# Subglacial Access Working Group (SAWG):
# Access Drilling Priorities in Greenland

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## Summary


The Greenland Ice Sheet (GIS) contains ~7 meters of sea-level equivalent, suggesting a potentially profound effect on near-future human civilization and infrastructure in the currently warming climate. New evidence suggests nearly complete deglaciation of Greenland within the past ~1 Myr (Schaefer et al., 2016), but the pattern of deglaciation in space and time, as well as how common near-complete deglaciation has been over the Pleistocene, remain underconstrained. Modern ice-sheet models, which are used to forecast the sea-level contribution from Greenland, are rapidly improving; the extent to which they converge on projections of ice-sheet evolution across common forcings and boundary conditions is being tested by the ISMIP6 effort (Nowicki et al., 2016). The geothermal flux boundary conditions and the presence and character of subglacial tills (sediments), in particular, are datasets where improvements would improve the accuracy of ice-sheet model projections (Brinkerhoff et al., 2011; Pollard et al., 2012; Rogozhina et al., 2012). A new wealth of geophysical measurements have informed new, Greenland-wide maps of geothermal flux, yet such maps are tied to direct, in situ geothermal flux measurements rather sparsely and without complete consistency (Greve et al., 2017). The recent emergence of a subglacial till - hydrology model alongside indirect measurements of seasonal evolution of tills have pointed to an important role of subglacial tills in Greenland hydrology and ice flow. Presence or absence, as well as mechanical character, of these tills are not presently well constrained at the regional or ice-sheet scale, limiting future inclusion in ice-sheet models.

It should be possible to both collect cosmogenic isotope samples from subglacial bedrock cores (to inform patterns of past deglaciation) and to make direct measurements of the geothermal flux at the same subglacial access points. Promising sites for this work lie in northern Greenland, where (i) paleo-ice-sheet models suggest that past deglaciations initiated, (ii) Cenozoic passage of the Iceland Hot Spot implies elevated geothermal fluxes, and (iii) the basal ice is likely currently frozen.

Observations of subglacial tills will require separate boreholes, as locations with tills are poor targets for cosmogenic exposure dating, and thawed locations (which we expect to correlate with the presence of sediments) are not suitable for inferring geothermal flux.

# Compelling Research Questions

## Overarching Question:

*How stable is the Greenland Ice Sheet under forcings similar to today's climate, and what is its likely near-future contribution to sea level rise?*

## Question Group 1: Ice-sheet extent during Pleistocene interglacials

**Motivation**: Under future climate forcing, the evolution of the ice sheet may mirror previous deglaciation patterns under similar forcings, e.g. Pleistocene interglacials.

A. How did the Greenland Ice Sheet respond to warming during past interglacial periods?
B. How did the response to warming differ across sectors of the Greenland Ice Sheet? Where did retreat occur first or fastest?
C. What was the magnitude of Pleistocene retreat and thinning of the Greenland Ice Sheet?

## Question Group 2: Boundary conditions and process controls on flow of the modern ice sheet

**Motivation**: Basal conditions are a primary influence on the dynamics of outlet glaciers and ice sheets.

A. Does the track of the Iceland Hot Spot across Northern Greenland coincide with higher geothermal fluxes compared to the rest of Greenland?
    a. New point observations of the geothermal flux are needed to further constrain basal thermal boundary condition datasets used for paleo- and modern ice sheet models.
    b. How sensitive is the rate and pattern of deglaciation to different spatial configurations of geothermal flux?
B. Does Northern Greenland host subglacial sediments that may facilitate seasonal evolution of subglacial hydrology, and thus overall ice flow, during deglaciation events?

The two question groups are united by the effect of the presence, absence, or development of subglacial tills, and the geothermal flux distribution, on historical deglaciation patterns.

# Scientific Rationale

Recent evidence shows that Greenland has been significantly deglaciated in the recent geologic past under climate conditions similar or only slightly warmer than today, meaning that the

Greenland Ice Sheet is a potentially large contributor to near-future sea-level rise (Bierman et al., 2016; Schaefer et al., 2016). Paleo ice sheet models underestimate ice retreat in the past, limiting confidence in our understanding of ice-sheet mechanics and in forecasts of modern ice-sheet evolution.

Access to the bed of the Greenland Ice Sheet provides samples of bedrock and basal sediments and direct geothermal flux measurements. Respectively, cosmogenic analysis of bedrock samples can constrain the ice-sheet response to past warming; samples of basal sediments can inform basal properties (drag coefficient, till depth and viscosity, hydrological processes, etc.) required by ice-sheet models; and geothermal flux measurements can supply basal thermal boundary conditions to ice-sheet models. These ultimately improve ice-sheet models used to evaluate past and future Greenland ice loss.

Subglacial access in locations targeted to the motivated science themes above are our priorities, but access there may also provide opportunities for additional science:

- Constraints on the timing of Greenland Ice Sheet inception
- Potential for life in atmospherically isolated subglacial sediments

## Sampling Requirements and Drilling Parameters

The scientific goals outlined in this document require samples of bedrock, access to and/or samples of basal sediments, and thermal profiles within basal ice or bedrock. The existing drilling technology and support infrastructure provided by the US Ice Drilling Program is sufficient for this work.

**Bedrock cores:** Cores ~5 m in length will be required to study cosmogenic nuclide profiles in subglacial and proglacial bedrock. Laboratory thermal conductivity/diffusivity measurements can be made on small portions of these bedrock core for use in geothermal studies.

A combination of the Winkie and ASIG drills can retrieve the desired ~5 m bedrock cores under GIS margins (ice thickness up to ~700 m), and thermistors for geothermal flux measurements can be placed into these holes and allowed to approach thermal equilibrium.

Retrieval of bedrock cores underneath the GIS interior (>2000 m of ice) will require a larger drilling system. However, retrieval of marginal bedrock cores (< 700 m ice thickness) should proceed first.

**Wet sediment samples:** Subglacial sediment samples (~1 m cores) could be used for mechanical testing to better understand the role of subglacial tills in modulating local ice flow. Requirements for retrieval of nontrivial volumes of subglacial sediment would likely require the ASIG or similar-scale drill with a core catcher. There could be substantial challenges, however, associated with accessing wet beds with such a drill and the associated drilling fluid. Locations where sediments underlie wet-based ice are expected to have the greatest influence on ice flow, yet retrieving sediments at such locations poses a significantly higher logistical challenge than coring frozen sediments.

**Geothermal flux:** To constrain geothermal flux at the Greenland Ice Sheet bed, thermistor strings (or other technology) can be placed in the subglacial bedrock boreholes left by cosmogenic-isotope sampling campaigns. NSF-supported development to emplace vertical Raman Distributed Sensing (DTS) cables has now progressing through testing and deployment on 10-100 m depth-scales. This technology can be ready for proposals to acquire profiles of basal ice temperature, eventually under ice >3000 m thick, to determine where beds are wet or frozen and to measure geothermal flux through frozen beds.

Local variations in geothermal flux, e.g., within ~5 km of the main hole, could be measured using non-retrieving melt-probe technology such as the Ice Diver. The relatively low cost and minimal logistical burden of melt-probe emplacement may enable deployment at multiple sites, yielding finer spatial resolution of geothermal flux.

# Target Locations

- Northern GIS margins will be the first target for bedrock cores for cosmogenic-isotope profiles, as some evidence suggests that this sector reacts first to climate warming (Bierman et al., 2016; Schaefer et al., 2016), and is likely cold-based (MacGregor et al., 2016). Pilot studies will inform future drilling plans in the GIS interior. Geothermal flux measurements could be made in the open bedrock holes at the northern pilot sites.
- The western Greenland margin likely hosts subglacial sediments locally, based on ongoing hydrological studies (Ryser et al., 2014; Walter et al., 2014) and new geophysics and modeling results (Bougamont, et al., 2014; Christoffersen et al., 2018; Kulessa et al., 2017). Previous drilling results suggest that the spatial extent of sediments is regionally, if not locally, variable (Harper et al., 2017). Careful site selection would be necessary, with bedrock topography (troughs) as a first-order constraint.
- The Iceland Hot Spot track is an area of interest for additional geothermal flux measurements. Any improvement in spatial coverage of direct geothermal flux measurements will be useful, but will be constrained severely by logistical costs. Thus, reducing costs is a priority, e.g., by emplacement of optical fiber temperature measurement infrastructure using melt probes.

# Target Timeline

**Short-term (<5 years):** Initial reconnaissance of sites for subglacial bedrock coring for cosmogenic nuclide profiles (~2020-2021, proposal in development). Retrieval of bedrock cores and from GIS margins and geochemical analyses, in addition to the deployment of sensors for geothermal flux measurements (~2021-2023). Reconnaissance for other locations of interest for the deployment of heat flux sensors that may diverge from the immediate interests of the cosmogenic community. Initial planning for subglacial sediment study sites.

**Long-term (>5 years):** Use results from the short-term studies to inform future sampling locations. For example, the resulting cosmogenic nuclide profiles and geothermal flux measurements from different sectors of the GIS margin may hint at locations of interest in the GIS interior that will be more logistically difficult to access and require larger drilling systems (e.g., RAID for cosmogenic bedrock profiles, or the Ice Diver for making holes for geothermal flux measurements). Complete subglacial sediment retrieval work, in addition to mechanical analyses. Collaborate with ice sheet and climate modelers.

## Support Requirements

The current IDP inventory can accomplish collection of the required bedrock and sediment cores. Support for the development of the Ice Diver (and/or similar melt probes) would enable efficient sparse measurements of geothermal flux at denser spatial scales than has been previously possible, especially at locations with thick (>1000 m) ice.

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