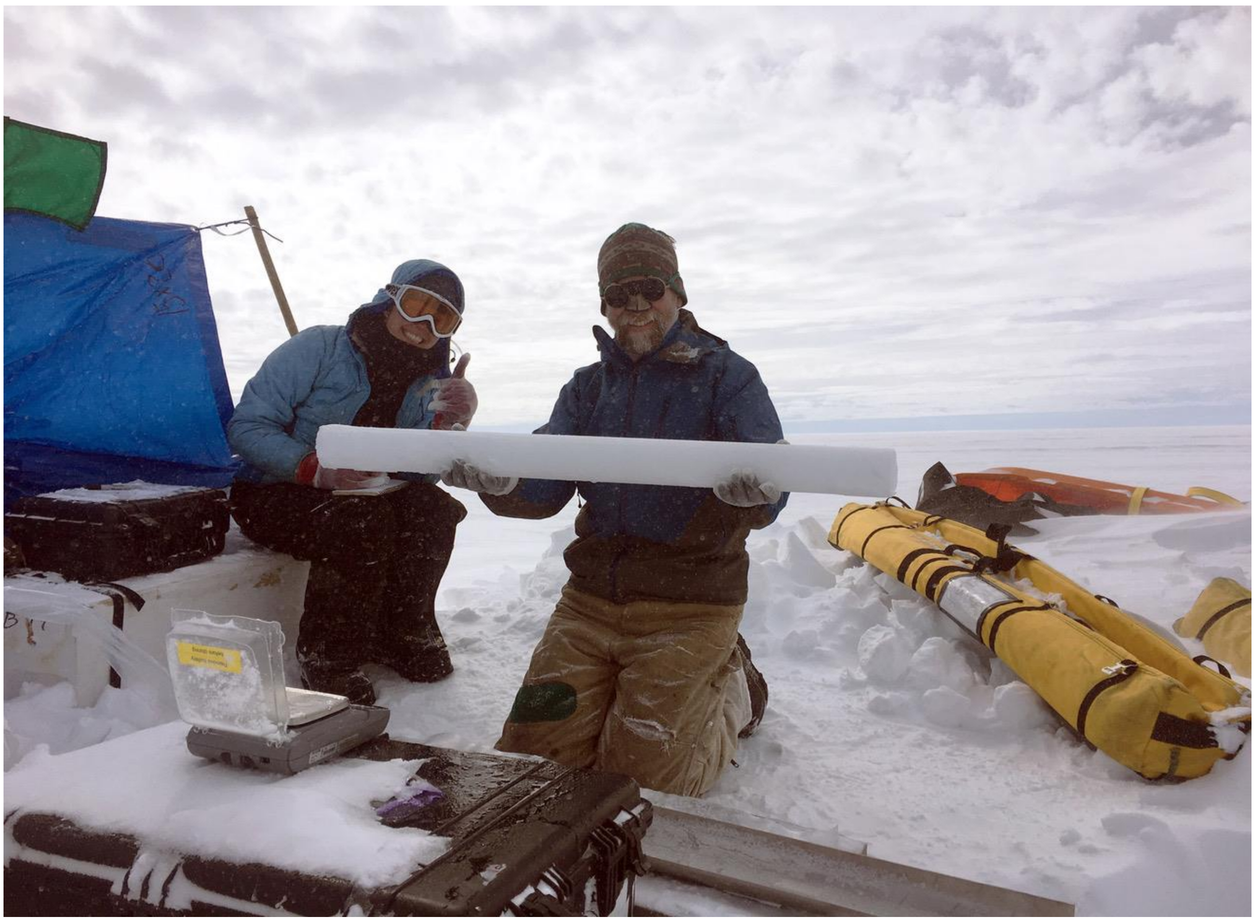
U.S. Ice Drilling Program

Long Range Science Plan 2017-2027

Prepared by the U.S. Ice Drilling Program Office in collaboration with its Science Advisory Board with input from the research community



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Cover photo: Scientists Bob Hawley and Karina Graeter on the GreenTrACS expedition in Greenland, with a firn core that they drilled from a depth 32-33 m using the IDDO hand auger and sidewinder system. (Photo credit: Gabe Lewis)

Snapshot of the 2017 updates in the Long Range Science Plan

The Long Range Science Plan 2017-2027 includes updated information in the following areas:

- *<u>Ice coring and drilling science goals</u>: In addition to modifying language to reflect projects that have been completed, language was added in places to include Antarctic coastal domes as an important area for international partnering. The Ice Dynamics and Glacial History section has been concisely expanded in the description of the importance of cosmogenic dating of sub-ice rock in areas of the Greenland Ice Sheet, and it now points out that cosmogenic dating of rock cores from under shallow ice can be assessed in some areas both in Antarctica and Greenland through rock core retrieval by the recently developed IDDO Agile Sub Ice Geological Drill and an IDDO adaptation of the Winkie Drill. In addition language was added in the climate section on 'Industrial and Instrumental' period to expand understanding of physical and chemical post-depositional processes to include impacts of cosmic rays, and to point out the need for high-resolution ice core measurements for synchronizing Greenland and Antarctic records in order to link to non-ice core climate records from the mid-latitudes in the section on large-scale global climate change.*

- *<u>Science Planning Matrices</u>: Significant adjustments have been made to the Climate science planning matrix (table four), to the agile drilling projects both in the Arctic and the Antarctic as well as to the timeline for the deep drilling projects (Hercules Dome and Oldest Ice). Tables five and six have been adjusted to the updated time schedule for current projects, this adds a number of new projects for which proposals have been written and submitted, and reflects community planning articulated in the white papers from the IDPO Subglacial Science Planning Workshop in 2016.*

- *<u>Recommendations</u>: The section on Recommended Technology Investments has been updated to remove drill development projects that have been completed, and to articulate the IDPO Science Advisory Board prioritization on behalf of the research community. To name a few items: Drilling technology that will be needed soon and in the coming years; pursuit of enabling an Intermediate Depth – type drill ("Foro 3000") is high on the priority list for consideration for use at Hercules Dome; modifications to the RAM drill so that it is less logistically intensive; and finishing work on several drills are all high priority items. Scientific interest in retrieving ice cores from warm sites is driving the need for use of a hot water ice coring system to drill to 200 m in mid-latitude glaciers.*

Executive Summary

One of the most pressing problems facing society today is the greenhouse gas-induced climate change that is warming the Earth. This problem may potentially change many other aspects of global climate and environmental systems, including the possibility of abrupt impacts of change and sea level rise. A more sophisticated and predictive understanding of the mechanisms of climate change and the effects on sea level change are needed to plan for the future. Glaciers, ice sheets, and subglacial environments contain records of past atmospheric composition, climate, and ice thickness, which provide clues to understanding future climate. They also contain information relating to the physics of ice sheets and the processes that control their stability and response to climate change. Furthermore, the subglacial realm preserves unique biological, geochemical, and geological environments. Extracting this information involves drilling and coring of the polar ice sheets, a specialized and challenging endeavor that requires extensive planning, technology, and logistics.

The Ice Drilling Program Office (IDPO) was established by the National Science Foundation (NSF) to lead integrated planning for ice coring and drilling and provision of drills and drilling services. The IDPO and its Science Advisory Board (SAB) update this Long Range Science Plan (LRSP) annually, in consultation with the broader research community. The purpose of this plan is to articulate goals and make recommendations for the direction of U.S. ice coring and drilling science in a wide variety of areas of scientific inquiry, and to make recommendations for the development of drilling technology, infrastructure and logistical support needed to enable the science. A companion document, the Long Range Drilling Technology Plan is available online (http://icedrill.org/scientists/scientists.shtml - drillingplan) and it addresses some of the goals articulated here. Specific recommendations for the next decade for a variety of areas including climate change, ice dynamics, glacial history, subglacial geology and ecosystems, and the use of the polar ice sheets as a scientific observatory include the following:

Recommended science goals

1. Past Climate change: Present-day climate change can only be fully understood in context of the past; well-dated histories of climate and the atmosphere over a wide range of time scales are needed to understand climate forcing and response. White papers by the International Partnerships in Ice Core Sciences (IPICS - http://pastglobalchanges.org/ini/end-aff/ipics/intro) describe broad science targets for ice coring and articulate the need for spatially-distributed arrays of recovered ice cores that target the past 200, 2,000 and 40,000 years, from the last interglacial, and extracting an ice core that reaches 1.5M years. The U.S. ice coring community was intimately involved in originally establishing the IPICS goals; recommendations for achieving those goals, together with additional goals that are primarily U.S. priorities, are outlined below. In addition, members of the U.S. community are leading efforts to gain critical samples of ice prior to 800,000 years ago, for evidence of the atmosphere from times when the Earth had 40,000-year climate cycles.

- Drilling of spatially-distributed ice cores and boreholes to support both IPICS goals and U.S. initiatives of investigations of past climate and atmosphere over the past 200 to 40,000 years should continue. Understanding climate signals in remotely-sensed data, understanding climate 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 ago will include multiple scientific traverses in Greenland for study of the ice sheet under the currently changing climate. Recent projects in the Arctic include the 1,000-2,000 year annual record from Denali (Mt. Hunter), Alaska that is providing important constraints on North Pacific climate and tropical teleconnections during the Medieval Climate anomaly, Little Ice Age, and modern warming. In Antarctica proposed science includes an international French-Italian-U.S. scientific traverse from Dome C to South Pole and shallow ice core drilling at Law Dome.

- 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.
- Hemispheric and global climate records extending 40,000 years into the past include recently completed ice-coring projects in Antarctica from Roosevelt Island and from the South Pole Ice (SPICE) core project. Retrieving 40,000-year records from Hercules Dome (as part of a record extending further back at that site) is a priority for the U.S. community. Additionally, several U.S. investigators may be involved in the Danish core from EastGRIP, Greenland. Targeted ice coring to investigate ice, ocean, and atmospheric dynamics along the dynamic Amundsen Sea Coast of Antarctica, and near Camp Century along the northwest coast of Greenland, are in the planning stages.
- A climate 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. The search for sites from which to extract Eemian ice in Greenland, both by coring and through horizontal sampling of blue ice ablation zones, should continue. Eemian ice was recovered from the Camp Century 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 climate and glacial histories of the West Antarctic Ice Sheet (WAIS) during the last interglacial, and is the primary motivation for planned deep drilling at Hercules Dome. Hercules Dome is the highest-priority, next deep ice core for the U.S. community. Understanding evidence from Antarctica, where the climate record may have evidence of changes in the WAIS during the last interglacial period are important, since WAIS history for this time is poorly known and because large sea level rise due to current climate warming may occur if the WAIS becomes destabilized.
- Blue-ice paleoclimate records are already providing unlimited samples for atmospheric and ultra-trace component studies and can further enable new types of measurements that have previously been impossible for very old ice, including the possibility of ice older than 800,000 years. Blue-ice studies at Mt. Moulton, Taylor Glacier, and Allan Hills exemplify discoveries from this realm. so far; such studies at blue ice sites should continue.
- Ice cores and borehole observations reaching ages between 800,000 years and 1.5M years (or beyond) are significant and may provide new insight into the effects of greenhouse gases on climate and the observed change in periodicity of glacial cycles during the mid-Pleistocene. The search to identify sites suitable for extracting ancient ice.. Extraction of deep ice cores for million-year-old ice, a potential goal for eight to twelve years into the future, should be coordinated with international partners through the IPICS "Oldest Ice" project. In the near term, "snapshots" of time periods beyond 800,000 years are potentially available from blue ice regions or areas of discontinuous deposition, and developing further understanding of these regions and sampling them is a priority, for they contain very old ice. Currently U.S. scientists are working to retrieve and understand samples of ancient ice from blue ice regions that provide snapshots of climate as it existed more than a million years ago.

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 and climate can be inferred from radar-detected layers combined with ice core and borehole measurements. Specific recommendations include:

- Ice-ocean interactions are not yet well understood. Boreholes to deploy instruments to measure conditions at ice-ocean interfaces are high priority; recent studies of Pine Island Glacier and Whillans Ice Stream are steps toward understanding how perturbations at ice-ocean interfaces impact the interior ice sheet.
- Hydraulic conditions in glaciers and ice sheets exert strong control 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 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 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 West Antarctic Ice Sheets is recorded by cosmogenic nuclides in subglacial bedrock. Samples from beneath these ice sheets will provide information on their thickness and configuration during paleoclimates warmer than the present, and help identify their sensitivity to future possible climate change. Short cores of bedrock from targeted sites are needed to address questions concerning the extent of the ice sheets during past interglacial climates, and the onset of continental glaciations.

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 paleoclimates on geological timescales, crustal heat flow, lithospheric stress, ground truth for geophysical imaging, constraints on geodynamical evolution, and relationship with past supercontinents. 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 exists 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 sediments and ecosystems is needed to establish the diversity, and physiology of microbes and their relationships to past climates and their current 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 while doing so in a clean manner that maintains scientific integrity and environmental stewardship. The recent study of subglacial Lake Whillans is a step toward achieving this goal.

4. Ice as a scientific observatory: Polar ice sheets and mid-latitude ice caps archive evidence of past climate 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 climate 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 ices; 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 (e.g. IceCube) 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 refrozen water.
- Future planned projects (e.g. the Askaryan Radio Array (ARA) and Generation-2 Ice Cube (G-2IC)) require multiple boreholes drilled to at least 150 m deep (ARA) and 2,500 m deep (G-2IC) and forsee significant calibration studies of the surrounding ice volume. Better understanding of ice attenuation at radio and deep UV wavelengths are particularly desired.
- 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.
- Novel basal ice structures that have been remotely sensed but whose existence is not well understood should be investigated.

Recommended 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. In the past decade there has been an increase in research proposed by the ice science community but the NSF budget has been generally flat. The following principles guiding development of new drills and technologies are recommended:

- Designs require that the supporting logistical needs do not impede execution of the science.
- 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 IDPO 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 or replicated 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 inter-changeability 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.

Recommended Technology Investments

The following investments in drilling technologies are needed to accomplish science goals planned for the next decade. Investments prioritized by time, from consensus of the IDPO Science Advisory Board, include:

Priority 1 (needed this year)

- Maintain and upgrade agile equipment in inventory, including: Hand Augers, Sidewinders, the 4” Electromechanical Drills, the 3” Electrothermal Drill, the 3.25” Badger-Eclipse Drills, the Stampfli Drill, Logging Winches, the Small Hot Water Shot Hole Drills, the Blue Ice Drill, the Prairie Dog, the ASIG Drill and the Winkie drill.
- Maintain and upgrade the Intermediate Depth Drill.
- Finish building a second Blue Ice Drill for wide-diameter drilling to 200 m.
- Finish building the Sediment Laden Lake Ice Drill.

- Finish cost estimate, construction schedule and detailed design for upgrading the Intermediate Depth Drill to 3,000 m ('Foro 3000').
- Finish the RAM Drill modifications for modularity, weight reduction, and ease of logistics based on existing IDPO Science Requirements for rapidly creating shot holes.
- Conduct Antarctic field trials of the Rapid Access Ice Drill (RAID)[1] .

Priority 2 (needed in the next 3 years)

- Finish building the Foro Drill system.
- Modify the Badger-Eclipse (or Foro) drill for drilling to 700 m under conditions of limited logistics based on established IDPO Science Requirements.
- Upgrade the Electrothermal Drill to allow for coring to 300 m through temperate and poly-thermal firn and ice. The drill needs to be agile and light weight (transportable by helicopter).
- Build Foro 3000 components (i.e. IDD add-on components).
- Build a Scalable Hot Water Access drill for creating access holes in ice from 50 m up to approximately 1,000 m depth[2] with modular potential to be used for clean access.
- Develop IDPO Science Requirements for a hot water drilling system that can be used to recover ice core samples from warm sites (e.g., Chile, NZ, Asia) to 200 m depth.
- Investigate a rapid hole qualifier (temperature and caliper) for use with RAID and other borehole logging applications.

Priority 3 (needed in 3 to 5 years)

- Build replicate components of the IDD drill to enable same-year use in both the Arctic and Antarctic.
- Continue to evaluate options for new drilling fluids, and exploring/testing shallow drill fluid columns.

Community development

Sustained investment in the education, training and early career mentoring of the next generation of ice coring and drilling scientists and engineers is imperative to ensure that science discoveries from ice cores and boreholes continue through the coming decades. The IDPO will continue to work in concert with the scientific community and NSF to assist young scientists with technologies needed to support their research, provide them with opportunities for communication of their science to the public, and foster support for the ice coring and drilling community. Productivity of the science community also depends on drillers and engineers who have experience in mechanical ice coring and hot water drilling; an ongoing strategy for maintaining this expertise is important.

Introduction

One of the most pressing environmental issues of our time is the greenhouse gas-induced climate and environmental change, including the possibility of abrupt changes. A more sophisticated and predictive understanding of the mechanisms of climate change and the effects on sea level change are needed to plan for the future. Glaciers, ice sheets, and the subglacial environment contain records of past climate and ice thickness, which provide clues to understanding future climate.

[1] RAID has been fabricated by DOSECC Exploration Services, LLC for the University of Minnesota.
[2] The IDDO Conceptual Study for the ScHWD found that scalable capability deeper than 1,000 m would require different components that are not practical for use between 50-1,000 m.

Ice core records have led to many important discoveries; for example, the discovery that dramatic changes in climate can occur abruptly, in less than ten years (NRC, 2002) revolutionized climate science and also has important implications for policy. This finding contributed to the fundamental understanding of the climate system, which led to the 2007 award of the Nobel Peace Prize to the Intergovernmental Panel on Climate Change (IPCC) for climate science. More recently, studies of the stability of the West Antarctic Ice Sheet (WAIS) in the face of near-future warming raise the troubling possibility of large sea level change in the very near future (e.g., Joughin et al., 2014). A recent study of bedrock below the summit of the Greenland Ice Sheet raises questions about the ice sheet's resilience to climate change (Schaefer et al., 2016). Furthermore, many basic questions about Earth's climate system remain unresolved. For example, what are the climate linkages between the Northern and Southern Hemispheres? How do atmosphere-ocean-ice interactions affect the cryosphere? How quickly can sea level rise? How sensitive is climate to greenhouse gases? What were polar climates and global levels of greenhouse gases like prior to the mid-Pleistocene transition ~ 900,000 years ago? Recent and emerging results from the WAIS Divide Ice Core have contributed new insights on some of these questions (e.g. WAIS Divide Project Members, 2013, 2015) and new scientific plans, in both Antarctica and Greenland, address many more.

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. Iken, 1981; 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. The greatest uncertainties in sea level rise projections for the 21st century are associated with the possibility of rapid dynamic responses of the ice sheets to climate and sea level change.

Subglacial environments represent a barely tapped resource of deep time understanding. 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 and rock basin archives. Recovering these records for intervals of past warm periods will contribute to our understanding of future ice sheet behavior under a warming climate.

New and emerging studies show that subglacial environments harbor unique microbial ecosystems and that these microbial communities are metabolically active and thus play a critical role in subglacial weathering. The extent to which microbial activity alters the chemistry of subglacial efflux and the effect 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, and may help inform our search for extraterrestrial life.

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. Challenges with this drilling approach include keeping access holes open for long periods and operating under conditions of differential ice flow movement. 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 U.S. ice coring and drilling community has led and participated in fundamental and vital scientific discoveries for more than 60 years. These discoveries require drilling and coring of the polar ice sheets, a specialized and challenging endeavor that requires extensive planning, technology, and logistics. This Long Range Science Plan was established by the U.S. Ice Drilling Program Office (IDPO), working with its Science Advisory Board (SAB), associated working groups, and the broader research community, to articulate the direction for U.S. ice coring and drilling science for the next decade. The science direction provides a foundation as well as direction for the Ice Drilling Design and Operations (IDDO) Long Range Drilling Technology Plan for developing some of the 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. SAB-recommended updates to the IDPO Long Range Science Plan are 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, approved by the SAB and the final version for the year is posted to the icedrill.org website in summer.

Science goals articulated in this document are all interconnected, but for convenience in associating science endeavors with appropriate drilling technology, they are described in four categories: climate change; ice dynamics and glacial history; subglacial geology, sediments and ecosystems; and 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 the development of technologies, so that the support for the science will be ready when needed.

Ice Coring and Drilling Science Goals

I. Past Climate Change

Earth's climate system involves local, regional, hemispheric, and global phenomena. It is impossible to understand global climate 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. Issues articulated by many U.S. scientists (e.g., ICWG, 2003) were central to the themes in the IPICS white papers (Brook and Wolff, 2006); hence a number of the categories below reflect those themes.

1. Industrial and Instrumental Period (200-year Array): The broad goal of an array of ice core records spanning the industrial (last 200 years) and instrumental (last 100 years) period is to establish ice core records of human impacts on the climate, cryosphere and atmosphere, study modern surface processes, and calibrate models and remote sensing data with *in situ* data. As shallow ice cores (generally <200 m), these records 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 and climate, yet the impacts in polar and remote high-latitude and high-elevation regions are not fully understood. 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 or in selected areas of Antarctica and the Arctic such as Summit Greenland, Disko Bay, and Law Dome) and internationally coordinated scientific traverses (e.g., International Trans-Antarctic Science Expedition, Norwegian-U.S. Scientific Traverse of East Antarctica). While shallow coring has been done in several 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 hydrocarbons.
- 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 climate models.
- Elucidate air-snow exchange processes and transfer functions between atmospheric aerosols and gases and snow composition on ice sheets and alpine glaciers.
- 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.
- Produce detailed temporal and spatial (regional-scale) maps of climate and environmental parameters (e.g., temperature, accumulation rate, atmospheric and snow chemistry), and anthropogenic impacts.
- Develop an inventory of microbes 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 climate forcing and geohazard studies.

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

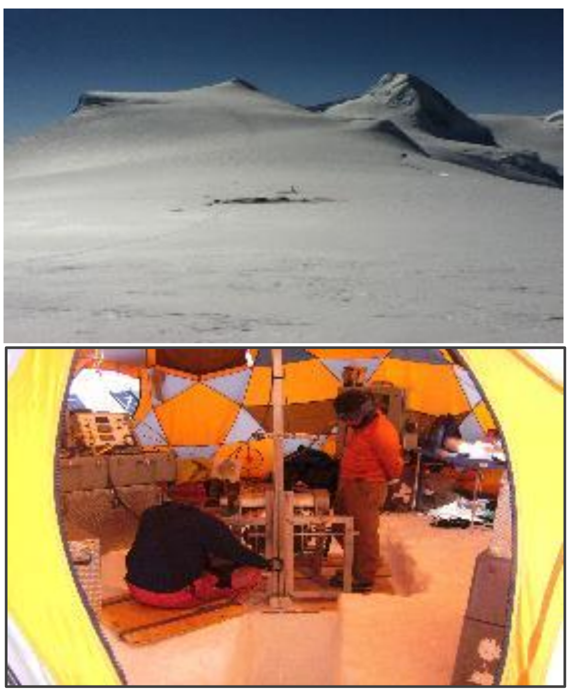
Individuals and small groups conduct studies of these types across glaciological settings ranging from the Greenland and Antarctic ice sheets, to ice caps and alpine glaciers in low, mid, and high latitudes. Versatile drills required for 200-year arrays exist in the current U.S. inventory, but are in need of upgrade. They are used often but 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 1. The Long Range Drilling Technology Plan describes the agile drills in detail and discusses their current condition. New additions that may be required include an upgraded thermal drill for collection of cores from temperate ice where water is present. The applications of a thermal drill include both alpine regions and areas of the polar ice sheet where surface melting is significant, and where recently-discovered firn aquifers are undergoing study.

2. Pre-Industrial Baseline (**2,000-year array)**: 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 climate variability, yet short enough that relevant climate boundary conditions have not changed appreciably. Thus, this period represents a critical pre-industrial baseline against which to compare 20th century changes in climate, the cryosphere, and atmospheric composition and chemistry. Existing quantitative reconstructions of climate 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 climate 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.
- Evaluating 20th 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 Climate Anomaly phenomena, and constraining their relationships with regional climate patterns like the North Atlantic Oscillation (NAO), Arctic Oscillation (AO), El Nino Souther Oscillation (ENSO), and Monsoons.
- Calibrating local, regional, and global climate 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 Climate 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 climate-forcing mechanisms that are regionally variable (e.g.,

greenhouse and reactive gases, sulfate, terrestrial dust and associated biological material, black carbon aerosols), and the record of solar variability.

- Assessing the relative roles of anthropogenic and natural forcing on climate evolution prior to and into the industrial period.
- Quantifying anthropogenic pollution sources and emission levels prior to the industrial revolution, from early metal smelting activities.



Scientific drilling on the Mt. Hunter Plateau of Denali 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*

New coring associated with this effort will include the Arctic, Antarctic, and mid-latitude sites. Several countries, including the United States, are considering new coring associated with the 2,000-year array theme. Recent, current, and desired future U.S. or U.S./International efforts include South Pole; Central Alaska Range (Mt. Hunter plateau); British Columbia (Mt. Waddington); Detroit Plateau on the Antarctic Peninsula; multiple ice domes along the Amundsen Sea Coast; the Aurora Basin in Antarctica; Hercules Dome (the 2,000-year record would be part of a deeper core); and high accumulation rate sites in Greenland. This list is not exclusive, but illustrates the diversity of discussions within the research community.

3. Large-Scale Global Climate Change (**40,000-year network)**: The past 40,000 years include the last glacial maximum, the glacial-interglacial transition, and our present warm period (the Holocene) as well as the sequence of abrupt swings (Dansgaard-Oeschger events) in climate as recorded in Greenland ice cores and other climate archives. The glacial-interglacial transition is the best-documented global response to large-scale changes in climate forcing, and the earlier abrupt changes are the best examples of this enigmatic process. The Holocene is one of the more stable climatic periods, potentially providing the conditions for an outburst of human societal development. The reason for this apparent constancy in Holocene climate as well as the linkage between pre-industrial climate swings and human development is still a matter of debate. To understand these phenomena we need to resolve their spatial and temporal evolution. Ice cores are uniquely placed to provide the contrasting polar elements of climate in high resolution as well as a suite of measurements (such as greenhouse gas concentrations). In addition, we need to understand the response of the Antarctic, Greenland, and other Arctic ice sheets to climate change. In particular, the contribution of the large ice sheets to the glacial-interglacial sea level change, and the temporal evolution over the last 40,000 years, are still matters of debate. The primary objectives of the 40,000-year ice core network include:

- Determining the detailed magnitude and relative timing of warming and climate forcing mechanisms (e.g. greenhouse gases) in Greenland and Antarctica during deglaciation, in order to evaluate mechanisms for large-scale global climate change.

- Developing spatial patterns of environmental parameters that relate to ocean surface conditions, including sea ice extent and biological productivity.
- Understanding the changes in magnitude and spatial pattern of sources and sinks of greenhouse gases on millennial and centennial time scales.
- Understanding the spatial and temporal evolution of rapid climate changes (e.g., Dansgaard-Oeschger events, the last glacial termination) related to changes in ocean and atmospheric circulation.
- Constraining the histories and budgets of atmospheric trace gases such as carbon monoxide, carbonyl sulfide, methyl chloride, and methyl bromide to elucidate changes in atmospheric chemistry and biogeochemical cycles over the glacial-interglacial transition.
- Synchronizing records in Greenland and Antarctica using high-resolution measurements of methane, dust, and isotopic ratios and providing records that can link to non-ice core climate records in mid- and low latitudes
- Investigating relationships between major changes in atmospheric circulation and CO_2 cycling in the Southern Ocean due to dust fertilization and ocean mixing.
- Quantifying climate - forcing magnitudes from explosive volcanism and solar variability.

Under the auspices of IPICS, the international scientific community is developing plans for a network of ice cores covering the past 40,000 years. Specific U.S. contributions to this network include the completed WAIS Divide core and the South Pole ice core (SPICEcore), and a desired future core at Hercules Dome. Greenland cores drilled at East Greenland Ice core Project (EGRIP), led by Denmark, will also contribute to IPICS goals. IPICS 40,000-year projects may vary in scope and logistical needs, but many are envisioned to be drilling campaigns conducted in one or two seasons with minimal logistics. Site-specific records of climate and 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 IDDO Intermediate Depth Drill was used to successfully drill the South Pole Ice Core to a depth of 1,751 m (age ~ 49,000 years).

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 Last Interglacial include:

- Quantifying the temperature, precipitation, atmospheric circulation, and sea-ice extent of Greenland and Antarctica during the LIG.
- 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.

- Establishing whether rapid climate change events occurred during the warmer world of the LIG.
- Comparing the evolution of the LIG with our present interglacial period, the Holocene.
- Investigating the detailed succession of ice age onset at the end of the LIG.

Existing ice core records of the last interglacial are primarily from low accumulation sites in Antarctica such as Vostok, Dome Fuji, and EPICA Dome C (EDC), where the time scale resolution capability is relatively coarse. However, the detailed behavior of polar climate, 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; however a complete and undisturbed stratigraphic sequence of the warming from the climate period MIS-6 has yet to be recovered. The search for sites with unfolded ice will continue in both polar regions along with efforts to interpret folded ice; likely 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.

The U.S. community, represented by the IDPO Ice Core Working Group (ICWG), has prioritized Hercules Dome as the next deep ice core site in Antarctica, due to its likely preservation of ice from the last interglacial period (Jacobel et al., 2005) and its sensitivity to a potential collapse of the West Antarctic Ice Sheet (Steig et al., 2015), as well as its potential to provide bubble-free ice (below the problematic bubble-to-clathrate transition zone) for gas studies during the last glacial-interglacial transition.

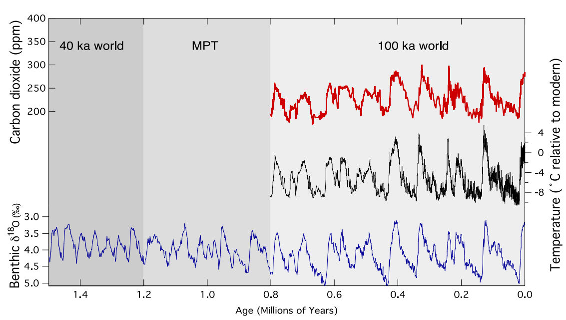
The bubbles visible in this piece of ice from an Antarctic ice core contain carbon dioxide and other gases that were trapped in the ice when formed many thousands of years ago. Ice cores provide the only natural archive of ancient air. Photo credit: *Oregon State University.*

5. Evidence from the ice sheet prior to 800,000 years B.P.: Each time ice cores have extended further back in time they have revealed new facets of climate dynamics. The record from the European Project for Ice Coring in Antarctica (EPICA) core at Dome C extends back to just over 800,000 years, and shows that different styles of glacial-interglacial cycles occur even under superficially similar external forcing. The Dome C site was selected to recover old, but not the oldest ice. 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, it is likely that ice older than 800,000 years is preserved in East Antarctica.

The primary reason to seek this older ice is to further understand one of the major puzzles of climate system history: Why did the climate 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 ~ 1.5 million years, including:

- Evaluating the CO_2-climate relationship 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 climate cycles 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 the 41k-year world.
- Determining if rapid climate change events like Dansgaard-Oeschger events were present during the 41k-year world.



The 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 drilling at very low accumulation rate sites in East Antarctica, for example at or near Dome A. 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). A variant of this approach would be to drill destructively (i.e., without producing core) to a depth corresponding to 800,000 years B.P. if it would save time and money while still recovering the older ice.

The second method is to make use of "blue ice" sites such as Taylor Glacier (Aciego et al., 2007), Mt. Moulton (Dunbar et al., 2008) and Allan Hills (Spaulding et al., 2013; Higgins et al., 2015) where old ice may outcrop at the surface via slow ablation or be present in the shallow subsurface. Continuous records may be difficult to find at such sites, but access is much easier, and small and less expensive projects are possible. 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 (see below) 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 resulted in a paper (Fischer et al., 2013) describing the current state of knowledge of possible oldest ice sites; although it is possible to use modeling to identify possible locations (Liefferinge and Pattyn, 2013) it has the general conclusion that more reconnaissance is needed before choosing a site. Choosing a location with confidence is still difficult – a main reason is 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. Regions of current attention for sites of oldest ice cores are the areas around Dome A, Dome F, and Dome C and the Aurora Subglacial Basin. The Rapid Access Ice Drill, which will be able to quickly create access holes for spatially-distributed measurements of geothermal heat flux in less than 1,000 m of ice with minimal logistics should facilitate site selection. There is a general consensus that several cores will need to be drilled, likely by different national groups and/or international partners. New and ongoing radar, laser altimetry, gravity and magnetic data from ICECAP and Antarctica's Gamburtsev Province (AGAP) airborne surveys are helping identify potential sites, but additional observations and model calculations are needed. 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.

Rapid sampling of and/or access to the near basal region of the East Antarctic ice sheet is needed for site selection for the oldest ice project because temperature and heat flow measurements are needed to constrain models of ice sheet dynamics that are needed to predict potential locations of old ice. The Rapid Access Ice Drill (RAID) should be useful for this purpose. In addition, a more agile drill that could create holes as deep as 1,000 m would accelerate discovery. There are complimentary international efforts to explore for oldest ice sites; these include a proposed European oldest ice site selection program that involves rapid access with several different new tools, including SUBGLACIOR, a novel hybrid mechanical and thermal drill with on board gas concentration and water isotope capability.

6. Pre-Quaternary atmosphere: The possibility that very old ice (>1.5 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 climate during times when global environmental conditions were very different from today. Such sites will likely range from blue ice locations, where drilling issues are essentially identical to those mentioned above, to debris-laden glaciers or similar environments, which will require specialized drilling equipment; for example the Agile Sub-Ice Geologic Drill may be useful in some cases.

Scientists have drilled a large-volume ice core on the Taylor Glacier ablation zone, Antarctica. Bubbles in the ice at the site contain evidence of ancient atmospheric composition. The Blue Ice Drill is an easily-transportable drill developed by IDDO that is capable of retrieving firn cores of approximately 9.5 inches in diameter and good quality, solid ice cores of the same diameter up to approximately 70 meters below the firn-ice transition. Photo credit: *Jeff Severinghaus*.

7. Large-volume sampling of climatic intervals 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 are made available. Examples include ^{14}C of CH_4 to trace methane hydrate destabilization during past warming events (Petrenko et al., 2009), nano-diamonds, ^{3}He, and micrometeorites as tracers of extraterrestrial impacts. In the case of traditional drill sites, replicate coring technology is 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. Blue ice areas such as Taylor Glacier and Allan Hills currently provide the best opportunities for rapid collection of large samples of ancient ice with relatively light logistics (e.g., Buizert et al., 2014). Ice sections ranging in age from Early Holocene to 1 Myr have already been clearly identified at these sites (e.g., Higgins et al., 2015; Korotkikh et al., 2011) and are ready for access/sampling by future projects. Continued studies at these sites that 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, hand augers, and chainsaws have all been successfully used. Continuing to maintain the capability to explore and utilize the ice at these sites is desired.

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). 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 climate during deposition. The ability to obtain larger 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 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 may offer important biotechnological applications (Cavvicholi et al., 2002). For example, recent 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).

9. Borehole Array for Spatial Variations in Climate: Although borehole observations do not provide a detailed climate history, an array of boreholes linked to an ice core can provide information on the spatial variability in climate history for any of the ice cores mentioned above. See section IV.1 below.

Summary

Advances in understanding climate 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 IDDO need to be repaired and maintained in good working condition so that they can be used for new projects. Clean hand augers and agile drills are needed for biological studies in glaciers. A drill capable of coring up to 3,000 m is needed, and could be developed either by modifying the Intermediate Drill for greater depths, or modifying the DISC drill for reduced logistical requirements. The large-diameter IDDO Blue Ice Drill for blue ice areas was 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, an additional Blue Ice Drill may be useful. Estisol-140 has replaced the IsoparK-HCFC-141b combo for use in deep drilling since HCFC-141b is no longer produced. 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. Table 1 lists characteristics for drills needed for the areas of the science outlined above.

Table 1. Requirements of drills for studies of climate change. More information on the drills needed to achieve the climate change science as discussed above is given in the IDDO Long Range Drilling Technology Plan.

	Diam. (cm)	Depth (m)	Drill-ing fluid	Ambient temp (C)	Clean coring?	Transport type	Site occupancy	Int'l aspects
<200 years	5-7	horizon-tal	none	-20	yes	Backpack	Days	US
<200 years	5	15	none	-30	some-times	Backpack	Days	US
200 year	7-10	400	none	-50	no	Twin otter/ lt traverse	Days/weeks	US
200 year	7-10	400	none	-5 warm ice	no	Twin otter/ lt traverse	Days/weeks	US
2k array	7-10	<1,500	TBD	-50	some-times	Twin otter/ lt traverse	Weeks/mo nth	US part of IPICS
40k array	10+	1-3k	TBD	-50	no	Twin otter/ Herc	1-2 seasons	US or shared
Interglacial	10+	1-3k	TBD	-50	no	Herc	Multiple seasons	US only or US-led
>800k years (old-est ice)	10+	3.5k	TBD	-50	no	Herc & traverse	Multiple seasons	IPICS
>Site selec-tion for 800k years (oldest ice)	2-4	<1,000	none	-50	no	Herc & traverse	2 days	IPICS
>800k years (blue ice)	25	5-20	none	-40	no	Twin otter	1-2 seasons	US/ maybe oth-ers
Pre-Quater-nary at-mosphere	7-25 rock-ice mix	200	none	-40	no	Helicopter	1-2 seasons	US/ maybe oth-ers
Tracers re-quiring large sam-ples	25	200^{+}	none	-40	no	Helicopter	1-2 seasons	US
Ancient mi-crobial life	25	200^{+}	none	-40	some-times	Helicopter twin otter, herc	1-2 seasons	US
Borehole Array	8	200 to 3.5k	TBD	-40	no	Twin Otter/Lt Travers	Week	US

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. For example, since the 1990s, satellites have shown accelerating ice loss in the glacier basins that drain more than one-third of West Antarctica into the Amundsen Sea. The rate of ice loss has doubled in the last six years and now accounts for a significant fraction of global sea level rise. Numerical model simulations have identified Thwaites Glacier as having the greatest potential, of Antarctic glaciers and ice streams, for contributing to future ice loss and consequent sea level rise on time scales of concern for human communities. However there is considerable uncertainty in the projections, and 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 data 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 climate 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, like the northeast Greenland ice stream is a major challenge to the international 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 climate change. Measurements and observations of present-day conditions are needed to develop and validate such models. 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 understand future ice-sheet response to local and global climate is to reconstruct its history. Histories of ice dynamics (thinning and divide location) and climate (accumulation and temperature) can be inferred from observations from ice cores and boreholes near ice divides. Ice core and bore hole data — including 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 much richer 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.

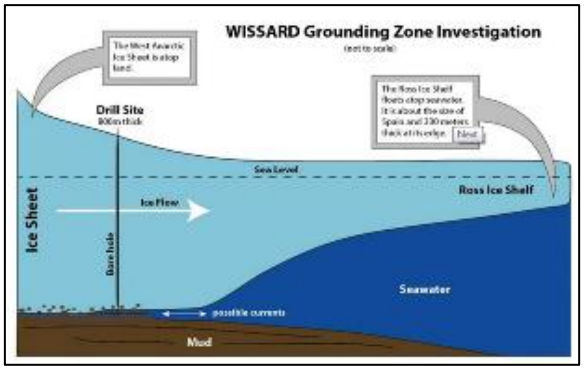
Specific observational data needed to improve and validate models of ice sheet response to environmental change include:

1. Basal conditions and geothermal flux: Direct measurements of bed conditions including frozen/thawed bed, basal pore 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. 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 varies 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 GRIP and Camp Century and higher values at NEEM (80 mW/m^2) and NGRIP (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 ~230 mW m^{-2} (Clow, 2012), and ~285 mW m-^{2} at Subglacial Lake Whillans (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 in less than one field season are needed to make basic measurements including temperature, heat flux, pressure, slip transducers, and to sample basal sediments and bedrock. The U.S. RAID drill is a step in this direction. Hot-water drills capable of accessing the bed through 500 m to 2,500 m of ice are urgently needed. 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 IDDO. The Rapid Air Movement Drill (RAM) is being refurbished and enhancements 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. Recent work indicates that ocean temperatures control rates at which the ice shelves melt, and emerging observations (Jenkins et al., 2010; Stanton et al., 2013) and model results (Favier et al. 2014; Pattyn et al., 2013; Gagliardini et al., 2010; Pollard and DeConto, 2009) indicate that sub-shelf melting exerts strong 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. 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 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 assess the role of fast-flowing ice streams and outlet glaciers on the stability of ice sheets. Conceptual geological models of grounding-line environments have been inferred from stratigraphic successions. Remote sensing studies using satellite observations and geophysical surveys have been conducted at grounding lines of major ice streams, but only one study at a modern grounding line has documented processes (Anandakrishnan et al., 2007; Alley et al., 2007; Horgan et al., 2013; Christianson et al., 2013). There has not been direct measurements or materials collected at grounding lines and grounding zones of fast-flowing ice streams and outlet glaciers. Small diameter access holes are needed to deploy instruments to measure spatial and temporal changes in these critical areas.

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 (Pettit et al., 2011, Bay et al., 2001) 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, and tilt in boreholes are now available and can be calibrated against ice core determinations. Rapid-access drills that can drill through ice up to 3,000 m thick are needed to deploy these 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 (Eemian, MIS-14, Pliocene) is an important indicator of future ice sheet vulnerability. Although a variety of indirect approaches have been used to constrain the history of ice sheets (glacial geology, paleoceanography, etc.), the most direct method is to determine the age of basal ice across an ice sheet bed. 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 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 may be able to provide a context for more recent observed changes in ice dynamics, particularly accelerated thinning in the most recent several decades.

Cosmogenic nuclides in bedrock beneath ice sheets can tell us about their former extent, and the timing and duration of past exposure periods. 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; Schaefer et al, 2016); determining their extent and thickness under warmer climates is more problematic. Much of the evidence is hidden beneath the present ice sheets. 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) for use near the ice margins. Under deep ice, rapid access drilling, for example using the RAID drill, to recover this evidence, and open up new and important perspectives on ice-climate linkages in a warmer world.

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 will be used to confirm that cosmogenic nuclides were produced *in situ*, and identify surfaces that constrain subglacial landscape evolution by subglacial erosion. 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., key problems can be addressed such as the vulnerability of the West Antarctic and Greenland Ice Sheets to future climate 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, and a variety of sites in Greenland including both interior sites (e.g., Schaefer et al., 2016) and peripheral sites that border key areas (e.g., North Greenland, NEGIS). Data from beneath high-altitude domes and plateaus in the Transantarctic Mountains 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 can be used to constrain long-term ice sheet stability (e.g., 36Cl, 26Al, 10Be), 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 (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 access holes, such as those from the Rapid Access Ice Drill and the IDDO Agile Sub-Ice Geological Drill, 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. Past responses of glaciers and ice sheets to climate and sea level change 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 climate. Intermediate depth (~1,000 m) cores at targeted coastal domes are needed to constrain the extent and timing of deglaciation. Finally, the collection of subglacial bedrock from both ice sheet interior and strategic periphery sites for the measurement of cosmogenic nuclides can provide direct constraints on past ice sheet history.

Table 2. Requirements of drills needed for studies of ice dynamics and glacial history. The Long Range Drilling Technology Plan discusses existing drills, as well as drills under development, that are capable of retrieving cores or creating access holes in ice sheets.

	Diam. (cm)	Ice Depth (km)	Core or hole	Ambient temp (C)	Clean access?	Transport type	Site occu-pancy	Int'l Aspects
Bed conditions	8	1-4	Hole	-50	maybe	twin otter/ lt traverse/ Herc*/trav*	<4 weeks	US & others
Geothermal flux	5-8	1-4	Hole	-50	no	Twin otter/ lt traverse/ Herc*/trav*	<4 weeks	US & others
Geologic coring for cosmogenic samples	6-10	0.1-2.5	Ice hole Rock core	-50	no	Helo sling load/ Baseler/ raverse	4-8 weeks	US
Nimble geologic coring under shallow ice	3-5	<.5	Ice hole Rock core	-30	no	Twin otter/ lt traverse	<4 weeks	US
Rheological properties	8	<4k	Hole	-40	no	Herc/ traverse	<4 weeks	US & others
Internal layering	8-10	<4k	Hole	-40	no	Herc/ traverse	<4 weeks	US & others
Sub-ice shelf/ice stream instru-mentation	10-25	<1k	Hole	-30	shelf-no; stream-yes	Twin otter/ helo/ herc/ traverse	2 weeks	US & others
Ice shelf ROV deployment	100	<1k	Hole	-30	no	Twin otter/ helo/Herc/ traverse	2-4 weeks	US & others
Grounding zone	8-75	<1k	Hole	-30	no	Herc/ traverse	2 weeks	US
Seismic imaging	5-10	~100 m	Hole	-40	no	Twin otter	Hours/days	US

III. Subglacial Geology, Sediments, and Eco-systems

Bedrock, sediments, and ecosystems existing within and beneath ice sheets remain largely unexplored because of the lack of rapid access. 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. Fundamental questions about the Antarctic Ice Sheet persist. What is the origin of the enigmatic Gamburtsev Subglacial Mountains and how have they influenced the overlying ice sheet? What is the composition, geothermal heat flux, and geotectonic history of East Antarctica, and how does it influence ice-sheet behavior? What were the dominant factors controlling the spatial extent and temporal variability of ice sheets during warm climate 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 East Antarctic ice sheet? Constraints on composition and age of basement rocks of interior East Antarctica would place better constraints on Precambrian provinces and evolution of the Antarctic shield for verifying current models. 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 Antarctic 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 past 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 have been collected near the margins. Interior subglacial basins also likely contain proxy records of paleoclimate 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 Antarctica 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. Lake Vostok and other subglacial lakes are thought to contain sedimentary records; these records have already been collected at Lake Ellsworth. 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 the Whillans and Kamb ice streams (e.g., Scherer et al., 1988). Shallow drilling of ice rises and acquisition of oversnow seismic reflection profiles radiating away from core sites will allow the deeper geometry of the strata to be evaluated for locating deeper drilling and 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 paleoclimate history. Two low regions within the Wilkes Land sector of East Antarctica (Aurora and Wilkes Subglacial Basins) appear as broad down-warped basins filled by marine and non-marine strata. They may contain evidence of the much debated past dynamics and paleoclimate of the East Antarctic Ice Sheet. 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 cause for concern about ice sheet stability.

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.

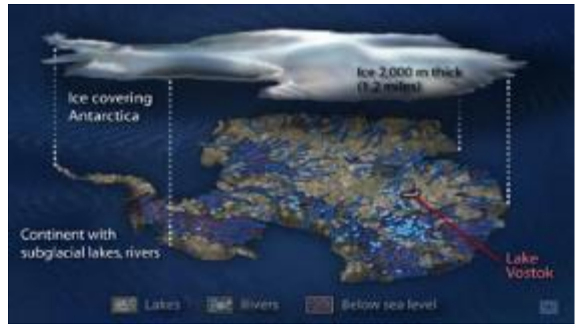
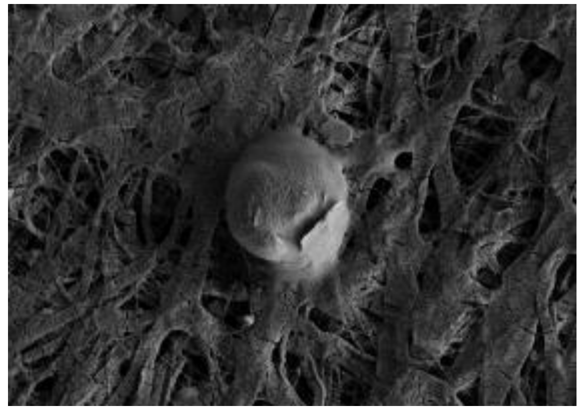


Illustration showing the aquatic system that scientists believe is buried beneath the Antarctic ice sheet. Photo credit: *National Science Foundation, Photo Gallery.*

3. Sub-ice microbial ecosystems and biogeochemistry: Aqueous and sedimentary subglacial environments in Antarctica and Greenland are inhabited by microorganisms 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 suggests these environments could contain large volumes of the greenhouse gas, methane, which could impact atmospheric methane 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 that they drain into. 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 material fluxes) is 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 and may force adaptation of subglacial biota to rapidly changing conditions.

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. 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. Exploration of life within subglacial lakes and their sediment has begun; the first reports on the microbiology of Subglacial Lake Whillans have been published (Christner et al, 2014). 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. Some subglacial meltwater is also transported over long distances within basal drainage systems, which again, likely discharge subglacial microbes and their metabolic products into circum-Antarctic seawater. Access holes through the ice 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 at an early stage, and it is best to conduct studies first at sites where the ice is not thick and logistics issues can be readily addressed.



Microbial ecosystems have been found under the West Antarctic Ice sheet (Christner et al, 2014). This photo shows a coccoid-shaped microbe with an attached sediment particle from subglacial Lake Whillans. Photo credit: *Trista Vick-Majors.*

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 a strong influence 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, microbial ecosystems, and maintaining systems of subglacial lakes. 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 as well as climate change.

Russian drillers accessed Subglacial Lake Vostok 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. The British attempted to access subglacial Lake Ellsworth in the interior of West Antarctica in 2012-13 but unfortunately were stopped due to operational problems during drilling. The U.S. successfully penetrated and sampled subglacial Lake Whillans upstream from the Siple Coast grounding line during the 2012-13 season. The new drill built for drilling Lake Whillans includes 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). The filtration technology was successful at reducing microbial bioload in the drilling fluid in accordance with the Antarctic Treaty Code of Conduct http://icedrill.org/documents/view.shtml?id=1057.

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. 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. A conceptual design is also needed for a drill that can provide clean access large enough to deploy subglacial rovers; this design should strive to minimize 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 below. Other subglacial access requirements are also covered above in Table 2. The Long Range Drilling Technology Plan discusses technical aspects of the drills.

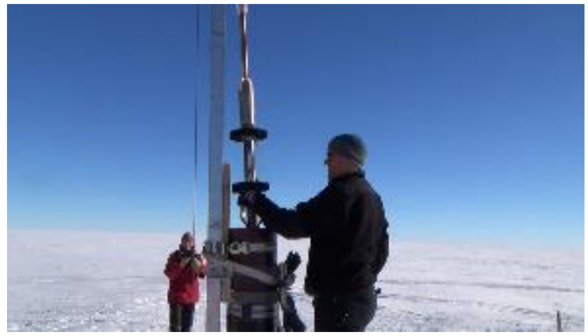
Table 3. Requirements of drills needed for studies of subglacial geology, sediments, and ecosystems. The IDDO Long Range Drilling Technology Plan discusses hot water and mechanical rapid-access drills that could provide clean access holes for the projects described above. Clean mechanical rapid-access drills do not currently exist; conceptual and engineering development is needed.

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

IV. Ice as a Scientific Observatory

Polar ice sheets and mid-latitude ice caps archive evidence of past climate 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 climate and ice dynamics: Borehole logging of both fast-access holes and boreholes originally drilled for ice cores greatly enhance evidence of climate 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, 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 climate history and ice flow.



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

1.1 Winches: Winch platforms that can support borehole-logging projects are important community resources. IDDO has three winches in inventory, one for intermediate depth (1.5 km) and two for deep (4 km) applications. IDDO has adopted a standard wireline for all community winches, a 3/16” four-conductor armored oil-patch cable with a 1” Gearhart-Owen cablehead. IDDO has also established a policy of deploying a trained operator to the field along with the IDDO winches, particularly the deep winches. Although this cost is not directly reflected in proposal budgets, a cost estimate is included with each proposal requiring IDDO 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.

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 IDDO 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 IDDO facility in Madison, WI. IDDO maintains a pressure chamber for testing tools up to pressures of 6 kpsi. The chamber is approximately a 10-foot cylinder with an inside diameter of 10 inches.

Pressure testing is especially important with Estisol 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. IDPO-IDDO also provides towers and sheave wheels needed for borehole access. If requested and resourced by NSF, IDPO-IDDO could preserve, maintain, extend borehole casings, and maintain the proper level of drill fluid compensation for existing boreholes. The Borehole Logging Working group will work with the ice borehole logging community to prioritize the boreholes requiring preservation.

1.3 Recent and current 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 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. Analysis of the SPICE core will take advantage of and supplement the wealth of existing South Pole data from shallow cores, snow pits, IceCube hot-water boreholes and meteorological observations. The SPICE Core borehole is pressure compensated by ESTISOL 140, providing a test bed for borehole logging in a new drill fluid. ESTISOL 140 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 SPICEcore project will be 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 proposed drill site to the IceCube and ARA arrays, the borehole will serve as an access point for calibration of existing and future South Pole in-ice physics and astrophysics experiments.

RAID: The RAID (Rapid Access Ice Drill) is a drill in development that will be capable of penetrating a 3,000 m ice sheet, and coring small samples of ice and subglacial basal rock. RAID is expected to produce five (5) boreholes every season, and these boreholes will potentially serve as scientific observatories for the study of ice and climate. RAID will require a dedicated logging winch integrated with the drilling platform, capable of reaching 3,000 m for logging immediately following the drill. The system could partly serve as a hole qualifier for evaluating the performance of the drill during development. 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 preservation: RAID has the potential to create many deep boreholes over a number of years. Preserving every RAID borehole indefinitely is impractical. The RAID project, with borehole logging scientists, will need to determine the scope of preservation efforts. The number of holes to preserve, the priority of holes and the duration of the effort will need to be weighed against cost and logistics.

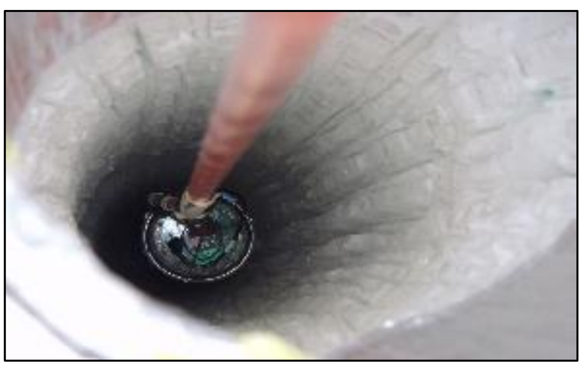
Borehole preservation effort could be separated into short-term (<5 years) and long-term time horizons. Preservation of each RAID borehole for 3 - 5 years will allow for repeat measurements, particularly in studies of borehole temperature and deformation. Uncased and under-balanced boreholes could be 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 should 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: IDDO 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 IDDO 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 Intermediate Depth Drill or the RAID. These logging measurements could also provide a baseline for longer-term borehole deformation studies.

1.5 Borehole Allocation Committee: The IDPO Borehole Logging Working Group (BLWG) is currently exploring formation of a special committee to advise IDPO on management of community resources as the logging 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 IDDO engineers, will ensure that new tools are safe and ready to deploy.

2. Ice as platform for physics and astrophysics: 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. For example, the now completed IceCube telescope uses ice at South Pole to detect high-energy neutrinos traveling to Earth from cosmic sources. The Enhanced Hot Water Drill (EHWD) developed for IceCube is a powerful and fast access drill capable of creating 2,500 m 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 as part of the IceCube project. IceCube will search for neutrinos from distant astrophysical sources. Photo credit: *Ethan Dicks, National Science Foundation.*

IceCube-Gen2 is a proposed facility for future Antarctic neutrino astronomy. IceCube-Gen2 will aim to increase the effective volume of IceCube by an order of magnitude, while only doubling the amount of in-ice instrumentation. The IceCube inter-string spacing of 125 m would be increased to 250 - 300 m, taking advantage of the long absorption lengths of optical photons in Antarctic ice, particularly South Pole ice from the early stages of the Last Glacial Period. This expanded array would improve detection capability in the PeV energy range and provide high statistics samples of extraterrestrial neutrinos, for better characterization of source distribution, spectrum and flavor composition. 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 proposed low-energy sub-array physics experiments such as PINGU (Precision IceCube Next Generation Upgrade) would be embedded within the IceCube array in order to use the existing detector as an electronic veto or active shield. PINGU objectives include the study of neutrino oscillations and mass hierarchy, dark matter, supernovae, and neutrino tomography of Earth's core. PINGU will deploy a relatively high density of photocathode (light sensors) in a small ice volume, requiring hot-water drills capable of making deep access holes at small spacing. The currently proposed PINGU geometry will have inter-string spacing of ~20 m and a three to five meters vertical spacing between sensors. These projects will enable research and development on the next generation of low-light photodetectors and the optical properties of *in situ* ice over short distance scales. Hot-water drill upgrades are aimed at improving the optical clarity of the refrozen water column, including filtration of large-particle impurities and degassing to avoid bubble formation.

Experiments to detect extremely high-energy neutrinos will make use of large areas of the polar ice sheet. The ARA experiment (Askaryan Radio Array), in early development at South Pole, is planning to instrument on the order of 100 km^2

of ice with radio antennas to detect radio pulses from so-called Greisen-Zatsepin-Kuzmin-scale (GZK) neutrinos. ARA would ultimately like to have holes at least 200 m deep and 15 cm in diameter; with holes 20 m apart and stations 2,000 m apart. In 2012-13, a hot-water drill was used to make approximately seven-inch holes to a depth of 200 m, at a rate of one hole per day. Thirteen holes were drilled in total, enough for two ARA stations. A novel aspect of the ARA drill is that the holes are pumped dry during drilling, partly because of science requirements and partly because of prohibitive energy loss using a lost-water method.

Due to its proximity to the IceCube and ARA detectors, the SPICE core borehole could serve as an access point for calibration beacons or standard candles, as part of the South Pole facility and infrastructure. These beacons could be operated at multiple depths and hence different ice temperatures, densities, fabrics and impurity levels. These unique measurements would have implications for radio and optical detection of high-energy neutrinos and also provide opportunities for basic glaciology research. 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 ARIANNA experiment (Antarctic Ross Ice shelf Antenna Neutrino Array) proposes to deploy a large array of surface radio antennas on the Ross Ice Shelf to observe cosmogenic GZK neutrinos. Log-periodic dipole antennas will be buried in pits approximately 6' x 6' x 0.5' and controlled by solar-powered relay stations. An effective and efficient means for digging and backfilling many such pits will need to be developed. The ARIANNA also anticipates taking two shallow (~100 m), 4"-6" cores from nearby for study of the firn-to-ice transition and for borehole-to-borehole radio tomography, as well as drilling one deep (~500 m), 4"-6" borehole.

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. A similar 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 extent of anthropogenic emissions and patterns of increase or decrease.

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 birth 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 in development. The borehole logging community is a strong proponent for repairing and maintaining boreholes at Greenland Summit (GISP2), Siple Dome, 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 IDPO Borehole Logging Working Group will prepare a list of boreholes in the U.S. program and will work with the community to create a prioritized list for maintenance and repair.

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 sections above. 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, matrices below 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 lettering in a matrix indicates projects that are currently funded, and blue lettering indicates those in the planning phase.

In Tables 4 – 7 below the letters denoting specific drills to be used are: A: agile sub-ice geological drill; b: badger-eclipse; B: blue ice drill; D: DISC drill; I: intermediate depth drill; L: borehole logging; lt: logging tower; R: RAID; W: Winkie drill.

Table 4: Past Climate Change Planning Matrix 2017-2027

	2017				2018				2019				2020				2021				2022				2023				2024				2025				2026				2027			
Past Climate	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																																												
Arctic agile drilling projects		x	x			x	x																																						
Greenland traverse		x	x																																										
Alaska agile drilling		x	x																																										
Col do Dome France						B	B																																						
Summit Greenland						B	B																																						
Antarctic agile drilling projects				x	x																																								
Taylor Dome firnification								x																																				
South Pole array								x	x																																				
South Pole-Dome C scientific traverse								x	x			x	x																																
McM Ice Shelf								x	x																																				
Thwaites shear zone												x	x			x	x																												
Law Dome 14CO (BID, 4", Eclipse drills)								B	B																																				
Antarctic peninsula firn aquifer								x	x																																				
Pre-industrial baseline & dynamics																																												
Siple Coast coastal dome																x	x																												
Amundsen Sea coastal dome																				x	x																								
Eclipse Icefield Alaska										x	x																																		
Agile drilling at Dome C (4" drill)																x	x																												
Large scale gobal climate change																																												
40k - Qaanaaq NW Greenland																																												
Intermediate depth coring																						I	I			I	I																		
Borehole logging at Qaannaaq																										L			L														
Basal ice glaciology																														I	I														
GISP2.1 Central Greenland (10km from Summit)																																												
Intermediate drill coring to 1650 m																						I	I			I	I																		
40k - South Greenland																																												
Intermediate depth coring South Greenland																														I	I														
Borehole logging at South Greenland																																		L										
Last Interglacial - Hercules Dome																																												
Site selection								x	x																																				
Site characterization - RAID (optional)												R	R																																
Drilling at Herc Dome																x	x			x	x			x	x																				
Borehole logging at Herc Dome																												L	L																
Last Interglacial & 2Ma ice - Allan Hills																																												
Paleo Ice Project (IDD) Allen Hills												I	I			I	I																												
Taylor Glacier (BID)								B	B			B	B			B	B																												
IPICS oldest ice																																												
Site selection												x	x			x	x			x	x																								
Prepare drill for Oldest Ice																										x	x	x	x																
Drilling for oldest ice																																x	x			x	x			x	x			

Table 5: Ice Dynamics and Glacial History Planning Matrix 2017-2027

	2017				2018				2019				2020				2021				2022				2023				2024				2025				2026				2027			
	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																																												
Rapid Access Ice Drilling																																												
Minna Bluff - RAID field test	R			R	R																																							
Sub-ice shelf mass balance																																												
SALSA - Subglacial Lake Mercer								x	x																																			
mid Ross Ice Shelf - hot water drilling																x	x																											
front Ross Ice Shelf - hot water drilling																				x	x																							
Ice dynamics																																												
SALSA - Subglacial Lake Mercer								x	x																																			
mid Ross Ice Shelf - hot water drilling																x	x																											
front Ross Ice Shelf - hot water drilling																				x	x																							
Glacial history & basal conditions																																												
SALSA - Subglacial Lake Mercer								x	x																																			
Hercules Dome - RAID												R	R																															
Rock exposure dating Ohio Range	W																																											
Continental drilling Antarctica																								x	x			x	x			x	x											
Remote sensing of basal conditions																																												
Antarctica				x	x			x	x			x	x			x	x																											
Greenland		x	x			x	x																																					

Table 6: Subglacial Geology, Sediments and Ecosystems Planning Matrix 2017-2027

	2017				2018				2019				2020				2021				2022				2023				2024				2025				2026				2027			
	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
Subglacial Geology, Sediments, & Ecosystems																																												
Rapid Access Ice Drilling																																												
Minna Bluff - RAID field test	R			R	R																																							
Bedrock geology																																												
Rock exposure dating Ohio Range	W																																											
Ong Valley				W	W																																							
Seymour Island sedimentology								W	W																																			
Mt Waesche												W	W																															
Thwaites												W	W			W	W																											
Hercules Dome - RAID												R	R																															
Continental drilling Antarctica																								x	x			x	x			x	x											
Subglacial hydrology & sediment dynamics																																												
SALSA - Subglacial Lake Mercer								x	x																																			
mid Ross Ice Shelf - hot water drilling																x	x																											
front Ross Ice Shelf - hot water drilling																				x	x																							
Microbial ecosystems & biogeochem																																												
SALSA - Subglacial Lake Mercer								x	x																																			
mid Ross Ice Shelf - hot water drilling																x	x																											
front Ross Ice Shelf - hot water drilling																				x	x																							

Table 7: Ice as a Scientific Observatory Planning Matrix 2017-2027

	2017				2018				2019				2020				2021				2022				2023				2024				2025				2026				2027			
	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
<u>Ice as a Scientific Observatory</u>																																												
Borehole logging																																												
South Pole	x			L	L			L	L																																			
Exploration of basal ice																																												
basal ice in Greenland																														I	I													
Ice as a platform for physics & astrophysics	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	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
South Pole ultra high energy neutrinos								A	A			A	A			A	A			A	A																							
South Pole Global Seismic Network	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	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x

Associated logistical challenges

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

- 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 identified by international partners and was used at South Pole for the SPICE core project. However, IDDO experienced adverse impacts and has indicated that they will most likely not use ESTISOL 140 for future drilling projects. Some of the adverse impacts have been mitigated, through use of long gloves. Ongoing discussions about drilling fluids will continue with the goal of identifying a more acceptable drilling fluid for future ice cores.
- Air support and science traverse capabilities to sites in Greenland and Antarctica are limited. With multiple science communities requesting flights or traverses, time at field sites must be carefully planned to optimize scientific productivity. There is an especially urgent need to increase tractors and sleds for scientific traverses in Antarctica in order to address the priority science goals identified in the 2015 National Academies Report.
- The National Ice Core Laboratory (NICL), funded by NSF, is the key location for processing and archiving of U.S. ice cores. Although some infrastructure upgrades and improvements have been made, the NICL is an aging facility that will soon reach full capacity. Expanding the ice core storage facility will require a major investment in infrastructure as the refrigerant used is no longer compliant and must be replaced.
- The community wishes to 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 recent measurements show that the borehole casing is sinking faster than would be expected from steady ice flow divergence. Follow-up borehole video revealed that the casing is collapsing and already not navigable by most logging instruments. The GISP2 casing should be repaired and maintained for current and future science, as should the casings of boreholes at Siple Dome and Taylor Dome. The IDPO Borehole Logging Working Group will produce a prioritized list of existing U.S. boreholes and the scientific reasons for their preservation.

Recommendations

Recommended science goals

1. Past Climate change: Present-day climate change can only be fully understood in context of the past; well-dated histories of climate and the atmosphere over a wide range of time scales are needed to understand climate forcing and response. White papers by the International Partnerships in Ice Core Sciences (IPICS - http://pastglobalchanges.org/ini/end-aff/ipics/intro) describe broad science targets for ice coring and articulate the need for spatially-distributed arrays of recovered ice cores that target the past 200, 2,000, and 40,000 years, from the last interglacial, and extracting an ice core that reaches 1.5M years. The U.S. ice coring community was intimately involved in originally establishing the IPICS goals; recommendations for achieving those goals, together with additional goals that are primarily U.S. priorities, are outlined below. In addition, members of the U.S. community are leading efforts to gain critical samples of ice prior to 800,000 years ago, for evidence of the atmosphere from times when the Earth had 40,000-year climate cycles.

- Drilling of spatially-distributed ice cores and boreholes to support both IPICS goals and U.S. initiatives of investigations of past climate and atmosphere over the past 200 to 40,000 years should continue. Understanding climate signals in remotely-sensed data, understanding climate 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 will include multiple scientific traverses in Greenland for study of the ice sheet under the currently changing climate. Recent projects in the Arctic include the 1000-2000 year annual record from Denali (Mt. Hunter), Alaska which is providing important constraints on North Pacific climate and tropical teleconnections during the Medieval Climate anomaly, Little Ice Age, and modern warming. In Antarctica proposed science includes an international French-Italian-U.S. scientific traverse from Dome C to South Pole and shallow ice core drilling at Law Dome.
- 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.
- Hemispheric and global climate records extending 40,000 years into the past include recently completed ice-coring projects in Antarctica from Roosevelt Island and from the South Pole Ice (SPICE) core project. Retrieving 40,000-year records from Hercules Dome (as part of a record extending further back at that site) is a priority for the US community. Additionally, several US investigators may be involved in the Danish core from EastGRIP, Greenland. Targeted ice coring to investigate ice, ocean, and atmospheric dynamics along the dynamic Amundsen Sea Coast of Antarctica, and near Camp Century along the northwest coast of Greenland, are in the planning stages.
- A climate 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. The search for sites from which to extract Eemian ice in Greenland, both by coring and through horizontal sampling of blue ice ablation zones, should continue. Eemian ice was recovered from the Camp Century 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 climate and glacial histories of the West Antarctic Ice Sheet during the last interglacial, and is the primary motivation for planned deep drilling at Hercules Dome. Hercules Dome is the highest-priority next deep ice core for the US community. Understanding evidence from

Antarctica, where the climate record may have evidence of changes in the WAIS during the last interglacial period are important, since WAIS history for this time is poorly known and because large sea level rise due to current climate warming may occur if the WAIS becomes destabilized.

- Blue-ice paleoclimate records are already providing unlimited samples for atmospheric and ultra-trace component studies and can enable further new types of measurements that have previously been impossible, and may also access ice older than 800,000 years. Blue-ice studies at Mt. Moulton, Taylor Glacier, and Allan Hills exemplify discoveries from this realm so far; such studies at blue ice sites should continue.
- Ice cores and borehole observations reaching ages between 800,000 years and 1.5M years (or beyond) are significant, for these data may provide new insight into the effects of greenhouse gases on climate 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. Extraction of deep ice cores for million-year-old ice, a potential goal for eight to twelve years into the future, should be coordinated with international partners through the IPICS “Oldest Ice” project. In the near term, “snapshots” of time periods beyond 800,000 years are potentially available from blue ice regions or areas of discontinuous deposition, and developing further understanding of these regions and sampling them is a priority, for they contain very old ice. Currently U.S. scientists are working to retrieve and understand samples of ancient ice from blue ice regions that provide snapshots of climate as it existed more than a million years ago.

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 and climate can be inferred from radar-detected layers combined with ice core and borehole measurements.
Specific recommendations include:

- Ice-ocean interactions are not yet well understood. Boreholes to deploy instruments to measure conditions at ice-ocean interfaces are high priority; recent studies of Pine Island Glacier and Whillans Ice Stream are steps toward understanding how perturbations at ice-ocean interfaces impact the interior ice sheet.
- Hydraulic conditions in glaciers and ice sheets exert strong control 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 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 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 West Antarctic Ice Sheets is recorded by cosmogenic nuclides in subglacial bedrock. Samples from beneath these ice sheets will provide information on their thickness and configuration during paleoclimates warmer than the present, and help identify their sensitivity to future possible climate change. Short cores of bedrock from targeted sites are needed to address questions concerning the extent of the ice sheets during past interglacial climates, and the onset of continental glaciations.

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 paleoclimates on geological timescales, crustal heat flow, lithospheric stress, ground truth for geophysical imaging, constraints on geodynamical evolution, and relationship with past supercontinents. 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 sediments and ecosystems is needed to establish the diversity, and physiology of microbes and their relationships to past climates and their current 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 while doing so in a clean manner that maintains scientific integrity and environmental stewardship. The recent study of subglacial Lake Whillans is a step toward achieving this goal.

4. Ice as a scientific observatory: Polar ice sheets and mid-latitude ice caps archive evidence of past climate 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 climate 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 (e.g. IceCube) 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 Askaryan Radio Array and Generation-2 Ice Cube) require multiple boreholes drilled to at least 150 m deep (ARA) and 2,500 m deep (G-2IC) and significant calibration studies of the surrounding ice volume. Better understanding of ice attenuation at radio and deep UV wavelengths are particularly desired.
- 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.
- Novel basal ice structures that have been remotely sensed but whose existence is not well understood should be investigated.

Recommended 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. In the past decade there has been an increase in research proposed by the ice science community but the NSF budget has been generally flat. The following principles guiding development of new drills and technologies are recommended:

- Designs require that the supporting logistical needs do not impede execution of the science.
- 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 IDPO 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 inter-changeability 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.

Recommended technology investments

The following investments in drilling technologies are needed to accomplish science goals planned for the next decade. Investments prioritized by time, from consensus of the IDPO Science Advisory Board, include:

Priority 1 (needed this year):

- Maintain and upgrade agile equipment in inventory, including: Hand Augers, Sidewinders, the 4” Electromechanical Drills, the 3” Electrothermal Drill, the 3.25” Badger-Eclipse Drills, the Stampfli Drill, Logging Winches, the Small Hot Water Shot Hole Drills, the Blue Ice Drill, the Prairie Dog, the ASIG Drill and the Winkie drill.
- Maintain and upgrade the Intermediate Depth Drill.
- Finish building a second Blue Ice Drill for wide-diameter drilling to 200 m.
- Finish building the Sediment Laden Lake Ice Drill.
- Finish cost estimate, construction schedule and detailed design for upgrading the Intermediate Depth Drill to 3,000 m (‘Foro 3000’)
- Finish the RAM Drill modifications for modularity, weight reduction, and ease of logistics based on existing IDPO Science Requirements for rapidly creating shot holes.
- Conduct Antarctic field trials of the Rapid Access Ice Drill (RAID)[1] .

Priority 2 (needed in the next 3 years)

- Finish building the Foro Drill system.
- Modify the Badger-Eclipse (or Foro) drill for drilling to 700 m under conditions of limited logistics based on established IDPO Science Requirements.
- Upgrade the Electrothermal Drill to allow for coring to 300 m through temperate and poly-thermal firn and ice. The drill needs to be agile and light-weight (transportable by helicopter).
- Build Foro 3000 components (i.e. IDD add-on components).
- Build a Scalable Hot Water Access drill for creating access holes in ice from 50 m up to approximately 1,000 m depth[2] with modular potential to be used for clean access.
- Develop IDPO Science Requirements for a hot water drilling system that can be used to recover ice core samples from warm sites (e.g., Chile, NZ, Asia) to 200 m depth.

[1] RAID has been fabricated by DOSECC Exploration Services, LLC for the University of Minnesota.
[2] The IDDO Conceptual Study for the ScHWD found that scalable capability deeper than 1,000 m would require different components that are not practical for use between 50-1,000 m.

- Investigate a rapid hole qualifier (temperature and caliper) for use with RAID and other borehole logging applications.

Priority 3 (needed in 3 to 5 years)

- Build replicate components of the IDD drill to enable same-year use in both the Arctic and Antarctic
- Continue to evaluate options for new drilling fluids, and exploring/testing shallow drill fluid columns.

Community development

Sustained investment in the education, training and early career mentoring of the next generation of ice coring and drilling scientists and engineers is imperative to ensure that science discoveries from ice cores and boreholes continue through the coming decades. The IDPO will continue to work in concert with the scientific community and NSF to assist young scientists with technologies needed to support their research, provide them with opportunities for communication of their science to the public, and foster support for the ice coring and drilling community. Productivity of the science community also depends on drillers and engineers who have experience in mechanical ice coring and hot water drilling; an ongoing strategy for maintaining this expertise is important.

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Acronyms

AGAP: Antarctica's Gamburtsev Province

ANDRILL: Antarctic Drilling Project

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

DISC: Deep Ice Sheet Coring

DOSECC: Drilling, Observation, Sampling of the Earths Continental Crust (drilling service)

EGRIP: East Greenland Ice core Project

EHWD: Enhanced Hot Water Drill

EPICA: European Project for Ice Coring in Antarctica

GISP2: Greenland Ice Sheet Program II

GZK: Greisen-Zatsepin-Kuzmin

HCFC: Hydrochlorofluorocarbon

ICECAP: A project name, not an acronym

ICWG: Ice Core Working Group

IDDO: Ice Drilling Design and Operations

IDPO: Ice Drilling Program Office

IPCC: Intergovernmental Panel on Climate Change

IPICS: International Partnerships in Ice Core Sciences

NEEM: North Greenland Eemian Ice Drilling

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 Sheet Subglacial Access Research Drilling