Workshop Report

U.S. Scientific Traverses on the Greenland Ice Sheet:

Community Planning Workshop

held via Zoom June 10-11, 2021

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September 28, 2021

Summary

The Greenland Ice Sheet (GrIS) melt rate, and hence its contribution to sea level rise, are accelerating under ongoing climate change, and the ice sheet and its geologic record hold the clues to modern and future climate and to the evolution of GrIS. Understanding this nexus is an urgent challenge for geoscience and society. However, access to the ice sheet for a broad range of scientific investigations by aircraft has become severely limited, and establishing ground-based access requires significant advance planning. On June 10 and 11, 2021, we led a U.S. science community planning workshop that was co-sponsored by the US Ice Drilling Program and the Summit Science Coordination Office. The goal was to identify and articulate compelling scientific priorities of the U.S. scientific community that would drive long-term planning of potential future scientific traverses on the Greenland Ice Sheet.

In total, 49 scientists registered for the Workshop, 42 from a wide spectrum of US Geoscience institutions, the NSF, the USGS and Polar Field Services, and 7 international colleagues from Australia, China, Denmark, Japan and Norway. The meeting agenda and presentations made by the participants are available on https://icedrill.org/meetings/us-scientific-traverses-gris-planning-workshop . The invited opening remarks by Jen Mercer (NSF) set the tone for a workshop full of excitement, outside-the-box thinking and visionary discussion about future research programs to address Arctic change in a timely way. With the upcoming limited traverses operating in North Greenland related to the NSF-funded 'GreenDrill' project in 2023 and 2024 as motivation, the participants engaged in discussions to identify important regions of the ice sheet where a ground-based mobile research traverse platform could enable future national and international science and education projects. After presentations by meeting participants, discussion converged on two regions, the Northwest and the Northeast areas of the Greenland Ice Sheet. The participants were then charged to synthesize the workshop discussions and emerging visions for White Papers on two future Greenland Ice Sheet Scientific Traverse programs, one for the Northwest and one for the Northeast. The two community White Papers that follow articulate community consensus on the most burning questions, forming the core of this report.

Background

Melting ice sheets dominate sea level rise, with the Greenland Ice Sheet (GrIS) accounting for the highest contribution to sea level rise at present (IPCC, 2018; SROC, 2019). Unprecedented and elevated rates of surface melt (Sasgen et al., 2020; Tedesco and Fettweis, 2020), new estimates that the GrIS ice-loss rate this century will exceed any ice-loss rate over the last 10,000 (Briner et al., 2020), together with direct paleo-observations showing that the GrIS melted away several times during the recent geological past (Christ et al., 2020; Schaefer et al., 2016), send a dramatic warning: the GrIS and thus the complex Arctic System are inherently unstable and currently exposed to unprecedented heat stress that is now rapidly transforming the Arctic.

Time is running short as impacts of sea level rise become dramatically visible along our coastlines. There is an urgent need for science to provide new knowledge and understanding of the GrIS melt during warm periods. Just as the remarkable scientific collaborations recently developed a COVID-19 vaccine in unprecedented speed, there is an urgent need for cutting-edge science to now rise to the challenge of improved understanding and predicting ice sheet instability and sea level rise.

Fueled by recent methodological break-throughs, the US science community is well equipped to lead and tackle the GrIS challenge together with our colleagues abroad and in coordination with local communities in Greenland and the Arctic. The cross-cutting and comprehensive expertise necessary to address the big GrIS-science and society questions has been developed mainly by NSF- and NASA-funded research over recent years. In particular, the NSF-funded 'GreenDrill' project is the catalyst for envisioning GrIS traverses that will establish logistical stepping-stones for a unique opportunity for U.S. scientific leadership with international partners: A '**Greenland Traverse (GreenT) – a mobile ground-based scientific research platform on the GrIS**'. A safe, reliable mobile traverse platform created to support multi-year science along a variety of traverse routes will provide US and international scientists with a science, education and outreach capability on the ice for the multi-disciplinary programs needed to most efficiently tackle the GrIS challenge.

The vision for the scientific traverse platform builds on the success of the ITASE and Norwegian-U.S. Antarctic scientific traverses of the past. For the longer term, new state-of-the-art scientific traverse infrastructure is needed for the Greenland Ice Sheet. In the near term, this could be initiated with an upgrade to the existing fleet of traverse infrastructure with an investment in modules for living and working, leading to a future scientific platform that lives on the Greenland Ice Sheet over the next decade. The versatile set of vehicles to power the traverse (snowcats, in addition to the Arctic Trucks recently purchased by NSF), could be flown on and off the ice sheet via C-130, would thus avoid use of aging Thule-based tractors, the high maintenance road/route onto and off the ice near Thule, and its associate safety and time constraints.

GreenT would usher in a novel, more diverse (and safer) era of GrIS research support, one that would have parallel advances in education, outreach and community inclusion. Research programs enabled by GreenT could include: (i) Strategic drilling and sampling of the sub-GrIS bedrock for ice sheet history and sensitivity to warming; (ii) Geothermal heat-flux measurements, and mapping the bedrock geology, critical for ice-sheet modeling; (iii) Ice cores that provide high-resolution climate records and shallow snow/firn/ice-core traverses providing surface mass balance measurements, snow and firn studies, and snow chemistry and pollution surveys; (iv) Ice-penetrating radar (now with notable absence of NASA ice bridge) and studies of glacier hydrology, firn aquifers; (v) various ground-truth observations in support of satellite data; (vi) biological and limno-ecological reconstructions of paleo flora and fauna of past warm periods of deglaciated Greenland from sub-ice sheet sediment archives (Paxman et al., 2021).

This report aims to articulate the excitement of the US community about the idea of at least a decade of scientific discoveries enabled by a Greenland Scientific Traverse, and in turn, to intensify the conversation with the NSF Arctic and Polar Science leadership about this exciting and urgent endeavor. The multi-disciplinary and diverse alliance formed at the virtual workshop provides new perspectives for both Northwest and Northeast Greenland Traverses, representing the first steps toward the design of a research, education and diversity program for the GreenT vision.

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White Paper 1: Science Priorities for a Northeast Greenland Traverse

IDP / Summit-SCO Greenland Scientific Traverse Planning Workshop

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1. Background

Northeast Greenland is glaciologically, climatologically, and geologically notable. It hosts the sole interior ice stream on the Greenland Ice Sheet. This region has a relatively low snow accumulation rate, but is known for its high susceptibility to ocean-driven dynamic retreat and thinning due to a marine over-deepening near the coast (An et al., 2021) and the presence of an ice stream that may facilitate transmission of coastal forcing to the interior. The deep interior of northeast Greenland is also impacted by the passage of the Icelandic hotspot (Rogozhina et al., 2016), and thus is suspected to have high and spatially variable basal heat fluxes. The interaction of the hotspot path with glacial cycling of the crust may have resulted in an elevated geothermal heat flux at the onset region of the Northeast Greenland Ice Stream (NEGIS) (e.g., Fahnestock et al., 2001; Martos et al., 2018; Smith-Johnsen et al., 2020; Alley et al., 2019). Although these processes are related via interactions between glacier dynamics, surface mass balance, tectonics, ocean dynamics, and paleoclimate, many sites of interest are geographically separated, complicating efforts to collect data using conventional targeted fieldwork, which is often supported by aircraft visiting specific sites.

The NSF-funded GreenDrill project is likely to be supported by ground-based traverses to multiple widely separated sites in spring and early summer of 2023 and 2024. The traverse provides a mobile hub for local ground-based and airborne investigations, including support for helicopters and smaller vehicles (snowmobiles or Arctic Trucks) that accompany the larger traverse vehicles, which enables access to remote and logistically challenging areas. The traverse route (likely originating from Summit or EastGRIP, see Figure 1) could be tailored to achieve science objectives on the way to sites near the ice margin. This white paper summarizes critical research questions proposed at the IDP/Summit-SCO Greenland Scientific Traverse Planning Workshop in order to identify the range of opportunities for transformative research directions that a traverse in Northeast Greenland would facilitate.

2. Scientific Rationale

Numerous outstanding questions about ice dynamics, climate, subglacial geology, glacial ecology, and biogeochemistry, can be targeted via a traverse in Northeast Greenland. This region is remarkable due to the presence of **Northeast Greenland Ice Stream (NEGIS)**, the most extensive, farthest inland ice stream that spans ~800 km from the coast to near the Greenland Ice Sheet's summit. About 12% of Greenland ice discharge occurs from this sector through three marine outlets of NEGIS: 79° North Glacier, Zachariæ Isstrøm, and Storstrømmen Glacier. Since the disintegration of the ice shelf of Zachariæ Isstrøm, the downstream sector of NEGIS has been out of balance (Mouginot et al., 2015;

Mayer et al., 2018). It is therefore critical to understand the role of NEGIS and its marine outlets in order to understand the overall response of the Greenland Ice Sheet to climate forcing. Moreover, the upstream sector of NEGIS hosts numerous **englacial features** that have been identified extensively in airborne radar sounding surveys (Bell et al., 2014; Panton and Karlsson 2015; Riverman et al., 2019). The impact of these subsurface features on ice dynamics remains unclear. The formation mechanism of these features is also not well-established, but they may be related to changes in subglacial hydrology and the distribution of **frozen versus thawed basal thermal regimes** (Bell et al., 2014; Wolovick et al., 2014). The basal thermal state of northeast Greenland is of immense importance for understanding the complicated flow of NEGIS and neighboring regions of the ice sheet, yet direct data on this glaciologically and geomorphologically critical parameter are lacking (Macgregor et al., 2016). Significant basal ice deformation structures in Northeast Greenland may have a strong influence on ice flow behavior, yet they remain severely understudied (Bell et al., 2014). Detailed study of **meltwater drainage** from the surface and the bed of the ice sheet into the ocean is also important for understanding **ice-sheet mass balance** changes at the **ice-sheet/ocean interface**, which have the potential to intensify ice-shelf basal melting or ice-front melt (Mouginot et al., 2015) of some of the last remaining large ice shelves of the ice sheet.

From a climatological perspective, Northeast Greenland is also unique. It is the most arid sector of Greenland and receives only a fraction of the precipitation that falls in other regions; indeed, recent estimates of basal melting at EastGRIP are nearly equivalent to accumulation rates (Zeising et al., 2021; Kjær et al., 2021). Constraining the **climatic history** of northeast Greenland using ice-core records spanning the Holocene, the last 2000 years, and the last 200 years remain crucial for placing modern observations into context and benchmarking model predictions. A full understanding of these data is only possible when **local and regional topographic effects**, including the post-depositional changes that are caused by erosion (e.g., wind scour) and redeposition, can be accurately described. While these effects can be mitigated by drilling at higher-elevation ice-divide sites, lower-elevation flank sites can provide records that are relatively more sensitive to local or regional conditions.

Finally, the long-term history of Northeast Greenland remains mysterious. Better understanding of the **age of basal ice** and the periods when this sector of the ice sheet **was smaller than it is today** are important constraints for improving projections of Greenland Ice Sheet response to climate change in the coming decades and centuries. Such projections also rely on a robust understanding of the **solid-Earth properties** of the lithosphere and mantle below Northeast Greenland, which require more detailed mapping to understand the potential for flexural (Stevens et al., 2016; Alley et al., 2019) and geothermal (e.g., Rogozhina et al. 2016) impacts on ice-sheet dynamics. Finally, frozen-bedded regions, favored in Northeast Greenland outside of NEGIS, lead to the preservation of basal sediments and cosmogenic-nuclide inventories in the substrate, which contain valuable and direct evidence of past ice-sheet extent.

3. Driving Scientific Questions

- How did passage of the Icelandic hotspot influence crustal structure and ice/solid Earth interactions in Northeast Greenland?

- Does NEGIS facilitate inland transmission of coastal acceleration and thinning resulting from exposure of remaining ice tongues to warm ocean water?
- Does the absence of englacial structures in the NEGIS interior, but presence of englacial structures at the NEGIS margin hint at formation mechanisms and/or role in ice dynamics?
- Do low accumulations rates imply that Northeast Greenland reacts differently to climatic forcing than other areas of the ice sheet?
- Is the history of this portion of the ice sheet unique due to the presence of an inland ice stream?
- Do ice-marginal areas in northeast Greenland preserve longer records of ice-sheet change than in warmer, wetter, and more glaciologically and geomorphologically active areas of the ice sheet?

4. Technology and Measurements

Several types of technology and equipment would be beneficial for addressing the science questions listed above as part of a Northeast Greenland traverse, while also better ensuring the health and safety of traverse participants. Here we first focus on technologies that have operational and scientific applications, and then discuss measurements that are more specifically geared towards science objectives.

A primary safety concern of a traverse is crossing both visible and buried crevasses. Many other risks associated with fieldwork from fixed camps are also minimized by the presence of traverse vehicles, including hazards associated with polar bears, inclement weather, and exposure to cold and wind. The risks from small crevasses, which are harder to detect, are also minimized, as track vehicles distribute weight efficiently and may be less likely to collapse a snow bridge or may even span a small crevasse. Large crevasses, however, still present substantial risks. Early warning crevasse detection systems are thus an important component of a traverse. At present, this is generally done with human operators in the lead vehicle with a ground-penetrating radar (GPR) mounted on a boon that extends in front of the vehicle. This requires real time GPR interpretation to identify crevasse hazard, but continuous internal reflecting horizons (snow stratigraphy) imaged in the GPR data can also be interpreted to reveal recent (past few centuries to millennia) accumulation rate histories. Autonomous vehicles traveling farther ahead of the traverse (e.g., Lever et al., 2012) and autonomous crevasse detection technologies will further increase traverse safety (Williams et al., 2014; Walker and Ray, 2019) and could also increase scientific yield through collection of additional radar data.

Additional autonomous sensors can be used to collect data while traverses are under-way, such as snow-roughness along the traverse profile (e.g., Kukko et al., 2013; Lacroix et al., 2017). Autonomous vehicles can also be part of the traverse itself, either as the traverse vehicles (e.g., Cook, 2017) as traverse support vehicles (e.g., Lever et al., 2012), or as science vehicles that launch from and return to the traverse vehicles (e.g., Feng et al., 2018; Hoffman et al., 2019).

Autonomous observatories deployed along the traverse route offer the opportunity to collect in-situ high temporal resolution time series, which are rare in polar regions. GNSS receivers can collect data on ice motion, snow accumulation, and snow water content. Seismometers can be used to monitor iceberg calving, glacier sliding, and even sea-ice dynamics, and can be used to map crustal velocity and structure. Weather stations can collect meteorological measurements that are valuable constraints on climate and reanalysis products. Autonomous phase-sensitive radio echo sounders (ApRES) can be deployed at sites to collect long-term subsurface observations. Compared to commercial impulse radar systems, ApRES has the advantage of operating in an unattended mode on ice sheets up to a year due to it being a continuous wave system with relatively low power consumption (Nicholls et al., 2015). This makes ApRES an ideal instrument for annual to multiannual observations to examine long term changes of englacial and subglacial environments. Such sites could provide critical ground-truth for remote-sensing operations and enable investigation of critical processes and parameters including (but not limited to) firn densification rates (e.g., Case et al., 2019), englacial and subglacial water storage (e.g., Kendrick et al., 2018), formation of englacial refrozen ice, changes in englacial strain and deformation rates (e.g., Young et al., 2019), as well as ice-shelf basal melting (e.g., Vaňková et al., 2021). Traverses will provide crucial logistical and science support to set up and maintain the operations of long-term ApRES surveying of remote parts of the Greenland ice sheet.

Finally, conventional ice-penetrating radar and active-seismic profiling can operate along the traverse and from fixed camps on the traverse route established for other reasons (most often drilling of firn, ice, or rock cores). Other geophysical measurements (electromagnetic methods and gravity) and surface mass balance studies can also operate from traverse camps. These techniques are often used to best site the core locations, but also are intrinsically valuable; operation from a traverse platform offers the potential to greatly expand the spatial coverage of these data.

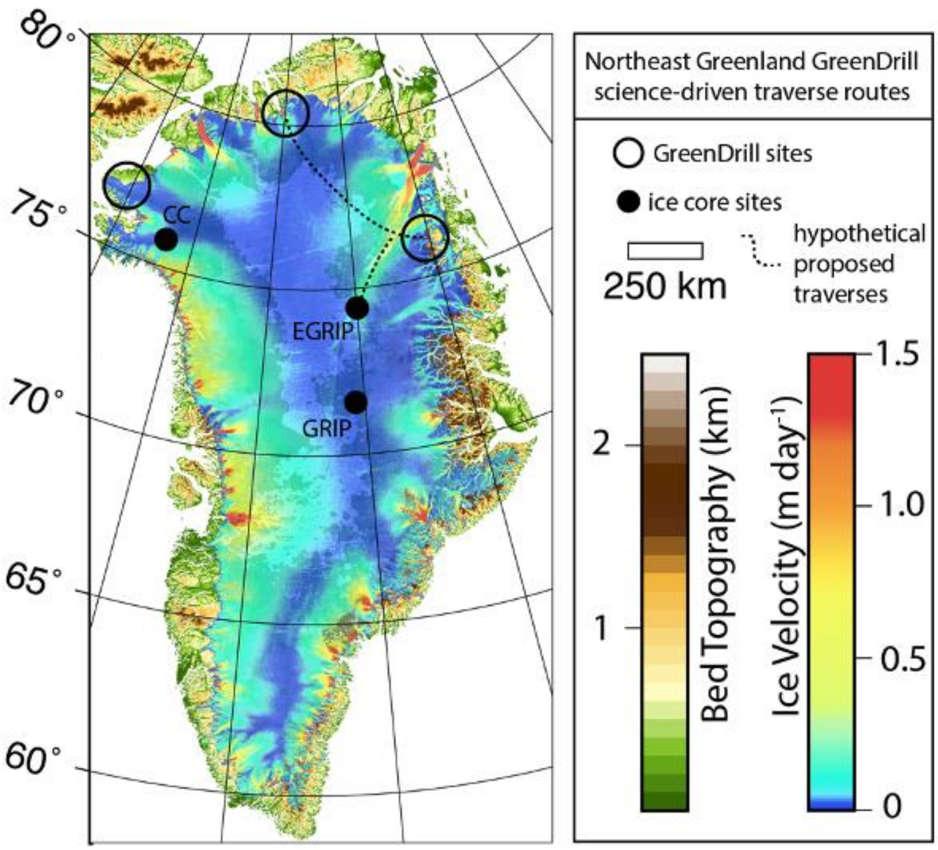

Figure 1. Map of Greenland with potential traverse routes associated with GreenDrill highlighted. CC: Camp Century, EGRIP: East Greenland Ice Core Project, GRIP: Greenland Ice Core Project.

5. **Possible Traverse Route & Key Sites**

Traverses provide a unique platform and environment for collecting data. Because traverses are generally slow but cover large areas, they support high-resolution and long-profile data collection. The NSF GreenDrill project will support use of ASIG and Winkie drills to obtain several-meter-long bedrock cores from the base of the ice sheet for cosmogenic nuclide studies. Basal ice will also be collected, which will be of interest for several scientific endeavors. We anticipate use of GreenDrill traverses and drilling sites as base camps for short traverse legs to support additional science goals (Figure 1). Each drilling base camp may serve as a logistical hub for surface-based science, including week- or weeks-long small traverses in the region. Traversing to the near-ice-margin drilling camps from EGRIP or Summit may provide additional opportunities for traverse-based science along those routes.

A traverse in Northeast Greenland offers many opportunities for advancing complementary science goals. A traverse perpendicular to ice flow, a traverse along a central NEGIS flowline, and a traverse that links GreenDrill sites to the ice-sheet margin all have the potential to be particularly impactful. In addition to all the measurements described below, a Northeast Greenland traverse would also provide opportunities to collect firn density and strain rate measurements, ground-penetrating radar profiles (repeat phase-sensitive measurements for ice deformation), seismic profiles, and more.

5.1 Across-flow traverse

Studies focused on investigating wind scour and flow related impacts on ice-core records could focus on lower-elevation (<2200 m), flank regions of northeast Greenland using shallow ice cores (30-40 m). These lower-elevation areas have greater surface topography than sites higher on the ice sheet, therefore providing ideal conditions to study the impacts of wind scouring on ice-core chemical, aerosol, and accumulation records. An upstream traverse would be required at each site to obtain a GPR profile to understand the flow history of the ice sampled by the core.

This traverse platform is ideally suited for ground-calibration of satellite remote-sensing products, when the traverse is near or under the satellite ground-track (e.g., Brunt et al., 2019a, b). Independent of satellites, non-science (e.g., transport or relocation) traverses have been used to collect science-of-opportunity data (Hawley, personal comm.), such as GPR profiles collected to detect and catalogue positions of crevasses.

Cross-profiles of NEGIS are of particular interest due to glaciological and geological changes that may occur across the shear margins of the ice stream (Christianson et al., 2014; Keisling et al., 2014; Holschuh et al., 2019). High-resolution depth-density measurements across the shear-margin of NEGIS would be informative to understanding shear-margin dynamics and providing constraints for the firn densification contribution to altimetry measurements of ice-surface height change in Northeast Greenland (Riverman et al., 2019). Such work would ideally include gridded surveys of ApRES, which would allow for long-term, unattended monitoring of densification, accompanied by conventional coring to provide additional validations for depth-density changes. ApRES measurements would also allow measurements of englacial deformation and velocity, which could be used to confirm hypotheses of substantial englacial velocity variability across shear margins (e.g., Holschuh et al., 2019).

5.2 Along-flow traverse

To expand on stand-alone shallow ice-coring at flank sites as described above, the collection of firn/ice cores in a coordinated approach **sequentially along a flowline** would allow for a more thorough and precise understanding of the impact of depositional processes. Of particular interest in Northeast Greenland would be the collection of cores along a flowline in NEGIS accompanied by continuous radar and seismic profiling along the traverse route. For ice cores recovered in a transect following a flowline, wind scour should leave a distinct imprint in the firn/ice-core records at different depths specific to the upstream topography for each site (Vallelonga et al., 2014). Such work would ideally involve collecting a transect of 4-5 ice cores and GPR data along an upstream 10-80 km long traverse. For studies on ice-core depositional processes, the IDP Prairie Dog or SideWinder drill could be used to recover shallow cores up to 40 m deep—which would extend back as long as ~200 years for some areas in Northeast Greenland—in 9-12 hours. Deeper cores (~100 m; 2-3 days), collected by a drill such as the lightweight IDP Stampfli drill, would provide much better datasets to evaluate such processes. Collection of such shallow cores would be coupled with traverse-based upstream GPR measurements to relate upstream surface and near-surface geometry, and bedrock topography to changes observed in the ice-core accumulation and chemical records.

5.3 Traverse to margin

The logistical infrastructure provided by a traverse would facilitate collecting large ice samples from areas around the margin where ice that is tens of thousands of years old outcrops at the surface (Macgregor et al., 2020). In particular, noble gases measured in these large ice samples can provide an independent age estimate, which can refine the age-depth models used to date ice cores and offer new insights into the long-term history of Northeast Greenland.

5.4 Continuous/frequent measurements along the traverse route

- Ice-penetrating radar
- Density (surface)
- Firn strain gauges
- ApRES
- GNSS
- Active-source seismic imaging

5.5 Measurements requiring 1-2 days

- Shallow firn/ice cores (20–30 meters)
- Large ice samples
- Grid of depth density measurements (ApRES and conventional coring)
- Ground-based gravity grids
- Passive seismometer deployments
- Electromagnetic measurements

5.6 Measurements requiring >1 week

- Deeper firn/ice cores (50–100 m)
- Dense, gridded geophysics surveys (active source seismic and ice-penetrating radar) for 3D topography and upper crustal structure

6. Target Timeline

The GreenDrill project will be drilling on the ice-sheet surface near Victoria Fjord and in Dronning Louise Land, currently planned for boreal summer 2024. Several weeks of drilling will take place at each site, from which Arctic Trucks and a helicopter will take team members to nearby sampling sites. Thus, it would be advantageous for the community to develop a targeted strategy for Northeast Greenland traverse(s) that can maximize science outcomes with ample time for preparation before a boreal summer 2024 field deployment.

7. Conclusion

The most obvious unique feature in the northeast sector of the ice sheet is the Northeast Greenland Ice Stream. Although clearly an ice-dynamic feature, its presence is linked to the subglacial geological features that allow its fast flow, including the influence of the Icelandic hotspot track and widespread shallow subglacial sediments that facilitate fast flow. Coastal over-deepenings expose this ice stream to possible marine instability, linking ice dynamics to oceanographic forcing. Due to low accumulation rates, mass balance on this portion of the ice sheet may be uniquely sensitive to ice-dynamic feedbacks. Thus, there are several questions linked to the Northeast Greenland Ice Stream that can be addressed through a traverse that can visit many sites across northeast Greenland. Beyond NEGIS, Northeast Greenland is geologically and climatologically unique as well as exceptionally remote. Thus, a traverse coordinated with GreenDrill will provide a robust, flexible platform for addressing a wide variety of science questions that would be otherwise logistically complicated and expensive to pursue.

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White Paper 2: Scientific Priorities for a Northwest Greenland Traverse

IDP / Summit-SCO Greenland Scientific Traverse Planning Workshop

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Background

The northwest (NW) sector of the Greenland Ice Sheet (GrIS) has been changing rapidly since at least the 1990s. Winter / summer temperatures in Greenland have increased by 4.4°C / 1.7°C since 1991 with the strongest increase of ~6–6.5°C (winter temperatures) in west and northwest Greenland (Hanna et al., 2020). Warming and the resulting ice loss due to mainly a decreasing surface mass balance have led to ice surface thinning of up to ∼1 m/yr during the past two decades (The Imbie Team, 2020) and ice sheet mass loss of 262 ± 21 Gt/yr in NW Greenland (Colgan et al., 2016). Numerical ice sheet models predict that the glacier catchments in NW Greenland are likely to be among the first to undergo accelerated mass loss in the future in response to projected oceanic and atmospheric warming (Fürst et al., 2015; Pattyn et al., 2018). Northwest Greenland also appears to have experienced strong warming (particularly summer warming) during the Holocene Thermal Maximum and Eemian (LeCavalier et al., 2017; McFarlin et al., 2018; Axford et al., 2021), and was deglaciated at least once in recent geological history (Christ et al., 2021).

The NW GrIS exhibits a mixture of cold-based, polythermal, and temperate-based ice (MacGregor et al., 2016), yet the subglacial hydrology and interaction between ice and meltwater remains uncertain. Further, geophysical boundary conditions such as smaller-scale bed topography (Morlighem et al., 2017), geology (Henriksen et al., 2009), water and sediment distribution (Bowling et al., 2019), and heat flux (Rogozhina et al., 2016; Martos et al., 2018) remain poorly constrained. These properties influence ice flow dynamics, and affect the ice sheet response to changing climate. Atmosphere-snow-ice interactions are not well understood, but have implications for present and future drivers of ice sheet change. Aerosol loading, organics, and microbial composition are particularly unconstrained, with important implications for altering surface ice albedo and the biogeochemical cycling of carbon and nitrogen. Lastly, NW Greenland hosts two notable geologic features, the Hiawatha Crater (Kjær et al., 2018) and Camp Century Basin (Paxman et al., 2021). Both have the unique potential to provide insight on Greenland's past climatic history.

The glaciological history of NW Greenland is an urgent problem to understand against the backdrop of rapidly rising Arctic temperatures. Integrating ground-based observations from the ice surface, through the ice column, to the bed, and into the sediment is therefore crucial for improving our understanding of the response of northwest Greenland to past, present, and future climatic change.

Driving Scientific Questions

Question Group 1 (QG1): What are the patterns and processes driving modern ice mass loss, and what are its consequences?

Motivation: Understanding the dynamical processes involved in the ongoing change of the GrIS is important for ice sheet model calibration and for quantifying the triggers, feedbacks, and system instabilities that will play out over the coming decades.

- How are ice dynamics and surface mass balance (SMB) evolving in NW Greenland, and what are the most important driving climate forcings?
- How stable is the NW sector of GrIS today? Are there critical thresholds and/or tipping points that can be identified?
- What sea level contribution in the near future (20–300 years) is realistic and what is the global pattern of sea level change that will result? How is modern ice sheet melt affecting terrestrial and marine environments and ecosystems?
- How do surface materials (e.g., particulates, dissolved organics/nutrients, microbes) contribute to albedo and ice sheet loss during the ablation season?
- How is firn evolution affected by atmospheric and glaciological changes in a warming climate?

Question Group 2 (QG2): How did GrIS change and was it stable during past warm periods?

Motivation: The behavior of the GrIS in northwest Greenland during past interglacial periods warmer than today provides analogues for potential change in the near future.

- How stable was the NW Greenland ice sheet during Plio-Pleistocene interglacials? How much and how fast did it retreat, and what was its contribution to sea level?
- What is the palaeo-glacial, -climatological, -chemical, -biological, and -ecological history of NW Greenland and how does it help predict the future?
- What can be learned about past conditions from ancient organics and DNA?
- What is the age of the Hiawatha crater, how much ice was present at the time of impact, and how did the impact affect local and global climate?

Question Group 3 (QG3): What are the basal conditions beneath the ice sheet?

Motivation: Conditions at the base of the ice sheet can exert a strong control on how the ice sheet responds to climatic change, and so are important boundary conditions for ice sheet models.

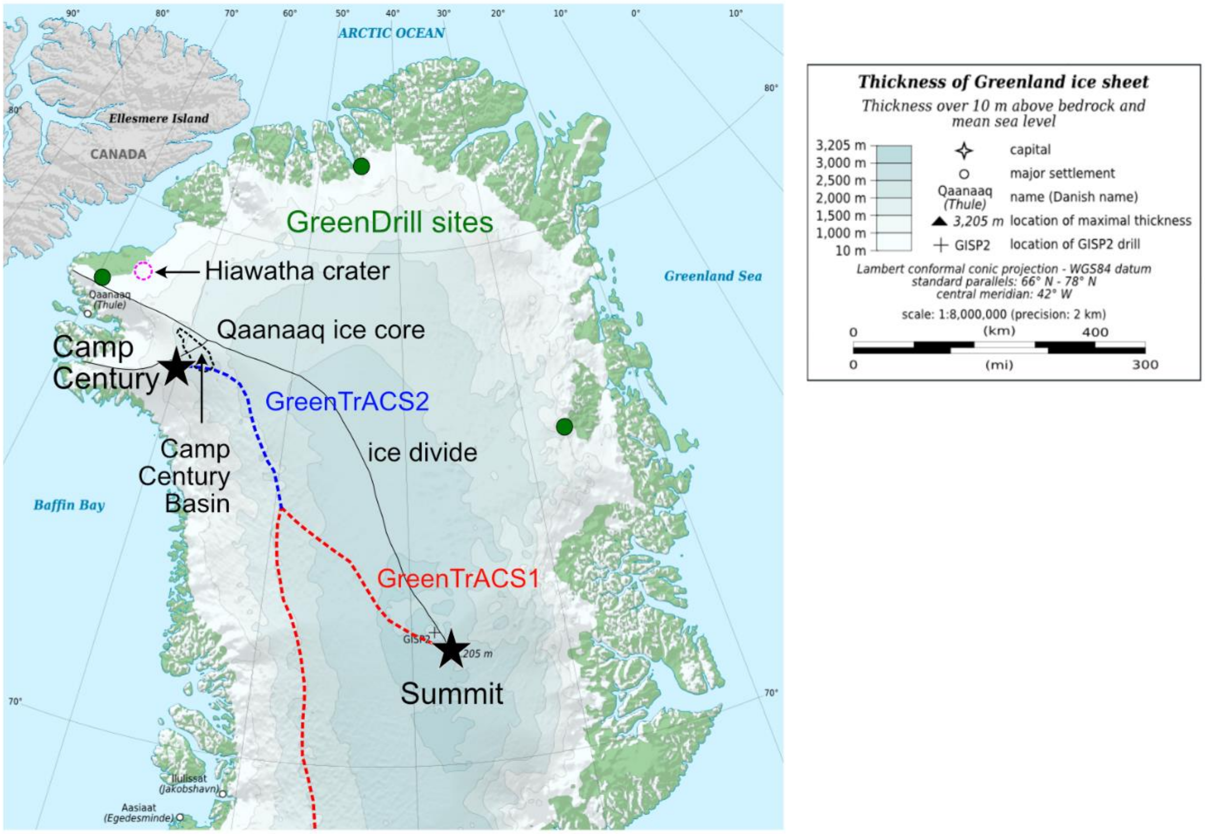
- What are the NW Greenland ice sheet basal properties (e.g., heat flux; frozen/melted; geology; basal friction)?
- What is the distribution of subglacial water, lakes, and sediment?
- What is the amount of glacial isostatic adjustment and what is the viscoelastic Earth structure beneath NW Greenland?
- How accurate is the bed topography derived from mass conservation away from regions of fast-flowing ice? What is the sensitivity of subglacial meltwater routing to uncertainties in bed elevation?
- What are the structure and dynamics of englacial and basal ice features (e.g. 'plumes'; Leysinger Viele et al., 2018; 'ice slab/lens'; MacFerrin et al., 2019)?
- How does ice-bed organic matter composition and character relate to geomorphology, basal ice melt, and microbial processes? What is the composition of the basal ice organic matter?

Scientific Rationale

The driving science questions above are united by their potential to be answered through geophysical and geochemical measurements along a ground-based traverse alongside ice and continental drilling. Measuring snow accumulation, surface melt and percolation, snow/firn properties (density, porosity), snow/firn chemistry (inorganic and organic), and surface albedo across NW Greenland would quantify recent SMB trends and climate drivers, and provide calibration/validation for regional climate models and remotely sensed data (QG1). The drilling of deep ice cores (1500–2000 m deep) in NW Greenland would help clarify the magnitude of warming and the GrIS response during past warmer climate intervals such as the Holocene Thermal Maximum and Last Interglacial (QG2). Access to basal ice and underlying sediment and bedrock would be valuable for constraining GrIS extent and stability, climate, ecosystems, and environmental conditions during older interglacial periods (QG2). Access to the bed and additional ground geophysical measurements would also provide important information about basal boundary conditions (geothermal flux, basal meltwater, geology, ice-sediment coupling), which are essential parameters for constraining numerical ice sheet models (QG3).

Possible Traverse Route & Key Sites

The map below identifies locations that are referenced in the text that follows.



<u>a. Traverse Route and Logistics:</u>

The research questions identified above can be addressed by measurements along a traverse from Summit or EGRIP to Hiawatha crater. This route aligns with two other traverses that are currently being developed: The GreenDrill project targets one site north of Qaanaaq and plans to approach it from either Summit or EGRIP. Additionally, GreenTrACS2 proposes a follow-on traverse from GreenTrACS1 that will extend from Summit to Camp Century approximately along the ~2000 m ice surface elevation contour and then west along the ice divide between NEEM and Camp Century.

The logistics of the proposed traverse would likely vary depending on which research questions were prioritized. Some of the research questions, such as those focused on modern surface mass balance (QG1) and continuous on-ice geophysical measurements (QG1 and QG3), require relatively light traverse vehicles such as Arctic Trucks and snow machines, and can be accomplished with small (<10) teams of mostly researchers. Other research questions, such as those requiring accessing and sampling deep ice and sub-glacial environments (QG2 and some in QG3), require heavier, tracked traverse vehicles capable of transporting larger loads (e.g. drills) across the ice sheet to discrete points. Such traverses may require a larger team of engineers and mechanics to maintain vehicles and loads.

b. Sites where measurements will take ~1-2 days:

- Various sites along the route, perhaps every 50-100 km along the route, or alongside “spurs” from the main route.
- Sites for altimetry validation with ICESat-2 and CryoSat-2

c. Sites where measurements will require 1 week or more at the site:

- Qaanaaq ice core (exact site TBD - general Camp Century area)
- Camp Century Basin
- Hiawatha Crater
- Certain measurements will require locations where ice is likely to be frozen to the bed (e.g. when drilling to access subglacial sediment / bedrock).

Measurements

a. Continuous/frequent measurements along the traverse route

- Acquisition of continuous GPR at various frequencies can be used to map firn thickness, firn structure (including melt layers), firn density, snow accumulation (QG1), and ice sheet basal conditions (QG3)
- Acquisition of continuous meteorological data (QG1)
- Acquisition of continuous high-precision differential GPS for ice sheet elevation data (QG1)

b. Measurements requiring 1-2 days

A number of types of measurement would provide powerful insights into the questions mostly listed in QG1, such as:

- shallow firn cores collected every 60-80 km to a depth of 30-50 m
- surface albedo measurements
- snow pit measurements of surface density, and sampling for chemistry/other analytes of interest (molecular carbon, etc.)
- upward-looking lidar cloud measurements
- weather station + GNSS IR measurements
- Cal-val satellite altimetry measurements with high-precision differential GPS
- Surface roughness measurements
- Small seismic surveys for ice sheet basal conditions (QG3)

In addition, borehole thermometry using Fiber Optic Distributed Temperature Sensing system (can be left in place if necessary) would connect to deeper ice drilling (see below), and allow for determination of geothermal heat flux (QG3).

c. Measurements requiring 1 week or more at the site

Drilling and recovery of deep ice cores (100s-2000 metres of ice), coring and recovery of basal material at the ice sheet bed, and seismic surveys at target sites such as the Camp Century Basin and Hiawatha Crater would help address questions pertaining to past climates and basal conditions within QG2 and QG3. Determination of particulate and dissolved organic matter composition and character (using optical property measurements from discrete meltwater samples) would target questions within QG1 and QG3. Also valuable would be a transect of firn cores along an ice flowline (QG1).

Target Timeline

The GreenDrill traverse to northwest Greenland is planned for 2023 and the GreenTrACS2 Summit to Camp Century traverse is planned for 2023 or 2024, if funded. As discussed in the Traverse Route and Logistics section, answering the questions identified here would require both a continuous traverse with lighter equipment as well as several heavy equipment field targets (drilling). The continuous traverse could include geophysical surveys to prepare and identify the specific drilling locations. In light of the rapidly changing Greenland Ice Sheet, this work could occur shortly after the GreenDrill and GreenTrACS2 traverse, if funded.

Conclusion

There is an urgent need to better understand how susceptible the Greenland Ice Sheet is to warming and how much it will contribute to future sea level rise. As the fastest warming area in Greenland, the NW region is a prime target for extensive analyses of past and present ice sheet dynamics. Additionally, the unique subglacial environments in NW Greenland are world-class sites for continental drilling to uncover regional climate archives. In this white paper we have identified key scientific questions along with the measurements and first-order traverse logistics that would be required to answer them. We hope that this document conveys the importance of answering these questions and can serve as a foundation to plan and fund future traverse and drilling efforts on the Greenland Ice Sheet.

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