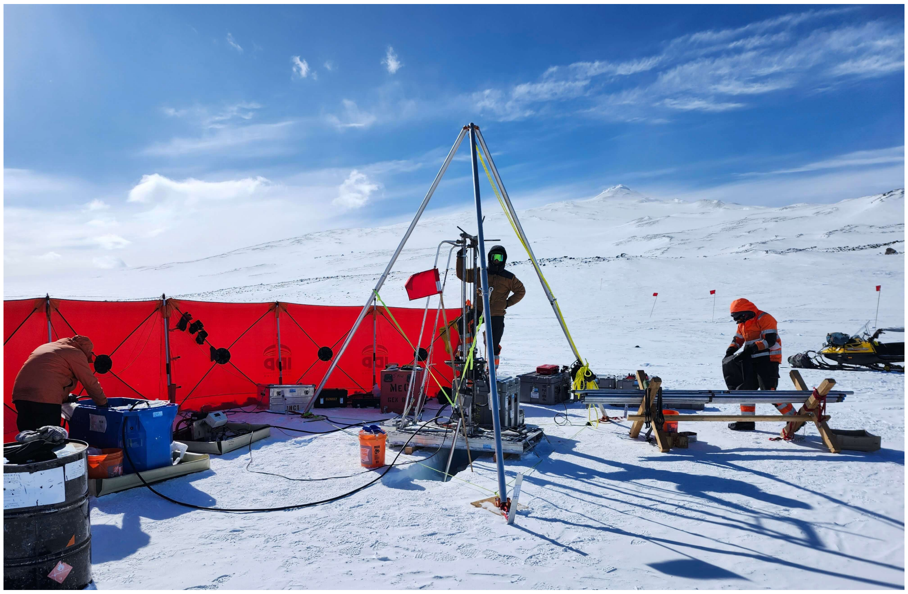
# Long Range Science Plan 2025-2035

Prepared by the NSF Ice Drilling Program in collaboration with its Science Advisory Board and with input from the research community



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Cover Photos:

IDP contract driller Forest Harmon operates the Winkie Drill at Mount Waesche, West Antarctica, during the 2024-2025 field season. *Credit: Nels Iverson*.

A subglacial porous lava bedrock core recovered with the Winkie Drill at Mount Waesche, Antarctica, during the 2024/25 field season. *Credit: Elliot Moravec*.

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## Introduction

The progress of national health, prosperity and welfare, and field operations of the national defense may all be influenced by changes in Earth's linked atmospheric-oceanic-continental systems, especially in times of rapid change. The Polar Regions have been the harbingers of change and continue to display dramatic environmental changes. A sophisticated and predictive understanding of the mechanisms of abrupt changes in Earth's linked systems across a wide range of spatial scales and time is needed to plan for the future. Glaciers, ice sheets, and subglacial environments contain evidence of the past and present that provide data that are crucial for predicting the response of the cryosphere and Earth's systems to ongoing future changes.

Ice core records have led to many important discoveries; for example, the discovery from the Greenland Ice Sheet Project 2 ice core showed that dramatic changes can occur abruptly, in less than ten years (NRC, 2002); this revolutionized large-scale environmental science and also has important implications for policy. The West Antarctic Ice Sheet (WAIS) Divide Core established the benchmark carbon dioxide record for the most recent glaciation. U.S. and U.K. collaboration on studies of the unstable Thwaites Glacier in West Antarctica has begun to provide evidence on the possibility of large sea level change in the near future (e.g., Joughin et al., 2014; Scambos et al, 2017). Recent studies of subglacial sediment and bedrock below the summit of the Greenland Ice Sheet (Schaefer et al., 2016; Christ et al., 2020; Christ et al., 2023) and the West Antarctic Ice Sheet (Balco et al., 2023) raise questions about ice sheet resilience to large-scale environmental change. Glacial ice at the Hercules Dome site in Antarctica archives evidence about the rate of demise of the West Antarctic Ice Sheet during the last interglacial with its large sea level rise; retrieving the Hercules Dome ice core remains highest priority for the U.S. ice core science community. Many other basic questions about Earth's systems remain unresolved, and new scientific plans, in both Antarctica and Greenland, will address a variety of questions.

Rapid changes in the speed of fast-flowing outlet glaciers and ice streams observed over the past decade have created an urgency to understand the dynamics of outlet glaciers and ice sheets. It has long been recognized that basal conditions exert strong control on the flow of glaciers and ice sheets; and boreholes drilled to the bed have been used to deploy instruments to measure basal properties (e.g., Engelhardt et al., 1990; Engelhardt and Kamb, 1998; Kamb, 2001; Truffer et al., 1999, 2006). These fundamental observations have advanced our understanding, and it is clear that spatial and temporal distribution of sediments and hydraulic conditions at the bed are key to understanding rapid changes in speed of glacial flow. Furthermore, in cases where the bed of outlet glaciers is slippery, perturbations at the grounding line propagate inland over short timescales (order of decades), which has the potential for rapid drawdown of inland ice (Payne et al., 2004; Shepherd et al., 2004; Price et al., 2008; Joughin et al., 2014; Rignot et al., 2014). Perturbations at grounding lines are triggered by changing ocean temperature and circulation (Jenkins et al., 2010), and/or subglacial hydrology or sediment dynamics (Anandakrishnan et al., 2007; Alley et al., 2007; Carter & Fricker, 2012; Christianson et al., 2012; Horgan et al., 2012). Defining the processes that control the dynamic stability of glaciers and ice sheets is crucial for predicting their response to future possible greenhouse gas emission scenarios. Great uncertainties in sea level rise projections for the 21st century are associated with the possibility of rapid dynamic responses of the ice sheets to ongoing warming.

Subglacial environments represent a deep repository of ice history, a resource that remains largely untapped. Most of our knowledge about subglacial environments comes from geophysical remote sensing and sparse data retrieved from access holes drilled to the bed, or sub-ice-shelf cavities. More detailed observations are needed to map and understand the variety and complexity of deep ice, subglacial geology, and the interface between them. The lithosphere under the Antarctic and Greenland ice sheets remains unknown except by extrapolation from coastal outcrops and remotely-sensed geophysical data. Subglacial environments also house records of past ice sheet dynamics and longer-term paleoclimatic histories in their sediment, fossils, and stratigraphic basin archives (Scherer et al., 1998; Coenan et al., 2019; Schaefer et al., 2023; Christ et al, 2021 and 2023; Venturelli et al., 2020; Siegfried, Venturelli et al., 2023). Recovering these records for intervals of past warm periods will contribute to our understanding of future ice sheet behavior under ongoing warming.

New and emerging studies show that subglacial environments harbor unique microbial ecosystems and that the biogeochemical activities of the microbial communities play a critical role in subglacial weathering and production/consumption of greenhouse gases (Martinsson et al., 2013; Christner et al., 2014; Michaud et al., 2016; Davis et al., 2023). Recent studies have illustrated the potential for subglacial water, and relict carbon from microfossil-bearing sediments, to supply critical carbon and nutrients to sub-ice-shelf waters (Vick-Majors et al., 2020, Hawkings et al., 2020; Venturelli et al, 2023), however, the extent to which microbial activity alters the chemistry of subglacial efflux and the effects of that efflux on global processes remain outstanding questions. There is considerable scientific and public interest in subglacial environments, particularly in relation to the discoveries of subglacial lakes beneath the Antarctic Ice Sheet and the unique life forms they may harbor. Microorganisms that exist under permanently dark and cold subglacial conditions have broadened our understanding of the phylogenetic and metabolic diversity of life on Earth (Achberger et al, 2016; Mikucki et al.2016; Davis et al, 2023); this has opened the door for research on available nutrients and carbon paleoclimatic research, and may help inform our search for extraterrestrial life. Genomes of microbes trapped under deep ice can provide indications regarding their period of separation from "contemporary" microbes. Hence, genomic data that establish timeframes of isolation for populations can contribute to understanding events of the past, for example the timing of the last WAIS collapse.

Technological developments are required to integrate geological drilling technologies with those of ice drilling, including clean access. The U.S. Antarctic Program complies with the Antarctic Treaty and other treaties to uphold protection of the environment, including activities that involve drilling through the ice (NRC 2007). Given the pristine nature of Antarctic subglacial environments in particular, the Scientific Committee on Antarctic Research (SCAR) has developed a Code of Conduct for access in order to "*recognize the value of these environments and the need to exercise wise environmental stewardship*." The US scientific community has taken a lead in advancing international management of the Antarctic subglacial environment by establishing and documenting methods for achieving microbially clean access hot water drilling systems (Priscu et al, 2013: Michaud et al, 2020), for use in standardizing drilling and coring systems in a quantifiable and verifiable approach. In the future, a facility such as the Ice Coring & Education (ICE) Silo, under conceptual development at the University of Nebraska, could construct custom columns of ice in a clean system for potential use in testing future development of novel drilling systems. The NSF Ice Drilling Program has pioneered proven engineering achievements including replicate coring in ice and the first retrieval of meters of bedrock cores from beneath many meters of glacial ice. Cutting-edge engineering will continue to enable future scientific discoveries from within and beneath glaciers and ice sheets.

The U.S. ice coring and drilling community has led and participated in fundamental and vital scientific discoveries for more than sixty years. These discoveries require drilling and coring of glaciers and the polar ice sheets, a specialized and challenging endeavor that requires extensive planning, technology, and logistics. This IDP Long Range Science Plan identifies U.S.-led science that will require ice drilling in glaciers and ice sheets. The accompanying IDP Long Range Drilling Technology Plan identifies actions for IDP drill maintenance and upgrade and development of new drills and technology. These paired plans enable the community to develop well-coordinated proposals while allowing the NSF to plan for budgets and logistics to facilitate the science. A draft update of the IDP Long Range Science Plan, including input from the IDP Science Advisory Board and the IDP Working Groups, is posted to the icedrill.org website each spring, with listserv invitations for comments and suggestions to enable broad community input. The document is then revised and the final version for the year is sent to the NSF and posted to the icedrill.org website in summer.

Science goals articulated in this IDP Long Range Science Plan are all interconnected, but for convenience in associating scientific endeavors with appropriate ice drilling technology, the science is described in four themes: 1) past changes; 2) ice dynamics and glacial history; 3) subglacial geology, sediments, and ecosystems; and 4) ice as a scientific observatory. These four goals and objectives are described below, together with an outline of their respective needs for drilling technologies. Planning matrices are also developed to provide a timeline for planning field readiness of ice drilling technologies, so that the engineering of drilling support for the science will be ready when needed.

# Ice Core Science and Drilling Science Goals

## I. Past Changes

Earth is a system that has regional, hemispheric, and global phenomena. It is impossible to understand large-scale changes without understanding both individual components of the system and the system as a whole, as evidenced by data from a large number of locations and over a range of time scales.

**1. Industrial and Instrumental Period**: Spatially distributed evidence from ice cores spanning the industrial and instrumental period (last 100-200 years) is still needed to establish human impacts on the environment, cryosphere and atmosphere. Associated studies of modern surface processes, calibration of models and correlating remote sensing data with in situ data are needed. Shallow ice cores (generally <200 m) are relatively easy to recover and consequently more records can be collected to evaluate spatial patterns of change.

Over the past 200 years, human activities have had significant impact on atmospheric composition yet the impacts in polar and remote high-latitude and high-altitude regions are poorly resolved. Shallow ice coring programs have been, and will continue to be done through individual or small-group projects at targeted sites (e.g., ice coring in mid-latitude temperate glaciers, Alaska, and in selected areas of the Arctic and Antarctic) and through internationally coordinated scientific traverses (e.g., International Trans-Antarctic Science Expedition, Norwegian-U.S. Scientific Traverse of East Antarctica) or other logistical models (e.g. RAICA US-South Korea collaboration collecting coastal West
Antarctic ice cores). Some of these shallow coring arrays must also be updated in coming years since many ice cores, including the International Trans-Antarctic Scientific Expedition cores, were established in the late 1990s to early 2000s and are thus missing the last 20 years of information. Returning to sites and taking firn cores to depths of 10-15 m would provide such an update. While shallow coring has been done in a number of locations, more cores are needed in order to understand whether observed patterns are regional, hemispheric, or global. Through a combination of over-snow science traverses and coordinated individual site efforts, an extensive array of relatively easy-to-recover ice core records, driven by individual and group proposals, is a mainstay of the ice coring community with the following objectives:

- Determine accumulation rate and temperature changes on the Greenland and Antarctic ice sheets and in alpine regions where instrumental records are rare.
- Understand changes in the chemistry and isotopic composition of the atmosphere during the Industrial Period, including greenhouse gases, acidic species, oxidants, toxic metals, and trace species such as carbon monoxide and hydrocarbons.
- Understand stability and rapid changes along coastal areas of the West Antarctic Ice Sheet. Ice core records, strategically placed on ice domes along the WAIS coast (e.g., Neff 2020), will provide high-resolution (annual) records of natural variability in ice, ocean, and atmospheric dynamics in which to place the recent observations in context, including extreme events and newly appreciated processes such as atmospheric rivers (e.g., Wille et al., 2022).
- Constrain surface mass balance processes including accumulation, surface melt, runoff and refreezing, and evaluate areas of water retention in perched water tables and aquifers in Greenland and Antarctica. These data can also be used to ground-truth high-resolution models.
- Improve understanding of relevant physical and chemical processes related to snow deposition and post-depositional changes

(including metamorphism, in situ chemical processes, interactions with cosmic rays, etc.) and their effects on atmospheric chemistry preservation and interpretation of geochemical signals (including atmospheric) at larger depths.

- Calibrate snow/firn/ice properties measured remotely (e.g., borehole, ground, airborne, and satellite-based measurements) with in situ data, thereby allowing interpolation based on remote sensing data.
- Extract firn air from shallow boreholes to reconstruct the recent evolution of the atmospheric composition and study air movement in the porous firn layer.
- Produce detailed temporal and spatial (regional-scale) maps of environmental parameters (e.g., temperature, accumulation rate, atmospheric and snow chemistry), and anthropogenic impacts.
- Develop an inventory of microbes and available nutrients within ice to improve understanding of the role of microbes related to geological, chemical, and climatological changes.
- Improve records of global and local volcanism for large-scale forcing and geohazard studies.
- Quantify perturbations to atmospheric composition from anthropogenic pollution sources relative to the preindustrial atmosphere (e.g., aerosols, metals).

Individuals and small groups conduct studies of these types across glaciological settings ranging from the Greenland and Antarctic ice sheets, to ice caps and alpine glaciers in low, mid, and high latitudes. Versatile drills required for 200-year ice coring exist in the current U.S. inventory, and are in high demand; they need to be upgraded and continuously maintained so that they are functional and can be quickly deployed to the field. Requirements for drills to achieve these and other ice coring goals are listed in table one. The IDP Long Range Drilling Technology Plan describes the agile drills in the IDP inventory in detail and discusses their current condition.

Part of an ice core retrieved from Mt Hunter Plateau of Denali, Alaska exhibits layering and dust carried to the area from afar. Photo credit: *Brad Markle, Univ. Washington*

**2. Pre-Industrial Baseline**: The late Holocene (ca. the last two millennia) is an important temporal focus because it is long enough to allow investigation of annual to centennial variability, yet short enough that relevant boundary conditions have not changed appreciably. Thus, this period represents a critical pre-industrial baseline against which to compare 20$^{th}$ century changes in the cryosphere, atmospheric composition and chemistry. Existing quantitative reconstructions of large-scale environmental changes spanning the past two millennia continue to be debated, in part due to a lack of annually-resolved records prior to 1600 B.P. in many areas, and due to the highly regional nature of many processes. A coordinated international effort to recover a spatial array of annually resolved and calibrated 2,000-year ice core records has several primary objectives:

- Determining regional and high-resolution temporal patterns of temperature, precipitation, sea ice extent, and atmospheric composition and chemistry to better understand forcing and particularly feedbacks that will also operate in the near future.
- Evaluating 20$^{th}$ century warming, precipitation, atmospheric circulation, sea ice, and atmospheric composition and chemistry changes in the context of the past 2,000 years.
- Establishing the extent and regional expression of the so-called Little Ice Age and Medieval Anomaly phenomena, and constraining their relationships with regional

patterns like the North Atlantic Oscillation (NAO), Arctic Oscillation (AO), El Niño Southern Oscillation (ENSO), and Monsoons.
- Calibrating local, regional, and global models against a recent but sufficiently long pre-anthropogenic period.
- Determining the sensitivity of alpine glaciers and ice sheet margins to the relatively warm Medieval Anomaly and relatively cold Little Ice Age, with implications for the impact of future warming on water resource availability and sea level rise.
- Quantifying spatial and temporal patterns of forcing mechanisms that are regionally variable (e.g., greenhouse and reactive gases, sulfate, terrestrial dust, biological material, and carbon aerosols [black and biogenic carbon]), and the record of solar variability.
- Assessing the relative roles of anthropogenic and natural forcing on large-scale environmental evolution prior to and into the industrial period.
- Quantifying anthropogenic emission sources and levels prior to the start of the industrial revolution (1760s), such as from early metal smelting, biomass burning, or other human activities.
- Improve understanding of how natural sources of greenhouse gases and aerosols are responding to high latitude change.

New coring associated with these efforts will include Arctic, Antarctic, and mid-latitude sites. Recent and desired future U.S. or U.S./International efforts include Central Alaska Range; Canada (Eclipse Icefield); Detroit Plateau on the Antarctic Peninsula; multiple locations on the coastal WAIS ice shelves and ice domes; the Aurora Basin in Antarctica; Hercules Dome (the 2,000-year record would be part of a deeper core); Greenland coastal ice caps, high accumulation rate sites in Greenland, and Northwest (Qaanaaq) and South Dome sites (the 2000-year record would be part of a deeper core). This list is not exclusive, but illustrates the diversity of discussions within the research community.

Scientific drilling on the Mt. Hunter Plateau of Denali, Alaska provides a 2,000-year record of precipitation and atmospheric circulation in Central Alaska. Drilling at this site was accomplished by wind and solar energy without the need for gas-fueled generators. Photo credit: Top) *Seth Campbell, CRREL; Bottom) Dom Winski, Dartmouth/U.Maine*

**3. Large-Scale Global Change**: Large changes driven by external forcing have involved significant interactions among ice sheets, carbon cycle, vegetation, dust, ocean and atmospheric circulation resulting in rapid changes in regional conditions. Understanding Earth system dynamics especially in times of rapid transitions is critical to making improvements in current Earth system models for assessment of future change. Incomplete evidence about processes and dynamics of abrupt millennial scale change and regional impacts requires evidence from ice cores to develop more complete knowledge of the underlying mechanisms. Ice cores are uniquely placed to provide the contrasting polar elements in high resolution and are the only source of past atmosphere allowing measurements of greenhouse and other trace gases. Scientific challenges include the following:
- Further develop ice core proxies for different aspects of the Earth system, for example to reconstruct conditions at the ocean surface

(e.g., sea ice, marine biological productivity, ocean evaporation conditions), and in the boreal continental biosphere (e.g., forest fires, land ice extent).

- Continue to improve understanding of forcings on millennial and orbital timescales (greenhouse gases, solar irradiance, aerosols, temperature, snowfall rates).
- Improve the absolute and relative chronologies of individual ice cores, in the ice solid and gas phases, and construct consistent multi-ice-core chronologies.
- Develop methods to synchronise ice core records to those from other palaeo archives, in particular for previous glacial cycles where radiocarbon is unavailable.
- Increase the spatial and temporal coverage of the deep ice core network to identify spatial patterns and regional differences in climatic, environmental, and glaciological conditions.
- Apply newer methods to improve the resolution of data from some existing sites. Quantify and understand the spatial and temporal evolution of rapid changes, and assess how this varies with background conditions (orbital forcing, greenhouse gas concentration, land ice masses).
- Construct, using ice cores carefully synchronized to other records, the sequence of events (including forcings and responses) through several glacial-interglacial transitions at highest resolution possible.
- Use these reconstructions with Earth system modelling to provide a stringent test of mechanisms. This will require an increase in modeling capability to assess changes at sufficient resolution through multiple terminations.

Under the auspices of IPICS, the international scientific community aspires to a network of ice cores. Specific U.S. contributions to this network include the completed WAIS Divide core and the South Pole ice (SPICE) core, and the upcoming core at Hercules Dome. In Greenland, two potential sites in the Northwest (Qaanaaq) and at South Dome would also contribute to IPICS goals. The projects may vary in scope and logistical needs, but many are envisioned to be drilling campaigns conducted in two or three seasons with minimal logistics. Site-specific records of environmental change are the primary objective; it will not be necessary to undertake the full suite of measurements possible in an ice core, although clearly such measurements provide data for a variety of future projects. The Foro 1800 drill was used to successfully drill the South Pole Ice Core to a depth of 1,751 m (age ~ 49,000 years), and the Foro 3000 drill will be used at Hercules Dome. Individual and small group projects targeting specific aspects of atmospheric variability on millennial to glacial timescales can be conducted at low-accumulation sites such as Dome C, Antarctica or at ice margin sites with agile drill systems and moderate logistics requirements.

**4. High-resolution Records of the Last Interglacial; A Warm-Earth Analog**: The Last Interglacial (LIG) period (~130k to 110k years ago) was warmer than present due to differences in Earth's orbital configuration, and can provide clues about how the Earth will respond as human activities continue to force global warming. Critical science priorities for ice cores spanning the LIG include:

- Determining whether the West Antarctic Ice Sheet experienced partial or total collapse during the LIG, and determining the extent of the Greenland Ice Sheet during this warmer time. These objectives are critical for constraining sea level rise estimates in a warmer world.
- Quantifying the temperature, precipitation, atmospheric circulation, and sea ice extent of Greenland and Antarctica during the LIG.
- Establishing whether rapid change events occurred during the warmer world of the LIG.
- Determining whether the lack of an abrupt change during the deglacial warming (i.e., Bolling Allerod warming and Antarctic Cold Reversal) contributes to an "overshoot" and a warmer interglacial.
- Comparing the evolution of the LIG with the recent Holocene.

- Investigating glacial inception at the end of the LIG.

Existing ice core records of the last interglacial are primarily from low accumulation sites in East Antarctica are insensitive to changes in the marine segments of the ice sheets. The detailed behavior of polar environmental conditions, greenhouse gases, ice sheet size, and other earth system attributes recorded by ice cores are not well known for this period, and require high-accumulation conditions. Results from the North Greenland Eemian (NEEM) ice core in Greenland, and similar results from other Greenland ice cores, have shown that the Eemian record located there is at least partially recoverable, but not in stratigraphic order. Large volumes of ice from the last interglacial have been shown to outcrop at the surface of Taylor Glacier, Antarctica; a record of the MIS6-5 transition has been recovered from folded ice at the Allen Hills (Yan et al., 2019).

The bubbles visible in this piece of ice from an Antarctic ice core contain carbon dioxide and other gases that were trapped in the ice when formed many thousands of years ago. Ice cores provide the only natural archive of ancient air. Photo credit: *Oregon State University.*

The search for sites with undisturbed ice will continue in both polar regions along with efforts to interpret folded ice; potential targets are relatively high accumulation sites in Antarctica, such as Hercules Dome, where Last Interglacial ice is likely to be preserved, and possible new sites in Greenland, including near the Camp Century site in Northwest Greenland. Almost a decade ago and reaffirmed since then, the U.S. science community, represented by the IDP Ice Core Working Group (ICWG), prioritized Hercules Dome as the next deep ice core site in Antarctica. The Hercules Dome site has likely preservation of ice from the last interglacial period (Jacobel et al., 2005) and a sensitivity to a potential collapse of the WAIS (Steig et al., 2015), as well as the potential to provide bubble-free ice (below the problematic bubble-to-clathrate transition zone, e.g., Neff 2014) for gas studies during the last glacial-interglacial transition.

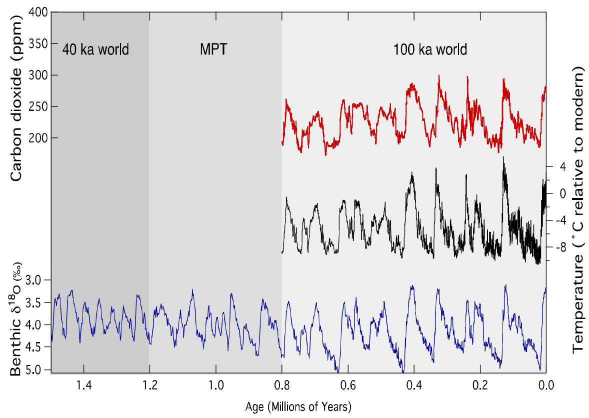
**5. Evidence from the ice sheet prior to 800,000 years B.P.**: Each time ice core measurements have extended further back in time, the data reveals new facets of the dynamics. Currently, the oldest record, from the EPICA core at Dome C, Antarctica, extends back to just over 800,000 years, and shows that different styles of glacial-interglacial cycles occur even under apparently similar external forcing. Antarctic ice sheet inception is thought to have occurred 35 million years ago, and although basal processes may have removed or altered the very oldest ice in many places, ice older than 800,000 years is preserved in East Antarctica. Recently, the European Beyond-EPICA project announced the recovery of possibly a 1.2 million year old continuous ice at Dome C, although formal dating is needed to confirm this claim.

The primary reason to seek ice older than 800,000 years is to further understand one of the major puzzles of Earth system history: Why did the system change from a dominantly 41k- to a 100k- year glacial cycle about one million years ago? Numerous research objectives related to this transition, and the earlier time period, could be addressed with ice core records extending back to ~ 1.5 million years, including:

- Evaluating $CO_2$ relationships prior to 800 ka, to determine whether the change to 100-kyr cycles and/or the long-term cooling trend from 1.5 – 0.8 Ma was related to changes in greenhouse gas concentrations.
- Clarifying whether 23k-year cycles, linked to orbital precession, are present in ice core records prior to the transition to 100-kyr cycles around 1 Ma. The 23k-year cycles are

not present in marine proxy records of this age, but are present in both marine records and ice cores after the transition.

- Investigating the high-resolution nature of glacial transitions during times of 41k-year cycles.




100,000-year 'sawtooth' variability in Antarctic climate over the last 800,000 years is mirrored by generally, similar variability in atmospheric carbon dioxide (as well as methane and nitrous oxide, not shown) and global ice volume inferred from deep ocean oxygen isotope records from marine calcium carbonate. Whether Antarctic climate followed the ice volume record prior to this time, when ice volume records are dominated by a 40,000-year period, is not known, neither are the mean levels of greenhouse gases and the temporal variability of those levels. *Figure from Severinghaus et al. (2013).*

There are two complementary, but very different, ways of accessing ice older than 800,000 years. The first is deep ice core drilling at very low accumulation rate sites in interior East Antarctica. This has the advantage of recovering a continuous record, which, in the younger part, can be compared to other ice cores (an important consideration for drilling at very low accumulation sites where record integrity may be an issue). Drilling at such a site requires a large amount of logistics support.

The second method is to make use of "blue ice" sites such as at Allan Hills (Spaulding et al., 2013; Higgins et al., 2015), Taylor Glacier (Aciego et al., 2007), Mt. Moulton (Dunbar et al., 2008) in East Antarctica where old ice outcrops at the surface via slow ablation or be present in the shallow subsurface. Continuous records require careful site selection; however, discoveries are possible from sites with easier access for drilling, through smaller and (logistically) less expensive science projects. A site in the Allan Hills (Kehrl et al., 2018) has been shown by ice penetrating radar to likely have a continuous record to ~250 ka with several hundred more meters of ice below for the possibility of continuous records extending to 1 million years. Different drilling requirements are needed for the two approaches. Development of blue ice sampling techniques should continue, given the potential for large volume sampling, very old ice and the possibility that continuous ice core records will not be discovered. Consideration of sites where only old ice might be preserved (for example, areas where there is no accumulation today but has been in the past) should also continue.

The IPICS "Oldest Ice" workshop (Fischer et al., 2013) described possible oldest ice sites in East Antarctica for consideration. The European project "Beyond EPICA" collected a deep core at a site near Dome C. This "little Dome C" site is shallower than the existing Dome C ice core site to limit the chance of basal melting. Tentative dating suggests this core is 1.2 million years old. A deep Oldest-Ice core near Dome Fuji is being drilled by the Japanese program. The Australian "million-year ice core" project is drilling at a site called "North Patch" near Dome C. Choosing a location with confidence is still difficult; mainly due to poorly-known geothermal heat flux. Determination of the spatial variability of geothermal heat flux is critical to the identification of potential drilling sites for oldest ice. Large regions remain unexplored which may have the optimal site conditions for Oldest Ice. The Rapid Access Ice Drill (RAID, Goodge & Severinghaus, 2016), once deployed on the ice sheet in Antarctica, should be able to create rapid deep access holes for spatially distributed measurements of geothermal heat flux to facilitate site selection. Field tests in 2019-20 demonstrated the drill's ability to cut ice boreholes quickly, take cores of subglacial rock, and deploy borehole logging tools for ice-age validation (Goodge et al., 2021). There are also additional efforts for oldest ice site selection programs that involve rapid access with new tools under development such as ICEDIVER (Winebrenner, 2021). New and ongoing radar, laser altimetry, gravity and magnetic data from ICECAP and Antarctica's Gamburtsev Province (AGAP) and COLDEX airborne surveys are helping identify potential drill sites in East Antarctica. In Greenland, locations on the west side of the east mountain range where the first ice sheet originated might result in ice more than one million years old. Since the stratigraphy is likely to be disturbed in that area, methods for dating ice that is not in order stratigraphically should be further developed before drilling for ice older than 800,000 years in Greenland.

**6. Pre-Quaternary atmosphere**: The possibility that very old ice (>3 million years) is preserved in special environments (for example, in debris-laden glaciers) in Antarctica (e.g., Yau et al., 2015) is exciting because it would provide a window into the composition of the atmosphere and environment during times when global environmental conditions were very different from today. A period of considerable interest is the mid-Pliocene warm period (3.3-3.0 million years BP), that is well-characterized via global proxy compilations and model intercomparison studies, and sometimes considered a potential analog for Earth's future. The Allan Hills site, where ice as old as 6 million years has been recovered, remains the most promising location for such work. The extreme strain that the ice has experienced at the Allan Hills site has resulted in very brittle ice so that dry drilling of ice cores has been a challenge; improving the ice core quality at this site is a priority for drilling COLDEX ice cores. In other regions, some debris-laden glaciers contain ancient mixtures of ice and rock, which requires specialized drilling equipment. The IDP Agile Sub-Ice Geologic Drill (ASIG) has proven to be useful in retrieving rock cores from beneath glacial ice and also in drilling cores composed of ice/rock mixtures.

**7. Large-volume sampling of climatic intervals and tracers of high interest**: Rare isotopes, ultra-trace species, micro-particles, biological materials, and other measurements that have not yet been fully exploited in ice core research offer new opportunities for discovery if large volumes of ice (e.g., individual samples larger than approximately 800 $cm^3$) are made available. Examples include $^{14}C$ of $CH_4$ to trace methane hydrate destabilization during past warming events (Petrenko et al., 2017), nano-diamonds, $^{3}He$, and micrometeorites as tracers of extraterrestrial impacts, and $^{14}C$ of CO as a tracer for atmospheric oxidizing capacity or past cosmic ray flux (depending on site characteristics). In the case of traditional drill sites, multiple cores or use of replicate coring technology are needed to obtain larger sample sizes, and in situ melting has been suggested (but not yet successfully used) as a means of sampling large volumes of air from deep ice core sites. A large-volume ice coring effort has been conducted at the Law Dome DE-08 and Dome C sites in East Antarctica, and promising future sites include Das 2 and South Dome in Greenland.

Blue ice areas such as Allan Hills and Taylor Glacier, Antarctica currently provide the best opportunities for rapid collection of large samples of ancient ice without a heavy logistics burden (e.g., Buizert et al., 2014). Ice sections ranging in age from Early Holocene to 6 M-year have already been clearly identified at these sites (e.g., Korotkikh et al., 2011; Yan, 2019; Shackleton et al, in review) and are ready for access/sampling at the NSF Ice Core Facility by future projects. Continued studies at these sites would provide more detailed and complete age maps of the desired outcropping ice areas.

Depending on the site and scientific target, a range of ice drilling and sampling tools may be appropriate. The Blue Ice Drill, Eclipse Drill, Foro 400 drill, 4" drill, hand augers, and chainsaws have all been successfully used. Continuing efforts to maintain and upgrade the capability to explore and retrieve the ice at these sites are needed.

A large-volume ice core drilled on the Taylor Glacier ablation zone, Antarctica. Bubbles in the ice at the site contain air with direct evidence of ancient atmospheric composition. The Blue Ice Drill is an easily-transportable drill capable of retrieving quality firn cores of approximately 9.5 inches in diameter as well as quality solid ice cores of the same diameter with few cracks up to 70 meters below the firn-ice transition. Photo credit: *Jeff Severinghaus*.

**8. Ancient microbial life**: Ice sheets provide chronological reservoirs of microbial cells entombed during atmospheric deposition and studies have shown that microbial DNA and viable organisms can be recovered from ice cores collected from both Greenland and the Antarctic as well as temperate glaciers (e.g., Christner et al., 2001, 2003; Miteva et al., 2004). In addition, the distributions of microbial cells themselves can serve as climatic records in deep ice (Santibáñez et al., 2018), and the microbes/particles can provide information on snow crystal nucleation in the atmosphere (Schrod, 2020). Many questions remain regarding how these organisms survive in deep ice for tens to hundreds of thousands of years, the origin of these airborne microorganisms, and what their diversity and biogeographic distribution reveals about conditions during deposition. The ability to obtain larger ice volumes in conjunction with advances in molecular techniques such as metagenomic analyses (Simon et al., 2009) and methods that can amplify smaller quantities of nucleic acids will enable more detailed study of the genomic potential of resident microbes and available preserved organic carbon material (D'Andrilli et al., 2017a,b) and how they integrate with our understanding of ice core ecology. There is interest in investigating the physiology of microorganisms recovered from ice cores to elucidate unique physiological properties that enable them to survive in ice for extended periods of time and that may offer important biotechnological applications (Cavvicholi et al., 2002). For example, studies have shown novel, ultra small microbial isolates from deep Greenland glacier ice that may inform on how organisms survive energy deprivation for extended periods of time (Miteva, 2005). It remains unresolved whether entrapped microorganisms have the potential to alter gas records, which could offer additional explanation/interpretation for observed gas record anomaly. There is also interest in investigating the reservoir of ice core carbon, not only as paleo stores of carbon cycling signatures, but also as reservoirs of reactive carbon that may directly impact surrounding environments when exposed to the atmosphere with melting, calving, and retreat (D'Andrilli & McConnell, 2021).

Recent studies have characterized organic carbon materials within various Antarctic ice cores and shown changing carbon signals measurable from different conditions (spanning back to 27,000 years ago (D'Andrilli et al., 2017a, b) and within the Holocene of Arctic and the Antarctic ice cores (Grannas et al., 2006; Xu et al., 2018; King et al., 2019; Vogel et al., 2019; D'Andrilli & McConnell, 2021). High temporal resolution organic carbon data from the WAIS Divide ice core emphasized the highly complementary nature of carbon surveys with routinely surveyed geochemical assays in paleo atmospheric reconstructions (D'Andrilli et al., 2017a). Notably, the preservation paradigm of geochemicals in ice cores also extends to biological and other organic materials, therefore it will become increasingly important to characterize their concentrations and qualitative nature now, in the ice, before it melts to reconstruct our past, learn about our present, and help better predict their impacts in future warming. The inclusion of organic material (OM) chemical characterizations in ice coring efforts improves geochemical and biological paleo atmospheric composition interpretations at broad and fine scales, ice sheet carbon storage assessments and comparisons with other ecosystem OM, understanding of signatures arising from preservation mechanisms, and the ability to predict the fate of carbon in ice sheets in the Arctic and Antarctic.

**9. Borehole Array for Spatial Variations:** Although borehole observations cannot directly sample ice to provide a detailed history, an array of boreholes linked to an ice core can provide information on the spatial variability for any of the ice cores mentioned above in this report. Notably, the Wide Angle Topographic Sensor for Operations and Engineering (WATSON) instrument has thus far shown a unique microscale approach to OM and microbial distribution within the ice sheets and in the future requires a joining of the microscale, fine scale, and broad scale ice core researchers to best understand small to large spatial variations of materials in ice. (Eshelman et al., 2019; Malaska et al., 2020). Discoveries from ice borehole research will continue as additional technology is developed. See also section IV.1 below.

**Summary**

Advances in understanding the past require arrays of ice cores with depths ranging from tens of meters to 3,000 m, and the requirements for the coring or sampling vary. Agile drills currently at IDP-Wisconsin should be continually maintained in excellent working condition so that they can be used for new projects. Biologically-clean hand augers and agile drills are needed for biological studies in glaciers. The Foro 3000, capable of coring up to 3,000 m has been created in the same family of drills as the Foro 1650 (aka Intermediate Depth Drill for coring up to 1,650 m). The large-diameter Blue Ice Drill for shallow drilling in blue ice areas has been used successfully on Taylor Glacier, Antarctica, and elsewhere. With continued science attention to blue ice areas as well as to large-volume sampling in general, a re-designed Blue Ice Drill that can successfully retrieve samples from 200 m depths would be useful. Estisol-140 is used as drilling fluid in deep drilling. While Estisol-140 had some issues in the first season of use, changes to the drill and handling procedures in the second season mitigated many of the issues. Neither Isopar-K nor Estisol-140 are ideal for biological and OM chemistry measurements in ice cores. For those types of research, the outer layers of the ice cores must be shaved off manually or within the continuous flow analysis melting system, since they introduce large contaminants into the measurements (Christner et al., 2005; D'Andrilli et al., 2017b). Table 1 lists characteristics for drills needed for the areas of the science outlined in the previous sections that are available through IDP. In addition to the drills in Table 1, several U.S. universities have university-owned drills that may be available by request directly to the university, for example, the WISSARD/SALSA clean access drill, Roving Drill, and Shot-hole Drill at the University of Nebraska-Lincoln, and also the Rapid Access Ice Drill (RAID) at the University of Minnesota.

**Table 1. Requirements of ice coring drills for scientific studies.**

| | Diam (cm) | Depth (m) | Ambient temp(C) | Clean coring ? | Transport type | Site occupancy | Int'l aspects | Drill Name |
|---|---|---|---|---|---|---|---|---|
| <200 years | 5-7 | Horiz. | -20 | yes | Backpack | Days | US | - |
| <200 years | 5 | 15 | -30 | sometimes | Backpack | Days | US | Hand auger |
| 200 year | 7-10 | 400 | -50 | no | Twin otter/ lt traverse | Days/ weeks | US | Eclipse, 4", Foro |
| 200 year | 7-10 | 400 | -5 warm ice | no | Twin otter/ lt traverse | Days/ weeks | US | Thermo-mechanical |
| 200 year | 7-10 | 400 | -15 | no | Ship/helo | Days/weeks | US or shared | Eclipse, 4", Foro |
| 2k array | 7-10 | <1,500 | -50 | sometimes | Twin otter/ lt traverse | Weeks/ month | US part of IPICS | 700 Drill, Foro 1650 |
| 40k array | 10+ | 1-3k | -50 | no | Twin otter/ Herc | 1-2 seasons | US or shared | Foro 1650, Foro 3000 |
| Interglacial | 10+ | 1-3k | -50 | no | Herc | Multiple seasons | US only or US-led | Foro 1650, Foro 3000 |
| >800k years | 10+ | 3k | -50 | no | Herc & traverse | Multiple seasons | IPICS | Foro 3000 |
| Site selection oldest ice | 2-4 | <1,000 | -50 | no | Herc & traverse | 2 days | IPICS | RAID |
| >800k years (blue ice) | 25 | 70-200 | -40 | no | Twin otter | 1-2 seasons | US | Blue Ice Drill |
| 1Ma Allan Hills | 10 | 1200 | -40 | no | Bassler / Herc | 3 seasons | US | FORO 1650 |
| Pre-Quaternary atmosphere | 7-25 rock-ice mix | 200 | -40 | no | Helicopter | 1-2 seasons | US | ASIG |
| Tracers; large diameter cores | 10-25 | $200^{+}$ | -40 | no | Helicopter/Basler/ Traverse | 1-2 seasons | US, Australia, France | Blue Ice Drill; 4" Drill |
| Ancient microbial life/ organic material | 25 | $200^{+}$ | -40 | sometimes | Helicopter twin otter, herc | 1-2 seasons | US | ScHWD |
| Borehole Array | 8 | 200 to 3.5k | -40 | no | Twin Otter/Lt Traverse | Week | US | RAID |

Additional information on the drills is given in the IDP Long Range Drilling Technology Plan.

## II. Ice Dynamics and Glacial History

Rapid changes in speed of fast-flowing tidewater glaciers, outlet glaciers, and ice streams observed over the past decade create an urgency to understand their dynamics. In West Antarctica, ongoing rapid loss of ice in the regions of Thwaites Glacier and the Amundsen Sea is occurring, with possible accelerated loss due to ocean-driven melting at the grounding zone and nearby areas (e.g., Smith et al., 2020). A complete retreat of the Thwaites Glacier basin and resulting release on surrounding ice in West Antarctica has the potential to eventually raise global sea level by several meters. It is possible that processes such as hydrofracture and ice cliff failure could lead to a more rapid collapse of Thwaites Glacier within the next few decades. Reducing uncertainty in the projected contribution of Thwaites Glacier to sea level rise requires substantial and coordinated collaborations involving a multidisciplinary, international scientific community. The Ross Sea sector of the Antarctic Ice Sheet, with its spatially diverse and changing natural environment, can facilitate process studies through field sampling and field measurements which will be used in evaluating the current state of the ice sheet, quantifying the glaciological and oceanographic processes that may play a role in rapid decay of the ice sheet, and interpreting past ice sheet changes from subglacial and ice-proximal geologic records to understand ice sheet sensitivity to forcing on different timescales. In general, predicting responses of glaciers and ice sheets to future possible environmental change requires models that incorporate realistic ice dynamics (Alley and Joughin, 2012). Ice loss on the Greenland Ice Sheet is also happening at a dramatic rate, and contains an additional 7.4 meters of sea level equivalent. Predicting dynamic ice loss of major ice streams in Greenland and Antarctica are major challenges to the international research community. For both the Antarctic and Greenland Ice Sheets, understanding the history of past ice sheet change is key for pinpointing ice sheet sectors most sensitive to change. Understanding the timing and extent of ice sheet response to the past interglacial, using evidence from within and beneath the ice sheet, will inform predictions of future changes. Measurements and observations of present-day conditions are needed to develop and validate such models, as are geological and geochronological observations of past ice sheet history and ice core evidence of past rates of change. Properties of the ice and the ice-bed interface exert strong control on the flow of glaciers and ice sheets. Instruments deployed down boreholes drilled to the bed are needed to collect basic data concerning the spatial and temporal distribution of ice properties, sediments, and subglacial hydrology.

Another approach to aid understanding of future ice-sheet response to local and global conditions is to reconstruct its history. Histories of ice dynamics (thinning and divide location) and environment (accumulation and temperature) can be inferred from observations from ice cores, basal ice samples, and boreholes near ice divides. Ice core and borehole data, including basal ice samples for gas analysis, depth-profiles of age, layer thickness, temperature, ice fabric, and bubble density all provide constraints for ice flow models. For example, the depth-age relationship contains information about past accumulation and past thinning; a thin annual layer at depth could imply either low accumulation in the past or ice sheet thinning (Waddington et al., 2005; Price et al., 2007). Radar-detected layers can also be used to infer the flow history of glaciers and ice sheets and the history contained in the layers is more complete if their age is known (Waddington et al., 2007, Dahl-Jensen et al., 2013); ice cores can be used to date intersecting radar layers. The high-quality radio echo sounding data from the Center for Remote Sensing of Ice Sheets (CReSIS) and Operation IceBridge both in Antarctica and Greenland make it possible to detect internal layers reaching to the bedrock. Disturbances, folding, and larger structures are observed that strongly influence the local ice dynamics and point towards the need for more complex and anisotropic ice deformation relations.

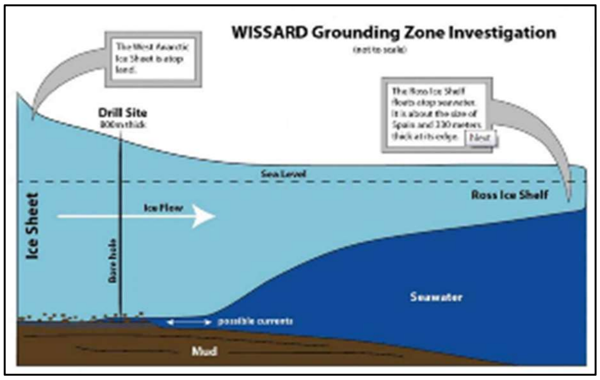
Specific observational data needed to improve and validate models of ice sheet response to environmental change include:

**1. Basal conditions and geothermal flux**: Direct measurements of bed conditions including frozen/thawed bed, basal pore water pressure, slip, and sediment properties and deformation are needed to develop and test realistic models of the controls on the fast flow of ice streams and outlet glaciers. Determination of whether a bed is frozen or thawed requires coupled thermo-mechanical flow models. A necessary boundary condition is a realistic realization of the geothermal flux. Geothermal flux has been determined at a few locations from borehole thermometry, but we expect the geothermal flux to vary significantly over spatial scales of less than 25 km (Fahnestock et al., 2001). In Greenland, borehole temperature reconstructions imply low values in south Greenland (<40 mW/m$^2$, values of 50 mW/m$^2$ at Greenland Ice Core Project (GRIP) and Camp Century and higher values at NEEM (80 mW/m$^2$) and North-GRIP (130 mW/m$^2$). Until recently the only measurement in West Antarctica was from Siple Dome (69 mW/m$^2$), but recent borehole temperature measurements from the WAIS Divide borehole indicate a geothermal flux of at least 90 mW m$^{-2}$ and possibly much higher (Cuffey et al., 2016). Measurements of ~285 mW m$^{-2}$ at Subglacial Lake Whillans were made (Fisher et al., 2015). Additional measurements are needed to provide boundary conditions for ice sheet models. Based on the data to date, geothermal flux values vary considerably throughout West Antarctica and further investigation is required to provide boundary conditions for ice sheet modeling.

Measurements at the bed of glaciers and ice sheets are hampered because of difficulties accessing the bed, and keeping boreholes open long enough to deploy sensors. Rapid-access drills that are portable and capable of drilling to the bed of glaciers and ice sheets multiple times within a several-month field season are needed to make basic measurements including temperature, heat flux, pressure, deformation, and slip, and to sample basal sediments and bedrock. The U.S. RAID drill may provide in this capability. Modular hot-water drills capable of cleanly accessing the bed through 500 m to 2,500 m of ice remain an urgent need. Logging tools to detect temperature, diameter, inclination, azimuth, and pressure are needed in connection with the production of ice boreholes.

**2. Remote sensing of basal conditions**: Remote sensing such as active and passive seismic arrays and radio echo sounding complement in situ measurements of bed conditions and englacial properties. Seismic imaging requires arrays of shallow holes for emplacing sources. The capability for producing large numbers of shallow holes (25 - 100 m depth, 5 - 10 cm diameter) should be maintained within IDP. The Rapid Air Movement (RAM) drill needs updates for increased portability, and increased efficiencies (drilling rate, reduced size, and power consumption) are needed to improve the agility of the RAM drill for creating shot holes.

**3. Sub-ice shelf mass balance**: Ice shelves buttress discharge from ice sheets and ice sheets grounded below sea level can become unstable after their buttressing ice shelves disintegrate in the Greenland and Antarctic ice sheets. Ocean temperatures control rates at which the ice shelves melt, and recent observations (Adusumilli et al. (2020), Schmidt et al (2023), Washam et al. (2023) and Lawrence et al (2023)) indicate that heterogeneous and small-scale oceanographic processes for sub-shelf melting exert significant control on the mass balance of ice sheets. Although measurements near the grounding line have been made and more are being conducted, coverage is still sparse. The melting process is determined by boundary layer physics that operate on spatial scales of centimeters. Access holes large enough for deploying instruments on moorings, autonomous underwater vehicles, and remotely operated vehicles are needed to acquire short-term spatially-distributed data. Additionally, long-term observatories at targeted sites are needed to document temporal variability. All these experiments should be directly related to grounding-zone studies and linked to oceanographic campaigns beyond the ice shelves.



Heat and mass exchange occurring in sub-ice shelf cavities impact ice flow and ice sheet mass balance. Image credit: *WISSARD project.*

**4. Grounding zone processes**: Improved understanding of processes in grounding zones is needed to holistically assess the role of ice-ocean interaction on the stability of ice sheets. Conceptual geological models of grounding-line environments have been inferred from stratigraphic successions, (e.g. Bart et al., 2017). Remote sensing studies using satellite observations and geophysical surveys have been conducted at grounding lines of major ice streams (Alley et al., 2007; Anandakrishnan et al., 2007; Christianson et al., 2013; Horgan et al., 2013), and studies of processes at modern grounding lines are underway. Records of environmental forcing relevant to grounding zone processes may be provided by 200+ yearlong ice core reconstructions at coastal Antarctic ice rises, and over WAIS since before the Eemian from an ice core at Hercules Dome. Few direct measurements or materials have been collected at grounding lines and grounding zones of fast-flowing ice streams and outlet glaciers (Begeman et al., 2018; Venturelli et al., 2020). Small diameter access holes are needed to deploy instruments to measure spatial and temporal changes in these critical areas. Shallow coring (~300 m) at Crary Ice Rise, Antarctica could provide a short (1000 year) record while also dating the timing of grounding at this site and possibly accessing marine ice-filled relic basal crevasses; this work is now underway as part of the international project: Sensitivity of the Antarctic Ice Sheet to 2 Degrees Celsius of Warming (SWAIS2C).

**5. Rheological properties of ice**: Rheological properties of ice depend strongly on temperature, impurities, and texture, including grain size and fabric (Cuffey and Paterson, 2010). Improved understanding of the controls on the rheology is needed to develop realistic models of deformation of ice sheets. These models are needed to help develop depth-age relationships in ice cores, understanding flow and shear, and also to establish past, present, and future responses to possible environmental changes. Folding of deep ice and large structures forming at the base of the ice are believed to be related to the rheological structure of ice. Studies at Siple Dome, Antarctica (Bay et al., 2001; Pettit et al., 2011,) and Dome C (Pettit et al., 2011), for example, have shown that strong vertical gradients in the effective viscosity of ice are likely present at depth in the ice sheets. These strong variations in ice rheology have the potential to lead to folding (such as at NEEM, Dahl-Jensen et al., 2013) or the formation of shear bands. Sensors that measure depth profiles of temperature, fabric, optical stratigraphy, tilt, and borehole diameter in boreholes are now available and can be calibrated against ice core properties. Rapid-access drills that can drill through ice up to 3,000 m thick are needed to deploy such sensors. In particular, the ability to drill multiple holes along a flow line can provide key spatial changes in ice properties. In addition, a system to rapidly access the ice sheet and then extract ice cores from selected depths would allow analyses of ice properties at depths of special interest; such a drill does not yet exist but should be planned.

**6. Glacial history**: Defining the extent and volume of ice sheets under paleoclimatic conditions warmer than the present (Mid-Holocene, Eemian, Marine Isotope Stages 11 and 14, and Pliocene warm periods in Greenland and Antarctica) is an important indicator of future ice sheet vulnerability. A variety of indirect approaches have been used to constrain the history of ice sheets (glacial geology, paleoceanography, etc.); dating the basal ice from the ice sheet that has moved across landscapes may help to inform constraints. Basal ice age can be modeled with age-depth flow models, or more directly by dating trapped air in basal ice. Slow-moving ice in the vicinity of ice divides contains a record of past ice dynamics (thinning and divide location). Depth profiles of age and temperature from ice cores and boreholes can be used to extract histories of accumulation and ice dynamics (Waddington et al., 2005; Price et al., 2007). Records from coastal domes and coastal ice caps are of special interest because they can be used to infer past extents of ice sheets and the history of deglaciation (Conway et al., 1999). Intermediate depth (~1,500 m) cores to measure depth-profiles of age and temperature at targeted coastal domes are needed to help constrain the deglaciation of ice sheets. Coring on ice domes near the Amundsen Sea Embayment, Antarctica may be able to provide a context for more recent observed changes in ice dynamics, particularly accelerated thinning in the most recent several decades.

Analysis of bed material (sediment or rock, in grab samples or in cores) is becoming a wide-open field in expanding our knowledge of glacial history and in characterizing past environments that drive ice sheet absence. For example, cosmogenic nuclides in sediment and bedrock beneath ice sheets can tell us about their former extent, and the timing and duration of past exposure periods (e.g. Schaefer et al, 2016; Balco et al., 2023). Techniques to estimate the size and shape of ice sheets during colder periods are well established (e.g., Mercer, 1968, Denton et al., 1989, Todd et al., 2010; Bentley et al., 2010; Stone et al., 2003; Hall et al., 2004; Anderson et al., 2014); determining their extent and thickness under warmer conditions is more problematic. Much of the evidence is hidden beneath the present ice sheets (e.g. Briner et al, 2022). Recovery of basal ice cores for gas analysis is useful when obtained in conjunction with analysis made in cores of basal material such as sediment and rock. Under shallow ice, nimble methods for reconnaissance recovery of short rock cores for cosmogenic nuclide techniques to quantify periods of exposure (ice free) and burial (ice cover) have been developed, for example the Agile Sub-Ice Geological Drill (ASIG) and ice-enabled Winkie drill for use near the ice margins (Boeckman et al., 2021; Kuhl et al., 2021; Braddock et al, 2024). Under very deep ice (greater than approximately 1,000 m), rapid access drilling using the RAID drill may open up new perspectives on ice conditions in a warmer world.

*Caption*: John Goodge and a colleague collecting specimens in the Transantarctic Mountains. Photo credit: *John Goodge/University of Minnesota-Duluth.*

Depth profile measurements on short (1-5 m) subglacial bedrock cores are used to confirm that cosmogenic nuclides were produced in situ, and identify surfaces that constrain subglacial landscape evolution by subglacial erosion (Balco et al., 2023; Balter Kennedy et al., 2021). Erosion reduces and ultimately erases the nuclide profile, so eroded surfaces must be avoided by targeting surfaces where ice is frozen to the bed. Note, however, that small amounts of erosion can be identified and the effects constrained using combinations of nuclides with different production profiles (Liu et al., 1994). With rapid access to subglacial bedrock in which cosmogenic nuclides can be measured, key problems can be addressed, such as the vulnerability of the West Antarctic, parts of the East Antarctic, and Greenland Ice Sheets to future warming, Pliocene ice-sheet collapse, and the onset of continental glaciation in Antarctica. Potential targets to address the interglacial extent of West Antarctic glaciation include Mt. Resnik, a subglacial peak which rises to within 330 m of the surface near the WAIS divide (e.g., Morse et al., 2002), ice rises particularly along the Siple Coast such as the Crary and Steershead ice rises (e.g., Scherer et al., 1998), the subglacial roots of nunataks (rocks emerging above the ice) in the Pine Island and Weddell Sea catchments. A variety of sites in Greenland including both interior sites (e.g., Schaefer et al., 2016) and peripheral sites and independent ice cap sites (Briner et al., 2022) would lead to impactful constraints on past ice sheet and sea level change. For example, targeting certain marine domains and areas bordering NEGIS would constrain past ice response in Greenland's most vulnerable areas. In addition, ongoing international studies of past ice thickness variations evidenced from multiple cosmogenic nuclides on nunatak altitude transects in Dronning Maud Land would benefit from future sampling of subglacial nunatak slopes. Data from beneath high-altitude domes and plateaus in the Transantarctic Mountains, and also from subglacial debris-rich ice from outlet glaciers that drain marine basin margins (e.g. Wilkes and Aurora basins), or from subglacial strata directly, could shed new light on the long-running debate over ice-sheet collapse in the Pliocene (e.g., Webb et al., 1984; Denton et al., 1993).

A variety of isotopes with varying half-lives (half-life: $t_{1/2}$) can be used to constrain long-term ice sheet stability (e.g., $^{37}$Cl, $^{26}$Al, $^{10}$Be), and new application of in situ $^{14}$C can constrain Holocene ice sheet changes. In Greenland for example, in situ $^{14}$C measurements from periphery ice drilling sites would provide ice sheet models with direct measures of ice sheet presence/absence during smaller-than-present ice sheet conditions during the Holocene thermal optimum. Eventually, measurements of long-lived radionuclides such as $^{53}$Mn ($t_{1/2}$ = 3.7 million years) and $^{129}$I ($t_{1/2}$ = 16.7 million years) paired with stable $^{3}$He and $^{21}$Ne may even provide constraints on the early Neogene onset of Antarctic glaciation, targeting samples from the subglacial Gamburtsev Mountains.

**Summary**

Understanding present and past behaviors of glaciers and ice sheets is essential for improving predictions of future behavior of ice sheets and sea level. Improved understanding requires fast-access drilling, such as those from the IDP Agile Sub-Ice Geological (ASIG) Drill, the IDP ice-enabled Winkie drill, the Rapid Access Ice Drill (RAID), and hot water access drills to enable fundamental measurements of: (i) physical conditions, including geothermal flux, and processes at the beds of glaciers and ice sheets; (ii) physical properties of the ice that affect ice flow and folding, (iii) physical processes at grounding lines and grounding zones of fast-moving ice streams and outlet and tidewater glaciers; (iv) ice-ocean interactions at grounding lines, and (v) analysis of subglacial bed material for records of ice sheet history. Past responses of glaciers and ice sheets and sea level changes also offer clues to future possible responses. Depth profiles of age and temperature from ice cores can be used to reconstruct past thickness and extent of ice sheets as well as environmental conditions. Basal ice cores in condition suitable for trapped gas analysis provide dating of the basal ice. Recovery of subglacial sediments that record paleo conditions and paleoenvironmental proxy information provide evidence of past conditions in area now covered by ice, including interglacial conditions that guide model projections of future warmth scenarios. Intermediate depth (~1,000 m) cores at targeted coastal domes are needed to constrain the extent and timing of deglaciation. For reconnaissance of sites for bedrock coring under shallow ice, the use of a very agile ice coring drill (e.g, Foro or Eclipse drill) along with a method of sampling rock at the ice-rock interface using the same or slightly modified drilling apparatus, would provide a logistically agile way of site selection for subsequent rock drilling of meters-long rock cores. The collection of basal ice cores for trapped gas analysis, and subglacial bedrock for cosmogenic nuclides from both strategic periphery sites and also from the ice sheet interior can provide direct constraints on past ice sheet history.

Table 2 below lists the characteristics required of drills for endeavors in subglacial science. The IDP Long Range Drilling Technology Plan discusses IDP drills available for retrieving cores or creating access holes in ice sheets. Note that the Clean Hot Water Drill (CHWD) in Table 2 is owned by the University of Nebraska-Lincoln (UNL). In addition to the CHWD, the following UNL drills may be available by direct request to UNL: the WISSARD/SALSA clean access drill, the Roving Drill, and Shot-hole Drill.

**Table 2. Requirements of drills needed for studies of ice dynamics and glacial history.**

| | Diam. (cm) | Ice Depth (km) | Core or hole | Ambient temp (°C) | Clean access? | Transport type | Site occupancy | Int'l Aspects | Drill Name |
|---|---|---|---|---|---|---|---|---|---|
| Bed conditions | 8 | 1-3 | Hole | -50 | maybe | Twin otter/ helo/lt traverse/Herc | <4 weeks | US & others | CHWD |
| Geothermal flux | 5-8 | 1-3 | Hole | -50 | no | Twin otter/ helo/lt traverse/Herc | <4 weeks | US & others | RAID |
| Geologic coring for cosmogenic samples and for basal ice samples | 6-10 | 0.1-2.5 | Basal ice core, Rock core | -50 | no | Helo sling load/ Baseler/ traverse | 4-8 weeks | US | Winkie/ASIG / RAID |
| Nimble geologic coring and basal ice coring under shallow ice | 3-5 | <.5 | Basal ice core, Rock core | -30 | no | Twin otter/helo/ lt traverse | <4 weeks | US | Winkie/ ASIG |
| Rheological properties | 8 | <3k | Hole | -40 | no | Herc/ traverse | <4 weeks | US & others | RAID/ CHWD |
| Internal layering | 8-10 | <3k | Hole | -40 | no | Herc/ traverse | <4 weeks | US & others | RAID/ CHWD |
| Sub-ice shelf/ice stream instrumentation | 10-25 | <1k | Hole | -30 | shelf-no; stream-yes | Twin otter/ helo/ herc/ traverse | 2 weeks | US & others | CHWD/ ScHWD |
| Ice shelf ROV deployment | 100 | <1k | Hole | -30 | no | Twin otter/ helo/Herc/ traverse | 2-4 weeks | US & others | CHWD/ ScHWD |
| Grounding zone | 8-75 | <1k | Hole | -30 | no | Helo/Herc/ traverse | 2 weeks | US | CHWD/ ScHWD |
| Seismic imaging | 5-10 | ~100 m | Hole | -40 | no | Twin otter/ helo | Hours/days | US | RAM/ SHWD |

## III. Subglacial Geology, Sediments, and Ecosystems

Bedrock, sediments, and ecosystems existing within and beneath ice sheets remain largely unexplored primarily because of a lack of logistical access to work in the deep field, and also because additional drilling technologies are required. Rapid access to subglacial environments is needed to address a wide range of science questions. Specifically:

**1. Bedrock geology**: The Antarctic continent and its lithospheric plate, play important but poorly understood roles in global tectonic architecture, leading to contradictory hypotheses. Antarctica is considered aseismic, but if so, it would be unique among all of the continents. Its plate is surrounded by mid-ocean-ridges, and hence should be under compression, yet there are active extensional regimes. The West Antarctic Rift System is one of the largest on Earth, and currently known attributes are unique, by having only one rift shoulder and by being largely below sea level. In Greenland, island-wide geophysical datasets have recently been synthesized to map the boundaries between first-order geological provinces beneath the ice sheet (MacGregor et al, 2024). Recovery of bedrock samples is essential to ground-truth these geophysical inferences, particularly in geological provinces with no known surface outcrop. Fundamental questions about bedrock beneath both the Greenland and Antarctic Ice Sheets persist. What is the origin of subglacial mountain ranges and how have they influenced the overlying ice sheet? What are the composition, geothermal heat flux, and geotectonic histories of Antarctica and Greenland, and how do they influence ice sheet behavior? What were the dominant factors controlling the spatial extent and temporal variability of ice sheets during warm periods in the past? What is the role and history of subglacial sediments in the interior? What are the physical conditions at the base of the ice sheets? The state of stress in basement rocks is required for evaluating seismicity and extensional regimes. Boreholes through the ice into crustal rocks are needed to conduct passive and active seismic experiments for delineating crustal structure. Continental topography is a significant control on glaciation; rising mountains and higher elevations focus snow accumulation and become nivation centers for ice sheets. Sampling bedrock to determine its age and constrain its cooling history using thermochronology is important for supercontinent reconstruction, understanding the tectonic history of the continent as well as reconstructing paleotopography for glaciological modeling of ice sheet history. Access boreholes to the ice sheet bed are required to recover short rock and sediment cores for these studies. Locations should be based on best estimates of bedrock geology, bed paleotopography, and plausible ice sheet extents based on models. In Greenland, the ice sheet has waxed and waned during the last 2.5 million years. Erosion of mountains and ice sheet modeling has simulated past changes, but access to old ice and basal rocks/material is needed for verification and full understanding.

**2. Subglacial basins and sedimentary records**: The records of glaciation and their variations in Antarctica are found in scattered terrestrial deposits and sedimentary basins and can be compared with offshore records that have been collected near the margins. Interior subglacial basins also likely contain proxy records of paleo conditions and ice sheet history to complement these records from the continental margins. Four main categories of sedimentary targets are: subglacial lakes, ice rises, West Antarctic sedimentary basins, and East Antarctic marine and terrestrial basins. Each category may have a variety of origins and histories because of differing locations relative to the ice sheet margin and magnitudes of past ice sheet fluctuations. Thus, they may provide valuable archives of paleo-ice sheet and paleoclimatic changes. Subglacial lakes occur throughout the continent, the largest being subglacial Lake Vostok. Subglacial lakes contain sedimentary records; sediments have been collected at the

Whillans Subglacial Lake (Hodson et al, 2016), and Mercer Subglacial Lake (Rosenheim et al., 2023; Siegfried et al., 2023).

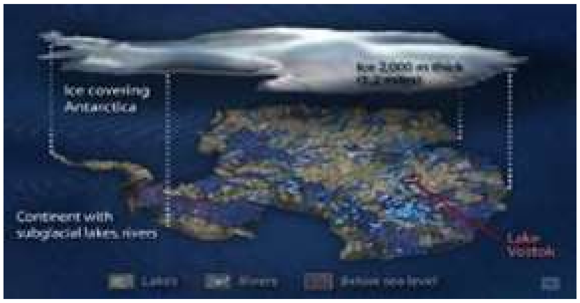



Illustration showing the aquatic system that scientists think is buried beneath the Antarctic ice sheet. Photo credit: *National Science Foundation, Photo Gallery.*

Subglacial ice rises can cause locally grounded "pinning points" that play an important role in buttressing the discharge of streaming ice from the ice sheet. Recovery of these sediments will provide Neogene and Quaternary paleo-environmental archives, but may also provide insights on till deformation processes downstream of ice streams. Shallow drilling of ice rises and acquisition of over-snow seismic reflection profiles radiating away from ice core sites will allow the deeper geometry of the strata to be evaluated for locating future drill sites for recovery of long, continuous records in adjacent marine basins. In West Antarctica, the stratigraphic record in various basins and probable rifted grabens may contain a mid-late Mesozoic and Cenozoic history of West Antarctic evolution and paleo condition history. Recently, Mengel and Levermann (2014) suggested that only a narrow, low coastal rim holds the portion of the East Antarctic ice sheet overlaying the Wilkes Subglacial Basin back, raising concern about ice sheet stability. In Northwest Greenland, airborne geophysical data have been used to infer the presence of subglacial sediments deposited in a lacustrine environment (Paxman et al, 2021). Accessing these sediments via subglacial drilling would enable the recovery of valuable archives of past environmental conditions and ice sheet history, as has been achieved elsewhere in the Arctic (Melles et al, 2012).

Access holes are also needed to recover longer sedimentary cores comparable to those from the continental margins. Also, the basins on the interior of the Transantarctic Mountains may be sites for good proxy records of past ice sheet dynamics. These are also excellent sites to measure geothermal heat flux to help constrain ice sheet bed conditions.

**3. Sub-ice microbial ecosystems and biogeochemistry**: Aqueous and sedimentary subglacial environments in Antarctica and Greenland are inhabited by microorganisms (e.g., Christner et al., 2014; Dubnick et al., 2017; Davis et al., 2023) and are a potentially large planetary reservoir of microbes and (microbially derived) organic carbon, perhaps of the same magnitude as that in the surface oceans. Modeling and direct measurements (Wadham et al., 2012; Michaud et al., 2017) suggests these environments could contain large volumes of the greenhouse gas, methane, which could greatly impact atmospheric concentrations in response to rapid deglaciation. It has also been hypothesized that the flux of dissolved elements and sediments in subglacial waters can enhance primary productivity in the marine environments they drain into (Hawkings et al., 2020; Vick-Majors et al., 2020). Elucidating the spatial and temporal distribution and dynamics of these aqueous environments, including their physical and chemical properties (such as temperature, salinity, and pressure) and associated biogeochemical processes (i.e., microbial communities and organic carbon material fluxes) are key to understanding ice sheet stability and the role of large continental ice sheets in global biogeochemical cycles. The rapid changes anticipated in the size of polar ice sheets may trigger significant reorganization of subglacial hydrologic conditions, which may feed back into acceleration of ice sheet retreat; the increased influx of subglacial water and microbial products into marine systems would further amplify these influences (Vick-Majors et al., 2016).

The long timescale of microbial entrapment in sub-ice environments relative to the lifetimes of microbial cells provides an opportunity to explore questions concerning rates of evolution, and constraints on biodiversity. The timing of microbial isolation from mixing with the 'surface' biosphere can inform how long an ice mass has existed. Microbial cells and their genomic material should also provide valuable information that can be linked to paleoclimatic change; such life forms may be the only biological survivors in areas covered by glaciations for millions of years. Icy systems on Earth also may provide crucial terrestrial analogs for extraterrestrial life surviving and persisting on icy planetary bodies in our solar system, such as Mars, Europa, or Enceladus. Of particular interest is the distribution and ecological function of the resident microbes, the extent to which biogeochemical weathering occurs, and the genetic diversity of microbial communities in subglacial lakes and sediments.

Furthermore, the forward motion of thick layers of water-saturated till beneath fast-flowing ice streams may provide a pathway for transportation of subglacial biological and diagenetic materials and weathering products to the surrounding ocean, as does the movement of debris-rich basal ice. The deep subglacial sediments may contain abundant microbial communities. Some subglacial meltwater is also transported over long distances within basal drainage systems, which again, likely discharge subglacial nutrients, microbes and their metabolic products into circum-Antarctic seawater. Biologically clean access holes through the ice and the acquisition of basal ice cores are needed for this science, and, for scientific and environmental integrity, these studies must be conducted with clean technology both during access and sample acquisition. This science is progressing and solutions to the logistical and drilling challenges for working in the deep field in Antarctica need to be addressed.

Microbial ecosystems have been found under the West Antarctic Ice sheet (Christner et al., 2014).

**4. Subglacial lakes and hydrological systems**: Subglacial hydrodynamics are an important yet poorly understood factor in ice sheet dynamics in both Antarctica and Greenland. The volume and distribution of water exert strong influences on the resistance of the bed to ice flow and therefore, is an important control over ice velocities. More than 400 subglacial lakes have been discovered in Antarctica. Measurements to quantify present-day lakes and subglacial hydrological systems are important for understanding ice dynamics, weathering and erosion of subglacial rock, sediment transport and jökulhlaup events (glacier-dammed lake outburst flood) and microbial ecosystems. Of particular interest is to establish the diversity of life in subglacial lakes, the degree of hydrological interconnectivity between lakes and the Southern Ocean, and their influence on the rest of the subglacial hydrological system. The lakes also house sedimentary evidence of ice sheet and geological histories and changes. Access holes and the ability to collect samples of water and sediments are necessary to understand these systems. In addition, data from Subglacial Lake Whillans suggests that in active hydrological systems, water geochemistry, microbial life, and hydrology are intimately connected (Vick-Majors et al., 2016), as in many other terrestrial and marine biospheres around the world. Understanding the temporal dynamics and geochemical ramifications of subglacial processes requires installation of sensor strings capable of collecting subglacial hydrological data including dissolved oxygen concentrations, current velocity and direction, and salinity.

Russian drillers accessed Subglacial Lake Vostok, Antarctica during the 2011-12 season, and then during 2012-13 successfully recovered an ice core (~30 m) of the frozen lake water that entered the borehole the year before. Hot water drilling at Lake Whillans, Antarctica included a filtration unit and UV-treatment system to decrease contaminants in the drilling water and provide clean access to the subglacial environment (Priscu et al. 2013), and it was used again to access Subglacial Lake Mercer in 2019 (Priscu et al. 2021). The filtration technology was successful at reducing microbial bioload and other contaminants in the drilling fluid as per the Antarctic Treaty Code of Conduct.

## Summary

Subglacial environments contain biologic, climatic, geologic, and glaciologic materials and information, much of which cannot be obtained elsewhere. Drills to create access holes are urgently needed to sample basal ice, subglacial water and sediments, and bedrock, but are notably missing from our capabilities within the IDP. Hole diameter requirements vary depending on instrumentation needed; clean technology is required (NRC, 2007), as is strict environmental review where the bed is wet, except for ice shelves and grounding zones at the end of drainage basins. Successful sampling will require that access holes receive regular maintenance, allowing the holes to remain open for several days. Differential ice motion may be a complicating factor, especially if the ice sheet is sliding at the bed. Given the logistical challenges in working in the deep field, modular hot water drilling technology and also technologies for sampling through ice boreholes should all strive to minimize the supporting logistical requirements.

The desired characteristics of the drills needed to create clean access holes for the science of the sub-ice environment are provided in Table 3. For accessing sensitive targets such as subglacial lakes, hot water drills should have temperature and depth sensors and “smart” drill heads; this technology needs to be developed. For the drills in Table 3, The IDP Long Range Drilling Technology Plan discusses hot water and mechanical rapid-access drills that could provide clean access holes for the projects described above in this report. Clean mechanical rapid-access drills do not currently exist; conceptual and engineering development is needed. Note that CHWD is the Clean Hot Water Drill owned by the University of Nebraska-Lincoln; in addition, the University of Nebraska-Lincoln owns the following drills that may be available by request directly to the university (D. Harwood): the WISSARD/SALSA clean access drill, the Roving Drill, and Shot-hole Drill.

**Table 3. Requirements of drills needed for studies of subglacial geology, sediments, and ecosystems**.

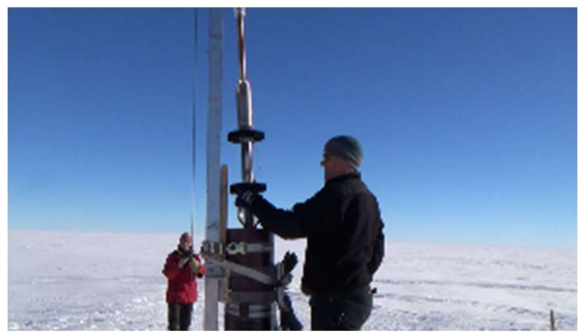
| | Diam. (cm) | Depth (km) | Core or hole | Ambient temp (°C) | Transport type | Site occupancy | Int'l aspects | Environ restrictions | Drill Name | |
|---|---|---|---|---|---|---|---|---|---|---|
| Sediments/ice sheet dynamics (Wet bed) | 10-25 | 0.2-3 | Hole, sediment core | -50 | Helo/Twin Otter/traverse/Herc | weeks | U.S. & others | Clean access | CHWD/ ScHWD | |
| Biogeochem (Wet bed) | 3-25 | <3 | Hole, sediment/rock, basal ice core | -50 | Helo/Twin Otter/traverse/Herc | weeks | U.S. & others | Clean access | CHWD/ ScHWD | |
| Bedrock geology/ Tectonics (Frozen bed) | 5-10 | 1-3 | Icehole, rock core | -50 | Herc/traverse | 4-8 weeks | U.S. | None (dry bed only) | RAID/ ASIG | |
| Geology/ ice sheet history (Wet bed) | 5-20 | <4k | Hole, rock core | -50 | Herc/traverse | weeks | U.S. & others | Clean access | - | |
| Deep Subglacial lake biogeochem (Wet bed) | 50-100 | 3-4k | Hole, sediment, basal ice core | -50 | Herc/TwinOtter /traverse | 4-8 weeks | U.S. & others | Clean access | CHWD | |

## IV. Ice as a Scientific Observatory

Polar ice sheets and mid-latitude ice caps archive evidence of the past and ice dynamics and also serve a variety of endeavors that use the ice as a platform for science. Borehole access to the interior of the ice sheet enables wide-ranging observations, from glaciology, climatology, and planetary science to experimental astroparticle physics.

**1. Borehole logging for past conditions and ice dynamics:** Borehole logging of both fast-access holes and boreholes originally drilled for ice cores greatly enhance evidence of the past and ice dynamics preserved in the ice. These analyses are difficult or impossible to obtain by other methods, and complement observations from ice cores and remote sensing platforms. Borehole logging is nondestructive, non-contaminating, continuous, and immune to core damage or drill depth errors and permits study of a large volume of ice in situ. Ice sheet boreholes serve as enduring scientific observatories. For example, borehole paleothermometry probes provide the most direct measurement of temperature histories and can be used to calibrate other paleoclimatic indicators. Optical borehole probes can rapidly obtain stratigraphic records, which are more coherent and detailed than can be reconstructed from core measurements. Borehole sonic loggers can provide continuous records of ice fabric that are difficult or impractical to obtain using thin sections of core. Repeated measurements of fabric, tilt, and hole deformation improve modeling of ice sheet behavior and stability over time as an ice sheet flows over uneven terrain. Logging multiple nearby rapid access holes permits advanced studies of past conditions and ice flow.

**1.1 Winches:** Winch platforms that can support borehole-logging projects are important community resources. IDP has three winches in inventory, one for intermediate depth (1.5 km) and two for deep (4 km) applications. IDP has adopted a standard wireline for all community winches, a 3/16" four-conductor armored oil-patch cable with a 1" Gearhart-Owen cable head. IDP has also established a policy of deploying a trained operator to the field along with the IDP winches, particularly the deep winches. Although this cost is not directly reflected in proposal budgets, a cost estimate is included with each proposal requiring IDP resources, for NSF budgeting purposes, as is the case with ice and rock coring drills. In certain cases, the PI or members of the PI's team may be trained and certified to operate the winches, particularly the intermediate depth winch.



Ryan Bay and Elizabeth Morton deploy borehole-logging instruments at Siple Dome, Antarctica. Photo credit: *Joseph Talghader.*

Pre-deployment winch telemetry testing of all logging tools is essential for successful fieldwork. Whenever possible, logging tools should be tested over the winch that will be used in the field. In some cases IDP leaves winches deployed to save logistical cost and effort, and tools must instead be tested on winch-cable systems that are electrically similar.
Pressure testing of new borehole tools prior to deployment is performed at an IDP facility in Madison, Wisconsin. IDP maintains a pressure chamber for testing tools up to pressures of 6 kpsi. The chamber is approximately a 3-meter cylinder with an inside diameter of 25.4 cm. Pressure testing is especially important with Estisol-140 drill fluid, since it is more aggressive than other drill liquids and even small leaks may damage internal components.

**1.2 Borehole preservation:** Where practical, drilling practices and materials should be chosen to produce and maintain clean uniform boreholes, and to keep the boreholes accessible. Anticipated failure modes of glacial boreholes include:

- “Natural” end-of-life borehole collapse: Depending on the strain regime, complete collapse of even a borehole fully compensated with fluid occurs over years and is largely unavoidable.
- Borehole collapse due to removal or failure of borehole casing**:** Premature collapse can be avoided by leaving the casing in place, proper casing design, and maintenance.
- Borehole burial: Burial of borehole casing by snow accumulation.
- Ice plug: An ice plug can form at the fluid level when a partial casing failure permits snow and ice to accumulate in the well.

Over time borehole-drilling fluids can become turbid, degrading optical measurements. Best practices should include avoiding the introduction of substances such as heavy greases in the borehole, and materials that can be dissolved by solvents used as drill fluids. IDP also provides towers and sheave wheels needed for borehole access. The IDP Englacial and Subglacial Access Working Group aims to work with community scientists to develop a strategy to make best use of available boreholes.

**1.3 Recent logging projects: WAIS Divide:** Several groups have logged the WAIS Divide ice core borehole in the 2014 to 2017 time frame. Measurements included temperature, optical, and seismic profiling, and an acoustic caliper along with a kHz acoustic fabric logger for the kHz range. WAIS Divide drilling included five replicate coring deviations and this logging activity was the first to be done in a borehole with deviation channels. The Replicate Coring System for the DISC drill was designed in order to make all deviations on the uphill side of the main borehole, so that logging tools naturally follow gravity and remain within the parent channel. The deviations did affect logging data and some issues were encountered while passing the deviations, in particular the acoustic logging tool was diverted into the side channel at the deviation with the most borehole damage near 3,000 m, but accessed the main borehole on a following attempt. Three other logging tools followed the main borehole and passed all deviations without incident. The deviation drilling and subsequent borehole logging at WAIS Divide was largely successful.

**South Pole Ice (SPICE) core:** The Foro 1650 (aka Intermediate-Depth Drill) was deployed to the South Pole for the 2014-15 and 2015-16 field seasons, successfully collecting 1,751 m of ice core. The SPICE Core borehole is pressure compensated by Estisol-140, which has caused convective problems in temperature logging because of its high viscosity. Estisol-140 has also exhibited a tendency to cloud, which could affect optical logging. The SPICE core project is a benefit to ongoing South Pole in-ice particle physics projects, by providing ground truth measurements of ice chemistry, fabric, and particulates for characterization of optical, radio, and acoustic signal propagation. Due to the proximity of the drill site to the IceCube and ARA arrays, the borehole continues to serve as an access point for calibration of existing and future South Pole in-ice physics and astrophysics experiments.

**Rapid Access Ice Drill (RAID):** The RAID drill can penetrate deep ice sheets and core small samples of ice and subglacial basal rock material (Goodge & Severinghaus, 2016), and it recently demonstrated capability for ice borehole logging (Goodge et al., 2021). RAID can produce 3-5 boreholes every season, and these boreholes will potentially serve as scientific observatories for the study of ice and records of the past. RAID will require a dedicated logging winch integrated with the drilling platform, capable of reaching 3,000 m for logging immediately following borehole cutting. Measurement of pressure will ensure that the borehole is properly compensated and optical dust logging will provide immediate verification of the depth-age model. Additional measurements could include temperature, diameter, borehole inclination/trajectory, and a camera. It would be desirable to rapidly log temperature and borehole diameter immediately after drilling, possibly at the same time as the optical dating. These preliminary readings could form baselines for subsequent measurements and time evolution studies. Infrastructure will be needed to manage future borehole logging projects that will make use of RAID boreholes.

**RAID borehole instrumentation and preservation:** RAID has the potential to create many deep boreholes over a number of years. Instrumenting and preserving every RAID borehole indefinitely is impractical. The RAID project, with englacial and subglacial research community, will need to determine the scope of instrumentation and preservation efforts. The science goals and the number of holes to instrument, preserve, the priority of holes and the duration of the effort will need to be weighed against cost and availability of logistics.

Borehole preservation effort could be separated into short-term (<5 years) and long-term time horizons. Preservation of each RAID borehole for 3 - 5 years will allow for repeat measurements, particularly in studies of borehole temperature and deformation. Uncased and under-balanced boreholes could be of interest for deformation studies, although removal of the casing and fluid head will limit the lifetime of the borehole to a few years.

RAID may also select a subset of holes for long-term preservation, to serve as observatories and to allow for future technology developments. Preservation would require leaving a sturdy casing in place, maintaining, and periodically extending the casing above the snow surface, as well as removal of ice plugs when necessary. Holes near ice divides could be kept open for decades in principle. In off-axis zones, shearing could severely limit borehole lifetime and closure may occur at discrete depths. In higher accumulation areas, it may be possible to use an extended casing supported by a lightweight tower to relieve maintenance effort. Qualifying tools (borehole diameter, inclination/trajectory, camera) could be useful for assessing borehole condition prior to fielding a more substantial logging mission. Holes selected for long-term preservation would likely be chosen to form a geographically diverse set.

**1.4 Borehole qualifying:** IDP does not currently maintain logging tools for verifying borehole parameters such as inclination, diameter, depth, roundness, temperature, etc. There is growing consensus in the logging community that IDP should develop this capability. A hole qualifying system could be deployed each season as a hole is drilled or upon hole completion. The information provided by such a logging system could be crucially important for drillers, particularly for drills with little or no down-hole sensing capacity, such as the Foro 3000, the Foro 1650, or the RAID. These logging measurements could also provide a baseline for longer-term borehole deformation studies.

**1.5 Borehole Allocation Committee:** The IDP Englacial and Subglacial Access Working Group (ESAWG) will be exploring formation of a special committee to advise IDP on management of community borehole resources as the research community continues to grow. These resources include winch and winch operators, logging tools and accessories, and borehole time. Pre-deployment reviews of logging projects, with participation by IDP engineers, will ensure that new tools are safe and ready to deploy.

**2. Ice as platform for physics and astrophysics**: Substantial efforts are under way to use glacial ice as a platform for study of fundamental physics and astrophysics. These experiments make use of polar ice as an abundant, clean, stable, low-background and transparent (to radio and optical waves) detection medium for observation of sub-atomic particle interactions.

**The IceCube Neutrino Observatory** (icecube.wisc.edu) uses the glacial ice sheet at the South Pole to detect the optical signals generated by high-energy neutrinos traveling to Earth from cosmic sources and interacting in the ice. The observatory includes over 5000 photo sensors instrumenting 1km$^3$ of clear ice down to 2.5 km depth. The Enhanced Hot Water Drill (EHWD) was developed for IceCube as a powerful, fast access drill capable of creating 2,500m deep, half-meter diameter boreholes at a rate of about three per week.

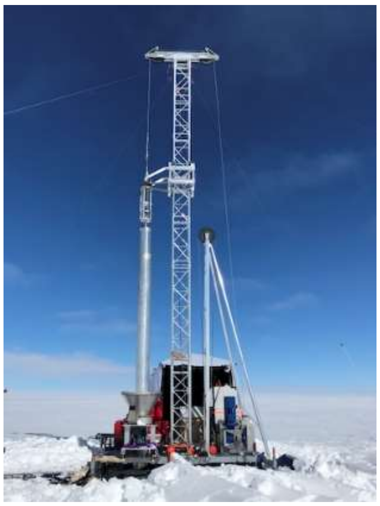
*A Digital Optical Module (DOM) is lowered into a hole in the ice at Amundsen-Scott South Pole Station for the IceCube project. IceCube detects neutrinos from distant astrophysical sources. Photo credit: Ethan Dicks, National Science Foundation.*

An upgrade to the IceCube detector, known as "the IceCube Upgrade", will add seven highly instrumented strings at the center of IceCube, and is planned for the South Pole field season 2025-26. The scientific objectives of the IceCube Upgrade include the study of fundamental properties of neutrinos (such as neutrino flavor changes and mass hierarchy), precision calibration of IceCube sensors, and a refined measurement of the optical properties of the ice. The Upgrade geometry will have inter-string spacing of ~20 m and three meters of vertical spacing between sensors at the most densely instrumented depths of the array. This detector will include a variety of sensors and calibration devices to take advantage of the large boreholes reaching a depth of up to 2650 m. Hot-water drill upgrades, aimed at improving the optical clarity of the refrozen water column, will include filtration of large-particle impurities and cold reaming to avoid bubble formation.

**IceCube-Gen2** is a proposed very large expansion for future Antarctic neutrino astronomy that includes an upgraded optical array, a surface array, and a radio detector array. With 120 additional strings 250 m apart, the optical array for IceCube-Gen2 will increase the effective volume of IceCube by an order of magnitude, while only doubling the amount of in-ice instrumentation. This expanded array will improve the detection capability in the PeV energy range by an order of magnitude and provide high statistics samples of extraterrestrial neutrinos, for better characterization of source distribution, spectrum and flavor composition. The IceCube-Gen2 radio array will expand the footprint of IceCube to cover 500 square kilometers with shallow and near-surface deep antennas. Presently, the ARA experiment at South Pole and the RNO-G experiment at Summit Station in Greenland use radio antennas to search for radio signals generated by neutrinos at ultra-high energies beyond 10 PeV.

IceCube-Gen2 will require improvements to the EHWD, including a more mobile and efficient hot water plant, and a modular sled-mounted drill system, which is less complex and requires a smaller operations crew. The radio array will require rapid drilling of 6-11" diameter holes to near surface depths of 150 m and the associated technology and engineering support. Detector stations will be spaced 1.25 km apart in a rectangular grid spaced away from the South Pole station along a power and communications backbone.

**ARA** currently consists of 5 stations with five strings of sensors deployed to 200 m. Due to its proximity to the IceCube and ARA detectors, the SPICE core borehole serves as an access point for calibration beacons or standard candles, as part of the South Pole facility and infrastructure. Calibration beacons can be operated at multiple depths and hence probe different ice temperatures, densities, fabrics and impurity levels. Targeted calibration campaigns allow for measurements that have implications for radio and optical detection of high-energy neutrinos and provide opportunities for basic glaciology research. In the future, radio-illuminating beacons could provide signals in the 100 - 1,000 MHz frequency range out to a radius of 20 km, thus permitting studies of neutrino detection over areas up to 1,000 $km^2$, and also help in understanding anomalous features seen in ice-penetrating radar surveys.



*The Big Rapid Access Isotope Drill (British Antarctic Survey) is set up for drilling for the Radio Neutrino Observatory in Greenland (tent cover not shown). Photo courtesy of Delia Tosi.*

**RNO-G** is currently in construction in Greenland with plans to instrument 40 $km^2$ using 35 stations. Seven stations have been deployed over the 2021 and 2022 summer field seasons. Each station includes three holes, drilled down to a nominal depth of 100 m, with the possibility of up to 200 m holes used for instrumentation in-situ calibration. In addition, three slots, three meters deep, are required for antennas deployed just below the surface. By using multiple probes in the same boreholes, it will be possible to link the firn density profile with its electromagnetic properties, improving our understanding of the ice properties. Drilling is conducted with the BigRAID (Big Rapid Access Isotope Drill) setup on a sled along with integrated weather sheltering. This drill is designed for fast access by removing ice chips from the hole, with no core extracted. The 11-inch holes are used for radio antennas to detect the radio pulses from high energy neutrinos. Field work over three to four Arctic summer seasons has been proposed and funding has been secured for the instrumentation.

**3. Seismic studies**: The Global Seismographic Network includes seismic monitoring stations for earthquakes and other events such as emissions from calving and sliding glaciers and ice sheets. The South Pole Remote Earth Science and Seismological Observatory has seismic equipment installed ~300 m deep within boreholes. Two additional low noise seismometers, developed by USGS, will be installed at 2400 m depth as part of the IceCube Upgrade and that will augment South Pole long period seismological observations. A similar remote observation network is planned for Greenland.

**4. Ice sheet as an archive of recent past atmospheric composition**: In the very cold areas of ice sheets where snow rarely melts, many decades of snowfall create a porous network of firn in the top many tens of meters of the ice sheet. The firn serves as an archive of atmospheric composition, with the oldest air existing at depth. Sampling firn air from various depths within boreholes drilled in the ice sheet enables, for example, observation of the patterns and extent of anthropogenic emissions

**5. Exploration of basal ice formation processes**: Radar imaging of basal conditions under the Antarctic and Greenland ice sheets reveals structures that have been proposed to result from accretion ice grown onto the base of the ice sheet. In order to acquire the ice to test this hypothesis, drilling at sites in Greenland, or near Dome A in East Antarctica, could access these ice features with the 1,500 m Intermediate Depth Drill.

**6. Meteorite collection**: Glaciers and ice sheets are sites for efficient collection of meteorites and micrometeorites. Micrometeorites yield clues to the origin and evolution of the solar system. Some are visible to the human eye on the surface of some blue ice areas, while others may be swept up inside melted water wells created in the ice at established field stations.

**Summary**

Ice sheets serve as a platform for a wide range of observations spanning many areas of science. In some areas, for example, firn-air studies and seismic monitoring proven-drills already exist for making the necessary access holes. Dedicated hot water drills have proven to be effective in creating deep boreholes in rapid succession. Other areas are at an early stage and will require further development of RAM drills or reverse circulation drills. A rapid access drill, with the capability to bore through several kilometers of ice to retrieve rock cores is nearly ready for deployment. The borehole logging community is a strong proponent for repairing and maintaining boreholes at Greenland Ice Sheet Project 2 (GISP2) site at the Summit site, at Siple Dome, Antarctica, and other sites. Identifying which boreholes need maintenance, prioritizing those with highest scientific value for future logging, and determining methods of repair are activities that need urgent attention. The IDP Englacial and Subglacial Working Group will prepare a list of boreholes in the U.S. program and will work with the community to create a prioritized list to be preserved for science.

## Science Planning Matrices

Goals to advance the frontiers of the science in ways that enable evidence-based decision making and that inspire the next generation of scientists are described in the previous sections of this report. Community planning for the execution of the science is important for providing coordinated scientific investigations, and also for planning the associated logistical and funding requirements. For each area described above, Tables 4 through 7 identify the current plans for timing of the field research. In cases where new technologies are needed, a timeline for the development of technologies is provided. Black font in a matrix indicates projects that are currently funded, and blue font indicates those in the scientific planning phase.

In Tables 4 to 7 below, the notation denoting specific drills to be used are: A: Agile sub-ice geological drill; b: Badger-eclipse; B: Blue ice drill; f: Foro 400 drill; F: Foro 3000 drill; I: Intermediate depth drill (Foro1850); L: Borehole logging; Lt: Logging tower; R: RAID drill; r RAM drill; Sc: Clean Scalable hot water drill; S: Stamphli drill; T: Thermomechanical drill; U: UNL CHWD drill; W: Winkie drill; 4: 4" drill; 7: 700 m coring drill, x: hand auger, sidewinder, or prairie dog.

### Table 4: Past Changes Planning Matrix 2025-2035

| | 2025 | | | | 2026 | | | | 2027 | | | | 2028 | | | | 2029 | | | | 2030 | | | | 2031 | | | | 2032 | | | | 2033 | | | | 2034 | | | | 2035 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Past Conditions** | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 |
| **Industrial period and glaciology** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| AON Greenland firn[1] | | x | x | | | x | x | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Paleo climate in alpine ice patches[2] | | x | x | | | x | x | | | x | x | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Utquigvik permafrost[3] | | x | x | | | x | x | | | x | x | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Taylor Dome firnification[4] | | | | b | b | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Meltwater Flask Glacier[6] | x | | | x | x | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Seymour Island[5] | | | | x | x | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Summit Ice[7] | | | | | | x | x | | | x | x | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Dye-2 Firn Evolution[4] | | | | | | x | x | | | x | x | | | x | x | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| RNO-G[12] | | | | | | 4 | 4 | | | 4 | 4 | | | 4 | 4 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Summit black carbon[2] | | | | | | | | | | | | | | x | x | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **Pre-industrial baseline & dynamics** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Eclipse Icefield Canada[8] | | | | | | | | | | s | s | | | 7 | 7 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Alpine 14ky record France[9] | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Summit Greenland Holocene[13] | | | | | | | | | | | | | | | | | | | | | | I | I | | | I | I | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **Large scale global climate change** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| *Hercules Dome[10]* | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Ice coring at Herc Dome | | | | | | | | F | F | | | F | F | | | F | F | | | F | F | | | | | | | | | | | | | | | | | | | | | | | |
| Replicate coring at Herc Dome | | | | | | | | | | | | | | | | | | | | R | R | | | | | | | | | | | | | | | | | | | | | | | |
| Borehole logging at Herc Dome | | | | | | | | | | | | | | | | | | | | L | L | | | | | | | | | | | | | | | | | | | | | | | |
| *Ancient ice: 3 Ma and greater* | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| COLDEX Intermed core Allan Hills[11] | | | | | | | | | | | | | | | | | | | | I | I | | | I | I | | | | | | | | | | | | | | | | | | | |
| COLDEX shallow cores (BID & 4")[11] | B | | | B | B | | | B | B | | | B | B | | | B | B | | | B | B | | | | | | | | | | | | | | | | | | | | | | | |

Points of Contact for projects in Table 4: [1]Harper; [2]Chellman, [3]Andreson; [4]Keegan; [5]Tobin; [6]Kingslake; [7]Bessel; [8]Kreutz; [9]McConnell; [10]Steig; [11]Brook; [12]Wissell; [13]Kurbatov

## Table 5: Ice Dynamics and Glacial History Planning Matrix 2025-2035

| | 2025 | | | | 2026 | | | | 2027 | | | | 2028 | | | | 2029 | | | | 2030 | | | | 2031 | | | | 2032 | | | | 2033 | | | | 2034 | | | | 2035 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 |
| **Ice Dynamics & Glacial History** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **Ice Dynamics** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Flask glacier melt dynamics[1] | | | | x | x | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **Glacial history** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Continental RAID drilling Antarctica[9] | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | R | R | | | R | R | | | R | R | | | |
| Seymore Island[10] | | | | x | x | | | | | | | w | w | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| IQ2300 - DML[11] | | | | | | | | | | | | w | w | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | z | | | |

Points of Contact for projects in Table 5: [1]Kingslake; [7]Goodge; [8]Tobin; [9]Lifton.

## Table 6: Subglacial Geology, Sediments, and Ecosystems Planning Matrix 2025-2035

| | 2025 | | | | 2026 | | | | 2027 | | | | 2028 | | | | 2029 | | | | 2030 | | | | 2031 | | | | 2032 | | | | 2033 | | | | 2034 | | | | 2035 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Subglacial Geology, Sediments, & Ecosystems** | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **Bedrock geology** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Continental RAID drilling Antarctica[1] | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | R | R | | | R | R | | | R | R | | | |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **Subglacial hydrology & sediment dynamics** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| South Pole lake[10] | | | | | | | | | | | | | | | | | | | | | | | | | | | | x | x | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **Microbial ecosystems & biogeochem** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| West Antarctica / Siple Coast[7] | | | | | | | | U | U | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

Point of Contact for projects in Table 6: [1]Goodge; [7]Vick-Majors; [10]Microbiology.

## Table 7: Ice as a Scientific Observatory Planning Matrix 2025 – 2035

| | 2025 | | | | 2026 | | | | 2027 | | | | 2028 | | | | 2029 | | | | 2030 | | | | 2031 | | | | 2032 | | | | 2033 | | | | 2034 | | | | 2035 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Ice as a Scientific Observatory** | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **RNO-G**[2] (Greenland) | | x | x | | | x | x | | | x | x | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **IceCube Update**[1] (drilling & logging; South Pole) | | | | LW | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **ICECube Gen2**[1] (optical, radio, & slots; South Pole) | | | | | | | | | | | | | | | | | | | | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | z | | | |

Points of Contact for projects in Table 7: [1]Karle; [2]Wissel

## Associated logistical challenges

In addition to planning the science and associated drilling technology, logistical challenges impact the timing and possibilities of the science field work. Challenges to conducting the field activities include:

- There remains an urgent need for reliable over-snow vehicles and sleds for scientific traverses in both Greenland and Antarctica in order to address the priority science goals identified in science community consensus documents, including the IDP Long Range Science Plan 2025-2035 (this document). In addition, the 2015 National Academies report "A Strategic Vision for NSF Investments in Antarctic and Southern Ocean Research" articulated the need for improved ground-based access to the deep field in Antarctica. Access to sites on the Antarctic and Greenland Ice Sheets has become very restricted due to the limited, aging fleet of LC-130 air support and few scientific traverse vehicles. With multiple science communities requesting flights or traverses to support their science on the ice sheets, access to the deep field remains a limiting factor in executing new scientific endeavors.

- The U.S. research community has been expressing the need for modular hot water drills for over a decade in order to enable clean access to the subglacial environment. That need remains unmet but could enable new scientific discoveries.

- The U.S National Science Foundation Ice Core Facility (NSF-ICF) in Denver is the main location for processing and archiving of U.S. ice cores for science. The NSF-ICF, which is fully funded by the NSF Office of Polar Programs and managed by the USGS, was originally built in 1993, but the infrastructure is now approaching end of its life. A new facility is being constructed in a location adjacent to the existing facility. Construction is expected to last until June of 2025, followed by testing of the trans critical CO2 freezer system through late 2025. Moving the ice core archive into the new facility is planned to occur in early 2026, with the expected reopening of the facility on March of 2026. The NSF-ICF will remain open to the scientific community during construction with facility updates to be provided on our website when construction starts. The NSF-ICF is preparing for the move by actively inventorying samples that are not in our database. The updated inventory in the NSF-ICF will be available for use and advertised through a variety of venues to enable broader participation across the science community, increase potential collaboration among researchers, and to provide an entry point for researchers new to the ice core community. Please reach out with any questions to nicl@usgs.gov.

- The community wishes to instrument and maintain key boreholes as long-term observatories for conducting measurements with existing and new instruments. GISP2 at Greenland summit is one of the most influential and widely cited records in paleoclimatology, but measurements have shown that the borehole casing is collapsing and already not navigable by most logging instruments. There are also boreholes in Antarctica. The IDP Englacial and Subglacial Working Group will lead community discussions to discuss an approach and selection method for prioritizing boreholes for instrumentation and preservation.

- Drilling ice cores deeper than ~300 m generally requires a drilling fluid mixture that has a density similar to ice to maintain core quality and prevent borehole closure. The fluid must also have a viscosity that is low enough to permit passage of the drill sonde through the fluid many times during the drilling process. Estisol-140 was used for the South Pole SPICE core and will likely be used for future drilling projects until an improved fluid is identified.

- An ice drill testing and calibration facility would be useful to engineers for testing during drill development and to scientists for englacial ice sensor development. The Ice Coring & Education (ICE) Silo, under conceptual development at the University of Nebraska-Lincoln, would be such a facility. UNL is investigating the repurposing of an abandoned Cold War Atlas-F missile silo. The UNL concept envisions a 150 foot ice column chamber, 10 foot diameter, within which a column of ice could be custom-built to replicate predicted ice, englacial, and subglacial conditions, all within a series of stacked 10 foot tall, individually refrigerated collars. An ice drilling/coring testing, calibration, and design facility in the continental U.S. would enable access for the science and engineering community to experiment with novel drilling instrumentation designs. Testing, modifying, and calibrating ice drilling tools in a controlled setting will reduce risk and enhance success of drilling in remote environments, and avoids the logistical limitations of testing on the Greenland or Antarctic ice sheets. The ice drilling test facility would also allow for the training of new drillers before deployment into the deep-field, contributing to the development of the next generation of polar engineers and scientists.

# Recommendations

## Recommended science goals

**1. Past Changes**: Present-day change can only be fully understood in context of the past; well-dated histories of past conditions and the atmosphere over a wide range of time scales are needed to understand forcings and responses. Drilling of spatially-distributed ice cores and boreholes at many locations to investigate past conditions and atmosphere over the past 200 to 40,000 years should continue. Understanding signals in remotely-sensed data, understanding impacts on the transition from snow to firn to ice on ice sheets, and calibrating high-resolution models, all require arrays of shallow cores covering a range of accumulation and melt rates both in Greenland and in Antarctica; these efforts should continue. Spatially-distributed shallow coring for records ranging from the recent past to 2,000 years in Greenland may investigate the ice sheet under the currently changes.

Specific goals include the following:

- Determining patterns of hydroconditions variability, feedbacks, and past extent of high-altitude glaciers and aerosol deposition requires ice coring in the North Pacific coastal mountain ranges.
- Determining the amount of meltwater retained and refrozen in the near surface firn (top ~60 m) on the Greenland Ice Sheet and on the Antarctic Peninsula is critical for improving estimates of surface mass balance under current warming conditions.
- Targeted ice coring to investigate ice, ocean, and atmospheric dynamics in WAIS coastal domes and coastal ice caps and along the dynamic Amundsen Sea Coast of Antarctica, and near Camp Century along the northwest coast of Greenland, are active and engaged on ongoing planning.
- A record from the last interglacial period (the Eemian, ~130k to 110k years ago) is key to predicting the response of glaciers and ice sheets to future warming. Eemian ice was recovered from the Camp Century, Greenland core in the 1960's, and an effort to retrieve an intermediate depth ice core from this region is in the planning stages. In Antarctica, extracting a record from Eemian ice is especially important for helping constrain environmental and glacial histories of the WAIS during the last interglacial, and is the primary motivation for the upcoming deep drilling at Hercules Dome, where replicate coring will retrieve deep ice with the compressed interglacial record. A deep ice core from Hercules Dome, *the highest-priority next deep ice core for the U.S. ice core science community* as determined by the IDP Ice Core Working Group and the proposal has been funded by NSF, will lead to understanding whether the WAIS collapsed during the last interglacial period (MIS5e), and if it did not collapse, then under what conditions was it stable? WAIS history during the Eemian is poorly known; because large sea level rise due to current warming may occur if the WAIS becomes destabilized, an understanding of the WAIS during the last interglacial is urgent.
- Blue ice areas are providing samples for atmospheric and ultra-trace component studies and can enable further new types of measurements that have previously been impossible, including analysis of ice up to 6M years old. Blue-ice studies at Allan Hills, Mt. Moulton, and Taylor Glacier have been fruitful from this realm so far; such studies at blue ice sites should continue, with other sites of interest including Elephant Moraine and Reckling Moraine
- Ice cores and borehole observations reaching ages between 800,000 years and 6 M years (and beyond) are significant, for these data may provide new insight into the effects of greenhouse gases and the observed change in periodicity of glacial cycles during the mid-

Pleistocene. The search to identify sites suitable for extracting ancient ice should continue. Through COLDEX, U.S. scientists will continue to retrieve samples of ancient ice from blue ice regions that provide snapshots of conditions that existed over several million years ago.

- An intermediate-depth (1200 m) core in the Allan Hills accumulation zone may give continuous ice as old as 1Ma and aid interpretation of discontinuous Allan Hills Blue Ice records; drilling such a core has been proposed by COLDEX.

**2. Ice dynamics and glacial history:** Rapid changes in the speed of fast-flowing outlet glaciers and ice streams observed over the past decade create an urgency to understand the dynamics of outlet glaciers and ice sheets. Ice sheet models that incorporate realistic physics and dynamics at appropriate spatial and temporal scales are needed to predict the "tipping point” when ice-loss becomes irreversible, resulting in ice-sheet collapse and rapid sea level rise. Observational data are needed to develop and validate the models. Measurements of the ice-bed interface (frozen-thawed, hard-soft bed conditions, sliding, shear), ice-ocean interactions (sub-shelf and basal melting-freezing rates), temperatures and ice deformation properties through the ice, geothermal bedrock conditions and ice-atmosphere interactions (surface mass balance) are key. Another approach to understanding future possible response of ice sheets is to examine their behavior in the past. Dated marine and terrestrial glacial deposits provide information about past ice volume. In regions where such data are not available, histories of ice-sheet thickness can be inferred from radar-detected layers combined with ice core and borehole measurements.

Specific recommendations include:

- Ice-ocean interactions are not fully understood. Boreholes to deploy instruments to measure conditions at ice-ocean interfaces are high priority for investigating ice sheet stability.
- Hydraulic conditions in glaciers and ice sheets exert strong controls on basal motion. Much has been learned through remote sensing methods, but direct measurements through boreholes to the bed are still needed to validate and interpret remote sensing data. Boreholes to the bed at targeted locations are urgently needed to measure geothermal fluxes and basal properties.
- Ice deformation in ice sheets, glaciers, and ice streams depend on temperature and ice rheology. Measurements of ice rheology from ice cores, and borehole logging measurements of temperature, diameter, inclination, and azimuth are needed to provide boundary conditions and constraints for modeling flow of ice sheets and fast-flowing outlet glaciers and ice streams.
- Knowledge of spatial and temporal variations of surface accumulation is critical for quantifying the mass balance of glaciers and ice sheets. Accumulation rate histories derived from short (~200 m) firn and ice cores can be extrapolated spatially to the catchment scale using radar-detected layers. Additional short cores at targeted locations are needed to provide a realistic assessment of surface accumulation over ice-sheet scales.
- Dated ice cores can be used to infer histories of thickness and configuration of ice sheets. Glacial histories contained in coastal ice domes are of particular interest because thickness change near the margins is large. The depth-age relationship from Siple Dome, Antarctica provided key information about the Holocene deglaciation of the central Ross Embayment, and the depth-age relationship from Roosevelt Island will help constrain the deglaciation of the eastern Ross Embayment. Depth-age profiles from Hercules Dome and other targeted locations are essential for understanding the timing and extent of deglaciation, for example, at ice domes near the outflow of the Amundsen Sea Embayment Antarctica, as well as in coastal domes of Greenland.

- The past extent and volume of the Greenland and Antarctic Ice Sheets are recorded by analysis of subglacial bed materials such as cosmogenic nuclide and luminescence signals in subglacial bedrock. Samples from beneath these ice sheets will provide information on their configuration during past interglacials to help constrain ice-sheet sensitivity to future possible change. Cores of basal ice and bedrock from strategically targeted sites around ice sheet peripheries are needed to pinpoint which ice-sheet sectors would add the first decimeters of sea level rise beyond present.

**3. Subglacial geology, sediments, and ecosystems:** Bedrock, sediments, and ecosystems existing within and beneath ice sheets remain largely unexplored because of the lack of rapid access drills. In particular, the physical conditions at the base of the ice sheets are virtually unknown, but remote sensing of liquid water in subglacial lakes and possibly interconnected hydrologic systems raises concern about thermal conditions and basal slip potential. Likewise, the unknown subglacial geology of Antarctica represents the last continental frontier of geologic exploration, including landscape evolution, past paleo conditions on geological timescales, crustal heat flow, lithospheric stress, ground truth for geophysical imaging, constraints on geodynamical evolution, and relationship with past supercontinents. Information on subglacial biodiversity and biogeochemistry is limited to the Siple Coast, with nothing known about other areas of the Antarctic continent. Subglacial sediments also contain information related to past ice sheet history. Rapid access to subglacial environments is needed to address a wide range of science questions.

Specifically:

- Direct sampling of the bedrock is needed to validate models of cratonic growth related to supercontinent assembly in the Mesoproterozoic between about 2.0 and 1.1 billion years ago and for constraining the Phanerozoic geological, tectonic, and exhumation history of the Antarctic continent. Strategic drill-site selection within mapped drainage basins (using products from the BEDMAP2 project) will also allow greater constraints on provenance studies that utilize onshore moraines and offshore glacial strata.
- There exist virtually no heat flow data for Antarctica. Penetration into bedrock provides the first opportunity to accurately measure the geothermal heat flux, which informs us about geotectonic conditions as well as geothermal contributions to ice sheet temperature.
- Evidence of Cenozoic ice sheet history preserved in sedimentary rocks of subglacial bedrock basins and in sediment deposits within subglacial lakes will provide further dimensions to the records known only from the margins of the continent and will also help to verify paleo-topographic reconstructions for ice sheet modeling. Likewise, access to subglacial bedrock can provide a unique opportunity to study Cenozoic landscape evolution and long-term ice sheet stability using low-temperature thermochronology and cosmogenic-isotope techniques.
- Direct measurements at grounding zones of fast-flowing ice streams and outlet glaciers are badly needed, as are data from sub-ice-shelf ocean cavities in order to provide basic information needed to model ice fluxes near grounding lines and into ice shelves – a critical interface for predicting future ice sheet dynamics.
- Direct measurements of bed conditions including frozen/thawed bed, basal pore pressure, slip, and sediments are needed to develop and test realistic models of the controls on the fast flow of ice streams and outlet glaciers.
- Significant wet environments exist below ice sheets and glaciers; sampling of subglacial habitats including sediments, water, and basal ice is needed to establish the diversity and physiology of microbes, available nutrients and organic materials, microbial relationships to the past, and ecosystem function below the ice. Continued support for developing methods and technologies for clean access to subglacial

environments and tools for biological and geochemical sampling are needed to investigate these subglacial systems in a clean manner that maintains scientific integrity and environmental stewardship. The recent studies of Whillans and Mercer Subglacial Lakes are initial steps toward achieving this goal, yet with over 650 subglacial lakes in Antarctica much remains to be discovered.

**4. Ice as a scientific observatory:** Polar ice sheets and mid-latitude ice caps archive evidence of the past, and ice dynamics and also serve as a unique platform to conduct observations and experiments concerning seismic activity, planetary sciences and experimental astrophysics, and other novel phenomena. Specifically:

- Borehole logging of both fast-access holes and boreholes originally drilled for ice cores are needed to fully exploit the histories of the past and ice dynamics preserved within the ice. For example, temperature logs are used to infer past temperatures and also the geothermal flux; optical logs yield detailed records of dust and volcanic events and will be important in searches for million year old ice; and sonic logs provide a continuous record of ice fabric and borehole deformation. Community winches to support borehole logging are important assets.
- In-ice physics and astrophysics experiments make use of polar ice as a clean, highly stable, low-background, and transparent (both optically and in the radio frequencies) detection medium for observation of sub-atomic particle interactions. New drilling techniques are under investigation, including cleaner drilling and removal of bubbles from the refrozen water.
- Future planned projects (e.g., the RNO-G and Generation-2 Ice Cube) require many boreholes drilled to at least 150 m deep (ARA, Gen2-Radio) and 2,600 m deep (Gen2-Optical) and significant calibration studies of the surrounding ice volume.
- Ice sheets are a quiet platform for seismic monitoring; the South Pole Remote Earth Science and Seismological Observatory has seismic equipment installed in boreholes about 300 m below the surface. A similar seismic observation network is planned for the Greenland Ice Sheet. The IceCube Upgrade will include 2 seismometer instruments at 2400 m depth sponsored by the USGS.
- Novel basal ice structures that have been remotely sensed but whose existence is not well understood should be investigated.

## Recommended Drill Life Cycle Cost and Logistical Principles

Although drills already exist that can achieve some science goals, new drilling technologies are needed to accomplish science goals planned for the next decade. The following principles guiding development of new drills and associated technologies are recommended:

- Drill designs require that the supporting logistical needs are available and do not impede the planned execution of the field science. Current limitations with Antarctic logistics reinforce the desirability of having modular equipment that can be transported by small aircraft and that require few operators on site.
- While developing the science requirements, logistical issues such as weight, size, costs, and time for development, must be clearly defined and transparent at the initial stage of planning. Scientists and engineers working together through IDP must assess the impact of changes as they arise during the engineering design and fabrication process.
- Drills, major drilling subsystems, and accompanying technology must be developed with consideration of potential use in future projects. The drills and technology must be versatile and well documented so that they can be used, maintained, and repaired by other engineers.
- Major drilling systems (e.g., sondes, winches, control and other major electronics systems) should be fungible to the maximum extent possible. Major component interchangeability and logistical agility should be essential deliverables for all new drilling technology projects.
- Engineering design teams must include individuals with field experience using appropriate ice drilling technology and/or other relevant field experience.
- Heavy traversing capability is urgently needed to improve access to many scientifically important regions of the Antarctic and Greenland Ice Sheets, including heavy traverse capability that will enable larger drilling systems in both rotary and hot-water formats, heavy tractor capacity, and berthing facility for personnel.

## Recommended Technology Investments

The following investments in drilling technologies are needed to accomplish science goals planned for the next decade. Investments are prioritized by time (but not prioritized within each Priority level) from consensus of the IDP Science Advisory Board, include:

### Priority 1 (needed in 2025-2026):

• Maintain and upgrade agile equipment in inventory, including: Hand Augers, Sidewinders, the 700 Drill, the Foro 400 Drill, the 4" Electromechanical Drills, the 3" Electrothermal Drill, the 3.25" Eclipse Drills, the Stampfli Drill, Logging Winches, the Small Hot Water Drills (HWD), the Blue Ice Drill, the Prairie Dog, the Agile Sub-Ice Geological Drill (ASIG), the Rapid Air Movement Drill (RAM) Drill, and the Winkie Drills.

• Complete the Science Requirements and Conceptual Design of next generation Blue Ice Drill

• Make minor improvements (stainless steel core barrel, extra cutters) to the existing Blue Ice Drill

• Describe/adapt the design and develop a cost estimate for the future build of a clean modular hot water drill (e.g. replicate the BAS/NZ modular drill for holes appx 200 - 1,000 m depth) that minimizes logistical footprint including fuel supply.

• Field test shallow wet ice core drilling capability at Allan Hills in the 2025-26 field season

### Priority 2 (needed in the next 3 years):

• Build a scalable hot water drill for clean modular subglacial access drilling that minimizes its logistical footprint including fuel supply (e.g. replica of the BAS/NZ drill)

• Finish the Conceptual Design and begin the Detailed Design for replicate coring capability for the Foro 3000 Drill.

• Evaluate success of the 2025-26 field test of shallow wet ice core drilling (using parts from other drills), including chip handling. Produce a draft document with the field test outcomes and recommend whether or not a stand-alone shallow wet ice coring drill should be built.

• Develop the Conceptual Design for collecting a small amount (chips to several cm) of sub-ice rock/mixed media/mud in a frozen regime using an intermediate or deep ice core drill in a fluid filled hole, for example with the Foro 3000 Drill.

• Investigate lighter weight sources of power and/or renewable energy technology to replace generators for drilling systems and ease demand on logistics.

• Identify procurement source and cost for potential purchase of a rapid hole qualifier (temperature and caliper) to meet the scientific need in borehole access applications.

• Establish Science Requirements for new drilling fluids for future ice and rock drilling projects, including clean ice core drilling (for biological and gas sampling) for future collaboration with international partners.

• Finish adapting a commercial drill rig for retrieving rock core from beneath 200 m of ice (BASE Drill)

• Implement modifications needed for the 700 Drill to increase core quality, length, and production rate.

**Priority 3 (needed in 3 to 5 years):**

- Develop the Detailed Design for a clean hot water basal ice coring sonde for a hot water drill that has the ability to integrate with other hot water drills or deep ice coring drills.
- Establish the IDP Science Requirements for identification and planning of borehole maintenance and fluid maintenance over time, including removing (or lowering) drilling fluid from a borehole (for example for freezing in a sensor).
- Continue investigation and modifications of the RAM 2 Drill to achieve the 100 m depth goal reflected in the system Science Requirements.
- Establish the Science Requirements for retrieving sidewall ice samples at specific depths in an existing borehole without using an ice coring drill.
- Write a summary paper outlining the results from past attempts and the prognosis for future use of shallow drill fluid columns for ice coring.

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## Acronyms

AGAP: Antarctica's Gamburtsev Province
ANDRILL: Antarctic Drilling Project
AO: Arctic Oscillation
ARA: Askaryan Radio Array
ARIANNA: Antarctic Ross Ice shelf Antenna Neutrino Array
ASIG: Agile Sub-Ice Geological (drill)
AUV: Autonomous Underwater Vehicle
BLWG: Borehole Logging Working Group
CReSIS: Center for Remote Sensing of Ice Sheets
DISC: Deep Ice Sheet Coring
DOSECC: Drilling, Observation, Sampling of the Earths Continental Crust (drilling service)
EDC: EPICA Dome C
EGRIP: East Greenland Ice core Project
EHWD: Enhanced Hot Water Drill
ENSO: El Niño Southern Oscillation
EPICA: European Project for Ice Coring in Antarctica
G-2IC: Generation-2 Ice Cube
GISP2: Greenland Ice Sheet Program II
GRIP: Greenland Ice Core Project
GZK: Greisen-Zatsepin-Kuzmin
HCFC: Hydrochlorofluorocarbon
ICECAP: A project name, not an acronym
ICWG: Ice Core Working Group
IDP: Ice Drilling Program
Sheet Subglacial Access Research Drilling
IPCC: Intergovernmental Panel on Climate Change
IPICS: International Partnerships in Ice Core Sciences
LIG: Last Interglacial
LRSP: Long Range Science Plan
NEEM: North Greenland Eemian Ice Drilling
NEGIS: Northeast Greenland Ice Stream
NGRIP: North Greenland Ice Core Project
NRC: National Research Council
NSF: National Science Foundation
PINGU: Precision IceCube Next Generation Upgrade
RAID: Rapid Access Ice Drill
RAM: Rapid Air Movement (drill)
ROV: Remotely Operated Vehicle
SAB: Science Advisory Board
SALE: Subglacial Antarctic Lake Environment
SCAR: Scientific Committee on Antarctic Research
SHALDRIL: Shallow Drilling on the Antarctic Continental Margin
SIeGE: Sub-Ice Geological Exploration
SPICE: South Pole Ice
WAIS: West Antarctic Ice Sheet
WISSARD: Whillans Ice Stream Subglacial Access Research Drilling Project