side of Mt Moses, approximately 10 km from the ridges that extend from Maish Nunatak (Fig. 1b). This would mean a long travel time (>1 hour by snowmobile) from the landing site to the nunatak itself. In addition, the area between Mt Moses and Maish Nunatak is an active ablation zone, where the presence of abundant tephras within the ice has resulted in differential melting producing an extensive area of deep potholes within the ice surface (labelled 'zone of extensive surface melting' in Fig. 14). Many of these metre-sized depressions of >50 cm depth were filled with slush during our visit. During warmer austral summers, such slush/water-filled depressions could persist, causing the area to easily become completely impassable on foot or by snowmobile. Therefore, the only plausible means for a drilling team and equipment to access Maish Nunatak is by helicopter, establishing a camp on one of the lower rocky outcrops of the nunatak. For most Antarctic field campaigns, helicopter support at this distance from an established base is unlikely to be a viable option. Thus, although not impossible, the difficulties of access are a major shortcoming for Maish Nunatak as a potential drill site.

https://doi.org/10.5194/egusphere-2024-1452
Preprint. Discussion started: 12 June 2024

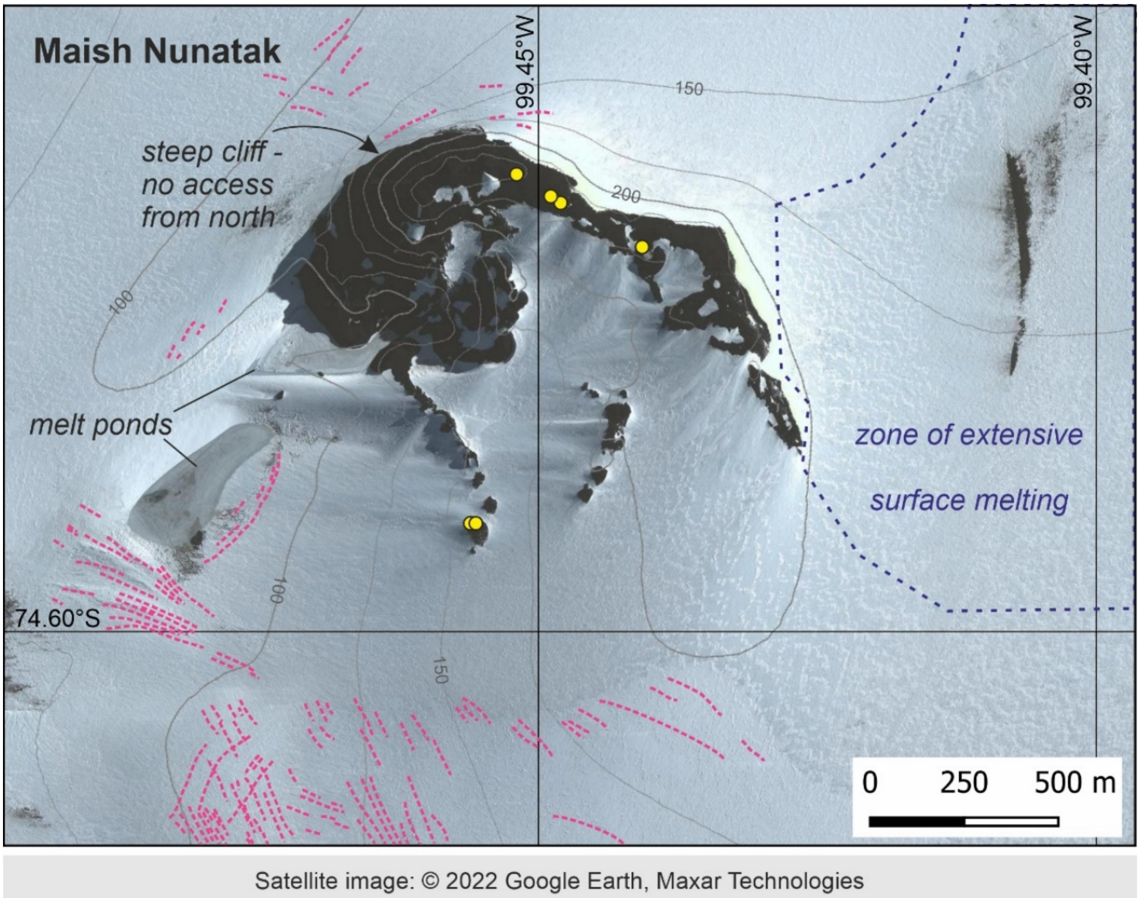


Figure 14. Satellite image of Maish Nunatak showing features that are important for drill site accessibility. Pink dotted lines show location of crevasses. Locations of erratic cobbles dated by Johnson et al. (2014) are indicated by yellow circles (see also Fig. 13b). No GPR surveys were undertaken at this site. Contours of surface elevation (at 25 m intervals) are from the REMA DEM (Howat et al., 2022). Satellite image ©2022 Google Earth, Maxar Technologies (imagery date: 2 March 2012).

Bedrock lithology: The bedrock lithology of Maish Nunatak is, however, relatively favourable for this study. It consists of basaltic pillow lava containing abundant fresh olivine phenocrysts, often clustered with plagioclase feldspar and occasional clinopyroxene, in a matrix of finer-grained feldspar and clinopyroxene groundmass (Fig. 15 a and b). The olivine, clinopyroxene and feldspar phenocrysts are typically 0.25-1.25 mm, 0.25-0.4 mm and 0.5-1.25 mm diameter, respectively (Fig. 15c and d), making the olivines and feldspars relatively easy to separate from the groundmass. Rarely, larger clinopyroxene phenocrysts (>1 mm diameter) are present. However, given their low overall abundance (<<5 %), the pyroxenes are unlikely to make suitable targets for cosmogenic nuclide measurement. This lithology is therefore similarly suitable for cosmogenic nuclide measurement as the Winkie Nunatak bedrock.

https://doi.org/10.5194/egusphere-2024-1452
Preprint. Discussion started: 12 June 2024

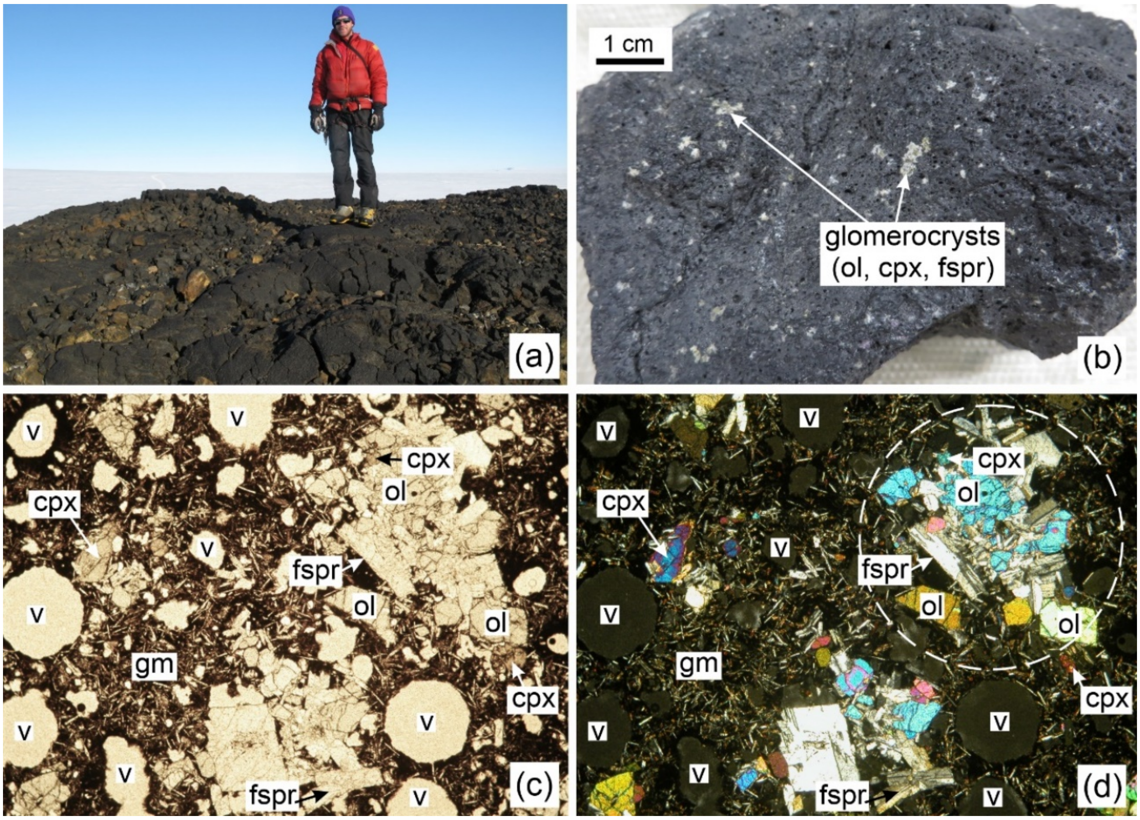


Figure 15. Photographs showing bedrock lithology at Maish Nunatak. (a) Field photograph of pillow lavas, with person for scale. **(b)** Close-up photograph of lava in hand specimen, showing prominent clusters (glomerocrysts) of olivine (ol), clinopyroxene (cpx) and feldspar (fspr). **(c)** Thin section photograph of lava (sample MAI-201; British Antarctic Survey ID R19.6.1), in PPL. Field of view is 8 mm. v=vesicle, gm=groundmass, cpx=clinopyroxene, ol=olivine, fspr=feldspar. **(d)** Thin section photograph of same lava as in panel c, in XPL. A glomerocryst is enclosed by the dashed white line. Field of view is 8 mm. v=vesicle, gm=groundmass (comprising feldspar and clinopyroxene crystals)

Glaciology: The ice sheet surfaces at Maish Nunatak consist predominantly of firn. These surfaces all have low-gradient slopes making them easily accessible for safe working. Furthermore, we did not observe crevassing proximal to the three south-facing bedrock ridges (Fig. 13), an observation which is consistent with the generally low-gradient ice surface slopes around the nunatak. However, the ice surface at the base of the most easterly of the three exposed bedrock ridges has a reverse slope, and there are several small bedrock outcrops visible beyond the end of the exposed portion of the middle ridge. Together, these observations suggest that sections of these ridges dip below the ice surface and re-emerge further along, rather than sloping continuously away from the main outcrop. The exposed bedrock surface of the westernmost of the three ridges is slightly steeper than the other two, suggesting that its subglacial extension may also be steeper, although this is unlikely to pose difficulties for drilling. Due to difficulties accessing Maish Nunatak in the 2019-20 season, GPR surveys were not undertaken there, so the underlying ice and subglacial bedrock topography remains unknown.

https://doi.org/10.5194/egusphere-2024-1452
Preprint. Discussion started: 12 June 2024

4.2.4 Summary of field survey results

Prior to field survey, we rejected Evans Knoll, World's End Bluff, Shepherd Dome, and Meyers and Inman nunataks as unsuitable for drilling. The decision over which of the remaining three potential drill sites (Winkie, Webber and Maish nunataks) is most suitable requires balancing of the relative importance of each of the criteria in Table 1. Whereas the suitability of the rock type for analysis and safe access for a field team are essential, there are trade-offs between ease of accessibility and likely ease of drilling/rock recovery (Briner et al., 2022); the latter will increase the speed at which samples can be collected (Braddock et al., 2024).

Based on lithological considerations alone, the most suitable bedrock for subglacial drilling is the basaltic lava at Winkie and Maish nunataks. In theory, it would be possible to recover and analyse the hyaloclastite bedrock at Webber Nunatak, but it would likely be very difficult to achieve both good core recovery and sufficient quantity of the desired mineral phases to permit successful analysis of cores from that site (considering the expected low in situ ^{14}C concentrations in subglacial bedrock [see Balco et al., 2023], at least 5 g of quartz or olivine should be targeted for each in situ ^{14}C measurement; Lamp et al., 2019; Pigati et al., 2010). Since quartz-bearing bedrock appears to be absent in the Hudson Mountains (section 4.2), cosmogenic nuclide measurements will need to be undertaken on olivine and potentially plagioclase feldspar or clinopyroxene instead of quartz.

Our field survey revealed that quartz-bearing erratics − predominantly granites and gneisses − are present on all nunataks in the Hudson Mountains, although their abundance varies markedly between nunataks. Considering the three remaining potential drill sites, erratic cobbles of granite lithology are very common at Winkie Nunatak and Maish Nunatak and exist, but are rare, at Webber Nunatak. Measurement of in situ ^{14}C in bedrock-erratic pairs for which the Holocene deglaciation history is already known (from ^{10}Be measurements of the erratics) would be a valuable tool for calibrating the local in situ ^{14}C production rate. The presence of abundant quartz-bearing erratics above the present ice margin at a site would thus provide an advantage for the analysis of subglacial bedrock cores from the same site, making nunataks where this is the case (Winkie and Maish Nunataks) more desirable than those with scarce glacial deposits (Webber Nunatak). However, access to Maish Nunatak for any drilling campaign would be extremely challenging and likely insurmountable without helicopter support due to the presence of the active ablation zone adjacent to the nunatak. Therefore, and in summary, of the three leading drill sites surveyed, both Winkie and Webber nunataks are feasible, but Winkie Nunatak is much more desirable due to its lithology, easier accessibility (surface conditions are challenging at Webber Nunatak) and more conducive subglacial morphology.

5 Conclusions

Bedrock cores recovered from beneath the Antarctic Ice Sheet can provide evidence for grounding line retreat inboard of present (i.e. a smaller-than-present ice sheet) during the Holocene, with subsequent readvance to its modern configuration

https://doi.org/10.5194/egusphere-2024-1452
Preprint. Discussion started: 12 June 2024

(Johnson et al., 2022; Balco et al., 2023). This paper outlines the criteria used for choosing a suitable site for subglacial bedrock drilling in the eastern Pine Island-Thwaites Glacier system. Two nunataks in the Hudson Mountains were selected as feasible for subglacial drilling based on (i) their location proximal to the modern grounding line, (ii) the presence of outcropping ridges oriented perpendicular to modern ice flow and the likelihood that those ridges would have become more exposed if the grounding line had retreated inboard of present, iii) suitability of the bedrock lithology for cosmogenic nuclide analysis, and (iv) accessibility. These are Winkie Nunatak (74.86°S / 99.78°W) and Webber Nunatak (74.77°S / 99.83°W). Neither site is a perfect fit to all the criteria. However, Winkie Nunatak, with its olivine-rich bedrock lithology, well-consolidated structure and likely absence of overlying till on the subglacial ridge surface, is the highest scoring choice. In contrast, the presence of potentially permeable and less well-consolidated crystal-poor hyaloclastite bedrock at Webber Nunatak would make it challenging to retrieve subglacial samples, and those collected would likely not provide sufficient quantity of the target mineral (olivine) for cosmogenic nuclide measurement. Thus, we propose that Winkie Nunatak is the most suitable site for a subglacial drilling campaign aiming to detect Holocene grounding line readvance in the eastern Pine Island-Thwaites Glacier system.

Postscript: Drilling at Winkie Nunatak was subsequently attempted in the 2022-23 season, but bedrock was not recovered. This outcome was due to factors unrelated to the choice of drill site, primarily a combination of weather conditions and logistical constraints that restricted the available time for drilling operations, and technical problems with clay transport and fluid circulation that made it impossible to penetrate a layer of mixed ice and till overlying the bedrock in the available time (see Braddock et al., 2024 for details). The metre-scale clay-rich ice/sediment layer could not have been detected in advance of drilling operations.

Appendix A

Method for radar survey and radar data analysis: A PulseEKKO 1000 GPR system with 200 MHz antennae was used to survey the snow surface at candidate drill sites. At Winkie Nunatak, a broad grid consisting of seven 400 m-long cross profiles was collected perpendicular to the ridge line, with the radar system towed on a wooden Nansen sledge behind a skidoo. These profiles were spaced at 100 m intervals away from the visible ridge line. A detailed grid of five 300 m-long lines was then collected at 25 m intervals along, and then parallel to, GPR line X-Y (Fig. 6). At Webber Nunatak, eight radar lines were collected perpendicular to the ridge expression at 50 m spacing, and one line was run away from the ridge tip through the centre of the grid. The lines increased in length from 150 m to 500 m with increasing distance from bedrock, due to the orientation of the steep ice slope running northwest, creating the rhomboid shape shown in yellow in Fig. 10. The skidoo travelled at 3-7 km/hr, with the system set to continuous collection mode with an in-field stack of 4. A hand-held Garmin GPS was used to locate the position of GPR survey lines.

Processing steps in the commercial GPR processing software package ReflexW (Sandmeier Scientific Software, version 7.2.2) included depth correction with a standard ice velocity of 0.168 m ns^{-1}, time-zero correction, background removal, high-pass frequency filtering (dewow), bandpass filtering and application of an energy-decay gain to compensate for geometric spreading losses in the radargram (cf. Daniels et al., 2004; Woodward et al., 2022). A number of migration algorithms were applied, which successfully removed artefacts at the bedrock reflector, but were unable to resolve crevasse edges clearly due to the irregular lineation of the crevasse tracks. Despite this, the distinctive GPR limbs from the largest crevasses allow crevasse location detection. The free, open-source seismic interpretation software OpendTect (2015) was employed to plot radargrams in real space using GPS coordinates. This enabled 3D analysis of GPR data and picking of the bedrock reflector. Picks were then exported into ESRI ArcScene to generate 3D plots of the ridge surface beneath the ice.

Author contributions

JSJ and JW undertook fieldwork in the Hudson Mountains and collected all the field observations and GPR data presented here. JSJ wrote the paper with assistance from GB (drilling operations) and JW (glaciology and radar). IN and KW processed the GPR data under the supervision of JW and SC. With the exception of Fig. 1 (see acknowledgements), JSJ and KW prepared all figures, with assistance from KAN and RAV. GB and BMG provided details of subglacial drilling equipment and methods, and the photographs shown in Fig. 3. JSJ, JW, SC, BMG, BH, DHR and GB obtained funding. All authors read and commented on the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

Data availability

All ground-penetrating radar data presented in the paper are publicly accessible in the UK Polar Data Centre at the following link: https://doi.org/xxxxxx (Woodward and Johnson, 2024).

Acknowledgements

Logistical support for this work was provided by British Antarctic Survey (BAS) and United States Antarctic Program. We thank BAS Field Guides Tom King and Ashley Fusiarski for assistance in the field, and BAS Field Operations Managers Al Davies and Nick Gillett for managing the project logistics in Antarctica. Elena Field and Nathan Fenney (BAS) prepared field maps. Laura Gerrish (BAS) helped prepare Figs. 1 and 4. John Fletcher (British Geological Survey, UK) prepared the rock thin sections shown in Figs. 7, 11 and 15, after samples were cut by Mark Evans (BAS). Eric Larour (NASA-Jet Propulsion

Laboratory, USA) kindly provided data from model simulations used in Fig. 4. John Smellie (Leicester University, UK) provided valuable information about glaciovolcanic processes and their products. This work was undertaken for the "Geological History Constraints" project, a component of the International Thwaites Glacier Collaboration (ITGC) and supported from the National Science Foundation (NSF: Grant OPP-1738989 and 2317097) and Natural Environment Research Council (NERC: Grants NE/S006710/1, NE/S006753/1 and NE/S00663X/1). GB was partially supported by the Ann and Gordon Getty Foundation. ITGC Contribution No. ITGC-126

References

Adams, J. R., Johnson, J. S., Roberts, S. J., Mason, P. J., Nichols, K. A., Venturelli, R. A., Wilcken, K., Balco, G., Goehring, B., Hall, B., Woodward, J., and Rood, D. H.: New ^{10}Be exposure ages improve Holocene ice sheet thinning history near the grounding line of Pope Glacier, Antarctica, The Cryosphere, https://doi.org/10.5194/tc-2022-82, 2022.

Arndt, J. E., Larter, R. D., Friedl, P., Gohl, K., Höppner, K., and the Science Team of Expedition PS104: Bathymetric controls on calving processes at Pine Island Glacier, The Cryosphere, 12, 2039–2050, https://doi.org/10.5194/tc-12-2039-2018, 2018.

Balco, G., Brown, N., Nichols, K. A., Venturelli, R. A., Adams, J. R., Braddock, S., Campbell, S. C., Goehring, B. M., Johnson, J. S., Rood, D. H., Wilcken, K., Hall, B. H., and Woodward, J.: Reversible ice sheet thinning in the Amundsen Sea Embayment during the Late Holocene, The Cryosphere, https://doi.org/10.5194/tc-2022-172, 2023.

Balter-Kennedy, A., Schaefer, J. M., Briner, J. P., Young, N. E., Walcott, C., Kuhl, T., Moravec, E., Keisling, B. A., Anandakrishnan, S., Stevens, N., and Brown, N.: First Results from GreenDrill: Exposure dating in sub-ice material from Prudhoe Dome, northwestern Greenland. Abstract, AGU Fall Meeting, San Francisco, USA, 2023a.

Balter-Kennedy, A., Schaefer, J. M., Schwartz, R., Lamp, J. L., Penrose, L., Middleton, J., Hanley, J., Tibari, B., Blard, P.-H., Winckler, G., Hidy, A. J., and Balco, G.: Cosmogenic ^{10}Be in pyroxene: laboratory progress, production rate systematics, and application of the ^{10}Be–^{3}He nuclide pair in the Antarctic Dry Valleys, Geochronology, 5, 301–321, https://doi.org/10.5194/gchron-5-301-2023, 2023b.

Bergelin, M., Balco, G., Corbett, L. B., and Bierman, P. R.: Production rate calibration for cosmogenic ^{10}Be in pyroxene by applying a rapid fusion method to ^{10}Be-saturated samples from the Transantarctic Mountains, Antarctica, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2024-702, 2024.

Bindschadler, R., Vornberger, P., Fleming, A. H., Fox, A. J., Mullins, J., Binnie, D., Paulsen, S. J., Granneman, B., and Gorodetzky, D.: The Landsat Image Mosaic of Antarctica, Remote Sensing of Environment, 112, 4214–4226, 2008.

Boeckmann, G. V., Gibson, C. J., Kuhl, T. W., Moravec, E., Johnson, J. A., Meulemans, Z., and Slawny, K.: Adaptation of the Winkie Drill for subglacial bedrock sampling, Ann. Glaciol., 62, 109–117, https://doi.org/10.1017/aog.2020.73, 2021.

Braddock, S., Hall, B. L., Johnson, J. S., Balco, G., Spoth, M., Whitehouse, P. L., Campbell, S., Goehring, B. M., Rood, D. H., and Woodward, J.: Relative sea-level data preclude major late Holocene ice-mass change in Pine Island Bay, Nat. Geosci., 15, 568–572, 2022.

Braddock, S., Venturelli, R. A., Nichols, K. A., Moravec, E., Boeckmann, G. V., Campbell, S., Balco, G., Ackert, R., Small, D., Johnson, J. S., Dunbar, N., Woodward, J., Mukhopadhyay, S., and Goehring, B.: Lessons learned from shallow subglacial bedrock drilling campaigns in Antarctica. Annals of Glaciology, https://doi:10.1017/aog.2024.12, 2024.

Bradley, S. L., Hindmarsh, R. C. A., Whitehouse, P. L., Bentley, M. J., and King, M. A.: Low post-glacial rebound rates in the Weddell Sea due to Late Holocene ice-sheet readvance, Earth Planet. Sc. Lett., 413, 79–89, https://doi.org/10.1016/j.epsl.2014.12.039, 2015.

Briner, J. P., Walcott, C., Schaefer, J. M., Young, N. E., MacGregor, J. A., Poinar, K., Keisling, B. A., Anandakrishnan, S., Albert, M. R., Kuhl, T., and Boeckmann, G.: Drill-site selection for cosmogenic-nuclide exposure dating of the bed of the Greenland Ice Sheet, The Cryosphere, 16, 3933–3948, https://doi.org/10.5194/tc-16-3933-2022, 2022.

Daniels, D. J.: Ground Penetrating Radar, 2nd edition. The Institution of Engineering and Technology, London, UK, 752 pp., ISBN 9780863413605, 2004.

Howat, I., Porter, C., Noh, M. -J., Husby, E., Khuvis, S., Danish, E., Tomko, K., Gardiner, J., Negrete, A., Yadav, B., Klassen, J., Kelleher, C., Cloutier, M., Bakker, J., Enos, J., Arnold, G., Bauer, G., and Morin, P.: The Reference Elevation Model of Antarctica – Mosaics, Version 2, Harvard Dataverse, v1, 2022. doi: https://doi.org/10.7910/DVN/EBW8UC. [Accessed 15 May 2024]

Jeong, S., Howat, I. M., and Bassis, J. N.: Accelerated ice shelf rifting and retreat at Pine Island Glacier, West Antarctica, Geophys. Res. Lett., 43 (22), 11720–11725, https://doi.org/10.1002/2016GL071360, 2016.

Johnson, J. S., Bentley, M. J., and Gohl, K.: First exposure ages from the Amundsen Sea Embayment, West Antarctica: The Late Quaternary context for recent thinning of Pine Island, Smith, and Pope Glaciers, Geology, 36(3), 223–226, 2008.

Johnson, J. S., Bentley, M. J., Smith, J. A., Finkel, R. C., Rood, D. H., Gohl, K., Balco, G., Larter, R. D., and Schaefer, J. M.: Rapid thinning of Pine Island Glacier in the early Holocene. Science, 343, 999–1001, 2014.

Johnson, J. S., Nichols, K. A., Goehring, B. M., Balco, G., and Schaefer, J. M.: Abrupt mid-Holocene ice loss in the western Weddell Sea Embayment of Antarctica, Earth Planet. Sc. Lett., 518, 127–135, https://doi.org/10.1016/j.epsl.2019.05.002, 2019.

Johnson, J. S., Pollard, D., Whitehouse, P. L., Roberts, S. J., Rood, D. H., and Schaefer, J. M.: Comparing glacial-geological evidence and model simulations of ice sheet change since the Last Glacial Period in the Amundsen Sea sector of Antarctica, J. Geophys. Res.-Earth., 126, e2020JF005827, https://doi.org/10.1029/2020JF005827, 2021.

Johnson, J. S., Roberts, S. J., Rood, D. H., Pollard, D., Schaefer, J. M., Whitehouse, P. L., Ireland, L. C., Lamp, J. L., Goehring, B. M., Rand, C., and Smith, J. A.: Deglaciation of Pope Glacier implies widespread early Holocene ice sheet thinning in the Amundsen Sea sector of Antarctica, Earth Planet. Sc. Lett., 548, 116501, https://doi.org/10.1016/j.epsl.2020.116501, 2020.

Johnson, J. S. and Smellie, J. L.: Zeolites compositions as proxies for eruptive palaeoenvironment, Geochem. Geophy. Geosy., 8, Q03009, 10.1029/2006GC001450, 2007.

Johnson, J. S., Venturelli, R. A., Balco, G., Allen, C. S., Braddock, S. C., Campbell, S., Goehring, B. M., Hall, B. L., Neff, P. D., Nichols, K. A., Rood, D. H., Thomas, E.R., and Woodward, J.: Existing and potential evidence for Holocene grounding-line retreat and readvance in Antarctica, The Cryosphere, https://doi.org/10.5194/tc-16-1543-2022, 2022.

Jones, R. S., Johnson, J. S., Lin, Y., Mackintosh, A. N., Sefton, J. P., Smith, J. A., Thomas, E. R., and Whitehouse, P. L.: Stability of the Antarctic Ice Sheet during the pre-industrial Holocene, Nat. Rev. Earth Environ., https://doi.org/10.1038/s43017-022-00309-5, 2022.

Joughin, I., Smith, B. E., and Medley, B.: Marine ice sheet collapse potentially under way for the Thwaites Glacier Basin, West Antarctica, Science, 344, 735–738, https://doi.org/10.1126/science.1249055, 2014.

Joughin, I., Shapero, D., Smith, B., Dutrieux, P., and Barham, M.: Ice-shelf retreat drives recent Pine Island Glacier speedup, Science Advances, 7, eabg3080, https://www.science.org/doi/10.1126/sciadv.abg3080, 2021.

https://doi.org/10.5194/egusphere-2024-1452
Preprint. Discussion started: 12 June 2024

King, M. A., Watson, C. S., and White, D.: GPS rates of vertical bedrock motion suggest late Holocene ice-sheet readvance in a critical sector of East Antarctica. Geophys. Res. Lett., 49, e2021GL097232, https://doi.org/10.1029/2021GL097232, 2022.

Kingslake, J., Scherer, R., Albrecht, T., Coenen, J., Powell, R.D., Reese, R., Stansell, N.D., Tulaczyk, S., Wearing, M.G., and Whitehouse, P.L.: Extensive retreat and re-advance of the West Antarctic Ice Sheet during the Holocene, Nature, 558, 430–434, 2018.

Koester, A. J. and Lifton, N. A.: Technical note: A software framework for calculating compositionally dependent in situ ^{14}C production rates, Geochronology, 5, 21–33, https://doi.org/10.5194/gchron-5-21-2023, 2023.

Kuhl, T., Gibson, C., Johnson, J., Boeckmann, G., Moravec, E., and Slawny, K.: Agile Sub-Ice Geological (ASIG) Drill development and Pirrit Hills field project, Annals of Glaciology, 1–14, https://doi.org/10.1017/aog.2020.59, 2020.

Lamp, J. L., Young, N. E., Koffman, T., Schimmelpfennig, I., Tuna, T., Bard, E., and Schaefer, J. M.: Update on the cosmogenic in situ ^{14}C laboratory at the Lamont-Doherty Earth Observatory, Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, 456, 157–162, https://doi.org/10.1016/j.nimb.2019.05.064, 2019.

Larour., E., Seroussi, H., Morlighem, M., and Rignot, E.: Continental scale,high order, high spatial resolution, ice sheet modeling using the Ice Sheet System Model (ISSM), J. Geophys. Res., 117, F01022, 2012.

Larour, E., Seroussi, H., Adhikari, S., Ivins, E., Caron, L., Morlighem, M., and Schlegel, N.: Slowdown in Antarctic mass loss from solid Earth and sea-level feedbacks, Science, 364, eaav7908, 2019.

Lifton, N., Jull, A., and Quade, J.: A new extraction technique and production rate estimate for in situ cosmogenic ^{14}C in quartz, Geochimica et Cosmochimica Acta, 65(12), 1953–1969, 2001.

Lopatin, B. G. and Polyakov, M. M.: Geology of the volcanic Hudson Mountains (Walgreen Coast, West Antarctica) (in Russian), Antarkt. Dokl. Komissii, 13, 36-51, 1974.

Mackintosh, A. White, D., Fink, D., Gore, D. B., Pickard, J., and Fanning, P. C.: Exposure ages from mountain dipsticks in Mac. Robertson Land, East Antarctica, indicate little change in ice-sheet thickness since the Last Glacial Maximum. Geology, 35 (6), 551–554. https://doi.org/10.1130/G23503A.1, 2007.

https://doi.org/10.5194/egusphere-2024-1452
Preprint. Discussion started: 12 June 2024

Mas e Braga, M., Jones, R. S., Newall, J. C. H., Rogozhina, I., Andersen, J. L., Lifton, N. A., and Stroeven, A. P.: Nunataks as barriers to ice flow: implications for palaeo ice sheet reconstructions, Cryosphere, 15, 4929–4947, https://doi.org/10.5194/tc-15-4929-2021, 2021.

Meredith, M., Sommerkorn, M., Cassotta, S., Derksen, C., Ekaykin, A., Hollowed, A., Kofinas, G., Mackintosh, A., Melbourne-Thomas, J., Muelbert, M. M. C., Ottersen, G., Pritchard, H., and Schuur, E. A. G.: Chapter 3: Polar Regions. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [Pörtner, H. -O., Roberts, D. C., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E., Mintenbeck, K., Alegría, A., Nicolai, M., Okem, A., Petzold, J., Rama, B., Weyer, N. M. (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 203–320, https://doi.org/10.1017/9781009157964.005, 2019.

Morlighem, M., Rignot, E., Binder, T., Blankenship, D., Drews, R., Eagles, G., Eisen, O., Ferraccioli, F., Forsberg, R., Fretwell, P., Goel, V., Greenbaum, J. S., Gudmundsson, H., Guo, J., Helm, V., Hofstede, C., Howat, I., Humbert, A., Jokat, W., Karlsson, N. B., Lee, W. S., Matsuoka, K., Millan, R., Mouginot, J., Paden, J., Pattyn, F., Roberts, J., Rosier, S., Ruppel, A., Seroussi, H., Smith, E. C., Steinhage, D., Sun, B., van den Broeke, M. R., van Ommen, T. D., van Wessem, M., and Young, D. A.: Deep glacial troughs and stabilizing ridges unveiled beneath the margins of the Antarctic ice sheet, Nat. Geosci. 13, 132–137, https://doi.org/10.1038/s41561-019-0510-8, 2020.

Mukhopadhyay, S.: "Ohio Range Subglacial rock core cosmogenic nuclide data" U.S. Antarctic Program (USAP) Data Center, doi: https://doi.org/10.15784/601351, 2020.

Neuhaus, S. U., Tulaczyk, S. M., Stansell, N. D., Coenen, J. J., Scherer, R. P., Mikucki, J. A., and Powell, R. D.: Did Holocene climate changes drive West Antarctic grounding line retreat and readvance?, The Cryosphere, 15, 4655–4673, https://doi.org/10.5194/tc-15-4655-2021, 2021.

Nias, I. J., Cornford, S. L., Edwards, T. L., Gourmelen, N., and Payne, A. J.: Assessing uncertainty in the dynamical ice response to ocean warming in the Amundsen Sea Embayment, West Antarctica, Geophys. Res. Lett., 46, https://doi.org/10.1029/2019GL084941, 2019.

Nichols, K. A.: A decade of in situ cosmogenic ^{14}C in Antarctica, Annals of Glaciology, 63 (87–89), 67–72, https://doi.org/10.1017/aog.2023.13, 2023.

https://doi.org/10.5194/egusphere-2024-1452
Preprint. Discussion started: 12 June 2024

Nichols, K. A., Rood, D. H., Venturelli, R. A., Balco, G., Adams, J., Guillaume, L., Campbell, S., Goehring, B. M., Hall, B. M., Wilcken, K., Woodward, J. W., and Johnson, J. S.: Offshore-onshore record of Last Glacial Maximum-to-present grounding line retreat at Pine Island Glacier, Geology 51(11), 1033–1037, https://doi.org/10.1130/G51326.1, 2023.

Pigati, J. S., Lifton, N. A., Jull, A. J. T., and Quade, J.: Extraction of In Situ Cosmogenic ^{14}C from olivine, Radiocarbon, 52, 1244–1260, https://doi.org/10.1017/S0033822200046336, 2010.

Rignot, E., Mouginot, J., and Scheuchl, B.: MEaSUREs Antarctic Grounding Line from Differential Satellite Radar Interferometry, Version 2. Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center, 2016. doi: https://doi.org/10.5067/IKBWW4RYHF1Q [16 May 2024]

Rignot, E., Mouginot, J., and Scheuchl, B.: MEaSUREs InSAR-Based Antarctica Ice Velocity Map, Version 2. Boulder, Colorado USA, NASA National Snow and Ice Data Center Distributed Active Archive Center, 2017. doi: https://doi.org/10.5067/D7GK8F5J8M8R [16 May 2024]

Rowley, P. D., Laudon, T. S., LaPrade, K. E., and LeMasurier, W. E.: Hudson Mountains, In: Volcanoes of the Antarctic Plate & Southern Oceans, LeMasurier, W. E. & Thomson, J. W. (eds.). Antarctic Research Series 48, 289–293, 1990.

Schaefer, J. M., Finkel, R. C., Balco, G., Alley, R. B., Caffee, M. W., Briner, J. P., Young, N. E., Gow, A. J., and Schwartz, R.: Greenland was nearly ice-free for extended periods during the Pleistocene, Nature 540, 252–255, 2016.

Small, D., Smedley, R., Dunai, T., Lees, T., Trabucatti, S., and Boeckmann, G.: New geological constraints on Holocene retreat-readvance of the West Antarctic Ice Sheet in the Weddell Sea Embayment, EGU General Assembly 2024, Vienna, Austria, 14–19 Apr 2024, EGU24-12136, https://doi.org/10.5194/egusphere-egu24-12136, 2024.

Smith, B., Fricker, H. A., Gardner, A. S., Medley, B., Nilsson, J., Paolo, F. S., Holschuh, N., Adusumilli, S., Brunt, K., Csatho, B., Harbeck, K., Markus, T., Neumann, T., Siegfried, M. R., and Zwally, H. J.: Pervasive ice sheet mass loss reflects competing ocean and atmosphere processes, Science, 368(6496), 1239–1242, https://doi.org/10.1126/science.aaz5845, 2020.

Spector, P., Stone, J., Pollard, D., Hillebrand, T., Lewis, C., and Gombiner, J.: West Antarctic sites for subglacial drilling to test for past ice-sheet collapse, The Cryosphere, 12, 2741–2757, https://doi.org/10.5194/tc-12-2741-2018, 2018.

Spector, P., Stone, J., and Goehring, B.: Thickness of the divide and flank of the West Antarctic Ice Sheet through the last deglaciation, The Cryosphere, 13, 3061–3075, https://doi.org/10.5194/tc-13-3061-2019, 2019.

https://doi.org/10.5194/egusphere-2024-1452
Preprint. Discussion started: 12 June 2024

Stone, J. O., Balco, G. A., Sugden, D. E., Caffee, M. W., Sass, L. C., Cowdery, S. G., and Siddoway, C.: Holocene deglaciation of Marie Byrd Land, West Antarctica, Science, 299, 99–102, 2003.

Stroncik, N. A. and Schmincke, H. U.: Palagonite – a review, Int. J. Earth Sci., 91, 680–697, https://doi.org/10.1007/s00531-001-0238-7, 2002.

Venturelli, R. A., Siegfried, M. R., Roush, K. A., Li, W., Burnett, J., Zook, R., Fricker, H. A., Priscu, J. C., Leventer, A., and Rosenheim, B. E.: Mid-Holocene Grounding Line Retreat and Readvance at Whillans Ice Stream, West Antarctica, Geophys. Res. Lett., 47 (15), https://doi.org/10.1029/2020GL088476, 2020.

Venturelli R. A., Boehman, B., Davis, C., Hawkings, J. R., Johnston, S. E., Gustafson, C. D., Michaud, A. B., Mosbeux, C., Siegfried, M. R., Vick-Majors, T. J., Galy, V., Spencer, R. G. M., Warny, S., Christner, B. C., Fricker, H. A., Harwood, D. M., Leventer, A., Priscu, J. C., Rosenheim, B. E., and SALSA Science Team: Constraints on the timing and extent of deglacial grounding line retreat in West Antarctica, AGU Advances 4, e2022AV000846, https://doi.org/10.1029/2022AV000846, 2023.

White, J. D. L. and Houghton, B. F.: Primary volcaniclastic rocks. Geology, 34, 677–680, 2006.

Woodward, J. W., Hein, A. S., Winter, K., Westoby, M. J., Marrero, S. M., Dunning, S. A., Lim, M., Rivera, A., and Sugden, D. E.: Blue-ice moraines formation in the Heritage Range, West Antarctica: Implications for ice sheet history and climate reconstruction, Quaternary Sci. Adv., 6, 100051, https://doi.org/10.1016/j.qsa.2022.100051, 2022.

Woodward, J. and Johnson J. S.: Ground-penetrating radar surveys at three nunataks in the Hudson Mountains in the Amundsen Sea sector of West Antarctica, NERC EDS UK Polar Data Centre [data set], https://doi.xxxxxxxxx, 2024.